

# MODELLING AND MAPPING FISHING IMPACT AND THE CURRENT AND POTENTIAL BIOMASS OF CORAL-REEF FISHES IN SOUTH FLORIDA



Phase 2 Interim Technical Report prepared by:

**Rachel Zuercher, David Kochan, & Alastair Harborne**  
**Florida International University**

Tropical Fish Ecology Lab, Department of Biological Sciences - Marine Sciences  
Program, Biscayne Bay Campus, 3000 NE 151 Street,  
North Miami, Florida 33181, USA

Tel: +1 (305) 919 4232  
email: rzuerche@fiu.edu; dkoch010@fiu.edu; aharborn@fiu.edu

May 15, 2020

## Acknowledgements

This project to map fishing impact and biomass on the Florida reef tract is a collaborative effort between:

- Alastair Harborne (Florida International University)
- Rachel Zuercher (Florida International University)
- David Kochan (Florida International University)
- Robert Brumbaugh (The Nature Conservancy)
- Kathleen Freeman (The Nature Conservancy)
- Rachel Layko (The Nature Conservancy)

We are very grateful to those people who have kindly donated data for the project, particularly Claire Paris (University of Miami) and Iliana Chollett (Smithsonian Center for Marine Conservation). Thanks to the many individuals at NOAA's Southeast Fisheries Science Center for their assistance accessing and interpreting federal data sources including Laura Jay Grove, Jeremiah Blondeau, Sarah Grove, Michael Jepson, Vivian Matter, Brent Stoffle, and Mandy Karnauskas. And thanks to staff at Florida's Department of Environmental Protection, Florida Fish and Wildlife Research Institute, Florida Fish and Wildlife Conservation Commission, Biscayne National Park, and the Florida Keys National Marine Sanctuary for their insight and feedback into draft versions of the models and maps presented here.

**Contents**

**Summary ..... 3**

**1. Introduction ..... 5**

    1.1. *The reefs of Florida*.....5

    1.2. *Mapping fishing and fish biomass in south Florida*.....6

    1.3. *Project aims* .....6

**2. Methods and data ..... 7**

    2.1. *Methods overview*.....7

    2.2. *Approach to modelling fishing impact* .....8

    2.3. *Fish survey data sets* .....9

    2.4. *Modelling current biomass* .....10

    2.5. *Mapping Florida’s reefs* .....11

    2.6. *Derivation of explanatory variables* .....12

    2.7. *Additional considerations for modelling potential biomass*.....16

    2.8. *Statistical analyses* .....17

**3. Results..... 17**

    3.1. *Fishing impact model*.....17

    3.3. *Interpretation of the fishing impact model*.....21

    3.4. *Current biomass model* .....21

    3.5. *Interpretation of the current biomass model*.....26

    3.6. *Area-specific models of current biomass* .....26

    3.7. *Species-specific models of current biomass* .....26

    3.8. *Generating a map of potential biomass* .....31

    3.9 *Exploring potential benefits of management actions* .....33

    3.10. *Generating maps of fish assemblage status and time to recovery* .....33

**4. Summary of patterns highlighted in the maps..... 35**

**5. Participation in meetings with state and federal management agencies ..... 35**

**Feedback from these meetings has been incorporated into the models and maps presented here. .... 35**

**6. Future Work ..... 35**

**7. Potential use of map products in marine management..... 36**

**References ..... 37**

**Appendix 1. List of fish species (and species groups) included in fish survey data used for this project.42**

**Appendix 2. Details of explanatory variables ..... 56**

*Area of reef*.....56

*Availability of nursery habitat* .....56

*Coral cover* .....57

*Depth*.....57

<i>Distance to deep water</i> .....	57
<i>Distance to fish spawning aggregation</i> .....	57
<i>Gravity of markets</i> .....	59
<i>Habitat type</i> .....	59
<i>Human population size and population per area reef</i> .....	59
<i>Latitude and longitude</i> .....	60
<i>Month</i> .....	60
<i>Number of larvae from upstream</i> .....	61
<i>Oceanic net primary productivity</i> .....	62
<i>Protected status</i> .....	62
<i>Complexity</i> .....	63
<i>Sea surface temperature</i> .....	63
<i>Wave exposure</i> .....	64
<i>Year</i> .....	64
<i>References (Appendix 2)</i> .....	65
<b>Appendix 3. Additional fish biomass model results</b> .....	<b>69</b>
<b>Appendix 4. Two-page introductory handout for the project</b> .....	<b>71</b>

## Summary

To assist in the management of fisheries and marine habitats in Florida, The Nature Conservancy (TNC) contracted Florida International University (FIU) to map coral reef fish and fisheries on the Florida reef tract from Martin County, FL to the Dry Tortugas. The aims of Phase 1, led by Rachel Zuercher and Alastair Harborne were to model and map fishing impact, model and map current fish biomass, and assess the potential benefit of conservation and management measures, such as the potential biomass on a reef following the cessation of fishing. Following completion of Phase 1 in September 2019, the project was extended for a Phase 2 to allow for further refinements to the products and modelling of sections of the reef tracts (e.g. Biscayne National Park, Middle Keys, and the Dry Tortugas) and individual species.

Using federally collected fish survey data from the NCRMP Reef Visual Census (RVC), the project had access to 3,983 fish surveys from coral reef and hardbottom habitats across the Florida reef tract. These data were collected following the RVC protocol, where divers record and estimate size for all fish species encountered. The fish survey data set were split, and fish data from 1,977 sites were used to statistically model fishing impact. This fishery-independent data set was used to model the biomass, at each site, of species that are included in the federally managed snapper-grouper fishery complex. These are species commonly landed in both commercial and recreational fisheries. The biomass data were modelled in relation to 25 potential predictor variables, such as the distance and size of nearby fish markets (market gravity) and sea surface temperature. These analyses demonstrated that biophysical gradients are important factors affecting the biomass of fishery species, particularly depth, reef complexity and coral cover. The human influence on fish populations, assumed to be through fishing, was predicted by the number of recreational fishermen within 50 km of a reef (based on the zip code that a fishing license was purchased under), the number of marina slips within 10 km of a reef, and market gravity, with fish biomass generally decreasing as the number of recreational fishermen, number of marina slips, and market gravity increased. Using the three fishing-related variables (i.e. considering biophysical influences as homogeneous across the region), the model was then used to extrapolate relative fishing impact (specifically the total cumulative impact of fishing on the fish assemblage) to all coral reef and hardbottom habitat sites across the Florida reef tract, and generate a continuous map at a resolution of 1 ha reef cells.

Estimates of fishing impact were then used as a key data layer, along with 17 environmental variables, to model the current biomass of all species (total biomass), of the snapper-grouper fishery complex, all fished species, all survey fishes, herbivorous species, and the marine life species (species collected for aquaria) using the remaining 2,006 sites where survey fish data were available. The snapper-grouper model demonstrated that biomass decreased with increasing fishing impact, and was also affected strongly by depth, complexity and net primary productivity at the site. There models of the other fish groups were similar to the snapper-grouper complex, but there were differences such as herbivores and the marine life species not being affected by fishing impact. The models for all five fish groups were then used to extrapolate estimates of current biomass across the reef tract to generate previously unavailable maps of fish biomass. Models were also generated for seven areas of the reef tract: the Coral ECA, Biscayne National Park, Upper Keys, Middle Keys, Lower Keys, and Dry Tortugas, plus the entire Florida Keys National Marine Sanctuary. These area-specific models highlight local drivers of fish biomass.

Finally, the model of current biomass was adjusted to represent two potential management scenarios: fishing impact reduced to zero to simulate the establishment of a no-take reserve (or, to estimate the

biomass possible on a reef given the biophysical conditions there), and coral cover increased to 15% and reef complexity increased by 15 cm to simulate coral restoration that also increases reef complexity. This allowed the production of maps estimating patterns of potential biomass across the region. Finally, using maps of predicted current and potential biomass under a simulated no-take reserve, the project generated a map of the predicted time of recovery following the cessation of fishing.

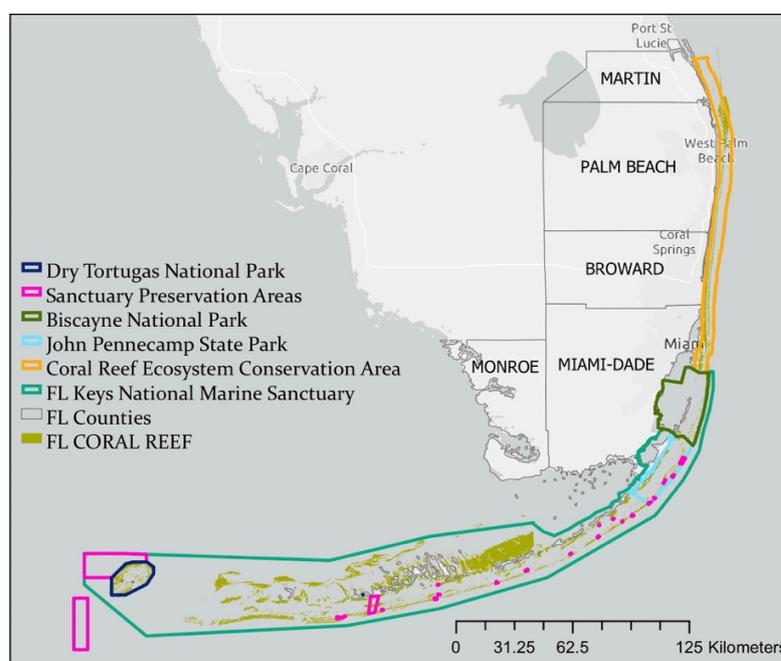
The maps generated by this project represent the first spatially explicit, continuous maps of fishing impact and current and potential biomass for the Florida reef tract. Although there may be further refinement before the end of the project (September 2020), they provide a version of final estimates of each metric, and thus can be provided to management agencies to support reef and fishery-related decisions. For example, as marine managers weigh multiple considerations, fishing impact and estimates of current and potential biomass can highlight potential reefs for protection if they represent low levels of conflict with fishing activity, a large potential for increased fish biomass following the cessation of fishing, or relatively intact fish assemblages that could be protected from any increases in anthropogenic impact. However, the project focus will now be on publishing the results in scientific journals and making the data layers available on the Mapping Ocean Wealth data portal.

## 1. Introduction

### 1.1. The reefs of Florida

The Florida coral reef tract stretches for ~550km across the counties of Martin, Palm Beach, Broward, Miami-Dade, and Monroe (Fig. 1). Monroe County includes the Florida Keys, a barrier reef that extends ~400 km southwest along an island archipelago from Key Biscayne near Miami to the Dry Tortugas region west of Key West (Ault et al. 2005). These reef areas have been extensively studied, and readers are referred to introductory texts for more detailed information (e.g. Dustan 2000, Riegl and Dodge 2008, Walker and Gilliam 2013, Shinn and Lidz 2018). Briefly, oceanographic conditions are considered marginal for coral growth, especially areas heavily influenced by water generated in Florida Bay and moving into the Atlantic (Riegl and Dodge 2008). Consequently, the best developed reefs are more isolated from Florida Bay, such as areas east of Key Largo. Forereefs often have a distinct spur and groove zones, there are multiple patch reefs further inshore, and the reefs support ~50 species of coral and over 500 species of fishes (Riegl and Dodge 2008).

The reefs of south Florida represent an economically vital resource, and in 12 months during 2000-2001 reef-related expenditures generated \$504 million in sales in Palm Beach County, \$2.1 billion in Broward County, \$1.3 billion in Miami-Dade County, and \$490 million in Monroe County (Johns et al. 2001). These expenditures provided 6,300 jobs in Palm Beach County, 35,500 jobs in Broward County, 18,600 jobs in Miami-Dade County and 10,000 jobs in Monroe County. The reefs support commercial and recreational fishing industries with rich histories in the Florida Keys and Southeast Florida (Ault et al. 1998, Shivlani 2014). However, like many reefs close to large urban populations, the marine ecosystem of south Florida is threatened by myriad stressors. These stressors include coral bleaching driven by climate change (Manzello 2015), coral diseases (Precht et al. 2016), overfishing of reef-associated species such as grouper and snapper (Ault et al. 1998, McClenachan 2009), loss of grazing species (Chiappone et al. 2002), decreasing water quality (Ward-Paige et al. 2005), anchor damage (Davis 1977), and invasive species such as lionfish (Ruttenberg et al. 2012). The stressors interact with natural threats, including damage from hurricanes (Blair et al. 1994) and cold-water thermal anomalies (Kemp et al. 2016). This combination of natural and anthropogenic stressors has led to increasing concerns of large-scale loss of coral cover (Palandro et al. 2008) and negative carbonate budgets leading to long-term loss of reef structure (Toth et al. 2018). Consequently, understanding the resilience of the system has been a major research focus (Maynard et al. 2017).



**Fig. 1.** Map of the Florida reef tract and major management areas.

These stressors include coral bleaching driven by climate change (Manzello 2015), coral diseases (Precht et al. 2016), overfishing of reef-associated species such as grouper and snapper (Ault et al. 1998, McClenachan 2009), loss of grazing species (Chiappone et al. 2002), decreasing water quality (Ward-Paige et al. 2005), anchor damage (Davis 1977), and invasive species such as lionfish (Ruttenberg et al. 2012). The stressors interact with natural threats, including damage from hurricanes (Blair et al. 1994) and cold-water thermal anomalies (Kemp et al. 2016). This combination of natural and anthropogenic stressors has led to increasing concerns of large-scale loss of coral cover (Palandro et al. 2008) and negative carbonate budgets leading to long-term loss of reef structure (Toth et al. 2018). Consequently, understanding the resilience of the system has been a major research focus (Maynard et al. 2017).

Efforts to ameliorate threats to the reef tract have been extensive, including the establishment of a Florida Keys National Marine Sanctuary (FKNMS) (Fig. 1). The FKNMS is managed by NOAA, and other parts of the reef are protected by a national park in the Dry Tortugas (managed by the Department of Interior), and John Pennekamp Coral Reef State Park (managed by the Florida Department of Environmental Protection) (Ault et al. 2005). Fisheries are managed by the Florida Fish and Wildlife Conservation Commission. In 1997, the FKNMS established a network of no-take marine reserves, comprising 22 Sanctuary Preservation Areas (SPAs) (mean size = 0.85 km<sup>2</sup>) and a larger (18.7 km<sup>2</sup>) Western Sambo Ecological Reserve (Bohnsack et al. 2007) (Fig. 1). These no-fishing areas, along with other regulations, have been successful at increasing fish populations and sizes (Bohnsack et al. 2007, Bohnsack 2011, Ault et al. 2013) and fish recruitment (Sponaugle et al. 2012b) within their boundaries. Protection of south Florida's reef has been augmented by the building of numerous artificial reefs (Baine 2001) and increasing efforts at reef restoration (van Woesik et al. 2018).

### *1.2. Mapping fishing and fish biomass in south Florida*

Since coral reef ecosystem services, including food provisioning from fisheries, are under threat from a wide range of human-caused stressors, we must incorporate these services into marine management decisions (Arkema et al. 2015). To facilitate this goal, The Nature Conservancy established the Mapping Ocean Wealth initiative<sup>1</sup> to spatially quantify the benefits that ocean ecosystems provide today. Under this umbrella, the project described here aimed to map and model reef fish and fisheries in South Florida to provide quantitative estimates of fish biomass, an important component of ecosystem benefits. The work provides analogous data to projects assisting marine management in Micronesia (Harborne et al. 2018) and The Bahamas. The data will be publicly available on the Mapping Ocean Wealth data portal<sup>2</sup>.

### *1.3. Project aims*

The original aims of the Florida mapping project were to create the following products:

- A model and map of each of the following:
  - Fishing impact (unitless, fishery-independent estimate of cumulative fishing impact)
  - Current biomass (estimated biomass of fish on the reef)
  - Potential biomass (estimated biomass of fish possible on the reef in the absence of fishing)
  - Estimated effects of additional management on fish biomass (i.e. estimates of potential fish biomass following simulated management actions such as increasing reef complexity)
  - Likely recovery rates for reef fish assemblages to reef carrying capacity
- Guidance on how to use the models and maps to support area-based fisheries management and conservation activities

The project was officially started on May 31, 2018 and was planned to conclude on August 31, 2019. However, following a range of stakeholder meetings where the results of this Phase 1 were discussed, it was decided that models of fish biomass in specific reef areas (e.g. upper and lower Keys) and species-

---

<sup>1</sup> <https://oceanwealth.org>

<sup>2</sup> <https://maps.oceanwealth.org>

specific models would be useful. Therefore, the project was extended for a Phase 2 until September 30, 2020. This report is based on the interim findings of Phase 2 ahead of a final technical report in September 2020.

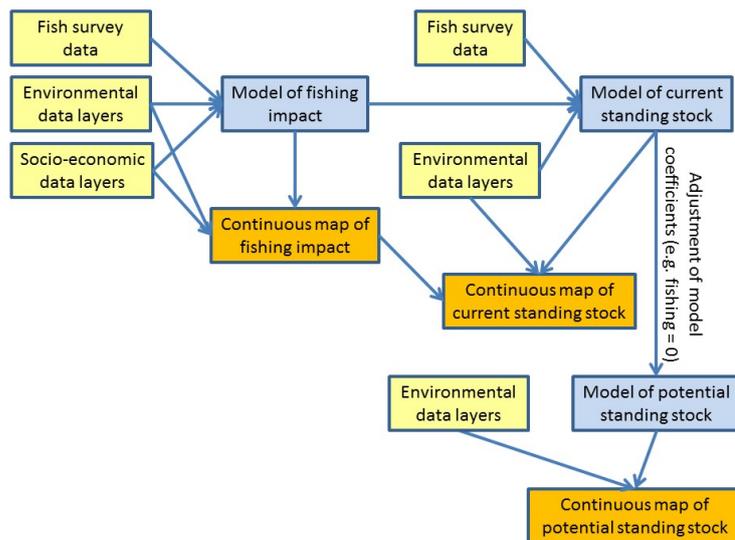
## 2. Methods and data

### 2.1. Methods overview

The major products of the project, namely the models and maps of fishing impact and current and potential biomass, use a range of data inputs and are interlinked (Fig. 2). Details of the fish survey data and predictive data layers are provided in subsequent sections, but the first step was to model fishing impact using metrics derived from fish survey data in relation to environmental (e.g. wave exposure) and socio-economic (e.g. recreational fisherman population) variables. The model of fishing impact used data independent of the data used to model biomass to ensure robust statistical models (i.e. we did not derive fishing impact from a dataset, then use the fishing impact metric to model biomass in the same dataset). The model of fishing impact was limited to locations where fish survey data were available, but it was used to extrapolate values across the region using continuous data layers of each significant explanatory variable, thus deriving a continuous map of fishing impact.

The predicted values of fishing impact were then a key input into the model of current biomass. Predicted fishing impact was combined with environmental data to model the biomass of the fish assemblage as recorded during fish surveys. The model was then combined with continuous variables throughout the Florida reef tract and derive a continuous map of current biomass. Finally, the coefficients of the model of current biomass can be adjusted to estimate potential biomass under different management initiatives. This report includes the results of adjusting fishing impact to zero, simulating the effects of a no-take reserve or other fisheries management tool, and providing

estimates of potential biomass on a reef given its biophysical conditions. It also includes increasing complexity (i.e. the maximum hard cover relief) to simulate a restoration effort that increases reef complexity. Given any future model outputs that identify the corresponding covariates as significant, other management approaches, such as increasing coral cover, could potentially be modelled, or the models could be used to simulate some of the potential effects of climate change (increasing sea surface temperatures). These adjusted models could then be combined with all significant environmental data layers to generate a continuous map of potential biomass under different management scenarios. A draft



**Fig. 2.** Overview of the methods for modelling and mapping fishing impact and fish biomass. Yellow boxes represent input data, blue boxes represent output models, and orange boxes represent output maps.

manuscript examining different management scenarios is currently being prepared for submission to a peer-reviewed journal.

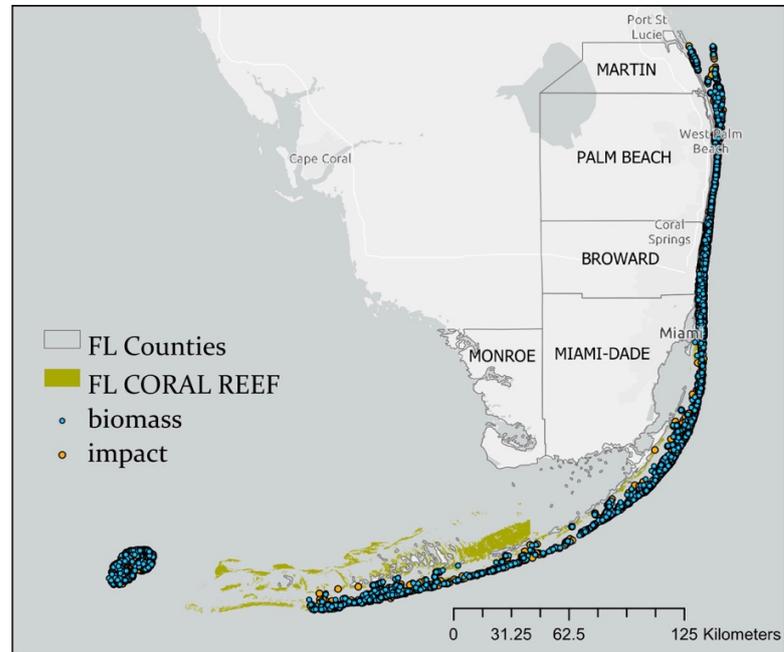
## *2.2. Approach to modelling fishing impact*

Researchers typically use fishery-dependent (e.g. catch data) or fishery-independent (e.g. underwater fish censuses) data to assess fishing impact. While catch data are available for the state of Florida, they lack the spatial resolution required for the models and maps produced by this project. Furthermore, there are concerns about the reliability of fisheries-dependent data sets focused on recreational fishing, a major component of reef fisheries in Florida. Consequently, this project used fishery-independent data derived from surveys of fish assemblages at sites across the Florida reef tract. Where survey data are available there are many different options for inferring fishing impact, and many approaches have been discussed in the general fisheries literature (e.g. Jennings 2005, Shin et al. 2005, Shin et al. 2010). The use of indicators of fishing impact has subsequently extended into coral reef fisheries and has included maximum size or age at female maturation as an indicator of vulnerability (Jennings et al. 1999, Stallings 2009, Taylor et al. 2014a), and measuring fishing impacts by the calculation of size-spectra (Graham et al. 2005), average length of caught fish (Kronen et al. 2010), mean size of parrotfishes (Vallès and Oxenford 2014, Vallès et al. 2015), and mean length, trophic level and density of large fishes (Guillemot et al. 2014). While we have explored several of these indicators, including length-based metrics, this report provides models and maps of fishing impact based on the biomass of species that are part of the federally permitted snapper-grouper complex, a group that is economically and socio-culturally important for both commercial and recreational fisheries in Florida (NOAA 1983, Seeteram et al. 2019). During testing, this metric was superior to other indicators of fishing impact.

Critically, the maps of fishing impact generated by the project represent relative, unitless patterns of estimated total exploitation impact, as opposed to absolute fishing rates as measured by metrics such as catch per unit effort. This distinction is important because the project highlights areas that have been heavily impacted by fishing (e.g. low biomass of groupers and snappers), rather than identifying areas that are currently being heavily fished. Highly impacted sites may also be currently heavily fished, but equally these sites may be lightly fished because catches are limited and fishermen have moved to more profitable locations. However, light fishing impact may be sufficient to limit any recovery of heavily impacted sites. Equally, some sites may currently be heavily fished, but have little evidence of fishing impact (e.g. large biomass of groupers and snappers) because the site has only recently been exploited. Furthermore, the metric of fishing impact used in this report is scaled from 0-1 based on maximum and minimum values predicted within the geographic range of the Florida reef tract. This scale would change if more heavily fished sites were included from elsewhere within the region, such as from the heavily fished reefs of Jamaica (Hughes 1994) or if more pristine sites were included, such as the reefs in Exuma Cays Land and Sea Park in the Bahamas. Consequently, it is important to recognise that references to high or low fishing impact are high or low for the Florida reef tract, and that a fishing impact value of 0 does not mean that the fish assemblage shows no impacts of fishing. Rather, an impact value of 0 signifies the lowest fishing impact on the Florida reef tract. Additionally, it is important to note that equal values of fishing impact on pavement habitats versus high complexity coral reef habitat do not signify that equal number of fishermen have been or are exploiting that site. Instead, it is simply that the cumulative impact on the snapper-grouper assemblage is equal. However, for clarity the maps for coral-reef habits and hard-bottom pavements are displayed separately because, although they may be equally close to large human populations (a key driver of fishing pressure), fishing effort may not be equally distributed between habitat types.

### 2.3. Fish survey data sets

The derivation of the maps and models produced by the project was entirely parameterised using existing fish survey data collected by NOAA's National Coral Reef Monitoring Program (NCRMP) Reef Visual Census (RVC) survey in the Dry Tortugas, the Florida Keys, and Southeast Florida (Table 1, Fig. 3). As such, the survey technique was consistent across all survey data used. Survey sites were split to provide a wide geographic range of data for both the fishing impact and biomass models. Notably, NCRMP has not surveyed the region between Key West and the Dry Tortugas, nor do large numbers of surveys exist for hardbottom pavement areas in the Florida Keys. However, our models are able to extrapolate fishing impact and fish biomass estimates to those regions using NCRMP surveys done in areas with similar biophysical conditions. While we note that benthic assemblages on hardbottom habitats in the northern latitudes of the Florida reef tract are distinct from those in the Florida Keys, the biophysical variables included in our models capture the aspects of this variability that are relevant to fishing impact and fish biomass (Walker and Gilliam 2013, Ames 2017).



**Fig. 3.** Location of NCRMP RVC survey sites used in the fishing impact (orange) and biomass (blue) models.

**Table 1.** Summary of fish survey data used for the project.

Region	Dates	Number of sites	Fishing impact model	Biomass model
SEFCRI	2005-2018	1430	716	714
Florida Keys	2005-2018	1960	963	997
Dry Tortugas	2005-2018	786	411	375
<b>Total</b>		<b>4176</b>	<b>2090</b>	<b>2086</b>

Briefly, the NCRMP data were collected to assess reef health across the region and document species composition, size, abundance, density and related metrics of the fish assemblage (NOAA 2017). For this survey, divers count all fish species using the Reef Visual Census (RVC) point count method and size them to the nearest  $\text{cm}^3$  (Bohnsack and Bannerot 1986, Brandt et al. 2009). At each survey site, two pairs of divers conduct point counts in the water column above a 7.5 meter radius circle on the reef surface.

<sup>3</sup> For some species, when more than 10 individuals are counted, only minimum, maximum and estimated mean size are recorded.

At each site, benthic cover (e.g. cover of live coral) is measured using point intercept transects and complexity is estimated based on the maximum vertical relief of the substrate.

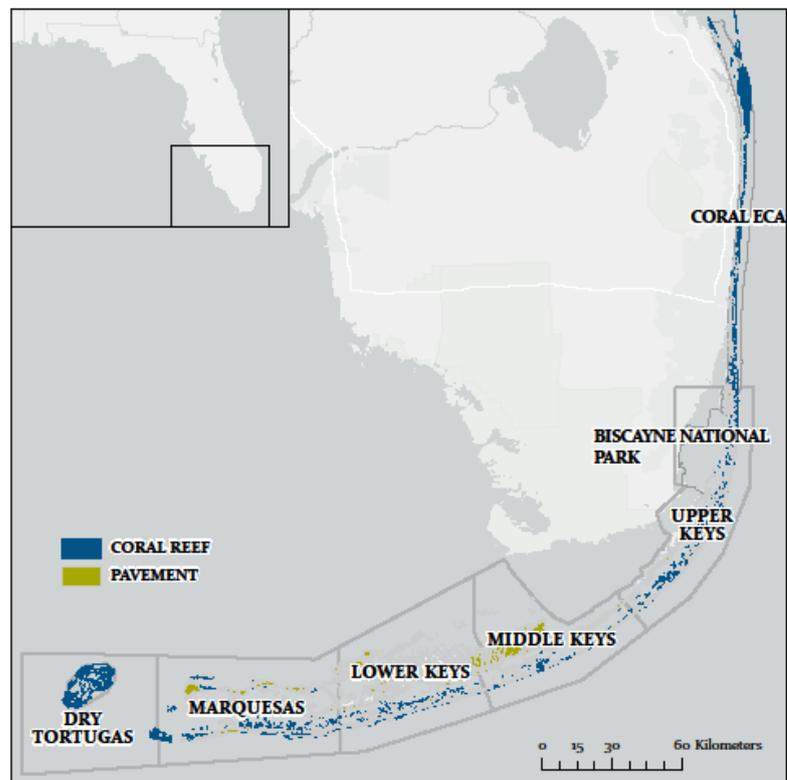
We calculated the biomass of each fish recorded using a set of allometric parameters derived from a range of sources including Stevens (2018), Bohnsack and Banner (1988) and FishBase (Froese and Pauly 2010). Data were extracted for every survey as kg 177 m<sup>-2</sup> (the area of a point count), then converted to kg ha<sup>-1</sup> for map presentation. A list of all fish species recorded in the RVC surveys and whether they are part of the federal snapper-grouper fishery complex can be found in Appendix 1. In summary, the snapper-grouper complex includes groupers, snappers, grunts, triggerfishes, porgies, and several others. These are species landed in commercial fisheries across the Caribbean region (Ault et al. 1998), and are popular species for recreational fisheries (O'Toole et al. 2011).

#### 2.4. Modelling current biomass

We modelled biomass across the Florida reef tract for five focal fish groups, species in the snapper-grouper complex, all fished species, herbivorous fishes, species in the marine life complex (saltwater fishes harvested nonlethally for commercial aquarium wholesale and retail dealers), and total biomass which includes all species documented in RVC surveys.

We also generated area-specific models of current biomass for sections of the Florida reef tract: the Coral ECA, Biscayne National Park, the Upper Keys, the Middle Keys, the Lower Keys, the Dry Tortugas (Fig. 4), and the entire FKNMS. No surveys were conducted in the Marquesas. While the reef-tract scale model of current biomass provides the most complete overview of the drivers of fish biomass, it may be of interest to some end users to see small-scale

drivers. For example, at a reef tract scale sea surface temperature may be important given the variability from Martin County to the Dry Tortugas, but these temperatures will be less important in individual sections where variability is negligible. Similarly, fishing impact varies significantly along the reef tract, but tends to be more homogeneous within a single section. Thus the models for current biomass were run for each reef section to show these local drivers. Inevitably these models are less powerful because they only use a subset of the data (sites surveyed in that reef section) and therefore any resulting maps are less useful for interpretation than the full reef-scale map. Consequently, only the full reef tract models



**Fig. 4.** Locations of the reef sections modeled separately within Phase 2 of the project. Map also shows distribution of coral reef and pavement habitats.

are presented in this report. Reef-tract scale estimates of fishing impact were used in these area-specific models.

In addition, we developed models and maps of the current abundance of individual species. Such maps provide detail that is inevitably lost in maps of total reef fish biomass, and can provide species-specific guidance for management. Models were created for all common species found on the reef tract, but here we focus on one ecologically important species (the stoplight parrotfish *Sparisoma viride*) and two economically important species (the yellowtail snapper *Ocyurus chrysurus* and hogfish *Lachnolaimus maximus*).

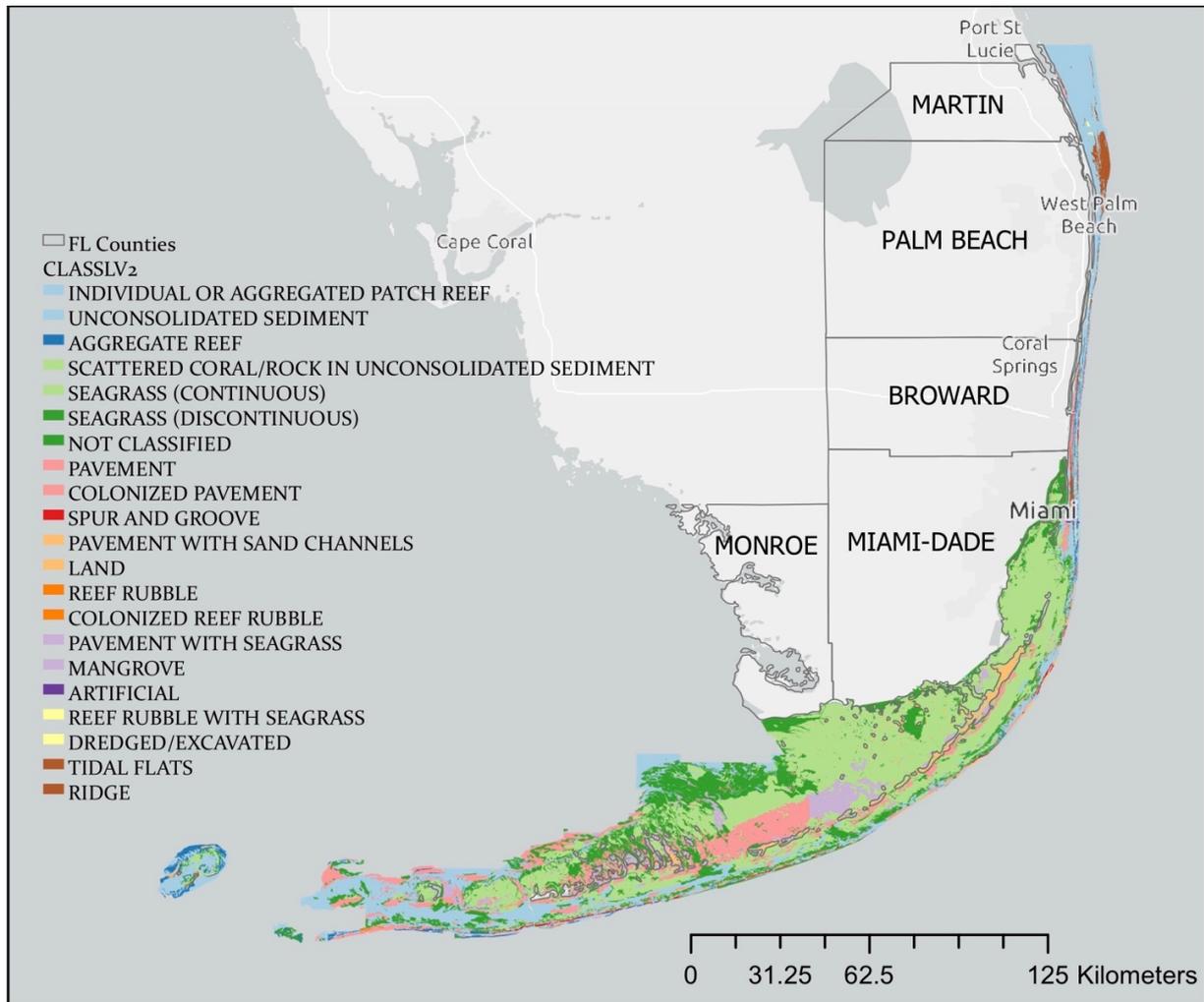
## 2.5. Mapping Florida's reefs

Establishing the extent of reef areas along the Florida reef tract was critical for the project, and we used the maps generated by the Florida Fish and Wildlife Conservation Commission (Fig. 5). The Unified Florida Reef Tract Map (UFRTM) is a compilation of various remote and field-based mapping efforts and uses a thematically rich habitat classification scheme (FWC 2016). Level 2 was appropriate for identifying the habitats that would be included in the modelling and mapping work. We include coral reef and hardbottom habitats assigned the following Level 2 classifications: Aggregate Reef, Individual or Aggregated Patch Reef, Spur and Groove, Ridge (coral habitats), Reef Rubble, Colonized Reef Rubble, Pavement, Colonized Pavement, and Pavement with Sand Channels (hardbottom / pavement habitats) (Fig. 5). We excluded habitats in less than 2 m water depth to exclude pavement habitats especially unsuitable for coral growth, and because several of the geospatial data layers of biophysical variables are lacking data in very nearshore areas. This yields a Coral Reef and Hardbottom habitats layer with a diverse range of coral-supporting habitats. To address the possibility that distinct processes affect fish biomass on coral reef (e.g. Aggregate Reef) versus low-relief pavement habitats (e.g. Colonized Pavement), we ran separate experimental models for each of these habitat groups. Results suggested that similar factors were influencing biomass across all coral and hardbottom habitats, and so no separate Coral Reef or Pavement models are presented here. Level 2 of the UFRTM classification scheme was also appropriate for distinguishing among the habitat types that we included, and was used as a categorical variable in the fishing impact and biomass models. For more information on the habitat classification scheme, see NOAA 2007.

The UFRTM Project maps are vector coverages, with habitats represented by polygons of varying size. However, to accurately model the Florida reef tract, the project required a raster (grid) coverage of identically sized cells. Rasterising a vector map requires a spatial resolution to be specified, which represents a trade-off of tractability versus accuracy. For example, as the cells become larger, there are fewer of them across the region and this improves computation times. However, small areas of reef may be lost as they are grouped with surrounding seagrass habitat. Smaller cells allow for a more accurate representation of the habitat distributions and allow the models to represent subtler gradients in environmental factors, but computation time is increased. Furthermore, very small cells may not be well parameterised because of the limitations of the explanatory data sets. Experimentation indicated that 100 x 100 m (1 hectare) cells represented an appropriate grid size that retains habitat detail, but is computationally tractable (~150,000 cells). Consequently, all maps products from the project are at a 1 ha resolution.

Other habitats not considered by the project, such as seagrass meadows, or areas of unconsolidated sediment with some coral cover, may have significant fish stocks and be exploited by fisheries. Rather

than being unimportant, their exclusion is a function of a lack of data to parameterise the models adequately, and the potential for significant inter-habitat variations in how fish assemblages respond to fishing and environmental gradients. However, the modelling and mapping techniques described in this report could be extended to other habitats if additional data were available.



**Fig. 5.** Classification Level 2 of the Unified Florida Reef Tract Project map, including the coral reef and hardbottom habitats included in the project.

## 2.6. Derivation of explanatory variables

The response variable at each fish survey site (e.g. biomass of species in the snapper-grouper complex) was modelled against a range of explanatory variables to assess the significant factors driving response variability across sites. These models were then used to extrapolate fishing impact and biomass across the entire reef tract. Consequently, the project required continuous data layers of numerous potentially important explanatory variables (Table 2 and 3). Note that two explanatory variables (coral cover and complexity) are available from the *in situ* fish surveys, and from NOAA NCRMP benthic surveys, but cannot be mapped continuously in Florida. For example, deriving a continuous data layer for coral cover requires information on a complex range of variables including recruitment, grazing pressure, wave

exposure, and the frequency of cyclones and bleaching events (Williams et al. 2015b). These data, and an understanding of how they interact to affect coral cover and the resilience of reefs, are not available. Therefore, coral cover and complexity were included in the models to assess whether they are important factors, but during the mapping extrapolation across unsurveyed cells this parameter was represented by the regional (Dry Tortugas, Florida Keys or Southeast Florida) mean values for each UFRTM classification Level 2 habitat type. A full description of the derivation of each variable, and a justification for its inclusion, is provided in Appendix 2.

**Table 2.** Variables used to model fishing impact at each survey site, including brief details of their derivation. Due to inter-variable correlations, not all variables were included in final models.

Variable	Description	Derivation
Area of reef within 20 km	Area of reef within 20 km of reef cell	UFRTM habitat maps
Area of reef within 200 km	Area of reef within 200 km of reef cell	UFRTM habitat maps
Artificial reefs	The number of artificial reefs within 1 km of reef cell	Data provided by various state and county government agencies
Availability of nursery habitat	Reef connectivity to mangrove and seagrass nursery habitat (separate layers for mangroves and seagrass)	Use of algorithm (Mumby 2006) in combination with UFRTM habitat maps
Coral cover	Coral cover at survey site	From fish survey data set
Depth	Depth of data collection	From fish survey data set
Distance to deep water habitats	Distance to 30m depth contour	30m contour derived from data available in Sbrocco and Barber 2013
Distance to fish spawning aggregation	Distance to nearest known snapper or grouper spawning aggregation	Location data for spawning aggregations provided by Todd Kellison (NOAA NMFS) and Ben Binder (FIU)
Community fishing engagement and reliance	Metrics of fishing engagement and economic reliance on fishing by fishing community	Data provided by Michael Jepson (NOAA NMFS) (Jepson and Colburn 2013)
Fishery activity: commercial	The number of Class 1 federal snapper-grouper permits within 50 km of reef cell; the average annual landings (lbs) of snapper-grouper complex species by county from 2012-2016	Data provided by NOAA NMFS SEFSC
Fishery activity: charter	The number of federal snapper-grouper permits assigned to charter vessels within 25 km of reef cell	Data provided by NOAA NMFS SEFSC
Fishery activity: recreational	The number of marine recreational fishing license holders within 50 km of reef cell	Data provided by the FWC
Fishery activity: tourism-related	The estimated number of tourism reef fishing days per year on a reef cell	Data on tourist hotel units publicly available from FGDL <sup>4</sup> ; estimates of tourist fishing days by county from Johns et al. 2001
Gravity of all potential fish markets (within a 500km radius)	Market gravity defined as population size divided by the square of travel time (a proxy for distance)	From Cinner et al. 2018
Habitat type	Level 2 classification of reef habitat type	UFRTM habitat maps
Human population	Number of people within 20 km and 50 km of a reef cell	LandScan human population data <sup>5</sup>

<sup>4</sup> Florida Geographic Data Library; <https://fgdl.org/metadataexplorer/>

<sup>5</sup> <https://landscan.ornl.gov/>

Human population per area reef	Number of people within $x$ km divided by area of fishable reef within $x$ km	LandScan human population data
Latitude	Latitude of survey site	From fish survey data set
Longitude	Longitude of survey site	From fish survey data set
Marina slips	The number of marina slips with 10 km	FWC data layer available online
Month	Month of data collection	From fish survey data set
Number of larvae from upstream	Estimate of relative number of larvae arriving at each reef from upstream sources only	Biophysical model of ocean currents provided by Claire Paris (University of Miami)
Oceanic net primary productivity (NPP)	Mean net primary productivity from monthly data 2012-2016	Oregon State University-modelled product derived from satellite data
Protected status	Whether the site is a no-take area or open to fishing; level of fishing protection	FWC and NOAA databases of marine protected areas
Complexity	Reef complexity	From fish survey data set
Sea surface temperature (SST)	Mean temperature of the coldest month	NOAA's CoRTAD satellite-based ocean temperature dataset <sup>6</sup>
Wave exposure	Wave exposure based on fetch and mean wind data	Data layer provided by I. Chollett (see Chollett et al. 2012)
Year	Year of data collection	From fish survey data set

<sup>6</sup> <https://www.nodc.noaa.gov/SatelliteData/Cortad/>

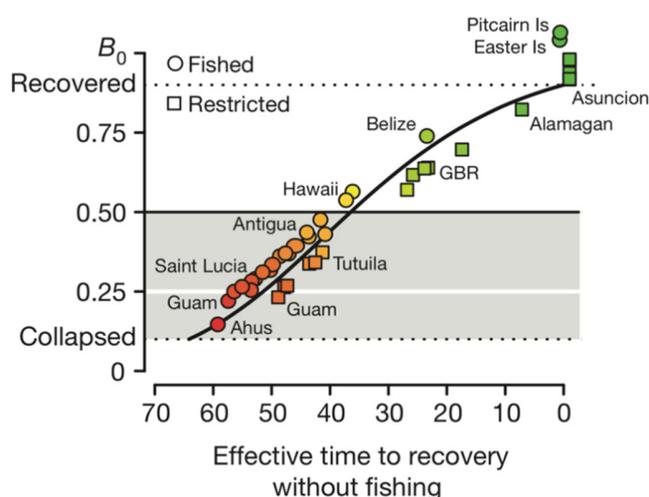
**Table 3.** Variables used to model biomass at each survey site, including brief details of their derivation. Due to inter-variable correlations, not all variables were included in final models.

<b>Variable</b>	<b>Description</b>	<b>Derivation</b>
Area of reef within 20 km	Area of reef within 20 km of reef cell	UFRTM habitat maps
Area of reef within 200 km	Area of reef within 200 km of reef cell	UFRTM habitat maps
Artificial reefs	The number of artificial reefs within 1 km of reef cell	Data provided by various state and county government agencies
Availability of nursery habitat	Reef connectivity to mangrove and seagrass nursery habitat (separate layers for mangroves and seagrass)	Use of algorithm (Mumby 2006) in combination with habitat maps
Coral cover	Coral cover at survey site	From fish survey data set
Depth	Depth of data collection	From fish survey data set
Distance to deep water habitats	Distance to 30m depth contour	30m contour derived from data available in Sbrocco and Barber 2013
Distance to fish spawning aggregation	Distance to nearest known snapper or grouper spawning aggregation	Location data for spawning aggregations provided by Todd Kellison (NOAA NMFS) and Ben Binder (FIU)
Fishing impact	Predicted fishing impact on 0-1 scale	From this project's fishing impact model
Habitat type	Level 2 classification of reef habitat type	UFRTM habitat maps
Latitude	Latitude of survey site	From fish survey data set
Longitude	Longitude of survey site	From fish survey data set
Month	Month of data collection	From fish survey data set
Number of larvae from upstream	Estimate of relative number of larvae arriving at each reef from upstream sources only	Biophysical model of ocean currents provided by Claire Paris (University of Miami)
Oceanic net primary productivity (NPP)	Mean net primary productivity from monthly data 2012-2016	Oregon State University-modelled product derived from satellite data
Protected status	Whether the site is a no-take area or open to fishing; level of fishing protection	FWC and NOAA databases of marine protected areas
Complexity	Reef complexity	From fish survey data set
Sea surface temperature (SST)	Mean temperature of the coldest month	NOAA's CoRTAD satellite-based ocean temperature dataset
Wave exposure	Wave exposure based on fetch and mean wind data	Data layer provided by I. Chollett (see Chollett et al. 2012)
Year	Year of data collection	From fish survey data set

### 2.7. Additional considerations for modelling potential biomass

As described previously, the map and model of potential biomass represents a hypothetical data layer of the potential biomass of fish at any location with no fishing (the fishing variable in the model reduced to 0). The map of potential biomass represents a target carrying capacity that might be reached within a well-enforced no-take reserve, or following implementation of another fisheries management tool, after sufficient time has elapsed to allow fish abundances to recover. However, there are myriad factors that will alter the carrying capacity, such as habitat quality that may be altered by disturbances (Abesamis et al. 2014), and this map should be viewed as only indicative of which reefs may be able to support higher biomasses of fishes in the absence of fishing or other stressors.

The time needed for fishes to fully recover in no-take reserves and reach a putative carrying capacity is an important research topic (Abesamis et al. 2014), encompassing complex questions of variability among fish families (McClanahan et al. 2007), predator-prey interactions that may lead to some species decreasing in abundance because of increasing abundances of carnivores (Micheli et al. 2004), and increasing abundances of herbivores increasing habitat quality by grazing macroalgae (Mumby and Harborne 2010). Noticeable differences in fish stocks are often visible within a few years (Halpern and Warner 2002, Russ et al. 2008), but up to 40 years may be needed for some predatory fishes (Russ and Alcala 2004). Providing additional insight into the recovery of species under scenarios of fishing cessation is beyond the scope of the project, but we provide broad spatial estimates of when biomass might recover using estimates of the ratio of current to potential biomass and recent, generic insights into the recovery of reef fishes. A global analysis of reef fish stock has provided an estimated relationship between the ratio of current to potential biomass and time to “recovery”, defined as reaching 90% of potential biomass (Fig. 6) (MacNeil et al. 2015). We used this relationship to estimate the time it would take each 1 ha cell to reach the threshold of 90% of potential biomass.



**Fig. 6.** The relationship between time to recovery (90% of potential biomass) following the cessation of fishing and current fishery status. Points highlight reef sites used to parameterize the relationship. Graph from MacNeil et al. 2015.

## 2.8. Statistical analyses

For models of both fishing impact and biomass, the final data set consisted of univariate response variables (e.g. biomass of species in the snapper-grouper fishery complex), and a large number of categorical and continuous explanatory variables. The relationships among explanatory and response variables may be curvilinear and include significant interactions that are difficult to predict *a priori*. Consequently, we use boosted regression trees (BRTs) during the modelling process. Explaining the mathematical basis of BRTs is beyond the scope of this report, and readers are referred to Elith et al. (2008) for an excellent introduction to the topic. Briefly, BRTs relate a response variable to explanatory variables by recursive binary splits (e.g. sites with high and low human populations) using an adaptive algorithm. BRTs essentially create an additive regression model and the relationships between the variables are visualised in a series of intuitively obvious graphs. Critically, BRTs have many advantages that are useful for the project including handling different types of predictors, accommodating missing data, being insensitive to outliers, fitting complex nonlinear relationships, automatically handling interactions, and being robust to fitting a large number of explanatory variables (Elith et al. 2008). Finally, models can easily be used to predict values at other locations, as required to transition from the models based on fish survey data to continuous reef tract-wide maps of fishing impact and biomass.

BRTs are generally insensitive to collinearity among explanatory variables (Soykan et al. 2014), but all explanatory variables (Tables 2 and 3) were first tested for correlations, and variables were removed so that there were no inter-variable correlations  $>0.8$  and no variable inflation factors (VIFs)  $>12.0$ . The remaining variables were then included in the BRT, along with a variable comprised of random numbers. This variable was included as a guide to which variables were most 'significant' (Soykan et al. 2014); variables which had less explanatory power than this random number variable were removed from the model to generate a final, minimal model including only the most important variables. BRT parameters (learning rate, tree complexity, and bag fraction) were calculated for each model by testing each across a series of values, and then using the values that gave the lowest model deviance (Elith et al. 2008). Model performance was assessed using the amount of deviance explained and the correlation between observed and model-predicted values.

## 3. Results

### 3.1. Fishing impact model

Inter-variable correlations among the range of variables proposed for inclusion (Table 2) revealed that longitude was highly correlated with sea surface temperature, and so longitude was removed from the model. Similarly, latitude was highly correlated with several socio-economic variables, and removed from the model. The two scales at which we calculated the area of reef habitat were correlated, and we retained the 20 km-scale as it more closely aligns with the scale at which most reef fish ecological processes occur. The two scales of the human population variable (20 km, 50 km), the variable representing the population per area of fishable reef, our metric of tourism-related fishing, and the number of recreational fishermen within 50 km were all highly correlated. We chose to include the variable capturing the number of recreational fishermen within 50 km. A much higher percentage of Monroe County residents engage in fishing activities relative to residents of Miami-Dade, Broward, Palm Beach and Martin counties. As such, we determined that the number of recreational fishermen (as opposed to the overall number of people) better captures fishing impact, rather than general anthropogenic impacts. We included this variable at the 50 km scale to best capture the distance that recreational fishermen likely travel to fish

(including travel over land), though few quantitative data exist to describe recreational fishing practices in south Florida. Finally, several additional fishing-related variables were highly correlated. In these cases, the variable with the finest spatial resolution was retained in the model. The biomass of snapper-grouper complex species underwent a  $\log(x + 1)$  transformation prior to inclusion in the model to improve normality of residuals while preserving zero values in the dataset.

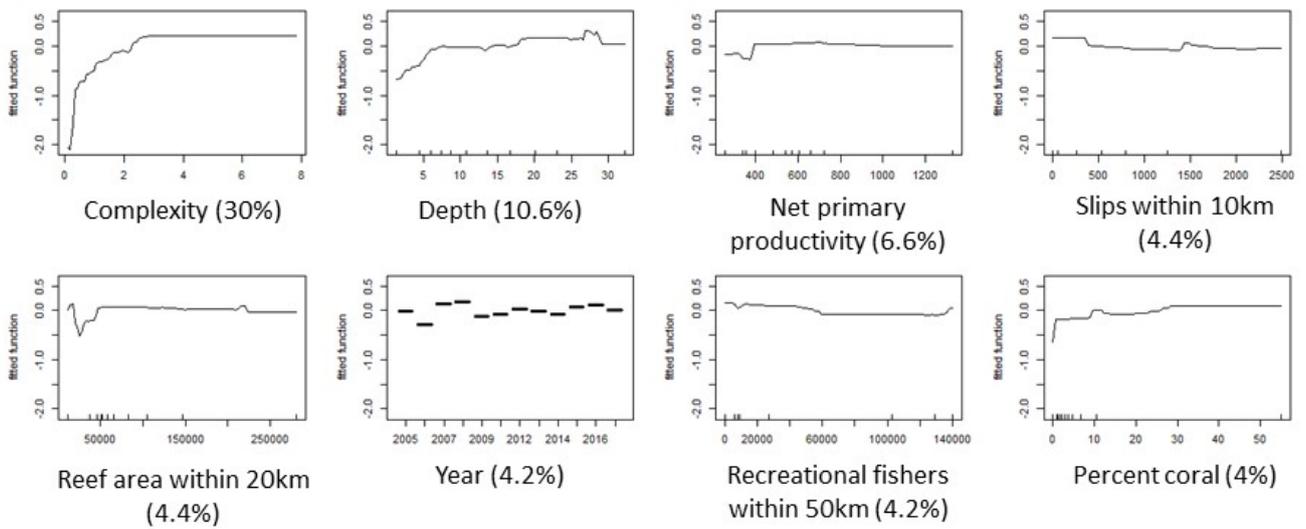
The fishing impact model resulted from a boosted regression tree analysis that provided a series of partial dependency plots that can be interpreted similarly to regression lines on traditional scatterplots (Fig. 7). Three human-related variables, the number of marina slips under 45 feet in length within 10 km, the number of recreational fishermen within 50 km, and total market gravity (not shown in Fig. 7) explained significant variation in the biomass of species in the snapper-grouper complex (4.4%, 4.2%, and 3.9% of explained variance, respectively). Additionally, six biophysical variables were important for explaining variation in snapper-grouper species biomass, including reef complexity (30%), depth (10.6%), oceanic net primary productivity (6.6%), reef area within 20km (4.4%), year (4.2%), and coral cover (4.0%).

This model was then used to predict fishing impact in every 1 ha cell along the reef tract considered by the project. Predictions were made from the model by classifying the significant variables into two categories. First, the number of recreational fishermen, marina slips, and market gravity variables were considered to relate entirely to fishing impact (generally higher fishing impact where recreational fishing population, accessibility via marinas, and the demand of local markets are highest). Values unique to each 1 ha cell (i.e. actual values for each cell) were used for these three variables. In contrast, the remaining variables were considered to be environmental or temporal drivers of fish abundance. The values of these variables in every 1 ha cell were set to their mean or the most common month and median year of data collection (August, 2014). This ensured that the predictions only represented the effects of fishing on the snapper-grouper complex, and not environmental gradients, as required for the map of fishing impact. Actual values of each variable in each cell would have been used if the aim was to predict actual biomass of species: but in this step we only wanted to investigate the effect of fishing on fish biomass, although we control for environmental variables when building the model.

It is important to note that fishing impact was not adjusted for habitat type. There are few data on how fishing effort is partitioned across habitats along the Florida reef tract, and indeed gear such as fish traps may be more effective on some habitats (Wolff et al. 1999). In the absence of the necessary data, all habitat types are considered to be equally impacted by fishing. However, actual catches are likely to vary between habitats because of the higher abundance of fish on some habitats. These habitat differences in fish biomass are accounted for in the maps of current and potential biomass because we have quantifiable links between, for example, reef complexity that is lower on pavements and higher on coral reef sites.

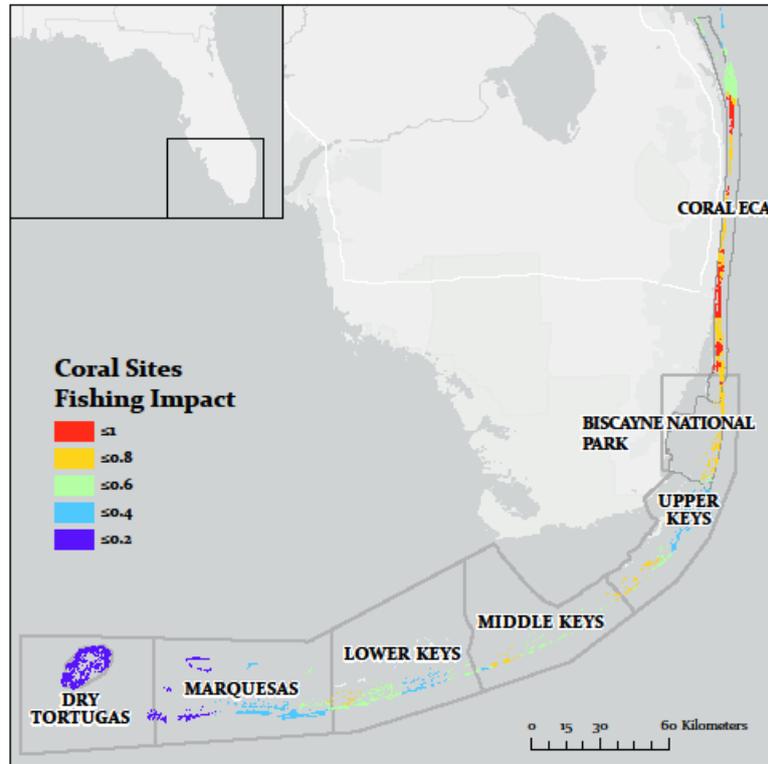
The fishing impact model explained 61% of the variability in the data set, and the correlation between observed and predicted values was 0.78. This exploratory power is considered acceptable given the challenges of the project: combining multiple data sets across a large geographic area and using a relatively crude fishery-independent metric of fishing impact.

Following predictions of human influences on the biomass of species of the snapper-grouper complex in each 1 ha cell, the predicted values were back transformed and then rescaled to range from 0 (lowest fishing impact on the reef tract) to 1 (highest fishing impact on the reef tract) and plotted (Map 1). As stated previously, it is important that these values are considered to reflect cumulative fishing impact relative to other areas on the Florida reef tract rather than a measure of current fishing effort.

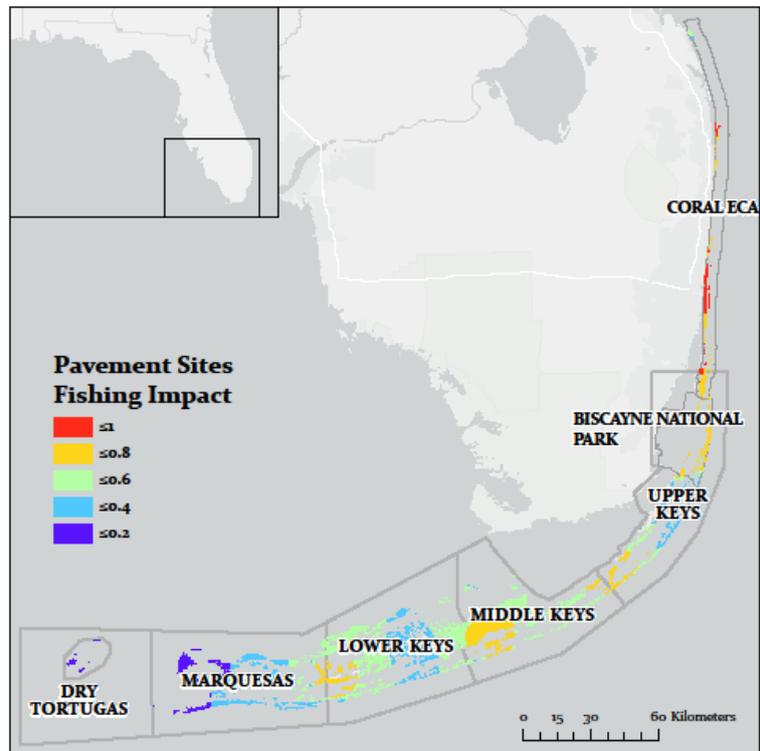


**Fig. 7.** Relationships between the 8 most important significant variables and the biomass of species in the snapper-grouper fishery complex (y-axis, values of log biomass of snapper-grouper species are normalised as opposed to showing actual biomass) as modelled by boosted regression trees. Values represent the percentage of explained deviance that was explained by each variable.

(a)



(b)



**Map 1.** Spatial distribution of predicted relative fishing impact (0 = low fishing impact) across the Florida reef tract on (a) coral-reef habitats and (b) pavement habitats.

### 3.3. Interpretation of the fishing impact model

The model for fishing impact (Fig. 7) shows that the biomass of snapper-grouper complex species typically decreased with increasing nearby populations of recreational fishermen and with the number of marina slips under 45 feet within a 10 km radius (representing fishing access). This is consistent with expectations and the literature (e.g. Cinner et al. 2013, Cinner et al. 2016). Similarly, increasing numbers of recreational fishermen within 50km of a reef cell and increasing market gravity influencing that cell decreased the abundance of snappers-grouper complex species. The limited deviance explained by habitat class (3.2%) suggests there may be limited difference in fishing pressure across habitats including pavement and coral sites.

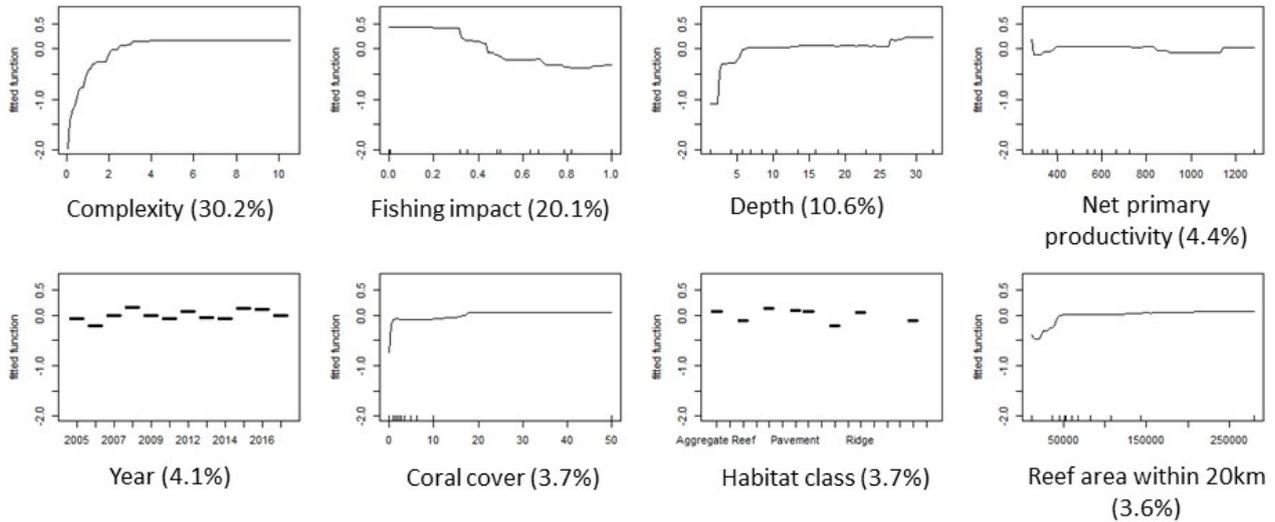
The biomass of snapper-grouper species was also affected by environmental gradients, and tended to be higher on deeper reefs, on more complex habitat types, and on reefs with higher net primary productivity. The relationship between biomass and depth is consistent with other literature finding that depth is a major factor in determining the fish assemblage on the Florida reef tract (Ames 2017). The importance of the habitat type and complexity variables reflects the well-established effect of structure on fish assemblages (Graham and Nash 2013). The importance of complex reefs for supporting fisheries underscores the importance of maintaining positive carbonate budgets for providing ecosystem services (Rogers et al. 2014), and reflects widespread concern about the loss of complexity on Caribbean reefs (Alvarez-Filip et al. 2009). This structure is predominantly created by coral, and thus fish abundance increasing with increasing coral cover. Coral cover also has a range of other benefits to fish, including providing settlement habitat to juveniles (Coker et al. 2014). The relationship between the abundance of fishes in the snapper-grouper complex was influenced by the area of reef within 20km, although the relationship was complex (Fig. 7). Reef area has multiple effects on fishes, including providing nursery habitats, increased productivity, greater environmental diversity (Dames et al. 2020). Year was also a significant variable, but how these changes reflect actual changes in fishing pressure versus other temporal patterns (e.g. variations in surveyors or fish recruitment) are unclear.

### 3.4. Current biomass model

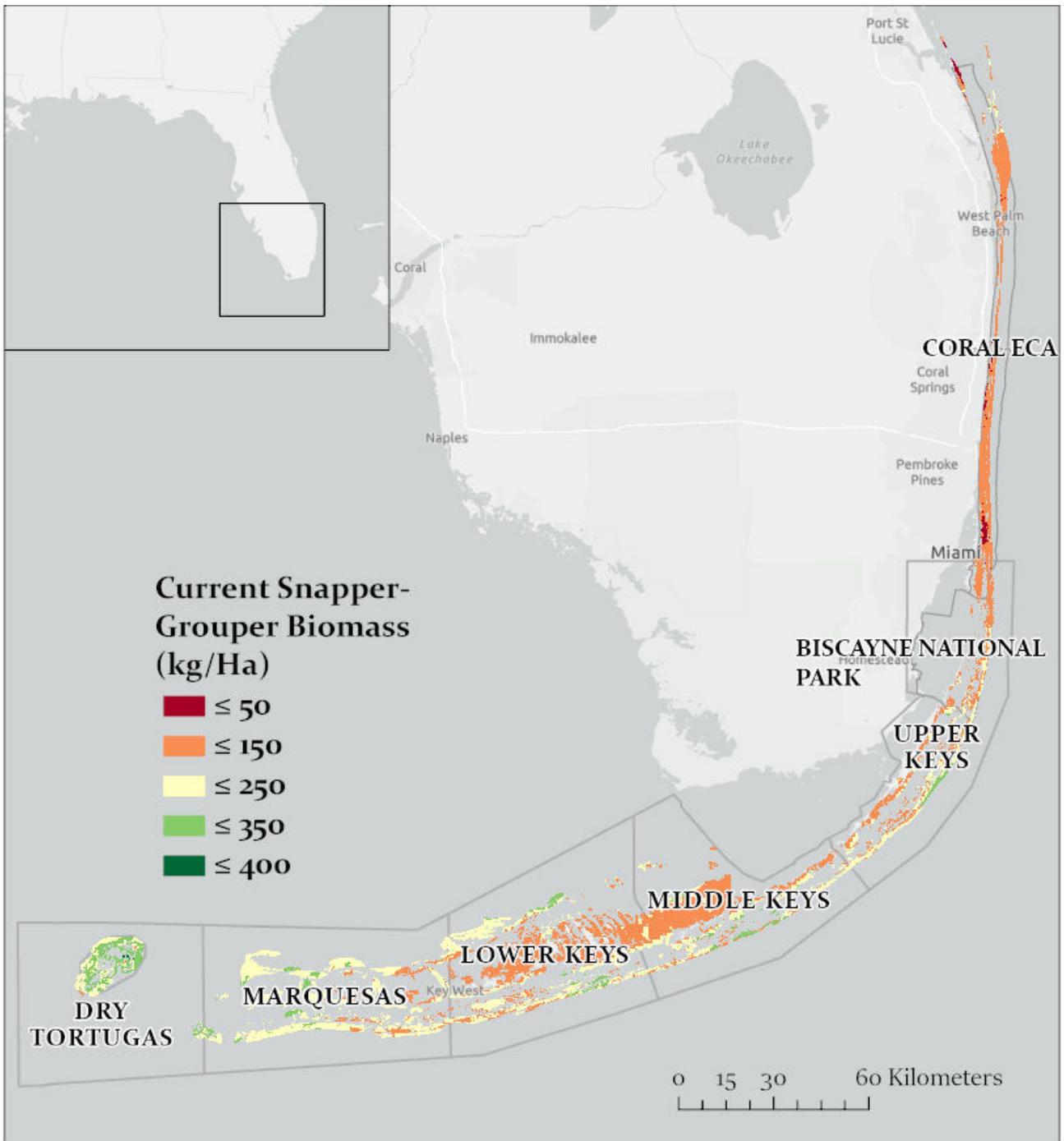
Similar to the model of fishing impact, correlations among the variables intended for inclusion in the biomass model (Table 3) led us to drop several variables. The total biomass response variable was log transformed to improve normality of residuals, and biomass variables with zeros in the dataset (all the other four fish groups) underwent a  $\log(x + 1)$  transformation to preserve zero values. Models were generated to predict the biomass for the following species groups: the snapper-grouper complex; all species (i.e. total biomass); fished species; herbivorous species; and marine life species (Table 4) (see species list in Appendix 1).

As an example of the results, the biomass model for the snapper-grouper complex species generated a boosted regression tree analysis that provided a series of partial dependency plots that can be interpreted in the same way as a regression line on a traditional scatterplot (Fig. 8). This model was then used to predict the biomass of snapper-grouper species in every 1 ha cell considered by the project (Map 2). Values specific to each reef cell were used for every variable, except that month and year were set to August 2014 (the most common month and median year for fish surveys in the dataset). The model explained 53.5% of the variability in snapper-grouper complex biomass, and the correlation between observed and predicted values was 0.75. This explanatory power is considered acceptable given the

challenges of the project: combining multiple data sets over a relatively large geographic area. Results of BRT models predicting the biomass of other fish species groups are summarized (Table 4) and the resulting maps shown (Map 3). The partial dependency plots and can be found in Appendix 3.



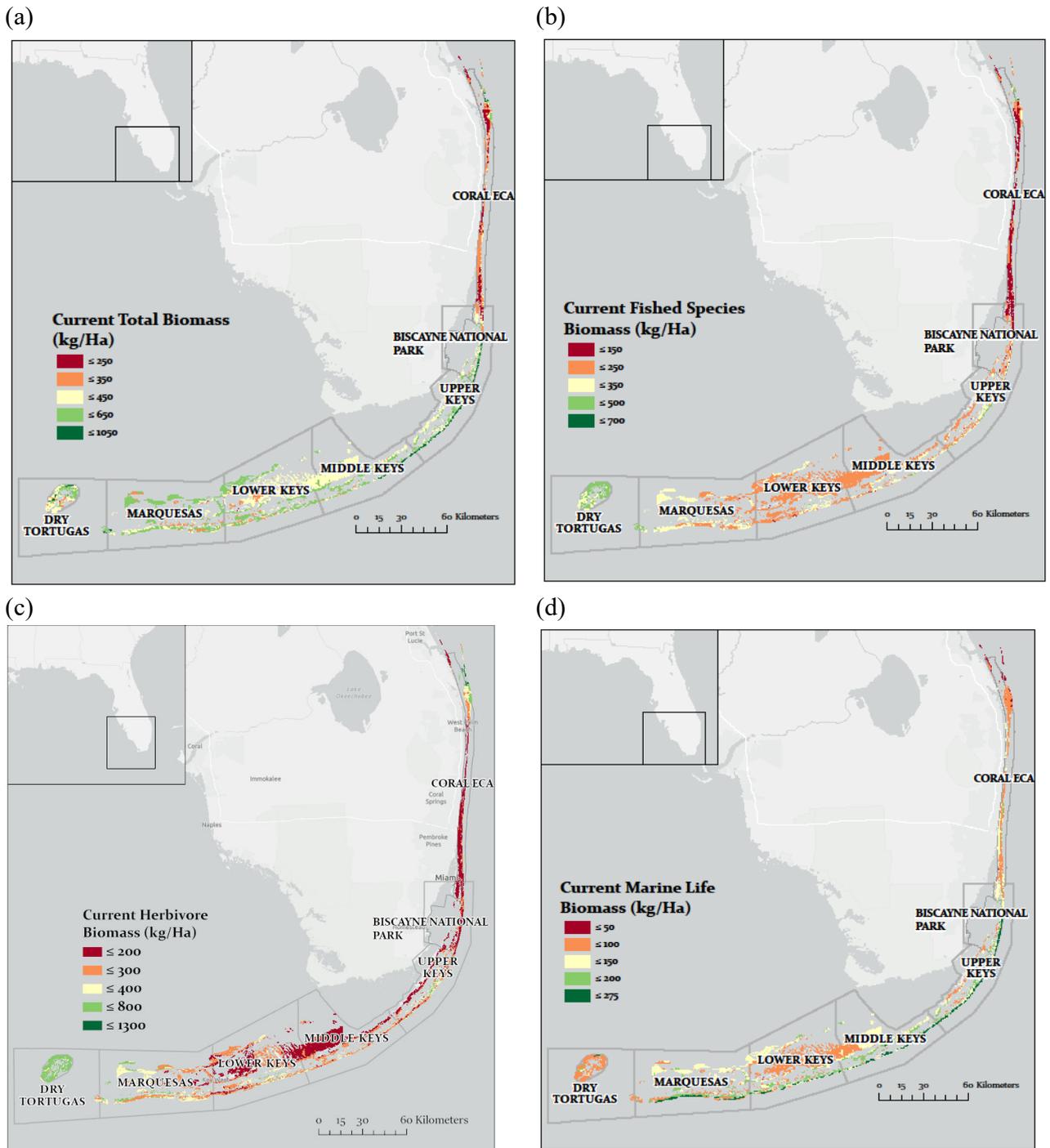
**Fig. 8.** Relationships between the 8 most significant variables and the current biomass of snapper-grouper complex species (y-axis, values of log biomass of snapper-grouper species are normalised as opposed to showing actual biomass) modelled by boosted regression trees. Values represent the percentage of explained deviance that was explained by each variable.



**Map 2.** Spatial distribution of estimated current biomass of all species in the snapper-grouper complex ( $\text{kg ha}^{-1}$ ) on the Florida reef tract.

**Table 4.** Comparison of boosted regression tree results of all biomass models.

<b>Species Group</b>	<b>Variance explained</b>	<b>Correlation between observed and predicted values</b>	<b>Top five explanatory variables (and percentage of variance explained)</b>
All species	47.1%	0.73	Reef complexity (40.6%), Fishing impact (9.2%), Depth (9.2%), Wave exposure (5.3%), Year (4.1%)
Fished species	49.1%	0.69	Reef complexity (38.0%), Fishing impact (9.2%), Depth (9.2%), Wave exposure (6.0%), Year (4.5%)
Snapper-grouper species complex	53.5%	0.75	Reef complexity (30.2%), Fishing impact (20.1%), Depth (10.6%), Net primary productivity (4.4%), Year (4.1%)
Herbivores	65.4%	0.81	Reef complexity (21.7%), Distance to deep water (9.2%), Year (9.1%), Depth (8.5%), Coral cover (8.1%)
Marine life species	56.8%	0.73	Reef complexity (35.4%), Distance to deep water (11.5%), Year (8.3%), Depth (7.3%), Coral cover (7.2%)



**Map 3.** Spatial distribution of estimated current biomass of (a) all surveyed species (b) fished species (c) herbivores and (d) marine life species ( $\text{kg ha}^{-1}$ ) on the Florida reef tract.

### 3.5. *Interpretation of the current biomass model*

The metric of fishing impact derived by the project appeared to capture important properties of variability in fishing across the Florida reef tract; when used to predict fish biomass in an independent data set it showed declining fish biomass with increasing fishing impact (Fig. 8). Furthermore, this negative relationship between fishing impact and was not seen for herbivorous and marine life species that are not heavily fished in Florida (Table 4, Appendix 3).

As found in the fishing impact model, fish biomass in the biomass model increased in more complex habitats, and also deeper habitats. Fish biomass varied with net primary productivity, although this relationship is complex (Fig. 8). Snapper-grouper biomass was higher on reefs with more coral cover, and this trend was particularly clear as coral cover increased from <1% to ~4% reef. Snapper-grouper biomass also increased with increasing reef habitat within 20km. In addition to these variables that vary among habitats, habitat type itself was also an important factor. Finally, year was a significant factor in the model, but there was no evidence of fish biomass consistently increasing or decreasing over time.

### 3.6. *Area-specific models of current biomass*

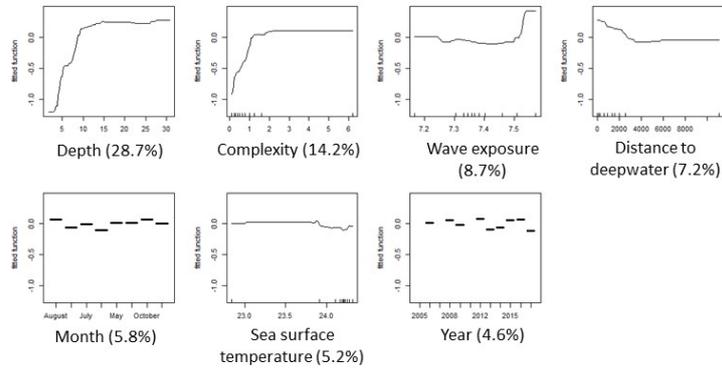
Area-specific models of current biomass were calculated for each group of species (all surveyed species, the snapper-grouper complex, all fished species, herbivores, and marine life species), but only the models for all surveyed species are shown here for brevity (Fig. 9 and 10). All of these models can be used to generate maps, but we recommend using the reef-tract-scale maps for visualisation and conservation planning because they use the full data set. Rather, the models are primarily for examining relatively small-scale drives of fish biomass.

The models for the six sections of the Florida reef tract, plus the entire FKNMS, demonstrated some differences among locations, but still highlight the primary importance of reef complexity as a driver of fish biomass (most important variable in 6 models, and second most important in the seventh). Similarly, fish biomass typically increased with increasing coral cover and depth. In general, variables that vary at the scale of the entire reef tract but not at more local scales, such sea surface temperature, wave exposure, and net primary productivity were less important in these models. However, for example, there appeared to be thresholds of wave exposure and connectivity to seagrass nurseries in the Middle Keys. Fishing impact also varies to a limited degree within each area, and its importance was limited. Larval connectivity only appeared to be important in the Lower Keys, possibly because of higher settlement rates (Sponaugle et al. 2012a).

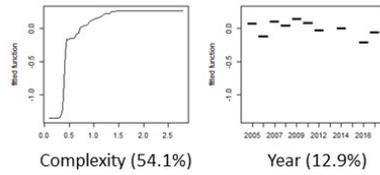
### 3.7. *Species-specific models of current biomass*

The models and maps of hogfish, yellowtail snapper, and stoplight parrotfish abundance (Fig. 11, Map 4) provide some information on the natural history of each species. For example, hogfish are less reliant on structure than many other species, but appear to use seagrass as nursery or foraging habitat. As expected, yellowtail snapper are heavily impact by fishing, but also increase on more complex, shallow reefs. Finally, the density of stoplight parrotfish reflect much of what is known about their biology. For example, they are more abundant on shallow, complex reefs (Bozec et al. 2013), and appear to benefit from connectivity to seagrass nursery areas (Harborne et al. 2016).

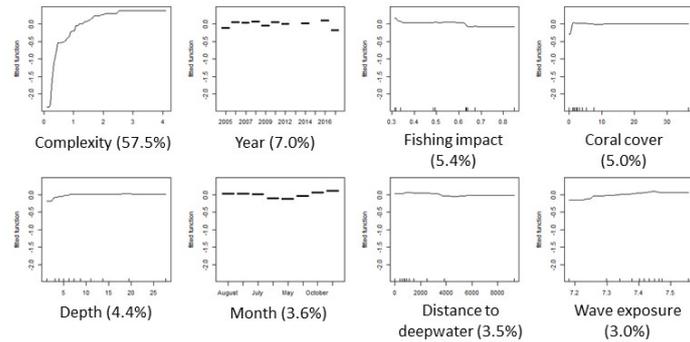
(a)



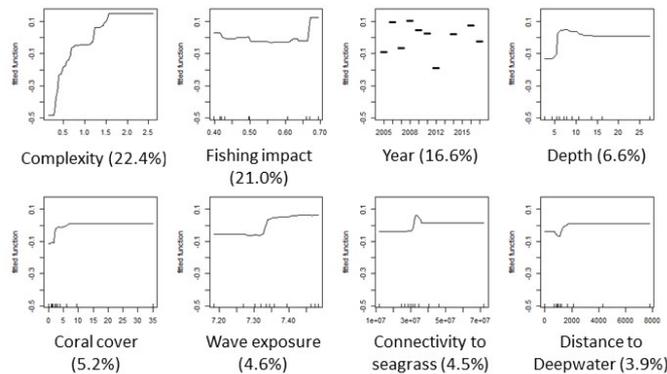
(b)



(c)

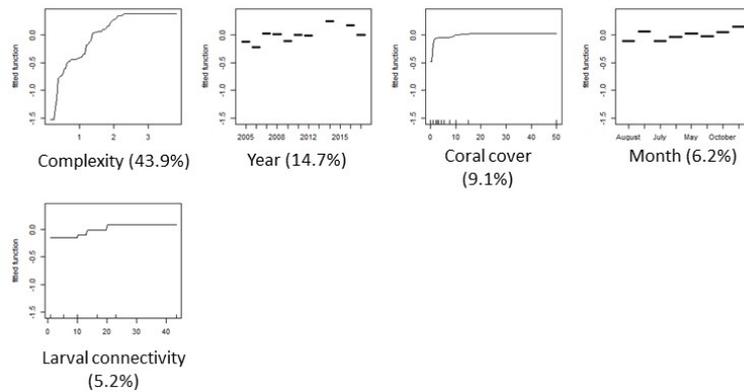


(d)

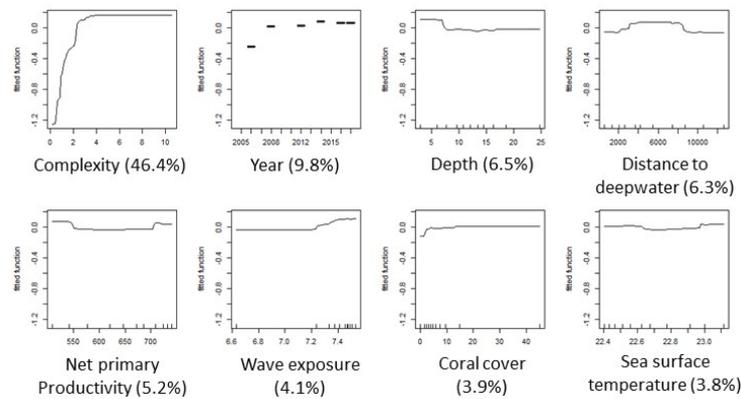


**Fig. 9.** Relationships between the 8 most significant variables (unless final model contained fewer variables) and the current biomass of all fished species (y-axis, values of log fish biomass are normalised as opposed to showing actual biomass) modelled by boosted regression trees for (a) Coral ECA, (b) Biscayne National Park, (c) Upper Keys and (d) Middle Keys. Values represent the percentage of explained deviance that was explained by each variable.

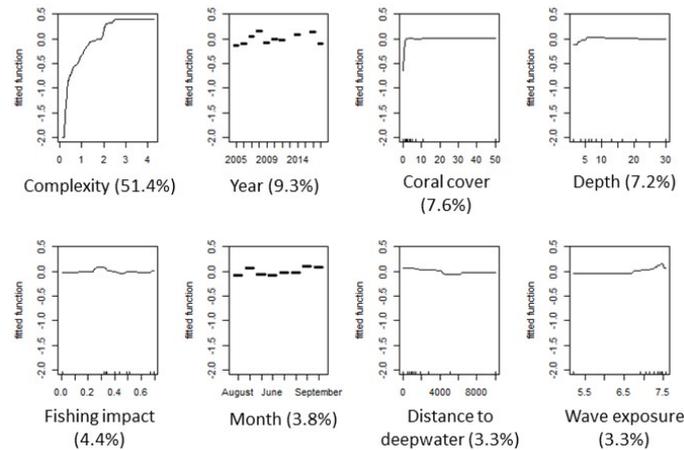
(a)



(b)

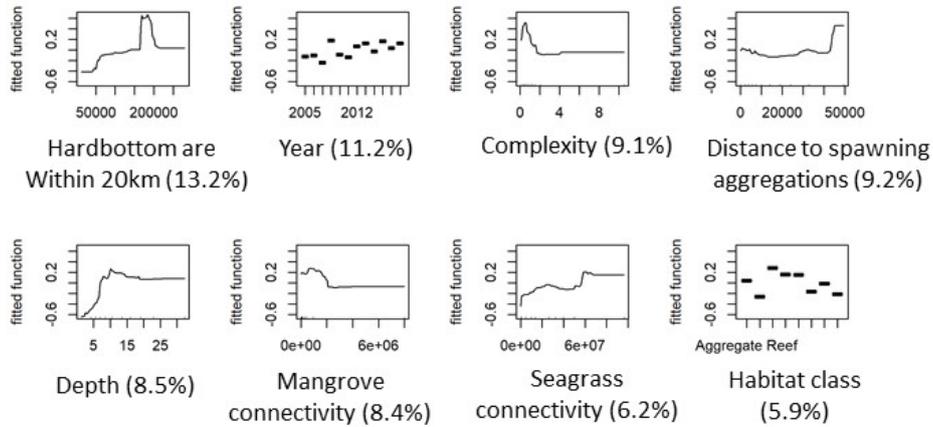


(c)

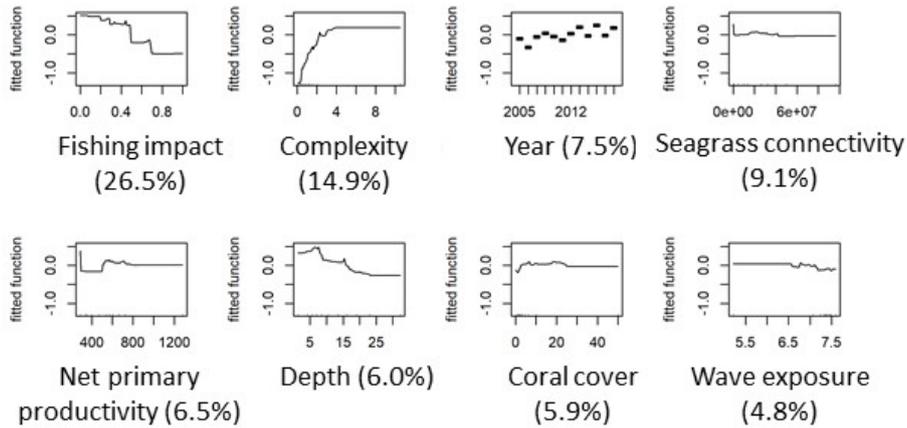


**Fig. 10.** Relationships between the 8 most significant variables (unless final model contained fewer variables) and the current biomass of all fished species (y-axis, values of log fish biomass are normalised as opposed to showing actual biomass) modelled by boosted regression trees for (a) Lower Keys, (b) Dry Tortugas, and (c) entire FKNMS. Values represent the percentage of explained deviance that was explained by each variable.

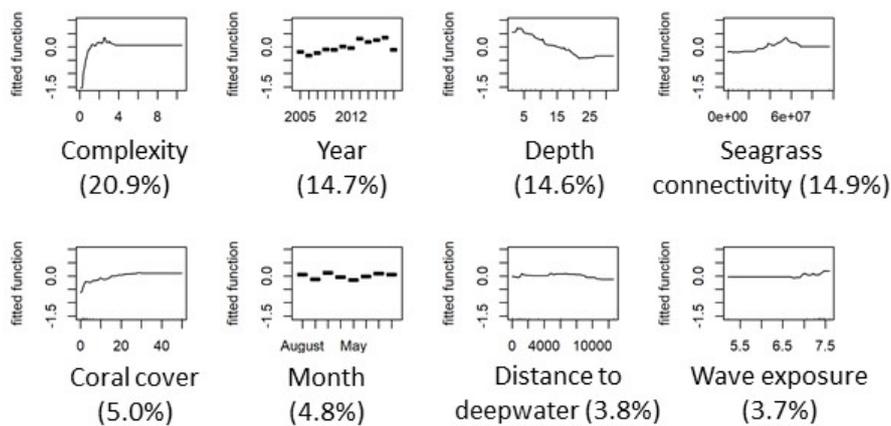
(a)



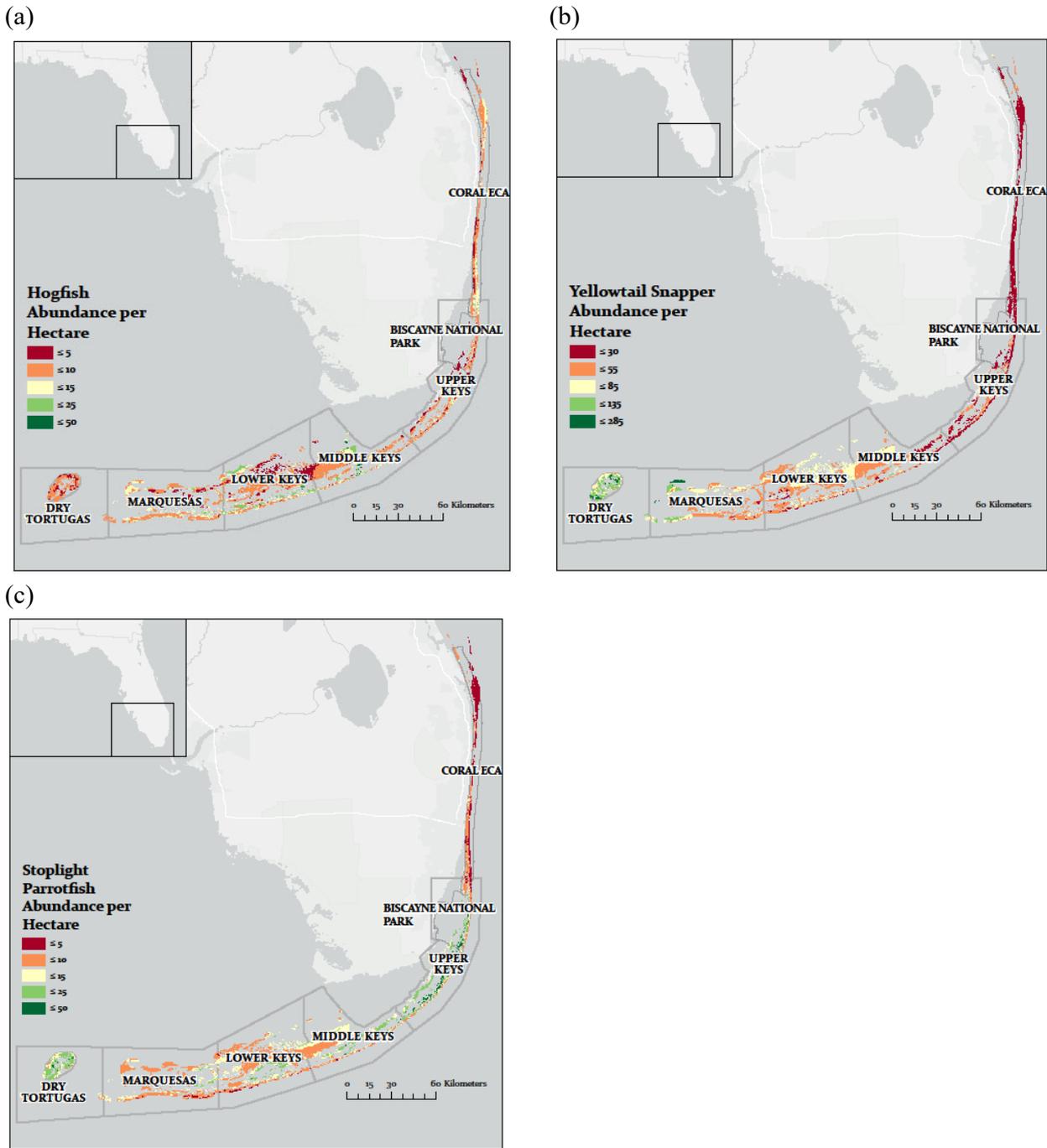
(b)



(c)



**Fig. 11.** Relationships between the 8 most significant variables and the current density of all fished species (y-axis, values of density are normalised as opposed to showing actual density) modelled by boosted regression trees for (a) hogfish, (b) yellowtail snapper, and (c) stoplight parrotfish. Values represent the percentage of explained deviance that was explained by each variable.

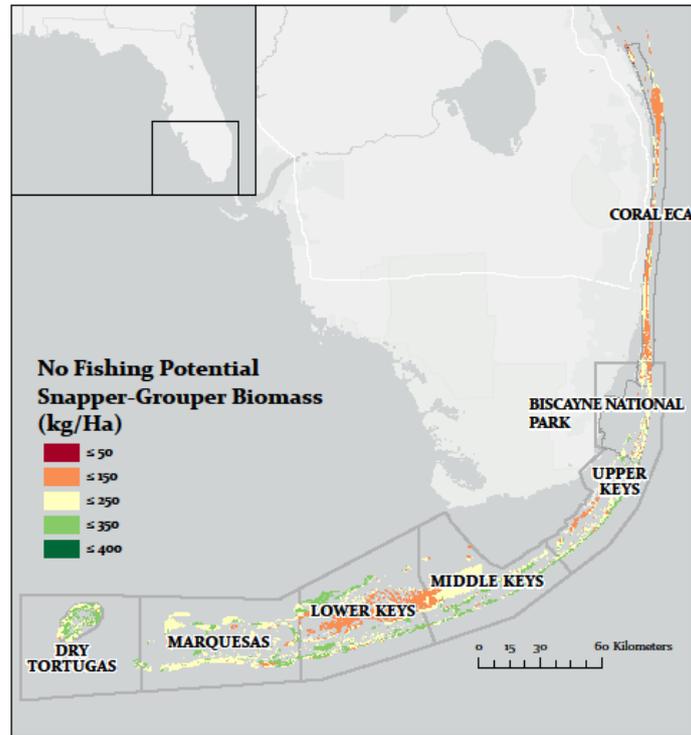


**Map 4.** Spatial distribution of estimated current density of (a) hogfish, (b) yellowtail snapper, and (c) stoplight parrotfish (number ha<sup>-1</sup>) on the Florida reef tract.

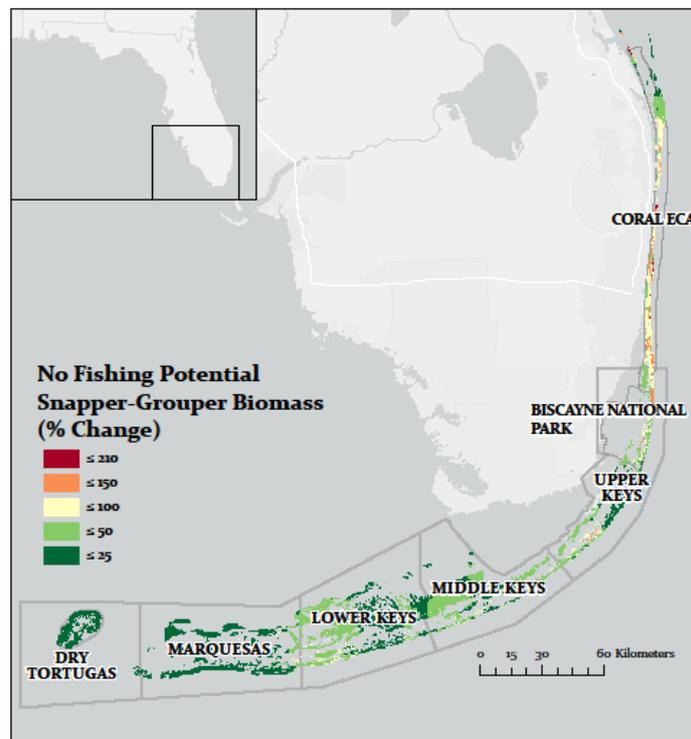
### 3.8. *Generating a map of potential biomass*

The map of potential biomass (Map 5a) represents a hypothetical data layer of the potential biomass of fish at any location with no fishing impact. It was created by predicting the biomass in each 1 ha cell with fishing impact set to 0 (as opposed to the value actually predicted by the fishing impact model). Note that rather than setting fishing to a true value of 0, this product is for a fishing impact of 0 as determined by current levels assessed along the reef tract. It is likely that the current index of 0 in Florida does not represent a truly natural biomass of fishes in the region, because of the wide ranging footprint of commercial and recreational fishing (Ault et al. 1998). Consequently, reefs untouched by fishing for a long period may be able to support more fishes than shown here (Map 5a). The map of potential biomass represents a carrying capacity that might be reached within a well-enforced no-take reserve. Because of the complex social-ecological processes on reefs, this map should be viewed as only indicative of which reefs may be able to support higher biomasses of fishes in the absence of fishing or other stressors. This map should also not be viewed as a proposal for additional no-take areas. Note that Map 5a shows only the predicted potential biomass for species in the snapper-grouper complex. Given that the project has also estimated the current biomass of fishes in this group (Map 2), the change under a no-fishing scenario can also be expressed as the potential percentage gain (Map 5b).

(a)



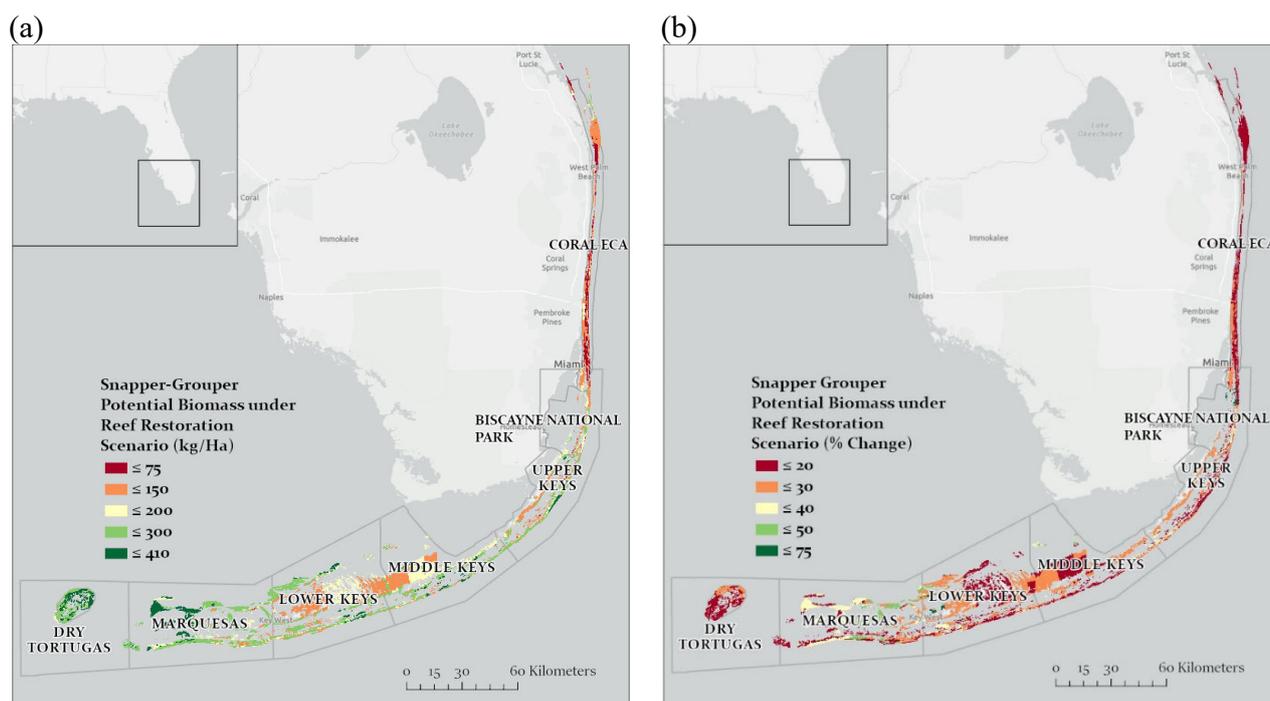
(b)



**Map 5.** Spatial distribution of (a) predicted potential biomass ( $\text{kg ha}^{-1}$ ) of all species in the snapper-grouper complex in the absence of fishing across the Florida reef tract and (b) percentage increase of snapper-grouper biomass compared to current estimates.

### 3.9 Exploring potential benefits of management actions

The map of predicted biomass allows us to explore the potential benefits of additional management actions. Map 6 illustrates the predicted potential biomass of the snapper-grouper complex species under the Restoring Seven Iconic Reefs management initiative proposed by NOAA, which proposes increasing coral cover to 15% and increasing average complexity by 15 cm. This could simulate a coral restoration program that also increases reef complexity over time.



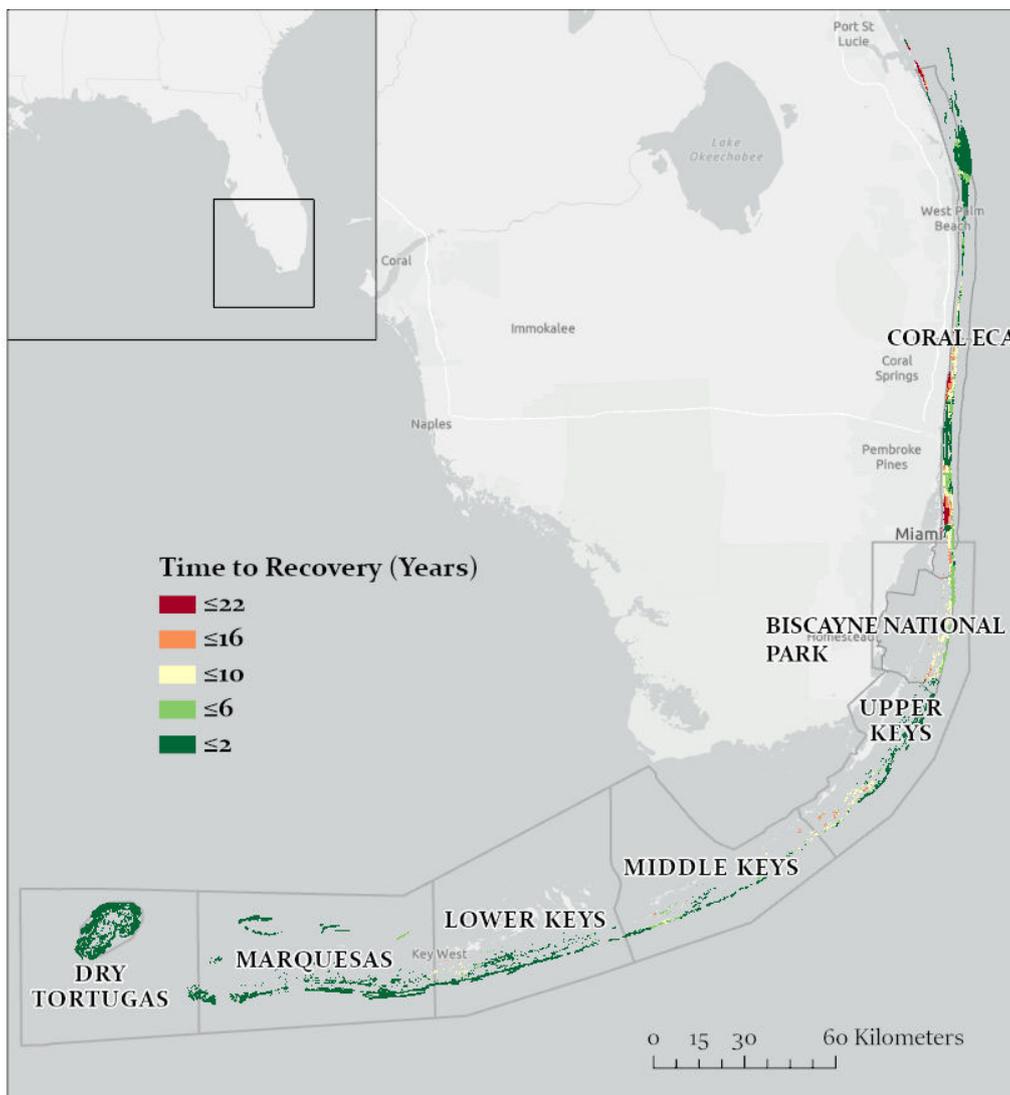
**Map 6.** Spatial distribution of (a) predicted potential biomass ( $\text{kg ha}^{-1}$ ) of all species in the snapper-grouper complex with a increase of coral cover to 15% and an increase of complexity by 15 cm and (b) percentage increase of snapper-grouper biomass compared to current estimates.

### 3.10. Generating maps of fish assemblage status and time to recovery

Previous studies have suggested that the ratio of current to potential fish biomass provides some insights into the status of the fishery and some ecological processes (McClanahan et al. 2011, Karr et al. 2015). For example, when this ratio falls below 0.5 it is possible that the reef is approaching an unsustainable fishery and potentially some thresholds of ecosystem processes. Conversely, reefs where this ratio is  $>0.9$  are considered to be virtually intact and with effectively no impacts on reef functioning (MacNeil et al. 2015). Although the majority of reefs on the Florida reef tract appear to be above the 0.5 threshold, this should be interpreted with caution because whether these thresholds are similar throughout the world is not clear. Consequently, negative impacts on reef functions may still occur when current biomass is at a higher proportion of potential biomass.

A global analysis of reef fish has provided an estimated relationship between the ratio of current to potential biomass and time to “recovery”, defined as reaching 90% of potential biomass (MacNeil et al. 2015). The project used this relationship to estimate the time it would take each 1 ha cell to reach this

threshold of 0.9 of potential biomass of all reef fish species (Map 7). Note that this was only done for coral reef sites, as the recovery curve is only parameterised for coral reefs. Our results show that for some areas in the region, reefs may not recover following the cessation of fishing for decades. However, these results should be interpreted with caution because of the relatively limited impact of fishing on the total biomass on Florida's reefs. Time to recovery for species in the snapper-grouper complex are likely to be much longer, especially given the functional extinction of many spawning aggregations. Unfortunately there are currently no recovery curves available for individual species groups. Furthermore, these estimates do not account for any other changes, positive or negative, associated with marine environments, such as improved habitat quality or biophysical changes due to climate change. These caveats underscore the need to expand management initiatives as soon as possible.



**Map 7.** Spatial distribution of the predicted time to recovery (90% of predicted potential biomass of all reef fish species, measured in years) following the cessation of fishing across the coral sites of the Florida reef tract.

#### **4. Summary of patterns highlighted in the maps**

The maps of fishing impact and biomass (Maps 1 and 2) highlight the expected patterns of high fishing impact in southeastern Florida adjacent to major population centres such as Miami and Ft. Lauderdale, and relatively low impact in the remote Dry Tortugas. Known centers of commercial and recreational fishing in the Florida Keys such as Islamorada, Marathon and Key West show increased fishing impact, though impact across the Keys remains lower than in the southeast region. In the Keys, impact is slightly lower in John Pennekamp State Park and in the vicinity of the more sparsely populated Cudjoe, Big Torch and Little Torch, Big Pine and No Name Keys. The areas of high and medium fishing impact showed decreased current biomass estimates, but the biomass of fishes was also affected by complex interactions of other factors including depth, complexity, habitat type and primary productivity. Consequently, the patterns of fish stocks along the Florida reef tract highlight significant heterogeneity.

Additionally, fishing impact was shown to impact different groups of fishes differently. As expected, fished species, including those in the snapper-grouper complex, were more strongly impacted by fishing than herbivores or the fish assemblage overall (which includes many small, unfished species). The models allow us to explore the impact of fishing on individual species, and other species groups of interest identified by the management community.

#### **5. Participation in meetings with state and federal management agencies**

One of the Services and Deliverables in the project contract was participation in an inception meeting. Though no formal inception meeting took place, Harborne and Zuercher attended several informal meetings. In addition, Harborne and Zuercher have attended and presented interim results at numerous meetings with state and federal resource managers including:

- Florida Fish and Wildlife Research Institute (6/29/2019)
- Florida Department of Environmental Protection (7/9/2019)
- Florida Keys National Marine Sanctuary (7/22/2019)
- Biscayne Bay National Park (8/14/2019)
- SEFCRI Technical Advisory Committee (10/30/2019)

Feedback from these meetings has been incorporated into the models and maps presented here.

#### **6. Future Work**

This report documents the work completed in Phase 1 and Phase 2 of this project, and there are likely to be further, relatively minor refinements included in the final report in September 2020. However, the focus of the project is now to disseminate the results. This is likely to occur through two mechanisms. The first is publication of the results in scientific journals, and the project team have already prepared a draft manuscript focusing on the drivers of fish biomass and how various management actions (reducing fishing, coral restoration, and increasing structure artificially) affect fish biomass. It is anticipated that this paper will be submitted for publication in summer 2020.

The second mechanism is by adding the data layers to the Mapping Ocean Wealth data portal to allow users to explore the products presented here. If paired with corresponding communication efforts, having the products online can increase awareness of the work, and increase their use in conservation planning.

It is also possible that resource managers will request additional products to help with their specific needs. We aim to meet these requests to the fullest extent possible given the capacities of the project team.

## **7. Potential use of map products in marine management**

The draft maps presented in this report are the first spatially explicit, continuous maps of fishing impact and current and potential biomass in south Florida. As described, these maps will be further refined and improved before the end of the project in September 2020. The maps provide a visually appealing overview of the current state of fishes and fishing in the region that can be used in a range of education and outreach exercises with multiple stakeholders. The maps also provide a baseline for future comparisons.

Finally, the maps of fishing impact and fish biomass implicitly represent aspects of ocean value, as they represent protein that has been, or could be, harvested. Such stocks therefore represent critical ‘natural capital’, and understanding its distribution is important. As such, these maps may have multiple uses for conservation and management. They could be used to identify priority sites for new reserve zones should managers wish to establish them. While many spatial planning exercises are limited by data availability (Pittman and Brown 2011), and data are rarely available on fishing and fish stock during the planning process despite being critical inputs, these maps fill that data gap for the Florida reef tract. The maps highlight areas with relatively low fishing impact (limited conflicts with fishers), high potential increases in fish biomass, or particularly high potential stocks that could lead to significant larval production to supply fished reefs. Alternatively, reefs that already have a high biomass and a low potential for improvement may be good choices for protected areas because they are already making important contributions to achieving ecological and social objectives (e.g. biodiversity protection and tourism and recreation). The maps could also be used to provide information when considering other types of fishery regulations, such as bag limits or minimum catch sizes. However, with all planning exercises and consideration of additional regulations, the benefits of management action must be contemplated in the context of trade-offs with a wide range of other ecological and socio-economic considerations (e.g., Seeteram et al. 2019).

Finally, while the results of reducing fishing to zero as would occur in a no-take reserve have been presented here, the models also provide the future opportunity to run scenarios for different management techniques. For example, management may increase coral cover by improving water quality or through restoration activities, or increase nursery connectivity by replanting mangroves. Both these actions would be expected to increase fish biomass even in the absence of changes in fishing impact, and the models would facilitate examination of the scale and spatial variations in these increases. Furthermore, if the cost of each action was known, this work could provide information on return on investments of different activities.

## References

- Abesamis, R. A., A. L. Green, G. R. Russ, and C. R. L. Jadloc. 2014. The intrinsic vulnerability to fishing of coral reef fishes and their differential recovery in fishery closures. *Reviews In Fish Biology And Fisheries* **24**:1033-1063.
- Alvarez-Filip, L., N. K. Dulvy, J. A. Gill, I. M. Côté, and A. R. Watkinson. 2009. Flattening of Caribbean coral reefs: region-wide declines in architectural complexity. *Proceedings Of The Royal Society B-Biological Sciences* **276**:3019-3025.
- Arkema, K. K., G. M. Verutes, S. A. Wood, C. Clarke-Samuels, S. Rosado, M. Canto, A. Rosenthal, M. Ruckelshaus, G. Guannel, J. Toft, J. Faries, J. M. Silver, R. Griffin, and A. D. Guerry. 2015. Embedding ecosystem services in coastal planning leads to better outcomes for people and nature. *Proceedings of the National Academy of Sciences of the United States of America* **112**:7390-7395.
- Ault, J. S., J. A. Bohnsack, and G. A. Meester. 1998. A retrospective (1979-1996) multispecies assessment of coral reef fish stocks in the Florida Keys. *Fishery Bulletin* **96**:395-414.
- Ault, J. S., J. A. Bohnsack, S. G. Smith, and J. G. Luo. 2005. Towards sustainable multispecies fisheries in the Florida, USA, coral reef ecosystem. *Bulletin of Marine Science* **76**:595-622.
- Ault, J. S., S. G. Smith, J. A. Bohnsack, J. G. Luo, N. Zurcher, D. B. McClellan, T. A. Ziegler, D. E. Hallac, M. Patterson, M. W. Feeley, B. I. Ruttenberg, J. Hunt, D. Kimball, and B. Causey. 2013. Assessing coral reef fish population and community changes in response to marine reserves in the Dry Tortugas, Florida, USA. *Fisheries Research* **144**:28-37.
- Baine, M. 2001. Artificial reefs: a review of their design, application, management and performance. *Ocean & Coastal Management* **44**:241-259.
- Bell, J. D., and R. Galzin. 1984. Influence of live coral cover on coral-reef fish communities. *Marine Ecology Progress Series* **15**:265-274.
- Blair, S. M., T. L. McIntosh, and B. J. Mostkoff. 1994. Impacts of Hurricane Andrew on the offshore reef systems of central and northern Dade County, Florida. *Bulletin of Marine Science* **54**:961-973.
- Bohnsack, J. A. 2011. Impacts of Florida coastal protected areas on recreational world records for spotted seatrout, red drum, black drum, and common snook. *Bulletin of Marine Science* **87**:939-970.
- Bohnsack, J. A., D. E. Harper, and D. B. McClellan. 2007. Coral reef fish response to FKNMS management zone: the first ten years (1997-2007). Progress Report to the Florida Keys National Marine sanctuary. PRBD 08/09-10.
- Bozec, Y. M., L. Yakob, S. Bejarano, and P. J. Mumby. 2013. Reciprocal facilitation and non-linearity maintain habitat engineering on coral reefs. *Oikos* **122**:428-440.
- Brett, J. R. 1971. Energetic responses of salmon to temperature. A study of some thermal relations in physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*). *American Zoologist* **11**:99-118.
- Chiappone, M., D. W. Swanson, S. L. Miller, and S. G. Smith. 2002. Large-scale surveys on the Florida Reef Tract indicate poor recovery of the long-spined sea urchin *Diadema antillarum*. *Coral Reefs* **21**:155-159.
- Chollett, I., S. W. J. Canty, S. J. Box, and P. J. Mumby. 2014. Adapting to the impacts of global change on an artisanal coral reef fishery. *Ecological Economics* **102**:118-125.
- Chollett, I., and P. J. Mumby. 2012. Predicting the distribution of *Montastraea* reefs using wave exposure. *Coral Reefs* **31**:493-503.
- Chollett, I., P. J. Mumby, F. E. Müller-Karger, and C. Hu. 2012. Physical environments of the Caribbean Sea. *Limnology and Oceanography* **57**:1233-1244.
- Cinner, J. E., N. A. J. Graham, C. Huchery, and M. A. MacNeil. 2013. Global effects of local human population density and distance to markets on the condition of coral reef fisheries. *Conservation Biology* **27**:453-458.
- Cinner, J. E., C. Huchery, M. A. MacNeil, N. A. J. Graham, T. R. McClanahan, J. Maina, E. Maire, J. N. Kittinger, C. C. Hicks, C. Mora, E. H. Allison, S. D'Agata, A. Hoey, D. A. Feary, L. Crowder, I. D. Williams, M. Kulbicki, L. Vigliola, L. Wantiez, G. Edgar, R. D. Stuart-Smith, S. A. Sandin, A. L. Green, M. J. Hardt, M. Beger, A. Friedlander, S. J. Campbell, K. E. Holmes, S. K. Wilson, E. Brokovich, A. J. Brooks, J. J. Cruz-Motta, D. J. Booth, P. Chabanet, C. Gough, M. Tupper, S. C. A. Ferse, U. R. Sumaila, and D. Mouillot. 2016. Bright spots among the world's coral reefs. *Nature* **535**:416-419.

- Coker, D. J., S. K. Wilson, and M. S. Pratchett. 2014. Importance of live coral habitat for reef fishes. *Reviews In Fish Biology And Fisheries* **24**:89-126.
- Cowen, R. K., C. B. Paris, and A. Srinivasan. 2006. Scaling of connectivity in marine populations. *Science* **311**:522-527.
- Dames, V., A. Bernard, C. Floros, B. Mann, C. Speed, J. Maggs, S. Laing, M. Meekan, and J. Olbers. 2020. Zonation and reef size significantly influence fish population structure in an established marine protected area, iSimangaliso Wetland Park, South Africa. *Ocean & Coastal Management* **185**:105040.
- Davis, G. E. 1977. Anchor damage to a coral reef on the coast of Florida. *Biological Conservation* **11**:29-34.
- Dorenbosch, M., M. G. G. Grol, I. Nagelkerken, and G. van der Velde. 2006. Seagrass beds and mangroves as potential nurseries for the threatened Indo-Pacific humphead wrasse, *Cheilinus undulatus* and Caribbean rainbow parrotfish, *Scarus guacamaia*. *Biological Conservation* **129**:277-282.
- Dustan, P. 2000. The Florida Keys. Pages 405-414 in C. R. C. Sheppard, editor. *Seas at The Millennium: An environmental evaluation*. Volume 1. Elsevier Science, Amsterdam.
- Ekebom, J., P. Laihonon, and T. Suominen. 2003. A GIS-based step-wise procedure for assessing physical exposure in fragmented archipelagos. *Estuarine Coastal and Shelf Science* **57**:887-898.
- Elith, J., J. R. Leathwick, and T. Hastie. 2008. A working guide to boosted regression trees. *Journal of Animal Ecology* **77**:802-813.
- Ferrari, R., M. Gonzalez-Rivero, J. C. Ortiz, and P. J. Mumby. 2012. Interaction of herbivory and seasonality on the dynamics of Caribbean macroalgae. *Coral Reefs* **31**:683-692.
- Froese, R., and D. Pauly. 2010. FishBase. Retrieved from <http://www.fishbase.org>.
- Fulton, C. J., D. R. Bellwood, and P. C. Wainwright. 2005. Wave energy and swimming performance shape coral reef fish assemblages. *Proceedings Of The Royal Society B-Biological Sciences* **272**:827-832.
- Gove, J. M., G. J. Williams, M. A. McManus, S. F. Heron, S. A. Sandin, O. J. Vetter, and D. G. Foley. 2013. Quantifying climatological ranges and anomalies for Pacific coral reef ecosystems. *PLoS ONE* **8**:e61974.
- Graham, N. A. J., N. K. Dulvy, S. Jennings, and N. V. C. Polunin. 2005. Size-spectra as indicators of the effects of fishing on coral reef fish assemblages. *Coral Reefs* **24**:118-124.
- Graham, N. A. J., and K. L. Nash. 2013. The importance of structural complexity in coral reef ecosystems. *Coral Reefs* **32**:315-326.
- Gratwicke, B., and M. R. Speight. 2005. The relationship between fish species richness, abundance and habitat complexity in a range of shallow tropical marine habitats. *Journal of Fish Biology* **66**:650-667.
- Guillemot, N., P. Chabanet, M. Kulbicki, L. Vigliola, M. Léopold, I. Jollit, and O. Le Pape. 2014. Effects of fishing on fish assemblages in a coral reef ecosystem: From functional response to potential indicators. *Ecological Indicators* **43**:227-235.
- Halpern, B. S., and R. R. Warner. 2002. Marine reserves have rapid and lasting effects. *Ecology Letters* **5**:361-366.
- Harborne, A. R., A. L. Green, N. A. Peterson, M. Beger, Y. Golbuu, P. Houk, M. D. Spalding, B. M. Taylor, E. Terk, E. A. Treml, S. Victor, L. Vigliola, I. D. Williams, N. H. Wolff, P. S. E. zu Ermgassen, and P. J. Mumby. 2018. Modelling and mapping regional-scale patterns of fishing impact and fish stocks to support coral-reef management in Micronesia. *Diversity and Distributions* **24**:1729-1743.
- Harborne, A. R., P. J. Mumby, F. Micheli, C. T. Perry, C. P. Dahlgren, K. E. Holmes, and D. R. Brumbaugh. 2006a. The functional value of Caribbean coral reef, seagrass and mangrove habitats to ecosystem processes. *Advances in Marine Biology* **50**:57-189.
- Harborne, A. R., P. J. Mumby, K. Żychaluk, J. D. Hedley, and P. G. Blackwell. 2006b. Modeling the beta diversity of coral reefs. *Ecology* **87**:2871-2881.
- Harborne, A. R., I. Nagelkerken, N. H. Wolff, Y.-M. Bozec, M. Dorenbosch, M. G. G. Grol, and P. J. Mumby. 2016. Direct and indirect effects of nursery habitats on coral-reef fish assemblages, grazing pressure and benthic dynamics. *Oikos* **125**:957-967.
- Hixon, M. A. 2011. 60 years of coral reef fish ecology: past, present, future. *Bulletin of Marine Science* **87**:727-765.
- Hixon, M. A., and J. P. Beets. 1993. Predation, prey refuges, and the structure of coral-reef fish assemblages. *Ecological Monographs* **63**:77-101.

- Houk, P., K. Rhodes, J. Cuetos-Bueno, S. Lindfield, V. Fread, and J. L. McIlwain. 2012. Commercial coral-reef fisheries across Micronesia: A need for improving management. *Coral Reefs* **31**:13-26.
- Hughes, T. P. 1994. Catastrophes, phase shifts, and large-scale degradation of a Caribbean coral reef. *Science* **265**:1547-1551.
- Huijbers, C. M., I. Nagelkerken, A. O. Debrot, and E. Jongejans. 2013. Geographic coupling of juvenile and adult habitat shapes spatial population dynamics of a coral reef fish. *Ecology* **94**:1859-1870.
- Jacquet, C., D. Mouillot, M. Kulbicki, and D. Gravel. 2016. Extensions of Island Biogeography Theory predict the scaling of functional trait composition with habitat area and isolation. *Ecology Letters*:doi:10.1111/ele.12716.
- Jennings, S. 2005. Indicators to support an ecosystem approach to fisheries. *Fish and Fisheries* **6**:212-232.
- Jennings, S., J. D. Reynolds, and N. V. C. Polunin. 1999. Predicting the vulnerability of tropical reef fishes to exploitation with phylogenies and life histories. *Conservation Biology* **13**:1466-1475.
- Johansen, J. L., D. R. Bellwood, and C. J. Fulton. 2008. Coral reef fishes exploit flow refuges in high-flow habitats. *Marine Ecology Progress Series* **360**:219-226.
- Johns, G. M., V. R. Leeworthy, F. W. Bell, and M. A. Bonn. 2001. Socioeconomic Study of Reefs in Southeast Florida. Hazen and Sawyer, Hollywood, FL.
- Jones, G. P., M. I. McCormick, M. Srinivasan, and J. V. Eagle. 2004. Coral decline threatens fish biodiversity in marine reserves. *Proceedings of the National Academy of Sciences of the United States of America* **101**:8251-8253.
- Karr, K. A., R. Fujita, B. S. Halpern, C. V. Kappel, L. Crowder, K. A. Selkoe, P. M. Alcolado, and D. Rader. 2015. Thresholds in Caribbean coral reefs: implications for ecosystem-based fishery management. *Journal of Applied Ecology* **52**:402-412.
- Kemp, D. W., M. A. Colella, L. A. Bartlett, R. R. Ruzicka, J. W. Porter, and W. K. Fitt. 2016. Life after cold death: reef coral and coral reef responses to the 2010 cold water anomaly in the Florida Keys. *Ecosphere* **7**:e01373.
- Kronen, M., F. Magron, B. McArdle, and A. Vunisea. 2010. Reef finfishing pressure risk model for Pacific Island countries and territories. *Fisheries Research* **101**:1-10.
- MacNeil, M. A., N. A. J. Graham, J. E. Cinner, S. K. Wilson, I. D. Williams, J. Maina, S. Newman, A. M. Friedlander, S. Jupiter, N. V. C. Polunin, and T. R. McClanahan. 2015. Recovery potential of the world's coral reef fishes. *Nature* **520**:341-344.
- Manzello, D. P. 2015. Rapid recent warming of coral reefs in the Florida Keys. *Scientific Reports* **5**:16762.
- Maynard, J., J. Byrne, K. Kerrigan, D. Tracey, K. Bohnsack, F. Pagan, J. Walczak, and G. J. Williams. 2017. Coral reef resilience to climate change in the Florida Reef Tract. Florida Department of Environmental Protection, Miami, FL.
- McClanahan, T. R., N. A. J. Graham, J. M. Calnan, and M. A. MacNeil. 2007. Toward pristine biomass: reef fish recovery in coral reef marine protected areas in Kenya. *Ecological Applications* **17**:1055-1067.
- McClanahan, T. R., N. A. J. Graham, M. A. MacNeil, N. A. Muthiga, J. E. Cinner, J. H. Bruggemann, and S. K. Wilson. 2011. Critical thresholds and tangible targets for ecosystem-based management of coral reef fisheries. *Proceedings of the National Academy of Sciences of the United States of America* **108**:17230-17233.
- McClenachan, L. 2009. Documenting loss of large trophy fish from the Florida Keys with historical photographs. *Conservation Biology* **23**:636-643.
- Micheli, F., B. S. Halpern, L. W. Botsford, and R. R. Warner. 2004. Trajectories and correlates of community change in no-take marine reserves. *Ecological Applications* **14**:1709-1723.
- Mora, C. 2008. A clear human footprint in the coral reefs of the Caribbean. *Proceedings Of The Royal Society B-Biological Sciences* **275**:767-773.
- Mora, C., O. Aburto-Oropeza, A. A. Bocos, P. M. Ayotte, S. Banks, A. G. Bauman, M. Beger, S. Bessudo, D. J. Booth, E. Brokovich, A. Brooks, P. Chabanet, J. E. Cinner, J. Cortés, J. J. Cruz-Motta, A. C. Magaña, E. E. DeMartini, G. J. Edgar, D. A. Feary, S. C. A. Ferse, A. M. Friedlander, K. J. Gaston, C. Gough, N. A. J. Graham, A. Green, H. Guzman, M. Hardt, M. Kulbicki, Y. Letourneur, A. López Pérez, M. Loreau, Y. Loya, C. Martinez, I. Mascareñas-Osorio, T. Morove, M. O. Nadon, Y. Nakamura, G. Paredes, N. V. C. Polunin, M. S. Pratchett, H. Reyes Bonilla, F. Rivera, E. Sala, S. A. Sandin, G. Soler, R. Stuart-Smith, E.

- Tessier, D. P. Tittensor, M. Tupper, P. Usseglio, L. Vigliola, L. Wantiez, I. Williams, S. K. Wilson, and F. A. Zapata. 2011. Global human footprint on the linkage between biodiversity and ecosystem functioning in reef fishes. *PLoS Biology* **9**:e1000606.
- Mosquera, I., I. M. Côté, S. Jennings, and J. D. Reynolds. 2000. Conservation benefits of marine reserves for fish populations. *Animal Conservation* **3**:321-332.
- Mumby, P. J. 2006. Connectivity of reef fish between mangroves and coral reefs: algorithms for the design of marine reserves at seascape scales. *Biological Conservation* **128**:215-222.
- Mumby, P. J., S. Bejarano, Y. Golbuu, R. S. Steneck, S. N. Arnold, R. van Woesik, and A. M. Friedlander. 2013. Empirical relationships among resilience indicators on Micronesian reefs. *Coral Reefs* **32**:213-226.
- Mumby, P. J., A. J. Edwards, J. E. Arias-González, K. C. Lindeman, P. G. Blackwell, A. Gall, M. I. Gorczyńska, A. R. Harborne, C. L. Pescod, H. Renken, C. C. C. Wabnitz, and G. Llewellyn. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature* **427**:533-536.
- Mumby, P. J., and A. R. Harborne. 2010. Marine reserves enhance the recovery of corals on Caribbean reefs. *PLoS ONE*:e8657.
- O'Toole, A. C., A. J. Danylchuk, T. L. Goldberg, C. D. Suski, D. P. Philipp, E. Brooks, and S. J. Cooke. 2011. Spatial ecology and residency patterns of adult great barracuda (*Sphyraena barracuda*) in coastal waters of The Bahamas. *Marine Biology* **158**:2227-2237.
- Palandro, D. A., S. Andréfouët, C. Hu, P. Hallock, F. E. Müller-Karger, P. Dustan, M. K. Callahan, C. Kranenburg, and C. R. Beaver. 2008. Quantification of two decades of shallow-water coral reef habitat decline in the Florida Keys National Marine Sanctuary using Landsat data (1984-2002). *Remote Sensing of Environment* **112**:3388-3399.
- Pittman, S. J., and K. A. Brown. 2011. Multi-scale approach for predicting fish species distributions across coral reef seascapes. *PLoS ONE* **6**:e20583.
- Pratchett, M. S., P. L. Munday, S. K. Wilson, N. A. J. Graham, J. E. Cinner, D. R. Bellwood, G. P. Jones, N. V. C. Polunin, and T. R. McClanahan. 2008. Effects of climate-induced coral bleaching on coral-reef fishes - Ecological and economic consequences. *Oceanography and Marine Biology: An Annual Review* **46**:251-296.
- Precht, W. F., B. E. Gintert, M. L. Robbart, R. Fura, and R. van Woesik. 2016. Unprecedented disease-related coral mortality in southeastern Florida. *Scientific Reports* **6**:31374.
- Riegl, B. M., and R. E. Dodge, editors. 2008. *Coral Reefs of the USA*. Springer, Dordrecht, Netherlands.
- Robertson, D. R., and J. M. Sheldon. 1979. Competitive interactions and the availability of sleeping sites for a diurnal coral reef fish. *Journal of Experimental Marine Biology and Ecology* **40**:285-298.
- Rogers, A., J. L. Blanchard, and P. J. Mumby. 2014. Vulnerability of coral reef fisheries to a loss of structural complexity. *Current Biology* **24**:1000-1005.
- Russ, G. R. 2002. Yet another review of marine reserves as reef fishery management tools. Pages 421-443 in P. F. Sale, editor. *Coral reef fishes: dynamics and diversity in a complex ecosystem*. Academic Press, San Diego.
- Russ, G. R., and A. C. Alcala. 2004. Marine reserves: long-term protection is required for full recovery of predatory fish populations. *Oecologia* **138**:622-627.
- Russ, G. R., A. J. Cheal, A. M. Dolman, M. J. Emslie, R. D. Evans, I. Miller, H. Sweatman, and D. H. Williamson. 2008. Rapid increase in fish numbers follows creation of world's largest marine reserve network. *Current Biology* **18**:R514-R515.
- Ruttenberg, B. I., P. J. Schofield, J. L. Akins, A. Acosta, M. W. Feeley, J. Blondeau, S. G. Smith, and J. S. Ault. 2012. Rapid invasion of Indo-Pacific lionfishes (*Pterois volitans* and *Pterois miles*) in the Florida Keys, USA: evidence from multiple pre- and post-invasion data sets. *Bulletin of Marine Science* **88**:1051-1059.
- Sherman, K. D., C. P. Dahlgren, J. R. Stevens, and C. R. Tyler. 2016. Integrating population biology into conservation management for endangered Nassau grouper *Epinephelus striatus*. *Marine Ecology Progress Series* **554**:263-280.
- Shin, Y.-J., L. J. Shannon, A. Bundy, M. Coll, K. Aydin, N. Bez, J. L. Blanchard, M. d. F. Borges, I. Diallo, E. Diaz, J. J. Heymans, L. Hill, E. Johannesen, D. Jouffre, S. Kifani, P. Labrosse, J. S. Link, S. Mackinson, H. Masski, C. Möllmann, S. Neira, H. Ojaveer, K. O. M. Abdallahi, I. Perry, D. Thiao, D. Yemane, and

- P. M. Cury. 2010. Using indicators for evaluating, comparing, and communicating the ecological status of exploited marine ecosystems. 2. Setting the scene. *ICES Journal of Marine Science* **67**:692-716.
- Shin, Y. J., M. J. Rochet, S. Jennings, J. G. Field, and H. Gislason. 2005. Using size-based indicators to evaluate the ecosystem effects of fishing. *ICES Journal of Marine Science* **62**:384-396.
- Shinn, E. A., and B. H. Lidz. 2018. *Geology of the Florida Keys*. University Press of Florida, Gainesville, FL.
- Soykan, C. U., T. Eguchi, S. Kohin, and H. Dewar. 2014. Prediction of fishing effort distributions using boosted regression trees. *Ecological Applications* **24**:71-83.
- Sponaugle, S., C. Paris, K. D. Walter, V. Kourafalou, and E. D'Alessandro. 2012a. Observed and modeled larval settlement of a reef fish to the Florida Keys. *Marine Ecology Progress Series* **453**:201-212.
- Sponaugle, S., K. D. Walter, K. Grorud-Colvert, and M. J. Paddock. 2012b. Influence of marine reserves on reef fish recruitment in the upper Florida Keys. *Coral Reefs* **31**:641-652.
- Stallings, C. D. 2009. Fishery-independent data reveal negative effect of human population density on Caribbean predatory fish communities. *PLoS ONE* **4**:e5333.
- Taylor, B. M., P. Houk, G. R. Russ, and J. H. Choat. 2014a. Life histories predict vulnerability to overexploitation in parrotfishes. *Coral Reefs* **33**:869-878.
- Taylor, B. M., S. J. Lindfield, and J. H. Choat. 2014b. Hierarchical and scale-dependent effects of fishing pressure and environment on the structure and size distribution of parrotfish communities. *Ecography* **37**:001-011. doi: 010.1111/ecog.01093.
- Toth, L. T., I. B. Kuffner, A. Stathakopoulos, and E. A. Shinn. 2018. A 3,000-year lag between the geological and ecological shutdown of Florida's coral reefs. *Global Change Biology* **24**:5471-5483.
- Vallès, H., D. Gill, and H. A. Oxenford. 2015. Parrotfish size as a useful indicator of fishing effects in a small Caribbean island. *Coral Reefs* **34**:789-801.
- Vallès, H., and H. A. Oxenford. 2014. Parrotfish size: A simple yet useful alternative indicator of fishing effects on Caribbean reefs? *PLoS ONE* **9**:e86291.
- van Woesik, R., K. Ripple, and S. L. Miller. 2018. Macroalgae reduces survival of nursery-reared *Acropora* corals in the Florida reef tract. *Restoration Ecology* **26**:563-569.
- Walker, B. K., and D. S. Gilliam. 2013. Determining the extent and characterizing coral reef habitats of the northern latitudes of the Florida Reef Tract (Martin County). *PLoS ONE* **8**:e80439.
- Ward-Paige, C. A., M. J. Risk, O. A. Sherwood, and W. C. Jaap. 2005. Clionid sponge surveys on the Florida Reef Tract suggest land-based nutrient inputs. *Marine Pollution Bulletin* **51**:570-579.
- Williams, I. D., J. K. Baum, A. Heenan, K. M. Hanson, M. O. Nadon, and R. E. Brainard. 2015a. Human, oceanographic and habitat drivers of central and western Pacific coral reef fish assemblages. *PLoS ONE* **10**:e0120516.
- Williams, S. M., I. Chollett, G. Roff, J. Cortés, C. S. Dryden, and P. J. Mumby. 2015b. Hierarchical spatial patterns in Caribbean reef benthic assemblages. *Journal of Biogeography* **42**:1327-1335.
- Wolff, N., R. Grober-Dunsmore, C. S. Rogers, and J. Beets. 1999. Management implications of fish trap effectiveness in adjacent coral reef and gorgonian habitats. *Environmental Biology of Fishes* **55**:81-90.

## Appendix 1. List of fish species (and species groups) included in fish survey data used for this project.

Scientific Name	Common Name	Family		Tropic group <sup>1</sup>	Species groups <sup>2,3,4</sup>
<i>Engraulidae species</i>	Anchovy Species	Anchovies	Engraulidae		✓
<i>Anchoa lyolepsis</i>	Dusky Anchovy	Anchovies	Engraulidae		✓
<i>Holacanthus species</i>	<i>Holacanthus</i> angelfish	Angelfishes	Pomacanthidae		
<i>Centropyge aurantonotus</i>	Flameback Angelfish	Angelfishes	Pomacanthidae		
<i>Pomacanthus species</i>	<i>Pomacanthus</i> angelfish	Angelfishes	Pomacanthidae	H	
<i>Centropyge argi</i>	Cherubfish	Angelfishes	Pomacanthidae		
<i>Holacanthus bermudensis</i>	Blue Angelfish	Angelfishes	Pomacanthidae		ML
<i>Holacanthus ciliaris</i>	Queen Angelfish	Angelfishes	Pomacanthidae		ML
<i>Holacanthus tricolor</i>	Rock Beauty	Angelfishes	Pomacanthidae		
<i>Pomacanthus arcuatus</i>	Gray Angelfish	Angelfishes	Pomacanthidae		ML
<i>Pomacanthus paru</i>	French Angelfish	Angelfishes	Pomacanthidae		ML
<i>Holacanthus townsendi</i>	Townsend Angelfish	Angelfishes	Pomacanthidae		ML
<i>Antennarius ocellatus</i>	Ocellated Frogfish	Anglerfishes	Antennariidae	P	ML
<i>Sphyaena barracuda</i>	Great Barracuda	Barracudas	Sphyaenidae	P	✓
<i>Sphyaena guachancho</i>	Guaguanche	Barracudas	Sphyaenidae	P	
<i>Sphyaena picudilla</i>	Southern Sennet	Barracudas	Sphyaenidae	P	
<i>Gramma loreto</i>	Fairy Basslet	Basslets	Grammatidae		ML
<i>Ogcocephalus nasutus</i>	Shortnose Batfish	Batfishes	Ogcocephalidae		ML
<i>Ogcocephalus sp.</i>	Batfish species	Batfishes	Ogcocephalidae		ML
<i>Priacanthus arenatus</i>	Bigeye	Bigeyes	Priacanthidae		
<i>Heteropriacanthus cruentatus</i>	Glasseye Snapper	Bigeyes	Priacanthidae		
<i>Albula vulpes</i>	Bonefish	Bonefishes	Albulidae		✓
<i>Lactophrys species</i>	Trunkfish species	Boxfishes	Ostraciidae		
<i>Lactophrys bicaudalis</i>	Spotted Trunkfish	Boxfishes	Ostraciidae		ML
<i>Acanthostracion polygonia</i>	Honeycomb Cowfish	Boxfishes	Ostraciidae		ML
<i>Acanthostracion quadricornis</i>	Scrawled Cowfish	Boxfishes	Ostraciidae		ML
<i>Lactophrys trigonus</i>	Trunkfish	Boxfishes	Ostraciidae		ML
<i>Lactophrys triqueter</i>	Smooth Trunkfish	Boxfishes	Ostraciidae		ML
<i>Peprilus triacanthus</i>	American Butterfish	Butterfishes	Stromateidae		✓
<i>Stromateidae species</i>	Butterfish species	Butterfishes	Stromateidae		
<i>Prognathodes aya</i>	Bank Butterflyfish	Butterflyfishes	Chaetodontidae		
<i>Chaetodon capistratus</i>	Foureye Butterflyfish	Butterflyfishes	Chaetodontidae		ML
<i>Chaetodon ocellatus</i>	Spotfin Butterflyfish	Butterflyfishes	Chaetodontidae		ML
<i>Chaetodon sedentarius</i>	Reef Butterflyfish	Butterflyfishes	Chaetodontidae		ML
<i>Chaetodon striatus</i>	Banded Butterflyfish	Butterflyfishes	Chaetodontidae		ML

<i>Prognathodes aculeatus</i>	Longsnout Butterflyfish	Butterflyfishes	Chaetodontidae		ML
<i>Astrapogon puncticulatus</i>	Blackfin Cardinalfish	Cardinalfishes	Apogonidae		ML
<i>Phaeoptyx xenus</i>	Sponge Cardinalfish	Cardinalfishes	Apogonidae		ML
<i>Apogon phenax</i>	Mimic Cardinalfish	Cardinalfishes	Apogonidae		ML
<i>Apogon lachneri</i>	Whitestar Cardinalfish	Cardinalfishes	Apogonidae		
<i>Apogon species</i>	Cardinalfish Species	Cardinalfishes	Apogonidae		
<i>Apogon binotatus</i>	Barred Cardinalfish	Cardinalfishes	Apogonidae		ML
<i>Apogon pseudomaculatus</i>	Twospot Cardinalfish	Cardinalfishes	Apogonidae		ML
<i>Apogon maculatus</i>	Flamefish	Cardinalfishes	Apogonidae		
<i>Apogon quadrisquamatus</i>	Sawcheek Cardinalfish	Cardinalfishes	Apogonidae		ML
<i>Astrapogon stellatus</i>	Conchfish	Cardinalfishes	Apogonidae		
<i>Apogon aurolineatus</i>	Bridle Cardinalfish	Cardinalfishes	Apogonidae		ML
<i>Apogon townsendi</i>	Belted Cardinalfish	Cardinalfishes	Apogonidae		ML
<i>Astrapogon sp.</i>	Cardinalfish species	Cardinalfishes	Apogonidae		ML
<i>Rachycentron canadum</i>	Cobia	Cobia	Rachycentridae		✓
<i>Entomacrodus nigricans</i>	Pearl Blenny	Combtooth Blennies	Blenniidae	H	
<i>Hypleurochilus bermudensis</i>	Barred Blenny	Combtooth Blennies	Blenniidae		ML
<i>Ophioblennius macclurei</i>	Redlip Blenny	Combtooth Blennies	Blenniidae	H	ML
<i>Scartella cristata</i>	Molly Miller	Combtooth Blennies	Blenniidae	H	
<i>Parablennius marmoreus</i>	Seaweed Blenny	Combtooth Blennies	Blenniidae		ML
<i>blenny species</i>	Blenny species	Combtooth Blennies	Blenniidae		ML
<i>Ariosoma balearicum</i>	Bandtooth Conger	Conger Eels	Congridae		
<i>Conger triporiceps</i>	Manytooth Conger	Conger Eels	Congridae	P	
<i>Heteroconger longissimus</i>	Brown Garden Eel	Conger Eels	Congridae		
<i>Fistularia tabacaria</i>	Bluespotted Cornetfish	Cornetfishes	Fistulariidae	P	ML
<i>Rhinoptera bonasus</i>	Cownose Ray	Cownose Rays	Rhinopteridae		
<i>Brotula barbata</i>	Atlantic Bearded Brotula	Cusk-eels	Ophidiidae		
<i>Abudefduf taurus</i>	Night Sergeant	Damselfishes	Pomacentridae	H	
<i>Abudefduf saxatilis</i>	Sergeant Major	Damselfishes	Pomacentridae		
<i>Chromis cyanea</i>	Blue Chromis	Damselfishes	Pomacentridae		
<i>Chromis enchrysur</i>	Yellowtail Reeffish	Damselfishes	Pomacentridae		
<i>Chromis insolata</i>	Sunshinefish	Damselfishes	Pomacentridae		
<i>Chromis multilineata</i>	Brown Chromis	Damselfishes	Pomacentridae		
<i>Chromis scotti</i>	Purple Reeffish	Damselfishes	Pomacentridae		
<i>Microspathodon chrysurus</i>	Yellowtail Damselfish	Damselfishes	Pomacentridae	H	ML
<i>Stegastes diencaeus</i>	Longfin Damselfish	Damselfishes	Pomacentridae	H	ML
<i>Stegastes adustus</i>	Dusky Damselfish	Damselfishes	Pomacentridae	H	ML
<i>Stegastes leucostictus</i>	Beaugregory	Damselfishes	Pomacentridae		
<i>Stegastes partitus</i>	Bicolor Damselfish	Damselfishes	Pomacentridae	H	ML
<i>Stegastes planifrons</i>	Threespot Damselfish	Damselfishes	Pomacentridae		ML

<i>Stegastes variabilis</i>	Cocoa Damselfish	Damselfishes	Pomacentridae	H	ML
<i>damselfish species</i>	Damselfish species	Damselfishes	Pomacentridae		ML
<i>Ptereleotris calliura</i>	Blue Dartfish	Dartfishes	Microdesmidae		
<i>Ptereleotris helenae</i>	Hovering Dartfish	Dartfishes	Microdesmidae		
<i>Callionymus bairdi</i>	Lancer Dragonet	Dragonets	Callionymidae		
<i>Umbrina coroides</i>	Sand Drum	Drums and Croakers	Sciaenidae		✓
<i>drum species</i>	Drum species	Drums and Croakers	Sciaenidae		✓
<i>Pareques acuminatus</i>	High-Hat	Drums and Croakers	Sciaenidae	H	ML
<i>Equetus lanceolatus</i>	Jackknife-Fish	Drums and Croakers	Sciaenidae		ML
<i>Equetus punctatus</i>	Spotted Drum	Drums and Croakers	Sciaenidae		ML
<i>Pareques umbrosus</i>	Cubbyu	Drums and Croakers	Sciaenidae		ML
<i>Odontoscion dentex</i>	Reef Croaker	Drums and Croakers	Sciaenidae		ML
<i>Manta birostris</i>	Giant Manta	Eagle and Manta Rays	Myliobatidae		
<i>Aetobatus narinari</i>	Spotted Eagle Ray	Eagle Rays	Aetobatidae		
<i>Stephanolepis setifer</i>	Pygmy Filefish	Filefishes	Monacanthidae	H	ML
<i>Monacanthus ciliatus</i>	Fringed Filefish	Filefishes	Monacanthidae	H	ML
<i>Aluterus schoepfii</i>	Orange Filefish	Filefishes	Monacanthidae		ML
<i>Aluterus scriptus</i>	Scrawled Filefish	Filefishes	Monacanthidae		ML
<i>Cantherhines macrocerus</i>	Whitespotted Filefish	Filefishes	Monacanthidae		ML
<i>Cantherhines pullus</i>	Orangespotted Filefish	Filefishes	Monacanthidae		ML
<i>Stephanolepis hispidus</i>	Planehead Filefish	Filefishes	Monacanthidae		ML
<i>Monacanthus tuckeri</i>	Slender Filefish	Filefishes	Monacanthidae		ML
<i>Aluterus monoceros</i>	Unicorn Filefish	Filefishes	Monacanthidae		
<i>Aluterus sp.</i>	<i>Aluterus</i> filefish	Filefishes	Monacanthidae		ML
<i>Mocanthus species</i>	<i>Mocanthus</i> filefish	Filefishes	Monocanthidae		ML
<i>Dactylopterus volitans</i>	Flying Gurnard	Flying gurnards	Dactylopteridae		
<i>Upeneus parvus</i>	Dwarf Goatfish	Goatfishes	Mullidae		
<i>Mulloidichthys martinicus</i>	Yellow Goatfish	Goatfishes	Mullidae		
<i>Pseudupeneus maculatus</i>	Spotted Goatfish	Goatfishes	Mullidae		
<i>Coryphopterus tortugae</i>	Patch-Reef Goby	Gobies	Gobiidae		
<i>Coryphopterus venezuelae</i>	Sand-Canyon Goby	Gobies	Gobiidae		
<i>Ctenogobius stigmaticus</i>	Marked Goby	Gobies	Gobiidae		
<i>Elacatinus chancei</i>	Shortstripe Goby	Gobies	Gobiidae		
<i>Elacatinus louisae</i>	Spotlight Goby	Gobies	Gobiidae		
<i>Elacatinus multifasciatus</i>	Greenbanded Goby	Gobies	Gobiidae		
<i>Elacatinus prochilos</i>	Broadstripe Goby	Gobies	Gobiidae		
<i>Gobiosoma grosvenori</i>	Rockcut Goby	Gobies	Gobiidae		
<i>Microgobius signatus</i>	Dashback Goby	Gobies	Gobiidae		
<i>Microgobius species</i>	Microgobius gobies	Gobies	Gobiidae	H	
<i>Risor ruber</i>	Tusked Goby	Gobies	Gobiidae		

<i>Syngnathus dawsoni</i>	Dashback Goby	Gobies	Gobiidae	H	
<i>Coryphopterus dicrus</i>	Colon Goby	Gobies	Gobiidae		ML
<i>Coryphopterus eidolon</i>	Pallid Goby	Gobies	Gobiidae	H	ML
<i>Coryphopterus glaucofraenum</i>	Bridled Goby	Gobies	Gobiidae		ML
<i>Coryphopterus personatus</i>	Masked Goby	Gobies	Gobiidae		ML
<i>Gnatholepis thompsoni</i>	Goldspot Goby	Gobies	Gobiidae	H	ML
<i>Elacatinus evelynae</i>	Sharknose Goby	Gobies	Gobiidae		ML
<i>Elacatinus macrodon</i>	Tiger Goby	Gobies	Gobiidae		ML
<i>Elacatinus oceanops</i>	Neon Goby	Gobies	Gobiidae		ML
<i>Microgobius carri</i>	Seminole Goby	Gobies	Gobiidae	H	ML
<i>Microgobius microlepis</i>	Banner Goby	Gobies	Gobiidae		ML
<i>Oxyurichthys stigmatophius</i>	Spotfin Goby	Gobies	Gobiidae		ML
<i>Nes longus</i>	Orangespotted Goby	Gobies	Gobiidae	H	ML
<i>Priolepis hipoliti</i>	Rusty Goby	Gobies	Gobiidae		ML
<i>Elacatinus xanthiprora</i>	Yellowprow Goby	Gobies	Gobiidae		ML
<i>Coryphopterus punctiptephorus</i>	Spotted Goby	Gobies	Gobiidae		ML
<i>Ctenogobius saepepallens</i>	Dash Goby	Gobies	Gobiidae		ML
<i>Elacatinus horsti</i>	Yellowline Goby	Gobies	Gobiidae		ML
<i>Coryphopterus lipernes</i>	Peppermint Goby	Gobies	Gobiidae		ML
<i>Elacatinus saucrum</i>	Leopard Goby	Gobies	Gobiidae		ML
<i>Coryphopterus sp.</i>	<i>Coryphopterus gobies</i>	Gobies	Gobiidae		ML
<i>goby species</i>	Goby species	Gobies	Gobiidae		ML
<i>Elacatinus randalli</i>	Yellownose Goby	Gobies	Gobiidae		ML
<i>Elacatinus dilepis</i>	Orangeside Goby	Gobies	Gobiidae		ML
<i>Bollmannia boqueronensis</i>	White-Eye Goby	Gobies	Gobiidae	H	ML
<i>Lophogobius cyprinoides</i>	Crested Goby	Gobies	Gobiidae	H	
<i>Bathygobius soporator</i>	Frillfin Goby	Gobies	Gobiidae		
<i>Emmelichthys atlanticus</i>	Bonnetmouth	Grunts	Haemulidae	P	
<i>Inermia vittata</i>	Boga	Grunts	Haemulidae		
<i>Anisotremus surinamensis</i>	Black Margate	Grunts	Haemulidae		✓
<i>Anisotremus virginicus</i>	Porkfish	Grunts	Haemulidae		✓, ML
<i>Haemulon album</i>	Margate	Grunts	Haemulidae		SG
<i>Haemulon aurolineatum</i>	Tomtate	Grunts	Haemulidae		SG
<i>Haemulon carbonarium</i>	Caesar Grunt	Grunts	Haemulidae		✓
<i>Haemulon chrysargyreum</i>	Smallmouth Grunt	Grunts	Haemulidae		✓
<i>Haemulon flavolineatum</i>	French Grunt	Grunts	Haemulidae		✓
<i>Haemulon macrostomum</i>	Spanish Grunt	Grunts	Haemulidae		✓
<i>Haemulon melanurum</i>	Cottonwick	Grunts	Haemulidae		SG
<i>Haemulon parra</i>	Sailor's Choice	Grunts	Haemulidae		SG
<i>Haemulon plumierii</i>	White Grunt	Grunts	Haemulidae		SG

<i>Haemulon sciurus</i>	Bluestriped Grunt	Grunts	Haemulidae		✓
<i>Haemulon striatum</i>	Striped Grunt	Grunts	Haemulidae		✓
<i>Orthopristis chrysoptera</i>	Pigfish	Grunts	Haemulidae		✓
<i>Haemulon sp.</i>	Grunt species	Grunts	Haemulidae		✓
<i>Rhinobatos lentiginosus</i>	Atlantic Guitarfish	Guitarfishes	Rhinobatidae		
<i>Hemiramphus brasiliensis</i>	Ballyhoo	Halfbeaks	Hemiramphidae		✓
<i>Chriodorus atherinoides</i>	Hardhead Halfbeak	Halfbeaks	Hemiramphidae		
<i>Sphyrna lewini</i>	Scalloped Hammerhead	Hammerhead Sharks	Sphyrnidae	P	
<i>Sphyrna mokarran</i>	Great Hammerhead	Hammerhead Sharks	Sphyrnidae	P	
<i>Sphyrna tiburo</i>	Bonnethead	Hammerhead Sharks	Sphyrnidae	P	✓
<i>Amblycirrhitus pinos</i>	Redspotted Hawkfish	Hawkfishes	Cirrhitidae		ML
<i>Clupeidae species</i>	Herring species	Herrings	Clupeidae		✓
<i>Harengula jaguana</i>	Scaled Sardine	Herrings	Clupeidae		✓
<i>Sardinella aurita</i>	Spanish Sardine	Herrings	Clupeidae		✓
<i>Harengula humeralis</i>	Redear Sardine	Herrings	Clupeidae		✓
<i>Jenkinsia sp.</i>	Herring Species	Herrings	Clupeidae		✓
<i>Trachinotus goodei</i>	Palometa	Jacks	Carangidae	P	✓
<i>Chloroscombus chrysurus</i>	Atlantic Bumper	Jacks	Carangidae		
<i>Seriola zonata</i>	Banded Rudderfish	Jacks	Carangidae		SG
<i>Trachurus lathami</i>	Rough Scad	Jacks	Carangidae		✓
<i>Decapterus sp.</i>	Scad species	Jacks	Carangidae		✓
<i>Selar crumenophthalmus</i>	Bigeye Scad	Jacks	Carangidae	P	✓
<i>Alectis ciliaris</i>	African Pompano	Jacks	Carangidae	P	✓
<i>Carangoides bartholomaei</i>	Yellow Jack	Jacks	Carangidae	P	✓
<i>Caranx crysos</i>	Blue Runner	Jacks	Carangidae	P	✓
<i>Caranx hippos</i>	Crevalle Jack	Jacks	Carangidae	P	✓
<i>Caranx latus</i>	Horse-Eye Jack	Jacks	Carangidae	P	✓
<i>Caranx ruber</i>	Bar Jack	Jacks	Carangidae	P	SG
<i>Decapterus macarellus</i>	Mackerel Scad	Jacks	Carangidae		✓
<i>Decapterus punctatus</i>	Round Scad	Jacks	Carangidae		✓
<i>Elagatis bipinnulata</i>	Rainbow Runner	Jacks	Carangidae		✓
<i>Seriola dumerili</i>	Greater Amberjack	Jacks	Carangidae	P	SG
<i>Trachinotus falcatus</i>	Permit	Jacks	Carangidae	P	✓
<i>Selene vomer</i>	Lookdown	Jacks	Carangidae		✓
<i>Seriola rivoliana</i>	Almaco Jack	Jacks	Carangidae	P	SG
<i>Oligoplites saurus</i>	Leatherjack	Jacks	Carangidae		✓
<i>Caranx lugubris</i>	Black Jack	Jacks	Carangidae	P	✓
<i>Caranx sp.</i>	Jack Species	Jacks	Carangidae		✓
<i>Lonchopisthus micrognathus</i>	Swordtail Jawfish	Jawfishes	Opistognathidae	P	
<i>Opistognathus maxilloso</i>	Mottled Jawfish	Jawfishes	Opistognathidae		

<i>Opistognathus aurifrons</i>	Yellowhead Jawfish	Jawfishes	Opistognathidae		ML
<i>Opistognathus whitehursti</i>	Dusky Jawfish	Jawfishes	Opistognathidae	P	ML
<i>Opistognathus macrognaathus</i>	Banded Jawfish	Jawfishes	Opistognathidae	P	ML
<i>Opistognathus sp.</i>	Jawfish species	Jawfishes	Opistognathidae		ML
<i>Labrisomus nigricinctus</i>	Spotcheek Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Labrisomus kalisheriae</i>	Downy Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Malacoctenus boehlkei</i>	Diamond Blenny	Labrisomid Blennies	Labrisomidae		
<i>Malacoctenus species</i>	Blenny Species	Labrisomid Blennies	Labrisomidae		
<i>Malacoctenus gilli</i>	Dusky Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Malacoctenus versicolor</i>	Barfin Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Labrisomus gobio</i>	Palehead Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Labrisomus nuchipinnis</i>	Hairy Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Malacoctenus macropus</i>	Rosy Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Malacoctenus triangulatus</i>	Saddled Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Paraclinus marmoratus</i>	Marbled Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Paraclinus nigripinnis</i>	Blackfin Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Labrisomus filamentosus</i>	Quillfin Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Labrisomus bucciferus</i>	Puffcheek Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Malacoctenus aurolineatus</i>	Goldline Blenny	Labrisomid Blennies	Labrisomidae		ML
<i>Syacium micrurum</i>	Channel Flounder	Large-tooth Flounders	Paralichthyidae	P	✓
<i>Syacium species</i>	Sand Flounder Species	Large-tooth Flounders	Paralichthyidae		✓
<i>Paralichthys albigutta</i>	Gulf Flounder	Large-tooth Flounders	Paralichthyidae		✓
<i>Bothus lunatus</i>	Peacock Flounder	Lefteye Flounders	Bothidae	P	✓
<i>Bothus ocellatus</i>	Eyed Flounder	Lefteye Flounders	Bothidae	P	✓
<i>Bothus species</i>	Lefteye Flounders	Lefteye Flounders	Bothidae		✓
<i>Synodus synodus</i>	Red Lizardfish	Lizardfishes	Synodontidae		
<i>Synodus saurus</i>	Bluestriped Lizardfish	Lizardfishes	Synodontidae	P	
<i>Synodus foetens</i>	Inshore Lizardfish	Lizardfishes	Synodontidae	P	
<i>Synodus intermedius</i>	Sand Diver	Lizardfishes	Synodontidae	P	
<i>Acanthocybium solandri</i>	Wahoo	Mackerels, Tunas, Bonitos	Scombridae		✓
<i>Sarda sarda</i>	Atlantic Bonito	Mackerels, Tunas, Bonitos	Scombridae	P	✓
<i>Scomberomorus cavalla</i>	King Mackerel	Mackerels, Tunas, Bonitos	Scombridae	P	✓
<i>Scomberomorus maculatus</i>	Spanish Mackerel	Mackerels, Tunas, Bonitos	Scombridae	P	
<i>Scomberomorus regalis</i>	Cero	Mackerels, Tunas, Bonitos	Scombridae	P	✓
<i>Euthynnus alletteratus</i>	Little Tunny	Mackerels, Tunas, Bonitos	Scombridae	P	✓
<i>Eucinostomus lefroyi</i>	Mottled Mojarra	Mojarras	Gerreidae		
<i>Gerres sp.</i>	Mojarra species	Mojarras	Gerreidae		

<i>Eucinostomus melanopterus</i>	Flagfin Mojarra	Mojarras	Gerreidae		
<i>Eucinostomus argenteus</i>	Spotfin Mojarra	Mojarras	Gerreidae		✓
<i>Gerres cinereus</i>	Yellowfin Mojarra	Mojarras	Gerreidae		✓
<i>Eucinostomus gula</i>	Silver Jenny	Mojarras	Gerreidae		✓
<i>Eucinostomus jonesii</i>	Slender Mojarra	Mojarras	Gerreidae		
<i>Gymnothorax nigromarginatus</i>	Blackedge Moray	Morays	Muraenidae		ML
<i>Enchelycore carychroa</i>	Chestnut Moray	Morays	Muraenidae		
<i>Echidna catenata</i>	Chain Moray	Morays	Muraenidae		
<i>Gymnothorax species</i>	Gymnothorax eels	Morays	Muraenidae	P	
<i>Muraenidae species</i>	Moray species	Morays	Muraenidae		
<i>Gymnothorax miliaris</i>	Goldentail Moray	Morays	Muraenidae		ML
<i>Gymnothorax funebris</i>	Green Moray	Morays	Muraenidae	P	ML
<i>Gymnothorax moringa</i>	Spotted Moray	Morays	Muraenidae	P	ML
<i>Gymnothorax vicinus</i>	Purplemouth Moray	Morays	Muraenidae	P	ML
<i>Gymnothorax saxicola</i>	Honeycomb Moray	Morays	Muraenidae		ML
<i>Muraena retifera</i>	Reticulate Moray	Morays	Muraenidae		ML
<i>Enchelycore nigricans</i>	Viper Moray	Morays	Muraenidae	P	ML
<i>Mugil cephalus</i>	Striped Mullet	Mulletts	Mugilidae	H	✓
<i>shark species</i>	Shark species	Multiple families	Multiple families		
<i>needlefish species</i>	Needlefish species	Needlefishes	Belonidae		
<i>Ablennes hians</i>	Flat Needlefish	Needlefishes	Belonidae	P	
<i>Platybelone argalus argalus</i>	Keeltail Needlefish	Needlefishes	Belonidae	P	
<i>Strongylura timucu</i>	Timucu	Needlefishes	Belonidae		
<i>Tylosurus crocodilus</i>	Houndfish	Needlefishes	Belonidae		
<i>Strongylura notata</i>	Redfin Needlefish	Needlefishes	Belonidae		
<i>Narcine bancroftii</i>	Lesser Electric Ray	Numbfishes	Narcinidae		
<i>Ginglymostoma cirratum</i>	Nurse Shark	Nurse Sharks	Ginglymostomatidae	P	✓
<i>Atherinomorus species</i>	Silverside species	Old World Silversides	Atherinidae		
<i>Atherinomorus stipes</i>	Hardhead Silverside	Old World Silversides	Atherinidae		
<i>Hypoatherina harringtonensis</i>	Reef Silverside	Old World Silversides	Atherinidae		
<i>Cryptotomus roseus</i>	Bluelip Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Nicholsina usta</i>	Emerald Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Scarus coelestinus</i>	Midnight Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Scarus coeruleus</i>	Blue Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Scarus iseri</i>	Striped Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Scarus guacamaia</i>	Rainbow Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Scarus taeniopterus</i>	Princess Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Scarus vetula</i>	Queen Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Sparisoma atomarium</i>	Greenblotch Parrotfish	Parrotfishes	Scaridae	H	ML

<i>Sparisoma aurofrenatum</i>	Redband Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Sparisoma chrysopterum</i>	Redtail Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Sparisoma radians</i>	Bucktooth Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Sparisoma rubripinne</i>	Yellowtail Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Sparisoma viride</i>	Stoplight Parrotfish	Parrotfishes	Scaridae	H	ML
<i>Sparisoma sp.</i>	<i>Sparisoma</i> parrotfishes	Parrotfishes	Scaridae	H	ML
<i>Scarus sp.</i>	<i>Scarus</i> parrotfishes	Parrotfishes	Scaridae	H	ML
<i>Amphelikurus dendritica</i>	Pipehorse	Pipefishes and Seahorses	Syngnathidae		
<i>Syngnathus scovelli</i>	Gulf Pipefish	Pipefishes and Seahorses	Syngnathidae		ML
<i>Hippocampus reidi</i>	Longsnout Seahorse	Pipefishes and Seahorses	Syngnathidae		ML
<i>Hippocampus erectus</i>	Lined Seahorse	Pipefishes and Seahorses	Syngnathidae		ML
<i>Syngnathus sp.</i>	Pipefish Species	Pipefishes and Seahorses	Syngnathidae		
<i>Cosmocampus elucens</i>	Shortfin Pipefish	Pipefishes and Seahorses	Syngnathidae		
<i>Hippocampus species</i>	Seahorse/Pipefish Species	Pipefishes and Seahorses	Syngnathidae		
<i>Chilomycterus atinga</i>	Spotted Burrfish	Porcupinefishes	Diodontidae		
<i>Chilomycterus antennatus</i>	Bridled Burrfish	Porcupinefishes	Diodontidae		ML
<i>Diodon holocanthus</i>	Balloonfish	Porcupinefishes	Diodontidae		ML
<i>Diodon hystrix</i>	Porcupinefish	Porcupinefishes	Diodontidae		ML
<i>Chilomycterus schoepfii</i>	Striped Burrfish	Porcupinefishes	Diodontidae		ML
<i>puffer species</i>	Puffer species	Porcupinefishes	Diodontidae		ML
<i>Calamus leucosteus</i>	Whitebone Porgy	Porgies	Sparidae		SG
<i>Calamus pennatula</i>	Pluma Porgy	Porgies	Sparidae		✓
<i>Archosargus rhomboidalis</i>	Sea Bream	Porgies	Sparidae	H	✓
<i>Calamus bajonado</i>	Jolthead Porgy	Porgies	Sparidae		SG
<i>Calamus calamus</i>	Saucereye Porgy	Porgies	Sparidae		SG
<i>Calamus penna</i>	Sheepshead Porgy	Porgies	Sparidae		✓
<i>Calamus proridens</i>	Littlehead Porgy	Porgies	Sparidae		✓
<i>Diplodus holbrookii</i>	Spottail Pinfish	Porgies	Sparidae		✓
<i>Archosargus probatocephalus</i>	Sheepshead	Porgies	Sparidae		✓
<i>Diplodus argenteus</i>	Silver Porgy	Porgies	Sparidae		✓
<i>Lagodon rhomboides</i>	Pinfish	Porgies	Sparidae		✓
<i>Pagrus pagrus</i>	Red Porgy	Porgies	Sparidae		SG
<i>Calamus nodosus</i>	Knobbed Porgy	Porgies	Sparidae		SG
<i>porgy species</i>	Porgy species	Porgies	Sparidae		✓
<i>Sphoeroides nephelus</i>	Southern Puffer	Pufferfishes	Tetraodontidae		
<i>Canthigaster jamestyeri</i>	Goldface Toby	Pufferfishes	Tetraodontidae		
<i>Canthigaster species</i>	Puffers	Pufferfishes	Tetraodontidae		

<i>Canthigaster rostrata</i>	Sharpnose Puffer	Pufferfishes	Tetraodontidae		ML
<i>Sphoeroides spengleri</i>	Bandtail Puffer	Pufferfishes	Tetraodontidae		
<i>Sphoeroides testudineus</i>	Checkered Puffer	Pufferfishes	Tetraodontidae		
<i>Echeneis naucrates</i>	Sharksucker	Remoras	Echeneidae		
<i>Remora remora</i>	Remora	Remoras	Echeneidae		
<i>Echeneis neucratoides</i>	Whitefin Sharksucker	Remoras	Echeneidae		
<i>Negaprion brevirostris</i>	Lemon Shark	Requiem Sharks	Carcharhinidae	P	
<i>Carcharhinus obscurus</i>	Dusky Shark	Requiem Sharks	Carcharhinidae	P	
<i>Carcharhinus plumbeus</i>	Sandbar Shark	Requiem Sharks	Carcharhinidae	P	✓
<i>Galeocerdo cuvier</i>	Tiger Shark	Requiem Sharks	Carcharhinidae	P	
<i>Rhizoprionodon terraenovae</i>	Atlantic Sharpnose Shark	Requiem Sharks	Carcharhinidae		✓
<i>Carcharhinus limbatus</i>	Blacktip Shark	Requiem Sharks	Carcharhinidae	P	✓
<i>Carcharhinus leucas</i>	Bull Shark	Requiem Sharks	Carcharhinidae	P	✓
<i>Carcharhinus falciformis</i>	Silky Shark	Requiem Sharks	Carcharhinidae	P	
<i>Carcharhinus perezii</i>	Reef Shark	Requiem Sharks	Carcharhinidae	P	
<i>Urobatis jamaicensis</i>	Yellow Stingray	Round Stingrays	Urotrygonidae		ML
<i>Istiophorus platypterus</i>	Sailfish	Sailfishes and Marlins	Istiophoridae		✓
<i>Pristis pectinata</i>	Smalltooth Sawfish	Sawfishes	Pristidae		
<i>Scorpaena species</i>	Scorpionfish Species	Scorpionfishes	Scorpaenidae		
<i>Scorpaena plumieri</i>	Spotted Scorpionfish	Scorpionfishes	Scorpaenidae	P	
<i>Scorpaenodes caribbaeus</i>	Reef Scorpionfish	Scorpionfishes	Scorpaenidae	P	
<i>Pterois volitans</i>	Red Lionfish	Scorpionfishes	Scorpaenidae	P	✓
<i>Serranus species</i>	Seabass species	Sea Basses and Groupers	Serranidae	P	✓
<i>Serranus phoebe</i>	Tattler	Sea Basses and Groupers	Serranidae		
<i>Epinephelus drummondhayi</i>	Speckled Hind	Sea Basses and Groupers	Serranidae		✓
<i>Epinephelus niveatus</i>	Snowy Grouper	Sea Basses and Groupers	Serranidae	P	SG
<i>Mycteroperca acutirostris</i>	Western Comb Grouper	Sea Basses and Groupers	Serranidae	P	✓
<i>Liopropoma mowbrayi</i>	Cave Basslet	Sea Basses and Groupers	Serranidae		ML
<i>Hypoplectrus gummigutta</i>	Golden Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Centropristis striata</i>	Black Sea Bass	Sea Basses and Groupers	Serranidae		SG, ML
<i>Centropristis ocyurus</i>	Bank Sea Bass	Sea Basses and Groupers	Serranidae		SG, ML
<i>Rypticus bistrispinus</i>	Freckled Soapfish	Sea Basses and Groupers	Serranidae		
<i>Diplectrum bivittatum</i>	Dwarf Sand Perch	Sea Basses and Groupers	Serranidae	P	

<i>Hypoplectrus aberrans</i>	Yellowbelly Hamlet	Sea Basses and Groupers	Serranidae		
<i>Parasphyraenops incisus</i>	Splitfin Bass	Sea Basses and Groupers	Serranidae		
<i>Serranus flaviventris</i>	Twinspot Bass	Sea Basses and Groupers	Serranidae	P	
<i>Serraniculus pumilio</i>	Pygmy Sea Bass	Sea Basses and Groupers	Serranidae	P	
<i>Mycteroperca species</i>	Grouper species	Sea Basses and Groupers	Serranidae		✓
<i>Diplectrum formosum</i>	Sand Perch	Sea Basses and Groupers	Serranidae	P	
<i>Epinephelus adscensionis</i>	Rock Hind	Sea Basses and Groupers	Serranidae	P	SG
<i>Cephalopholis cruentata</i>	Graysby	Sea Basses and Groupers	Serranidae	P	SG
<i>Cephalopholis fulva</i>	Coney	Sea Basses and Groupers	Serranidae	P	SG
<i>Epinephelus guttatus</i>	Red Hind	Sea Basses and Groupers	Serranidae	P	SG
<i>Epinephelus morio</i>	Red Grouper	Sea Basses and Groupers	Serranidae	P	SG
<i>Epinephelus striatus</i>	Nassau Grouper	Sea Basses and Groupers	Serranidae	P	✓
<i>Hypoplectrus chlorurus</i>	Yellowtail Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Hypoplectrus gemma</i>	Blue Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Hypoplectrus guttavarius</i>	Shy Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Hypoplectrus hybrid</i>	Hybrid Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Hypoplectrus indigo</i>	Indigo Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Hypoplectrus nigricans</i>	Black Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Hypoplectrus puella</i>	Barred Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Hypoplectrus tann</i>	Tan Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Hypoplectrus unicolor</i>	Butter Hamlet	Sea Basses and Groupers	Serranidae		ML
<i>Liopropoma eukrines</i>	Wrasse Basslet	Sea Basses and Groupers	Serranidae		ML
<i>Mycteroperca bonaci</i>	Black Grouper	Sea Basses and Groupers	Serranidae	P	SG
<i>Mycteroperca interstitialis</i>	Yellowmouth Grouper	Sea Basses and Groupers	Serranidae	P	SG
<i>Mycteroperca microlepis</i>	Gag	Sea Basses and Groupers	Serranidae	P	SG
<i>Mycteroperca phenax</i>	Scamp	Sea Basses and Groupers	Serranidae	P	SG
<i>Mycteroperca venenosa</i>	Yellowfin Grouper	Sea Basses and Groupers	Serranidae	P	SG

<i>Paranthias furcifer</i>	Atlantic Creolefish	Sea Basses and Groupers	Serranidae		
<i>Rypticus saponaceus</i>	Greater Soapfish	Sea Basses and Groupers	Serranidae		
<i>Serranus baldwini</i>	Lantern Bass	Sea Basses and Groupers	Serranidae	P	
<i>Serranus tabacarius</i>	Tobaccofish	Sea Basses and Groupers	Serranidae	P	
<i>Serranus tigrinus</i>	Harlequin Bass	Sea Basses and Groupers	Serranidae		
<i>Serranus tortugarum</i>	Chalk Bass	Sea Basses and Groupers	Serranidae		
<i>Epinephelus itajara</i>	Goliath Grouper	Sea Basses and Groupers	Serranidae	P	✓
<i>Mycteroperca tigris</i>	Tiger Grouper	Sea Basses and Groupers	Serranidae	P	✓
<i>Serranus annularis</i>	Orangeback Bass	Sea Basses and Groupers	Serranidae	P	
<i>Dermatolepis inermis</i>	Marbled Grouper	Sea Basses and Groupers	Serranidae	P	✓
<i>Epinephelus flavolimbatus</i>	Yellowedge Grouper	Sea Basses and Groupers	Serranidae	P	SG
<i>Alphesthes afer</i>	Mutton Hamlet	Sea Basses and Groupers	Serranidae	P	ML
<i>Liopropoma rubre</i>	Peppermint Basslet	Sea Basses and Groupers	Serranidae	P	ML
<i>Serranus subligarius</i>	Belted Sandfish	Sea Basses and Groupers	Serranidae		
<i>Schultzea beta</i>	School Bass	Sea Basses and Groupers	Serranidae		
<i>Rypticus maculatus</i>	Whitespotted Soapfish	Sea Basses and Groupers	Serranidae		
<i>grouper-sea bass species</i>	Grouper-Sea Bass species	Sea Basses and Groupers	Serranidae		✓
<i>Hypoplectrus sp.</i>	Hamlet species	Sea Basses and Groupers	Serranidae		ML
<i>Kyphosus sectatrix</i>	Bermuda Chub	Sea Chubs	Kyphosidae		
<i>Prionotus rubio</i>	Blackwing Searobin	Searobins	Triglidae		
<i>Triglidae species</i>	Sea Robin species	Searobins	Triglidae		
<i>Prionotus ophryas</i>	Bandtail Searobin	Searobins	Triglidae		
<i>Menidia sp.</i>	Silverside species	Silversides	Atherinopsidae		
<i>Myrichthys breviceps</i>	Sharptail Eel	Snake Eels	Ophichthidae		ML
<i>Myrichthys ocellatus</i>	Goldspotted Eel	Snake Eels	Ophichthidae		ML
<i>Myrichthys species</i>	Myrichthys eels	Snake Eels	Ophichthidae		
<i>Ophichthus ophis</i>	Spotted Snake Eel	Snake Eels	Ophichthidae		
<i>Ophichthidae species</i>	Snake Eel Species	Snake Eels	Ophichthidae		
<i>Ahlia egmontis</i>	Key Worm Eel	Snake Eels	Ophichthidae		ML
<i>Lutjanus campechanus</i>	Red Snapper	Snappers	Lutjanidae		SG
<i>Lutjanus analis</i>	Mutton Snapper	Snappers	Lutjanidae	P	SG

<i>Lutjanus apodus</i>	Schoolmaster	Snappers	Lutjanidae	P	
<i>Lutjanus buccanella</i>	Blackfin Snapper	Snappers	Lutjanidae	P	SG
<i>Lutjanus cyanopterus</i>	Cubera Snapper	Snappers	Lutjanidae	P	SG
<i>Lutjanus griseus</i>	Gray Snapper	Snappers	Lutjanidae		SG
<i>Lutjanus jocu</i>	Dog Snapper	Snappers	Lutjanidae	P	✓
<i>Lutjanus mahogoni</i>	Mahogany Snapper	Snappers	Lutjanidae	P	✓
<i>Lutjanus synagris</i>	Lane Snapper	Snappers	Lutjanidae		SG
<i>Ocyurus chrysurus</i>	Yellowtail Snapper	Snappers	Lutjanidae		SG
<i>Rhomboplites aurorubens</i>	Vermilion Snapper	Snappers	Lutjanidae	P	SG
<i>Pristipomoides aquilonaris</i>	Wenchman	Snappers	Lutjanidae	P	✓
<i>snapper species</i>	Snapper species	Snappers	Lutjanidae		
<i>Centropomus undecimalis</i>	Common Snook	Snooks	Centropomidae	P	✓
<i>Platax orbicularis</i>	Orbicular Batfish	Spadefishes	Ephippidae		
<i>Chaetodipterus faber</i>	Atlantic Spadefish	Spadefishes	Ephippidae		SG
<i>Sargocentron bullisi</i>	Deepwater Squirrelfish	Squirrelfishes	Holocentridae		
<i>Holocentrus adscensionis</i>	Squirrelfishes	Squirrelfishes	Holocentridae		
<i>Sargocentron coruscum</i>	Reef Squirrelfish	Squirrelfishes	Holocentridae		
<i>Neoniphon marianus</i>	Longjaw Squirrelfish	Squirrelfishes	Holocentridae		
<i>Holocentrus rufus</i>	Longspine Squirrelfish	Squirrelfishes	Holocentridae		
<i>Sargocentron vexillarium</i>	Dusky Squirrelfish	Squirrelfishes	Holocentridae		
<i>Myripristis jacobus</i>	Blackbar Soldierfish	Squirrelfishes	Holocentridae		ML
<i>squirrelfish species</i>	Squirrelfish Species	Squirrelfishes	Holocentridae		
<i>Astroscopus y-graecum</i>	Southern Stargazer	Stargazers	Uranoscopidae		
<i>Astroscopus guttatus</i>	Northern Stargazer	Stargazers	Uranoscopidae		
<i>Acanthurus bahianus</i>	Ocean Surgeon	Surgeonfishes	Acanthuridae	H	ML
<i>Acanthurus chirurgus</i>	Doctorfish	Surgeonfishes	Acanthuridae	H	
<i>Acanthurus coeruleus</i>	Blue Tang	Surgeonfishes	Acanthuridae	H	ML
<i>Acanthurus sp.</i>	Surgeonfish species	Surgeonfishes	Acanthuridae		ML
<i>Pempheris schomburgkii</i>	Glassy Sweeper	Sweepers	Pempheridae		ML
<i>Megalops atlanticus</i>	Tarpon	Tarpons	Megalopidae	P	✓
<i>Elops saurus</i>	Ladyfish	Tenpounders	Elopidae		✓
<i>Malacanthus plumieri</i>	Sand Tilefish	Tilefishes	Malacanthinae		✓
<i>Opsanus tau</i>	Oyster Toadfish	Toadfishes	Batrachoididae		ML
<i>Xanthichthys ringens</i>	Sargassum Triggerfish	Triggerfishes	Balistidae		
<i>Balistes caprisicus</i>	Gray Triggerfish	Triggerfishes	Balistidae		SG
<i>Balistes vetula</i>	Queen Triggerfish	Triggerfishes	Balistidae		✓, ML
<i>Canthidermis sufflamen</i>	Ocean Triggerfish	Triggerfishes	Balistidae		SG
<i>Melichthys niger</i>	Black Durgon	Triggerfishes	Balistidae	H	
<i>Balistes sp.</i>	Triggerfish species	Triggerfishes	Balistidae		✓, ML
<i>Enneanectes altivelis</i>	Lofty Triplefin	Triplefin Blennies	Tripterygiidae		

<i>Enneanectes species</i>	Triplefin species	Triplefin Blennies	Tripterygiidae		✓
<i>Enneanectes boehlkei</i>	Roughhead Triplefin	Triplefin Blennies	Tripterygiidae		
<i>Aulostomus maculatus</i>	Atlantic Trumpetfish	Trumpetfishes	Aulostomidae	P	ML
<i>Acanthemblemaria spinosa</i>	Spinyhead Blenny	Tube Blennies	Chaenopsidae		ML
<i>Emblemariopsis species</i>	<i>Emblemariopsis</i> blennies	Tube Blennies	Chaenopsidae		
<i>Acanthemblemaria species</i>	<i>Acanthemblemaria</i> blennies	Tube Blennies	Chaenopsidae		
<i>Chaenopsis ocellata</i>	Bluethroat Pikeblenny	Tube Blennies	Chaenopsidae		
<i>Chaenopsis species</i>	Pikeblenny species	Tube Blennies	Chaenopsidae		
<i>Emblemaria species</i>	<i>Emblemaria</i> blennies	Tube Blennies	Chaenopsidae		
<i>Emblemariopsis diaphana</i>	Glass Blenny	Tube Blennies	Chaenopsidae		
<i>Acanthemblemaria aspera</i>	Roughhead Blenny	Tube Blennies	Chaenopsidae		ML
<i>Acanthemblemaria chaplini</i>	Papillose Blenny	Tube Blennies	Chaenopsidae		ML
<i>Emblemaria pandionis</i>	Sailfin Blenny	Tube Blennies	Chaenopsidae		ML
<i>Hemiblemaria simula</i>	Wrasse Blenny	Tube Blennies	Chaenopsidae		ML
<i>Chaenopsis limbaughi</i>	Yellowface Pikeblenny	Tube Blennies	Chaenopsidae		ML
<i>Emblemariopsis bahamensis</i>	Blackhead Blenny	Tube Blennies	Chaenopsidae		ML
<i>Acanthemblemaria maria</i>	Secretary Blenny	Tube Blennies	Chaenopsidae		ML
<i>Stygnobrotula latebricola</i>	Black Brotula	Viviparous Brotulas	Bythitidae		ML
<i>Dasyatis americana</i>	Southern Stingray	Whiptail Stingrays	Dasyatidae		
<i>Halichoeres species</i>	Wrasse species	Wrasses	Labridae		
<i>Halichoeres burekai</i>	Mardi Gras Wrasse	Wrasses	Labridae		
<i>Bodianus rufus</i>	Spanish Hogfish	Wrasses	Labridae		
<i>Clepticus parrae</i>	Creole Wrasse	Wrasses	Labridae		ML
<i>Doratonotus megalepis</i>	Dwarf Wrasse	Wrasses	Labridae		ML
<i>Halichoeres bivittatus</i>	Slippery Dick	Wrasses	Labridae		
<i>Halichoeres garnoti</i>	Yellowhead Wrasse	Wrasses	Labridae		ML
<i>Halichoeres maculipinna</i>	Clown Wrasse	Wrasses	Labridae		ML
<i>Halichoeres pictus</i>	Rainbow Wrasse	Wrasses	Labridae		ML
<i>Halichoeres poeyi</i>	Blackear Wrasse	Wrasses	Labridae		ML
<i>Halichoeres radiatus</i>	Puddingwife	Wrasses	Labridae		
<i>Xyrichtys martinicensis</i>	Rosy Razorfish	Wrasses	Labridae		ML
<i>Xyrichtys novacula</i>	Pearly Razorfish	Wrasses	Labridae		ML
<i>Xyrichtys splendens</i>	Green Razorfish	Wrasses	Labridae		ML
<i>Lachnolaimus maximus</i>	Hogfish	Wrasses	Labridae		SG
<i>Thalassoma bifasciatum</i>	Bluehead	Wrasses	Labridae		
<i>Bodianus pulchellus</i>	Spotfin Hogfish	Wrasses	Labridae		ML
<i>Halichoeres cyanocephalus</i>	Yellowcheek Wrasse	Wrasses	Labridae	P	ML
<i>Halichoeres caudalis</i>	Painted Wrasse	Wrasses	Labridae		ML
<i>razorfish species</i>	Razorfish species	Wrasses	Labridae		ML

<i>Labrisomid sp.</i>	<i>Labrisomid</i> blenny species	Wrasses	Labridae		ML
-----------------------	----------------------------------	---------	----------	--	----

<sup>1</sup> Only ‘piscivore’ (P) and ‘herbivore’ (H) designations are included. Trophic information was collected from a variety of sources, notably from the NCRMP RVC master species list.

<sup>2</sup> ✓ = Fished species include species commonly landed in commercial and recreational fisheries (including species landed primarily for bait). Several species (Nassau Grouper, Goliath Grouper and Bonefish) that are currently prohibited from take or subject only to catch-and-release fisheries are included as fished species due to prior exploitation and catch-and-release mortality. Species exploited for the aquarium trade (i.e. those taken under commercial or recreational Marine Life permits) are not considered fished species for this project. Information regarding fishery status of each species was derived from a variety of sources, notably from the NCRMP RVC master species list.

<sup>3</sup> SG = Species in the federally permitted snapper-grouper complex fishery (NOAA 1983).

<sup>4</sup> ML = Species exploited for the aquarium trade (i.e. those taken under commercial or recreational Marine Life permits). See <https://myfwc.com/fishing/saltwater/commercial/marine-life/> and <https://myfwc.com/fishing/saltwater/recreational/marine-life/>

## References (Appendix 1)

NOAA National Marine Fisheries Service. 1983. Fishery management plan, regulatory impact review, and final environmental impact statement for the snapper-grouper fishery of the South Atlantic region. Pages 1-89.

## Appendix 2. Details of explanatory variables

### *Area of reef*

Biogeographic theory suggests that the area of reef available may affect fish assemblage structure (Jacquet et al. 2016) or concentrate fishing efforts in locations with limited habitat. In addition, recent work has shown reef size to have a significant, positive relationship with abundance and biomass of many fish species (Dames et al. 2019). Therefore, the available area of coral reef and/or hardbottom habitat close to each reef cell was measured from the Unified Florida Reef Tract habitat map (UFRTM). We calculated this variable at the 20 km and 200 km scale, but the two variables were highly correlated. As such, we included only the 20 km variable in the model, as 20 km represents the approximate high end of larval dispersal estimates for most coral reef fishes (Yeager et al. 2017).

### *Artificial Reefs*

Artificial reefs are known to attract fish, and potentially enhance fish production, thereby increasing biomass in a given area (Seaman 2000, Arena et al. 2007). The presence of an artificial reef may aggregate fish from natural reefs, or they might create habitat and foraging opportunities that increase overall fish biomass (Bohnsack 1989, Grossman et al. 1997). In addition, artificial reefs in Florida are used heavily by fishermen targeting reef fish species, and proximity to these known high biomass artificial reefs may impact fishing pressure on nearby natural reefs by either taking pressure off natural reefs or by increasing fishing on natural reefs nearby heavily targeted artificial reefs (Grossman et al. 1997, Johns et al. 2001). Because these numerous mechanisms effect natural reef biomass differently, predicting the directionality of the relationship between biomass and artificial reefs is difficult, and it is possible that several mechanisms are in operation on the Florida reef tract. The location of artificial reefs in Florida is documented in a Florida Fish and Wildlife Conservation Commission (FWC) GIS shapefile. We calculated the number of artificial reefs within 1 km of each natural reef pixel using the Point Statistics tool in ArcGIS Pro (Rosemond et al. 2018).

### *Availability of nursery habitat*

The availability of nursery habitats, particularly mangroves and seagrass beds, can significantly affect reef fish assemblage structure by increasing survival of juvenile fishes (Mumby et al. 2004, Harborne et al. 2016). Maps of continuous seagrass and mangrove stands adjacent to Florida coral reefs were derived from the UFRTM. Areas of discontinuous or patchy seagrass were not considered as nursery habitat in this project because of their limited functional importance as a nursery (Harborne et al. 2016). Connectivity to mangroves and medium-density and dense seagrass was calculated for all reef cells using a slightly modified version of the algorithm of Mumby (2006). There are few data on how far fish migrate from nursery habitats, but the only Florida and wider Caribbean estimates we are aware of all suggest increased populations up to 10 km (Dorenbosch et al. 2006, Mumby 2006, Huijbers et al. 2013). However, because prime fish habitat on the reef crest in Florida is slightly farther from mangrove nursery habitats, we use 12 km as the maximum distance of nursery influence. The algorithm measures the shortest distance across water between two target pixels and the connectivity metric between a reef site and all the pixels of a particular habitat (e.g. continuous seagrass) is then calculated as:

$$Connectivity_j = \sum_{i=1}^n D - c_{ij} \quad (1)$$

where  $D$  is the maximum possible distance between two pixels (10,000 m),  $i$  is a nursery habitat pixel from a total of  $n$  within the seascape,  $j$  is the pixel containing the reef survey site location, and  $c_{ij}$  is the shortest across-water distance (m) between the two pixels. Consequently, high connectivity represents a large number of nursery pixels relatively close to the reef site. Only mangrove pixels adjoining fully subtidal habitat were used in order to remove pixels of non-functional mangroves further inland.

### *Coral cover*

Coral cover provides fishes with food (Pratchett et al. 2008), refuge from predators and water flow (Hixon and Beets 1993, Johansen et al. 2008), and nesting sites (Robertson and Sheldon 1979). Consequently, numerous studies have linked coral cover to fish abundance (Bell and Galzin 1984, Jones et al. 2004, Gratwicke and Speight 2005), and it is likely to influence the abundance of many species considered in this project. We used data on coral cover that was estimated *in situ* for a subset of the RVC fish surveys in the Florida Keys. However, coral cover cannot be reliably modelled continuously across the entire reef tract. Therefore, predictions for the continuous maps of fishing impact and biomass were calculated using mean coral cover derived from NCRMP benthic surveys for the fishing impact model and habitat-specific (UFRTM Level 2 classification), regional means derived from NCRMP benthic surveys for the biomass model.

### *Depth*

While rarely affecting fish assemblages directly, depth is a proxy for numerous environmental gradients such as light intensity, temperature, and salinity that may affect fishes. Depth was measured during *in situ* surveys and these values were used in the models. To extrapolate these results to the entire reef tract we used a global depth data layer published by Sbrocco and Barber (2013). This data layer was selected from several bathymetry layers available for the region due to a higher correlation between depths in the global layer (modelled depths) and depths measured by divers during RVC surveys (actual depths).

### *Distance to deep water*

Reef walls represent transitional habitats between forereefs and pelagic environments, and these deeper reefs are important habitats for reef fishes such as planktivores (Harborne et al. 2006a). The approximate distance of each reef cell to these deeper habitats was calculated by measuring the Euclidean distance over water (using the Cost Distance tool in ArcGIS Pro) to the 30-meter bathymetric line as derived from the continuous bathymetric data layer described above (using the Contour List tool in ArcGIS Pro).

### *Distance to fish spawning aggregation*

Only some species migrate to mass spawning sites to reproduce, but these species include many groupers and snappers that represent a significant component of the fishery species considered in this project. This explanatory variable was calculated by measuring the distance over water to the nearest fish spawning aggregation site described by NOAA NMFS (Sherman et al. 2016, Fig. A1). This dataset includes only spawning aggregation sites that have been field-verified by NOAA employees.

### *Fishing activity*

We used several metrics to capture the commercial, charter and recreational fishing activity for each reef pixel considered in the project.

The FWC Marine Fisheries Trip Ticket Program<sup>7</sup> collects information on total volume of each species landed by commercial fisheries in Florida. These data are publicly available by fishing area. The Florida reef tract as defined in this study (Martin County to the Dry Tortugas) encompasses six fishing areas: Fort Pierce, West Palm Beach, Miami, Marathon, Key West, Tortugas, from northeast to southwest. We calculated the average annual pounds landed of all species in the snapper-grouper permit complex using a 10-year mean to capture they differences in fishery landings dynamics over the previous ten years between Southeast Florida and the Florida Keys (Johns et al. 2001). Because these data lack fine spatial resolution, every reef pixel within an FWC fishing area was assigned the same value.

Data on commercial and charter vessel permits in the snapper-grouper fishery are available from NOAA NMFS by the zip code associated with each permit. Though the zip code of reference for a given permit does not necessarily correspond to where the permitted vessel fishes, it is likely (especially for the charter fishery) that fishing occurs on reefs near the zip code of reference. We created GIS layers of the number of commercial and charter snapper-grouper permits, then calculated the number of each of these permits located within 25 km of each reef pixel for charter permits and 50 km for commercial permits. The distance of 25 km for charter vessels was selected to capture the distance travelled for a day trip (e.g. <https://www.gulfstreamkeywest.com/faq/>), but may not fully capture fishing done on 2-3 day trips leaving from the Keys and going to the Dry Tortugas (McClenachan 2009). Because commercial fishing vessels often travel further to fish, 50 km distance was used for commercial permits. The GIS layer of zip code polygons is a publicly available layer accessed through [census.gov](https://census.gov).

The environmental and socioeconomic impacts of recreational fishing have gained increasing awareness and attention from the scientific and management communities in recent decades (Lewin et al. 2019). In the state of Florida, where recreational fishing for reef species is economically valuable and socially important for coastal communities, direct and indirect effects of recreational fishing likely play a role in structuring reef fish assemblages (Johns et al. 2001). We used publicly-available data from the state of Florida on recreational fishing licenses. Each recreational license is associated with the zip code of the fisherman. Using these data, and census data describing county-level population in Florida, we calculated the percentage of people in each zip code with a recreational fishing permit. Using these percentages as a multiplier, we converted the population raster layer described below (see the *Human population size* variable) into a raster layer of the number of recreational fishermen within 50 km of each reef pixel to account for the distance that a typical recreational fisherman travels (including travel over land) to reef fish.

Fishing-related tourism is a major industry in Florida (Johns et al. 2001, Ditton et al. 2002). To account for tourism-based recreational coral reef fishing (which was not included in the recreational fishing license-derived metric above), we used statistics from Johns et al. 2001 and a publicly available dataset of hotel units in Florida from the Florida Geographic Data Library. The number of tourist reef fishing days (as estimated in Johns et al. 2001) was distributed across reef pixels relative to the number of hotel units within 50 km of that reef pixel, generating a metric of relative tourist fishing pressure for all reefs considered in the project with the exception of reefs in Martin County where no tourism estimates were available.

---

<sup>7</sup> <https://myfwc.com/research/saltwater/fishstats/commercial-fisheries/wholesale-retail-dealers/>

Finally, metrics of commercial and recreational fishery engagement and fishery reliance were provided by Michael Jepson at NOAA NMFS. Fishery engagement and reliance were calculated as part of a larger effort to develop fishing community social and vulnerability indices in the United States (Jepson and Colburn 2013). The fishing engagement metric relates to the presence of a commercial or recreational fishery in a given community based on landings and permits, and reliance relates to fishing activity relative to the population size of a fishing community. High engagement and/or reliance equates to a community dependent on the fishing industry. Each reef pixel in the project was assigned the commercial engagement and reliance metrics and recreational engagement and reliance metrics corresponding to the nearest fishing community. Because these metrics are derived from some of the same data used to derive the other variables related to commercial, charter and recreational fishing activity, only the variable representing the smallest spatial resolution was retained in each model following a test of inter-variable correlations.

### *Gravity of markets*

In addition to the basic variable capturing population, this project also considered the economic geography concept of ‘gravity’, as it has been demonstrated to be an important variable in global studies (Cinner et al. 2016). The gravity concept infers that potential interactions increase with population size, but decay exponentially with the effective distance between two points. For this project, we used a dataset of total market gravity within 500 km (the sum of the market gravity of every population center within 500 km) published in Cinner et al. (2018). This follows Cinner et al. (2016) in calculating gravity as the number of people in the population centre divided by the square of the travel time (rather than distance, to account for differences in travel time over different surfaces) between that centre and the reef cell.

### *Habitat type*

The models of both fishing impact and biomass contain a categorical variable for habitat type as described in the Unified Florida Reef Tract habitat map to include any variability that is not contained in the depth, coral cover, and complexity factors. Furthermore, within the fishing impact model this habitat variable may demonstrate differences in fishing pressure among habitat types caused by factors such as trap efficiency (Wolff et al. 1999). We used the UFRTM Level 2 classification which includes the following habitat types: Aggregate Reef, Individual or Aggregated Patch Reef, Spur and Groove, (Coral Reef and Hardbottom) Ridge, Reef Rubble, Colonized Reef Rubble, Pavement, Colonized Pavement, and Pavement with Sand Channels.

### *Human population size and population per area reef*

The size of local human populations has repeatedly been demonstrated to be an excellent proxy of fishing pressure on reefs (e.g. Mora 2008, Stallings 2009, Mora et al. 2011, Cinner et al. 2013). Therefore, it was anticipated to be a potentially key variable in the model of fishing pressure on Florida coral reefs. Standardised, rasterized, global data sets of human populations are available from Oak Ridge National Laboratory’s LandScan dataset<sup>8</sup>. LandScan uses census data in addition to remotely sensed images and multivariate modelling to derive their dataset. Data are highly correlated with population layers from the Socioeconomic Data and Applications Center (SEDAC), but was available for a more recent year (2017).

---

<sup>8</sup> <https://landscan.ornl.gov/>

LandScan estimates population at a resolution of 30 arc-seconds (~1 km). We tested this variable in the model at two scales: the human population size within 20 km and within 50 km to capture both the distance that smaller, private fishing vessels might travel, and that larger charter or commercial fishing vessels might travel (Clark et al. 2002, Gorospe et al. 2018). The 20 km distance likely encompasses the area in which land-based sources of pollution might impact the fish assemblage, though we expect that those effects are better captured by the coral cover variable.

Additionally, the impact of human population sizes on reef fisheries is likely dependent on the reef area available, and we followed other studies in calculating population size per square km of fishable reef (Stallings 2009, Houk et al. 2012, Taylor et al. 2014b, Williams et al. 2015a). Therefore, we divided the population size figure by the area of reef within the same distance, resulting in a metric of human population pressure per km<sup>2</sup>.

### *Latitude and longitude*

The reef fishes of the Florida reef tract are recognised as being located within a single biogeographic region in the western Atlantic (Kulbicki et al. 2013). Consequently, biogeography of fishes is unlikely to be as major a confounding factor in the analyses as when working across biogeographic regions. However, there may be small-scale biogeographic patterns (Walker 2012), therefore latitude and longitude were included in initial models of both fishing impact and biomass to account for any variation in fish assemblages and fishing effort across the region. Both latitude and longitude were highly correlated with other covariates in the model (e.g. sea surface temperature), and so were excluded in final models.

### *Marina slips within 10km*

For similar reasons that nearby population density may affect fishing impact, additional metrics of fishery access likely also play a role. We used a dataset developed by FWC and downloaded from the Florida Geographic Data Library<sup>9</sup>, that was initially produced for a state-wide report on boating access and marine facilities. The dataset contains location information for every marina and port in Florida, and includes the number of vessel slips at a facility, and the presence and number of launch ramps. From these data we derived continuous spatial layers of the number of marina slips within 25 km from each reef pixel included in the project to include the area within which most recreational fishermen travel to fish. Only marinas with access to South Atlantic reef habitats were included (e.g. marina slips within 25 km of a reef cell, but that were inland marinas with no ocean access were excluded). We also excluded boat repair facilities, as these were not considered facilities from which fishermen would access reefs. Finally, we only included boat slips that were 45 ft and smaller to exclude large vessels that are not likely being used for reef fishing.

### *Month*

Time of year can affect benthic assemblages and herbivory (Ferrari et al. 2012) and may represent aspects of fish spawning behaviour (Sherman et al. 2016). The month that a survey was undertaken was included as an explanatory variable in the model.

---

<sup>9</sup> <https://www.fgdl.org/metadataexplorer/explorer.jsp>

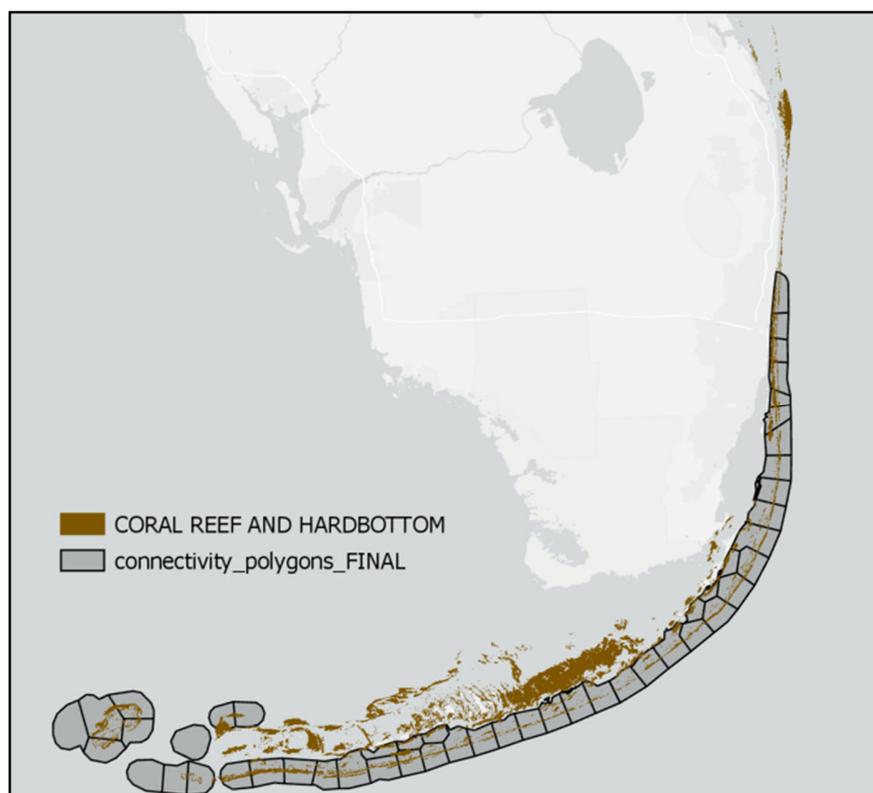
### *Number of larvae from upstream*

The importance of larval supply on the abundance of reef fishes has been a hotly debated topic, leading to a large literature on the relative importance of pre- and post-settlement processes (see Hixon 2011 for an overview of this debate). The debate is now generally less polarised, with the importance of pre- and post-settlement processes apparently varying among species and in space and time. To investigate the importance of larval supply in predicting fish biomass, we used a biophysical model of larval supply throughout the area (see Cowen et al. 2006 for a full description of the model)<sup>10</sup>. Briefly, polygons of reef habitat were identified throughout the Florida reef tract, and then ‘virtual larvae’ were released monthly within a computer simulation of oceanic conditions (Fig. A2.1). The virtual larvae were given behavioural characteristics (e.g. larval duration, depth preferences) of the bicolor damselfish, *Stegastes partitus*. They were then tracked within the model, and where they ‘settle’ was recorded (either back to the same reef, to a different reef, or lost into oceanic water). These data generate a connectivity matrix, showing the proportion of larvae moving from each polygon to every other polygon.

This connectivity matrix was used to determine the number of arrivals from upstream sources, following the removal of self-recruiting arrivals at each polygon (arrivals originating and settling at the same patch). This metric was calculated because local-retention patterns tend not to be reliable when extracted from biophysical models because they ignore all local processes (e.g. tides, local-scale eddies, and near-shore turbulence), however our metric was strongly correlated with total arrivals estimated by the model ( $p < 0.001$ ;  $R^2 = 0.9995$ ). The number of larvae arriving was adjusted to account for the amount of coral reef and hardbottom habitat in each polygon (since virtual larvae may be concentrated on a small patch of reef, so it is important to consider arrivals per unit area of reef). Note that these metrics are not estimates of actual numbers of larvae arriving at each polygon, but are values representing the relative strength of fluxes of larvae among polygons. Note that the larval arrival metrics are the same for every reef pixel within each polygon. Because the connectivity model does not extend to the furthest north reefs (nor does it cover pavement habitat north of the Keys), those cells were assigned no data values.

---

<sup>10</sup> Data supplied by Claire Paris, University of Miami



**Fig. A2.1.** The reef polygons (grey squares) included in the biophysical model of Florida reef tract larval connectivity. Note that connectivity estimates are only available for a subset of coral reef and hardbottom habitat pixels, and the model does not cover the entire northward extent of the reef tract.

### *Oceanic net primary productivity*

Variations in primary productivity can influence herbivorous fish assemblage structure (Mumby et al. 2013), and the total biomass of reef fishes (Williams et al. 2015a). Therefore, oceanic productivity was included in the models of fishing impact and fish biomass. High-resolution measures of productivity across the entire region are not possible, and the project used remotely sensed data on chlorophyll-*a* as a proxy of primary productivity on reefs. Although these chlorophyll-*a* data do not discriminate small-scale variations in productivity, they do capture larger-scale patterns in productivity across the region (Gove et al. 2013). Mean monthly net primary productivity estimates were obtained from the Oregon State University Ocean Productivity Standard Vertically Generalized Production (VGPM) model (Behrenfeld and Falkowski 1997)<sup>11</sup>. Remotely sensed estimates of productivity over reefs are confounded by bottom reflectance, so only data from pelagic areas around each reef pixel were used. These areas were identified using the protocol described in Gove et al. (2013): productivity data was excluded in cells with a depth of <30 m, and then cells with missing values were populated by interpolating values from surrounding cells (Yeager et al. 2017).

### *Protected status*

<sup>11</sup> <http://www.science.oregonstate.edu/ocean.productivity/index.php>

A large literature demonstrates that marine protected areas can effectively reduce fishing pressure and fundamentally change fish assemblages (e.g. Mosquera et al. 2000, Halpern and Warner 2002, Russ 2002). Consequently, whether a fish survey site was inside or outside a protected area was included within the model of reef fishing impact. Although whether fishing is allowed at a given site or not should be captured within the fishing impact data layer, protected status was also included in the model of biomass to account for any differential effects on all fishes compared to all just the recreationally and commercially important species that were included in the fishing impact model (i.e. the fishing impact model only considers fishing of commercially important species, and the effect of marine protection may be clearer in the biomass model that considers all species). NOAA's 2017 Marine Protected Area inventory was merged with a NOAA layer of Sanctuary Preservation Areas (SPAs), Ecological Reserves, and Research Only Areas, all areas that prohibit fishing. We generated two protected area layers. The first layer codes all areas under some form of marine protection by their level of fishing restriction as follows: No restrictions; Commercial fishing restrictions; Commercial and recreational fishing restrictions; Recreational fishing restricted; Commercial fishing prohibited and recreational fishing restricted; Commercial fishing prohibited; All fishing prohibited. Reef pixels not included in the marine protected area layer were considered to have no restrictions. The second layer categorizes a reef pixel as either 'Open to fishing' or 'No take'. Though the SPAs were classified as 'No take' areas, bait fishing is allowed by permit in the SPAs, and catch-and-release trolling is allowed in some of the SPAs. In addition, take of fish for research may occur in the Research Only Areas.

### *Complexity*

Reef complexity provides fishes with refuge from predators and water flow (Hixon and Beets 1993, Johansen et al. 2008), and is a major influence on reef fish assemblages (Graham and Nash 2013). We used data on complexity (maximum vertical hard relief) that was estimated *in situ* during a subset of RVC fish surveys in the Florida Keys. However, complexity cannot be reliably modelled continuously across the entire Florida reef tract. Therefore, predictions for the continuous maps of fishing impact and biomass were calculated using mean complexity derived from NCRMP benthic surveys for the fishing impact model and habitat-specific (UFRTM Level 2 classification), regional means derived from NCRMP benthic surveys for the biomass model.

### *Sea surface temperature*

Temperature is one of the primary abiotic factors influencing the physiological performance of fish (Brett 1971). Consequently, general patterns of variability in sea surface temperature were included in the models of fishing impact and fish biomass. Sea surface temperature data were obtained online from the Coral Reef Temperature Anomaly Database (CoRTAD)<sup>12</sup> for the years 2012-2016 at a 4 km resolution (Saha et al. 2018). Following Williams et al. (2015a), we calculated the mean temperature from the coldest month of each year (i.e. the lower climatological mean) at each reef location. Interpolation was used to estimate sea surface temperature values for reef pixels where no data were available in the CoRTAD dataset. The final metric was calculated as the mean temperature of the coldest month over the five-year period from 2012-2016.

---

<sup>12</sup> <https://www.nodc.noaa.gov/SatelliteData/cortad/>

### *Wave exposure*

Wave exposure can have significant effects on fish assemblages since the morphologies of some species are better adapted to dealing with high levels of water movement (Fulton et al. 2005), and it can have significant effects on benthic habitat type (Chollett and Mumby 2012). High wave exposure can also limit fishing boat access, reducing fishing pressure (Houk et al. 2012, Chollett et al. 2014, Taylor et al. 2014b).

Exposure was calculated using linear wave theory, which has successfully been used to predict habitat distribution and benthic beta-diversity on reefs (Harborne et al. 2006b, Chollett and Mumby 2012). Full details of the method are described elsewhere (Ekeboom et al. 2003), including their application to reefs (Harborne et al. 2006b, Chollett and Mumby 2012, Chollett et al. 2012). Wave exposure was calculated for the Florida reef tract as part of a project to categorise the physical environments of the region (Chollett et al. 2012)<sup>13</sup>. This data layer was used to assign a surface wave exposure to each coral reef and hardbottom habitat cell along the reef tract.

### *Year*

With the exception of inside marine protected areas, fishing typically increases over time with continually increasing impacts on fish assemblages. Inevitably, the large data set assembled for this project was not collected simultaneously; we use data from fish surveys undertaken from 2005 to 2016. Fish survey data collected in 2010 were excluded from both models due to anomalously cold temperatures and resulting fish kills that were observed to impact survey results in that year. Year of collection was included in the models of both fishing impact and fish biomass to account for any temporal variation in fish assemblages. Where year was a significant variable, values of fishing impact or fish biomass across the region were predicted across the continuous maps using 2016 to provide currently expected values that are most useful for ongoing management planning.

---

<sup>13</sup> Data supplied by Iliana Chollett

*References (Appendix 2)*

- Arena, P.T., L.K.B. Jordan, and R.E. Spieler. 2007. Fish assemblages on sunken vessels and natural reefs in southeast Florida, USA. *Hydrobiologia* 580:157-171.
- Bell, J. D., and R. Galzin. 1984. Influence of live coral cover on coral-reef fish communities. *Marine Ecology Progress Series* 15:265-274.
- Behrenfeld, M.J., and P.G. Falkowski. 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnology and Oceanography* 42: 1-20.
- Bohnsack, J.A. 1989. Are high densities of fishes at artificial reefs the result of habitat limitation or behavioral preference? *Bulletin of Marine Science* 44(2): 631-645.
- Brett, J. R. 1971. Energetic responses of salmon to temperature. A study of some thermal relations in physiology and freshwater ecology of sockeye salmon (*Oncorhynchus nerka*). *American Zoologist* 11:99-118.
- Brewer, T. D., J. E. Cinner, R. Fisher, A. Green, and S. K. Wilson. 2012. Market access, population density, and socioeconomic development explain diversity and functional group biomass of coral reef fish assemblages. *Global Environmental Change* 22:399-406.
- Brewer, T. D., J. E. Cinner, A. Green, and R. L. Pressey. 2013. Effects of human population density and proximity to markets on coral reef fishes vulnerable to extinction by fishing. *Conservation Biology* 27:443-452.
- Clark, B.M., M. Hauck, J.M. Harris, K. Salo, and E. Russell. 2002. Identification of subsistence fishers, fishing areas, resource use and activities along the South African coast. *South African Journal of Marine Science* 24: 425-437.
- Chollett, I., S. W. J. Canty, S. J. Box, and P. J. Mumby. 2014. Adapting to the impacts of global change on an artisanal coral reef fishery. *Ecological Economics* 102:118-125.
- Chollett, I., P. J. Mumby, F. E. Müller-Karger, and C. Hu. 2012. Physical environments of the Caribbean Sea. *Limnology and Oceanography* 57:1233-1244.
- Chollett, I., and P. J. Mumby. 2012. Predicting the distribution of *Montastraea* reefs using wave exposure. *Coral Reefs* 31:493-503.
- Cinner, J. E., N. A. J. Graham, C. Huchery, and M. A. MacNeil. 2013. Global effects of local human population density and distance to markets on the condition of coral reef fisheries. *Conservation Biology* 27:453-458.
- Cinner, J. E. et al. 2016. Bright spots among the world's coral reefs. *Nature* 535:416-419.
- Cinner, J.E. et al. 2018. Gravity of human impacts mediates conservation gains. *Proceedings of the National Academy of Sciences* 115(27): E6116-E6125.
- Cowen, R. K., C. B. Paris, and A. Srinivasan. 2006. Scaling of connectivity in marine populations. *Science* 311:522-527.
- Dames, V., A. Bernard, C. Floros, B. Mann, C. Speed, J. Maggs, S. Laing, M. Meekan, and J. Olbers. 2019. Zonation and reef size significantly influence fish population structure in an established marine protected area, iSimangaliso Wetland Park, South Africa. *Ocean and Coastal Management* 105040.
- Ditton, R.B., S.M. Holland, and D.K. Anderson. 2002. Recreational fishing as tourism. *Fisheries* 23(3): 17-24.
- Dorenbosch, M., M. G. G. Grol, I. Nagelkerken, and G. van der Velde. 2006. Seagrass beds and mangroves as potential nurseries for the threatened Indo-Pacific humphead wrasse, *Cheilinus undulatus* and Caribbean rainbow parrotfish, *Scarus guacamaia*. *Biological Conservation* 129:277-282.
- Ekebom, J., P. Laihonon, and T. Suominen. 2003. A GIS-based step-wise procedure for assessing physical exposure in fragmented archipelagos. *Estuarine Coastal and Shelf Science* 57:887-898.
- Ferrari, R., M. Gonzalez-Rivero, J. C. Ortiz, and P. J. Mumby. 2012. Interaction of herbivory and seasonality on the dynamics of Caribbean macroalgae. *Coral Reefs* 31:683-692.
- Fulton, C. J., D. R. Bellwood, and P. C. Wainwright. 2005. Wave energy and swimming performance shape coral reef fish assemblages. *Proceedings Of The Royal Society B-Biological Sciences* 272:827-832.
- Gorospe, K.D., M.J. Donahue, A. Heenan, J.M. Gove, I.D. Williams, and R.E. Brainard. 2018. Local biomass baselines and the recovery potential for Hawaiian coral reef fish communities. *Frontiers in Marine Science* 5: 162.
- Gove, J. M., G. J. Williams, M. A. McManus, S. F. Heron, S. A. Sandin, O. J. Vetter, and D. G. Foley. 2013. Quantifying climatological ranges and anomalies for Pacific coral reef ecosystems. *PLoS ONE* 8:e61974.

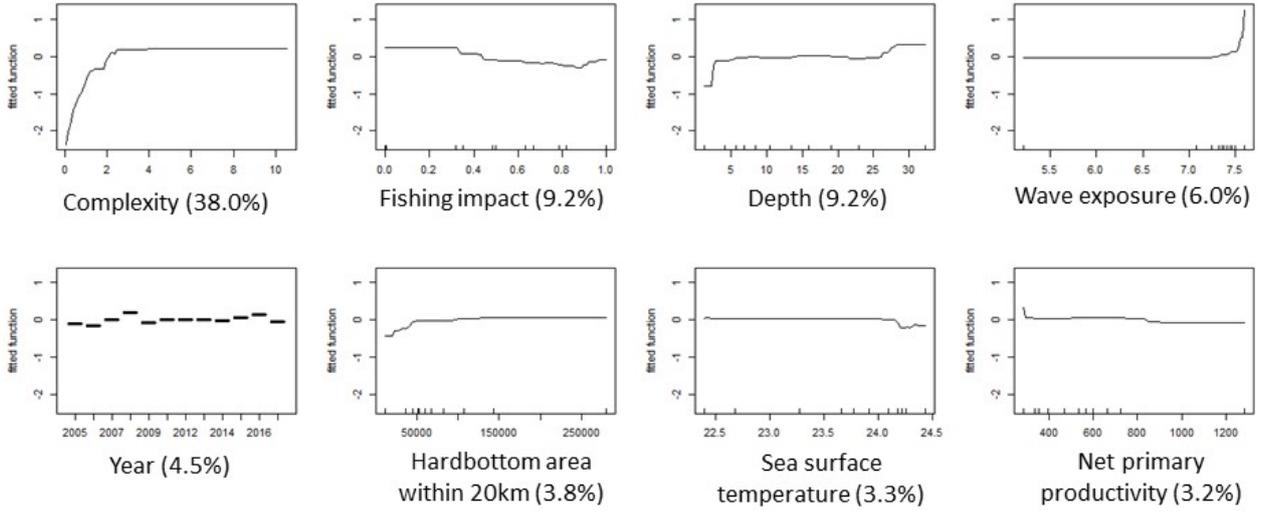
- Graham, N. A. J., and K. L. Nash. 2013. The importance of structural complexity in coral reef ecosystems. *Coral Reefs* 32:315-326.
- Gratwicke, B., and M. R. Speight. 2005. The relationship between fish species richness, abundance and habitat complexity in a range of shallow tropical marine habitats. *Journal of Fish Biology* 66:650-667.
- Grossman, G.D., G.P. Jones, and W.J. Seaman. 1997. Do artificial reefs increase regional fish production? A review of existing data. *Fisheries* 22(4): 17-23.
- Halpern, B. S., and R. R. Warner. 2002. Marine reserves have rapid and lasting effects. *Ecology Letters* 5:361-366.
- Harborne, A. R., P. J. Mumby, F. Micheli, C. T. Perry, C. P. Dahlgren, K. E. Holmes, and D. R. Brumbaugh. 2006a. The functional value of Caribbean coral reef, seagrass and mangrove habitats to ecosystem processes. *Advances in Marine Biology* 50:57-189.
- Harborne, A. R., P. J. Mumby, K. Żychaluk, J. D. Hedley, and P. G. Blackwell. 2006b. Modeling the beta diversity of coral reefs. *Ecology* 87:2871-2881.
- Harborne, A. R., I. Nagelkerken, N. H. Wolff, Y.-M. Bozec, M. Dorenbosch, M. G. G. Grol, and P. J. Mumby. 2016. Direct and indirect effects of nursery habitats on coral-reef fish assemblages, grazing pressure and benthic dynamics. *Oikos* 125:957-967.
- Hixon, M. A., and J. P. Beets. 1993. Predation, prey refuges, and the structure of coral-reef fish assemblages. *Ecological Monographs* 63:77-101.
- Hixon, M. A. 2011. 60 years of coral reef fish ecology: past, present, future. *Bulletin of Marine Science* 87:727-765.
- Houk, P., K. Rhodes, J. Cuetos-Bueno, S. Lindfield, V. Fread, and J. L. McIlwain. 2012. Commercial coral-reef fisheries across Micronesia: A need for improving management. *Coral Reefs* 31:13-26.
- Huijbers, C. M., I. Nagelkerken, A. O. Debrot, and E. Jongejans. 2013. Geographic coupling of juvenile and adult habitat shapes spatial population dynamics of a coral reef fish. *Ecology* 94:1859-1870.
- Jacquet, C., D. Mouillot, M. Kulbicki, and D. Gravel. 2016. Extensions of Island Biogeography Theory predict the scaling of functional trait composition with habitat area and isolation. *Ecology Letters* doi:10.1111/ele.12716.
- Jepson, M., and L.L. Colburn. 2013. Development of social indicators of fishing community vulnerability and resilience in the U.S. Southeast and Gulf regions. U.S. Department of Commerce, NOAA Technical Memorandum: NMFS-F/SPO-129, 64 p.
- Johansen, J. L., D. R. Bellwood, and C. J. Fulton. 2008. Coral reef fishes exploit flow refuges in high-flow habitats. *Marine Ecology Progress Series* 360:219-226.
- Johns, G.M., Leeworthy, V.R., Bell, F.W., and Bonn, M.A.. 2001. Socioeconomic study of reefs in Southeast Florida. National Oceanic and Atmospheric Administration.
- Jones, G. P., M. I. McCormick, M. Srinivasan, and J. V. Eagle. 2004. Coral decline threatens fish biodiversity in marine reserves. *Proceedings of the National Academy of Sciences of the United States of America* 101:8251-8253.
- Kulbicki, M., V. Parravicini, D.R. Bellwood, E. Arias-Gonzalez, P. Chabanet, S.R. Floeter, A. Friedlander, J. McPherson, R.E. Myers, L. Vigliola, and D. Mouillot. 2013. Global biogeography of reef fishes: a hierarchical quantitative delineation of regions. *PLoS One* 8(12): e81847.
- Lefcheck, J.S., B.B. Hughes, A.J. Johnson, B.W. Pfirman, D.B. Rasher, A.R. Smyth, B.L. Williams, M.W. Beck, and R.J. Orth. 2019. Are coastal habitats important nurseries? A meta-analysis. *Conservation Letters* e12645.
- Lewin, W-C., M.S. Weltersbach, K. Ferter, K. Hyder, E. Mugerza, R. Pallezo, Z. Radford, L. Zarauz, and H.V. Strehlow. 2018. Potential environmental impacts of recreational fishing on marine fish stocks and ecosystems. *Reviews and Fisheries Science and Aquaculture*, DOI: 10.1080/23308249.2019.1586829.
- Lindeman, K.C., R. Pugliese, G.T. Waugh, and J.S. Ault. 2000. Development patterns within a multispecies reef fishery: management applications for essential fish habitats and protected areas. *Bulletin of Marine Science* 66(3):929-956.
- Mbaru, E. K., N. A. J. Graham, T. R. McClanahan, J. E. Cinner. 2019. Functional traits illuminate the selective impacts of different fishing gears on coral reefs. *Journal of Applied Ecology*.

- McClenachan, L. 2009. Documenting loss of large trophy fish from the Florida Keys with historical photographs. *Conservation Biology* 23(3): 636-643.
- Mora, C. 2008. A clear human footprint in the coral reefs of the Caribbean. *Proceedings Of The Royal Society B-Biological Sciences* 275:767-773.
- Mora, C., et al. 2011. Global human footprint on the linkage between biodiversity and ecosystem functioning in reef fishes. *PLoS Biology* 9: e1000606.
- Mosquera, I., I. M. Côté, S. Jennings, and J. D. Reynolds. 2000. Conservation benefits of marine reserves for fish populations. *Animal Conservation* 3:321-332.
- Mumby, P. J., A. J. Edwards, J. E. Arias-González, K. C. Lindeman, P. G. Blackwell, A. Gall, M. I. Gorczynska, A. R. Harborne, C. L. Pescod, H. Renken, C. C. C. Wabnitz, and G. Llewellyn. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature* 427:533-536.
- Mumby, P. J. 2006. Connectivity of reef fish between mangroves and coral reefs: algorithms for the design of marine reserves at seascape scales. *Biological Conservation* 128:215-222.
- Mumby, P. J., S. Bejarano, Y. Golbuu, R. S. Steneck, S. N. Arnold, R. van Woosik, and A. M. Friedlander. 2013. Empirical relationships among resilience indicators on Micronesian reefs. *Coral Reefs* 32:213-226.
- Pratchett, M. S., P. L. Munday, S. K. Wilson, N. A. J. Graham, J. E. Cinner, D. R. Bellwood, G. P. Jones, N. V. C. Polunin, and T. R. McClanahan. 2008. Effects of climate-induced coral bleaching on coral-reef fishes - Ecological and economic consequences. *Oceanography and Marine Biology: An Annual Review* 46:251-296.
- Robertson, D. R., and J. M. Sheldon. 1979. Competitive interactions and the availability of sleeping sites for a diurnal coral reef fish. *Journal of Experimental Marine Biology and Ecology* 40:285-298.
- Rosemond, R.C., A.B. Paxton, H.R. Lemoine, S.R. Fegley, C.H. Peterson. 2018. Fish use of reef structures and adjacent sand flats: implications for selecting minimum buffer zones between artificial reefs and existing reefs. *Marine Ecology Progress Series* 587: 187-199.
- Russ, G. R. 2002. Yet another review of marine reserves as reef fishery management tools. Pages 421-443 in P. F. Sale, editor. *Coral reef fishes: dynamics and diversity in a complex ecosystem*. Academic Press, San Diego.
- Saha, K., X. Zhao, H. Zhang, K.S. Casey, B. Dexin, Sheekela, K.A. Kilpatrick, R.H. Evans, T. Ryan, J.M. Relph. 2018. AVHRR Pathfinder Version 5.3 Level 3 Collated (L3C) Global 4km sea surface temperature for 1981-Present. NOAA National Centers for Environmental Information. Dataset. doi: 10.7289/V52J68XX.
- Sbrocco, E.J., and P.H. Barber. 2013. MARSPEC: ocean climate layers for marine spatial ecology. *Ecology* 94(4):979.
- Seaman, W. 2000. *Artificial reef evaluation with application to natural marine habitats*. CRC Press. Boca Raton, FL.
- Sherman, K. D., C. P. Dahlgren, J. R. Stevens, and C. R. Tyler. 2016. Integrating population biology into conservation management for endangered Nassau grouper *Epinephelus striatus*. *Marine Ecology Progress Series* 554:263-280.
- Shideler, G.S., R.J. Araujo, B.K. Walker, J. Blondeau and J.E. Serafy. 2017. Non-linear thresholds characterize the relationship between reef fishes and mangrove habitat. *Ecosphere* 8(9): e01943.
- Stallings, C. D. 2009. Fishery-independent data reveal negative effect of human population density on Caribbean predatory fish communities. *PLoS ONE* 4: e5333.
- Taylor, B. M., S. J. Lindfield, and J. H. Choat. 2014. Hierarchical and scale-dependent effects of fishing pressure and environment on the structure and size distribution of parrotfish communities. *Ecography* 37:001-011. doi: 010.1111/ecog.01093.
- Walker, B. K. 2012. Spatial analyses of benthic habitats to define coral reef ecosystem regions and potential biogeographic boundaries along a latitudinal gradient. *PLOS ONE* 7(1):e30466.
- Williams, I. D., J. K. Baum, A. Heenan, K. M. Hanson, M. O. Nadon, and R. E. Brainard. 2015. Human, oceanographic and habitat drivers of central and western Pacific coral reef fish assemblages. *PLoS ONE* 10: e0120516. doi:10.1371/journal.pone.0120516.
- Wolff, N., R. Grober-Dunsmore, C. S. Rogers, and J. Beets. 1999. Management implications of fish trap effectiveness in adjacent coral reef and gorgonian habitats. *Environmental Biology of Fishes* 55:81-90.

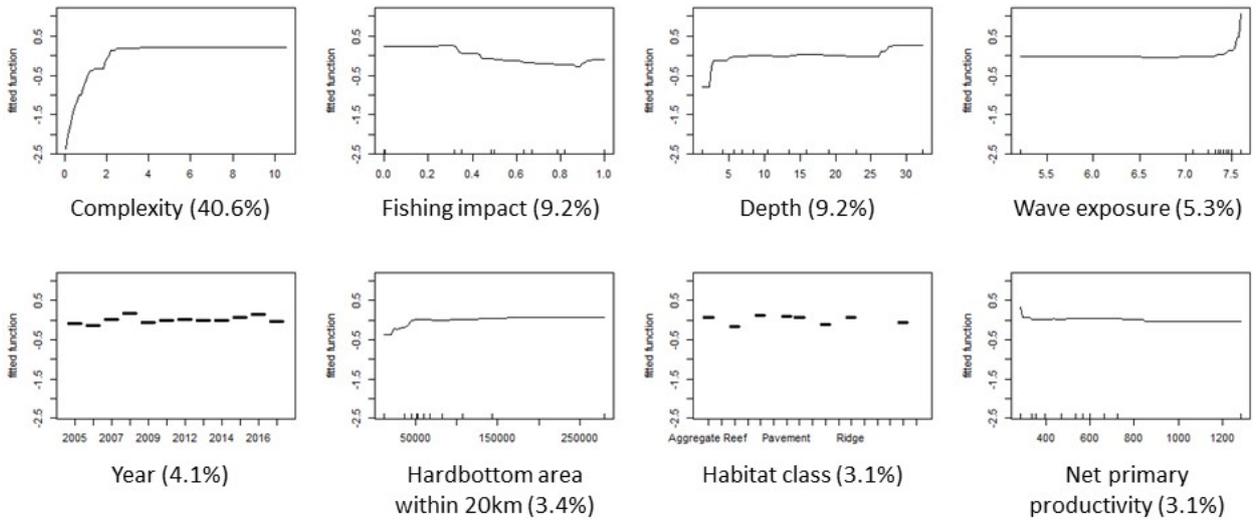
Yeager, L.A., P. Marchard, D.A. Gill, J.K. Baum, and J.M. McPherson. 2017. Marine socio-environmental covariates: queryable global layers of environmental and anthropogenic variables for marine ecosystem studies. *Ecology* 98(7):1976.

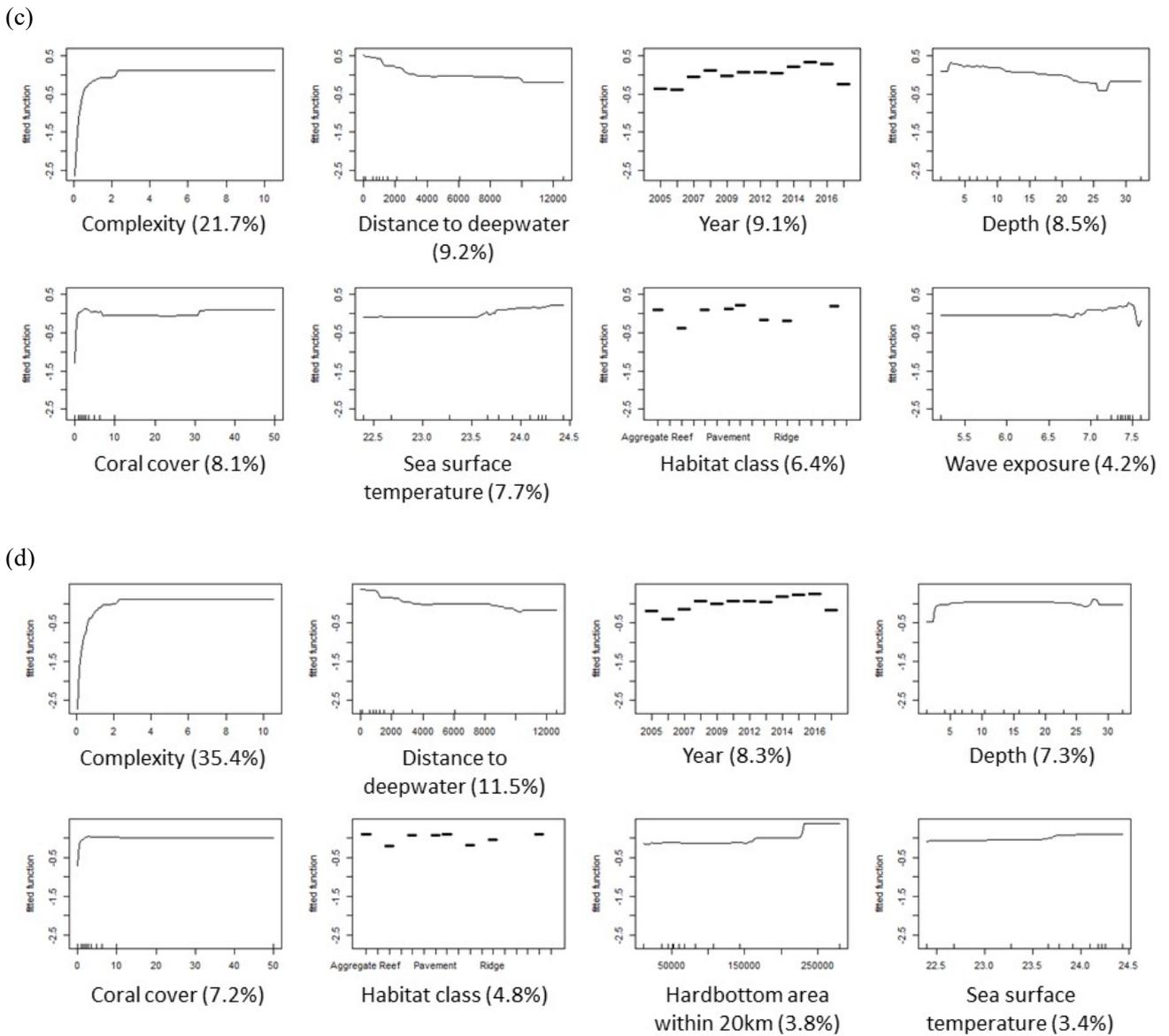
### Appendix 3. Additional fish biomass model results

(a)



(b)





**Fig. A3.1.** Relationships between the 8 most important significant variables and the biomass of (a) all fished species; (b) all species recorded in NCRMP RVC surveys; (c) herbivores; and (d) marine life species (y-axis, values of log biomass are normalised as opposed to showing actual biomass) modelled by boosted regression trees. Values represent the percentage of explained deviance that was explained by each variable.

## Appendix 4. Two-page introductory handout for the project

### MODELING AND MAPPING FISHING IMPACT AND FISH BIOMASS ON SOUTH FLORIDA'S CORAL REEFS

#### PROJECT OVERVIEW

Coral reef ecosystem services, including food provisioning from fisheries, are under threat from a wide range of human-caused stressors. To ensure that benefits such as fisheries are sustained, we must incorporate ecosystem services into marine management decisions. To facilitate this, The Nature Conservancy established the *Mapping Ocean Wealth* initiative to describe in quantitative and spatial terms what ocean ecosystems provide today. Under this umbrella, our project aims to map and model coral reef fisheries in South Florida to provide quantitative estimates of fish biomass, an important component of ecosystem benefits.



#### PROJECT OBJECTIVES

- Use fishery-independent data to model cumulative fishing impact on Florida's coral reefs
- Create a map of estimated fishing impact to be used in conservation planning
- Use spatially-explicit estimates of fishing impact and biophysical data to model and map biomass of reef fishes on Florida's coral reefs
- Use the fish biomass model to predict fishery outcomes under a range of management and environmental change scenarios
- Post data on the Mapping Ocean Wealth data portal (<https://maps.oceanwealth.org>)

#### MODELING AND MAPPING FISHING IMPACT AND BIOMASS

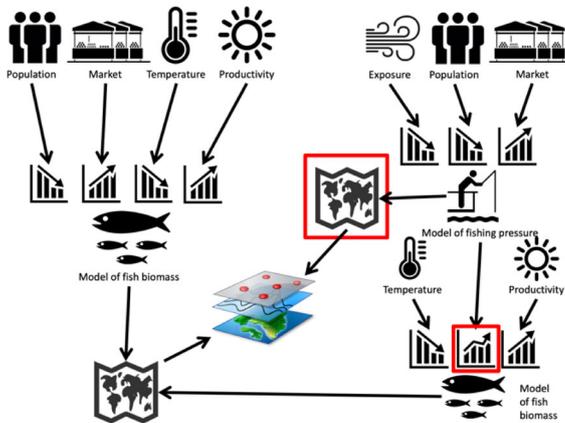


The first step will be to statistically model fishing impact using fishery-independent data on fish abundance and size. These data will be modelled in relation to a wide range of potential predictor variables, including biophysical data characterizing the coral reef and adjacent environment, and socio-economic data providing context to South Florida's fisheries. This model will be used to extrapolate fishing impact (specifically the total cumulative impact of fishing on the fish assemblage) to all coral reefs from Martin County to the Dry Tortugas, and to generate a map reflecting the predicted impact.

With this spatial data on fishing impact, we will then model current fish biomass at an independent set of sites where fish survey data are available. Fishing impact will be a key predictor variable. This model will generate a functional relationship between fishing and fish biomass for the region, while accounting for a range of environmental variables, such as sea surface temperature, that may impact biomass. This model will then be used to extrapolate estimates of current biomass to generate a continuous map that will be made available to fishery and marine managers.

**ANTICIPATED OUTCOMES**

The modeled fish biomass and resultant maps will be useful tools for exploring fishery outcomes under a range of management options (e.g. area-based fishing regulations) and environmental change (e.g. a change in coral cover) scenarios. This new 'Ocean Wealth' information can be used to help set realistic expectations for area-based management outcomes, aid in restoration decision-making, and provide managers information relating to fishery use for areas where few data currently exist. We aim to provide information to managers and stakeholders to improve understanding of ecological trade-offs and potential benefits that are predicted under different management and ocean use scenarios.



**PROJECT TEAM**

This project is a collaboration between Alastair Harborne's Tropical Fish Ecology Lab at Florida International University and The Nature Conservancy (TNC). The work supports the Mapping Ocean Wealth initiative, which aims to generate high quality, spatially-explicit data to reveal the economic and social benefits of coastal ecosystems, such as coral reefs, around the world.

For more on the *Mapping Ocean Wealth* initiative, visit <https://oceanwealth.org/>. For questions or to speak with someone about this project, please reach out:

**Rachel Zuercher**, FIU  
[rzuerche@fiu.edu](mailto:rzuerche@fiu.edu)

**Alastair Harborne**, FIU  
[aharborne@fiu.edu](mailto:aharborne@fiu.edu)

**Robert Brumbaugh**, TNC  
[rbrumbaugh@tnc.org](mailto:rbrumbaugh@tnc.org)

