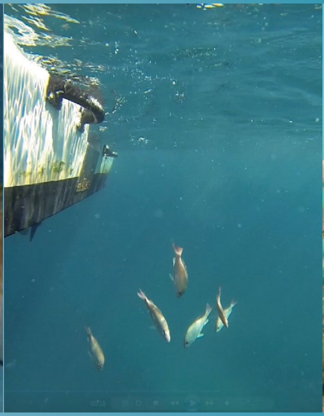
Movements of Reef Fish Across the Boundary of the Virgin Islands Coral Reef National Monument in Coral Bay, St. John USVI

NOAA National Centers for Coastal Ocean Science
Center for Coastal Monitoring and Assessment

M.S. Kendall, L. Siceloff, and M.E. Monaco

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Prepared by:
NOAA National Centers for Coastal Ocean Science (NCCOS)
Center for Coastal Monitoring and Assessment (CCMA)
Biogeography Branch
1305 East West Highway (SSMC-IV, N/SCI-1)
Silver Spring, MD 20910
USA

July 2016

Matthew S. Kendall
CCMA Biogeography Branch

Laughlin Siceloff
CCMA Biogeography Branch and Consolidated Safety Services-Dynamac, Inc.

Mark E. Monaco
Center for Coastal Monitoring and Assessment

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United States Department of Commerce	National Oceanic and Atmospheric Administration	National Ocean Service
Penny Pritzker Secretary	Kathryn D. Sullivan Administrator	Russell Callender Acting Assistant Administrator

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Matt Kendall, Biogeography Branch
National Oceanic and Atmospheric Administration
1305 East West Highway
SSMC 4, N/SCI-1
Silver Spring, MD 20910
Phone: (240) 533-0341
Email: Matt.Kendall@noaa.gov

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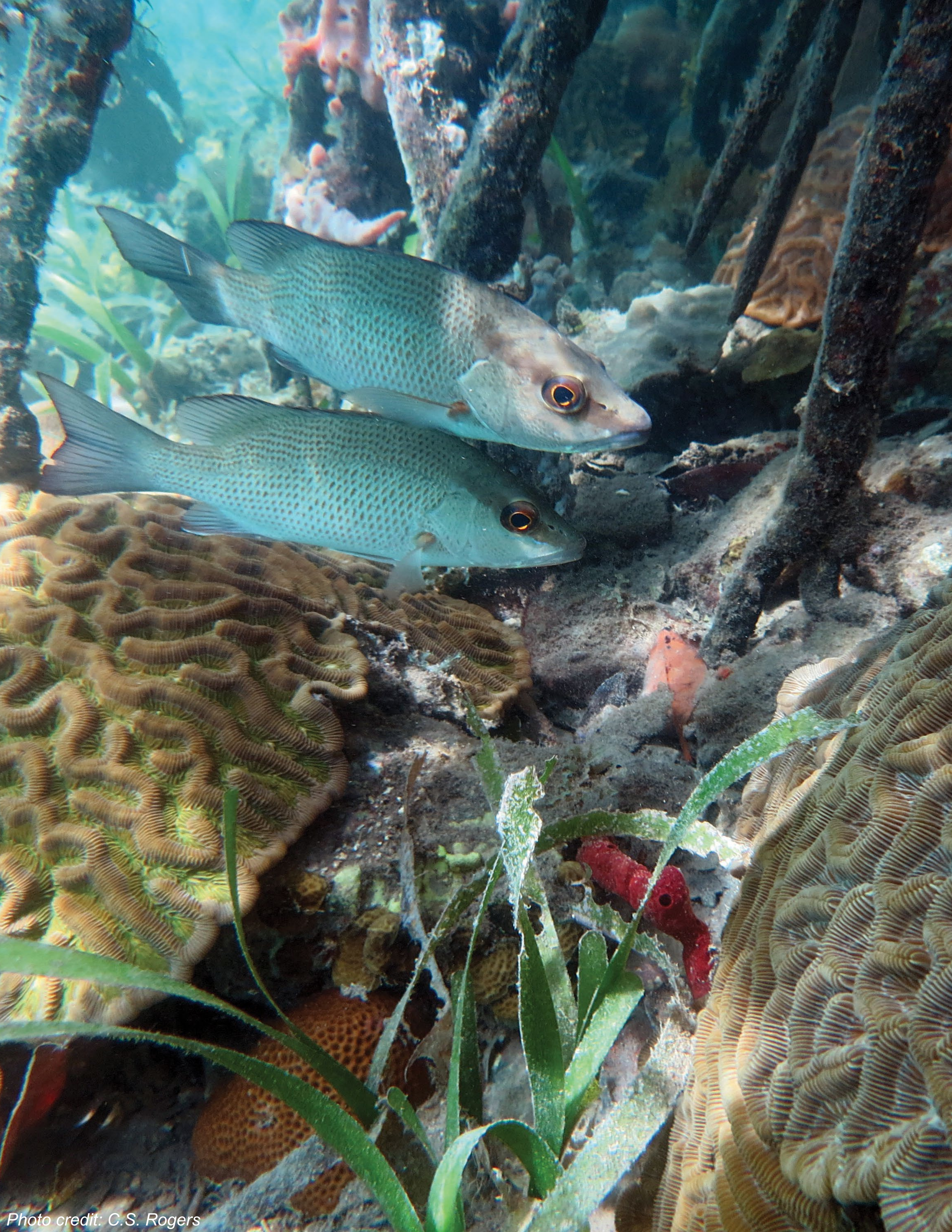
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EXECUTIVE SUMMARY

The Virgin Islands Coral Reef National Monument (VICRNM) was created to expand the protection of the marine ecosystems around St. John. Monument boundaries were not designed using ecological criteria, but were instead the result of historical land ownership and the Territorial Submerged Lands Act of 1974. This study used acoustic telemetry to investigate movements of reef fish relative to the boundary of the Coral Bay portion of the Monument and the protection that this Marine Protected Area (MPA) could offer. In this approach, acoustic transmitters are implanted into fish and their movements are logged on battery-powered acoustic-receivers (n=38) positioned within, outside, and along the boundary of the Monument. Specifically, we quantify residence time of reef fish within VICRNM, the frequency of movements across the VICRNM boundary, and locations of concentrated fish activity.

The National Park Service (NPS) manages the entire reef fish community within the Monument. Therefore, we set fish traps in various habitats throughout VICRNM to capture a diversity of species for tagging. Uniquely coded transmitters with a ~376 day battery life were implanted into 75 fish between August and December 2013. Minimum fish size was ~20 cm to accommodate tags. The fish tagged were from 17 species in 7 families with snappers (n = 38 fish) and grunts (n = 24) being the most common. Receivers were downloaded March 2015. Data were summarized to convey basic information about fish movements including: the time-span of detections, number of detections, percent of days detected, number of receivers visited, number and frequency of VICRNM boundary crossing events, proportion of detections inside versus outside VICRNM, and location of day versus night detections.

Receivers inside VICRNM typically detected more tagged fish than those outside or on the border, over half of the fish were never detected outside of the VICRNM boundary, and a large majority of the fish had a greater proportion of their detections inside the Monument than would be expected if they were moving randomly. In contrast to these encouraging statistics however, are several other variables. First, while some fish were potentially resident within the monitoring area for the whole duration of the study, most were not based on their detection period, and presumably emigrated from the detection area, had a home range partly outside the detection area, or were removed via natural or fisheries based mortality. The maximum duration of any inference is limited to ~1 year given the battery life of the transmitters.

Although not delineated with ecological criteria, the VICRNM boundary in Coral Bay appears to have coincidentally aligned with a key principle of MPA design for reef fish; the boundary does not cross through continuous reef habitat. Land ownership and the configuration of the bays in this area resulted in the boundary being placed roughly along the central-axis and deepest parts of Coral Bay. The boundary is in the sand or mud habitat that separates the reef and mangrove habitats that fringe opposite sides of the Bay. The boundary therefore rests on a physical feature that acts as a natural barrier to movements of many reef fish. Even those species that periodically move away from the reef do so over regular routes, across predictable distances, and have high site fidelity when returning to the reef. The VICRNM boundary also happens to completely encompass the deep, spur and groove reef that extends southward from Turner Point. This reef has among the highest values of diversity and abundance for reef fish around St. John.

It is clear that some fish species have the potential to be better protected by Monument boundaries than others. For example, *Lutjanus griseus* (gray snapper) were among the least mobile fish in the study. They were never detected outside VICRNM, and rarely moved beyond the confines of mangrove-lined bays. At the other end of the spectrum, *Ocyurus chrysurus* (yellowtail snapper) were detected on many receivers, frequently crossed the VICRNM boundary, and were detected for a shorter span than most other fish. Few detections and varied locations for *Lutjanus apodus* (schoolmaster snapper) likewise suggest that they did not remain in the study area. In addition, *Lutjanus synagris* (lane snapper) were among the more mobile species. They were detected at more receivers and crossing the boundary more often and regularly than many others. Haemulids (grunts) were in the middle of this spectrum, were detected at an intermediate number of receivers, and crossed the boundary a moderate number of times.

In addition to the general spatial patterns related to the Monument boundary, there were a few specific locations with concentrated fish activity. Both the number of fish and number of detections were highest at receivers at the mouths of Otter and Water Creeks and off the high-relief reef south of Turner Point including boundary receivers and one location outside the Monument. Daily patterns were also evident in that a much greater proportion of detections were during the night on most receivers outside the Monument.

Based on the overall findings, the Coral Bay portion of the Monument has the potential to offer partial protection to a majority of the fish studied here. However, even for fish that have a robust record of residence inside the Monument, their actual protection assumes compliance with no-take regulations. Investment in enforcement of existing regulations and monitoring of violations are warranted to realize the potential of this MPA. Management action could be focused on those species (e.g., *L. griseus*) and locations within the study area (e.g., small bays and reef off Turner Point) that would experience the greatest benefit.

Important next steps in this investigation include further analysis of the existing data from Coral Bay (e.g., graph theory and network analysis) as well as collection of additional field data. Comparing results among locations is critical to develop a general understanding of the processes governing movement networks and how other landscape settings may result in broader inferences on fish movements and implications for the design of MPA boundaries.

1.0. INTRODUCTION

1.1. Virgin Islands Coral Reef National Monument

National park entrance.
Photo credit: M. Kendall, Biogeography Branch, NOAA

The Virgin Islands Coral Reef National Monument (VICRNM) was created in 2001 by Presidential Proclamation 7399 (2001) to expand the protection of the marine ecosystems around the island of St. John. The area encompasses a diverse mosaic of inter-dependent habitats that are connected to each other through coastal currents and movements of reef biota (Friedlander et al., 2013a; Pittman et al., 2014a). Specifically, the Coral Bay region of the Monument includes a complex coastline with multiple smaller bays (e.g., Round Bay and Hurricane Hole which is comprised of Princess Bay, Borck Creek, Otter Creek, and Water Creek) and the most extensive mangrove habitat on St. John (Figure 1.1). The mangrove forests of this area provide habitat for many adult fish and invertebrates rarely found elsewhere, function as a nursery ground for many species that ultimately reside on coral reefs, harbor an unexpected diversity of corals, and may possess a unique range of chemical, shading, and thermal characteristics that offer corals a refuge from climate change (Boulon, 1992; Rogers, 2009; Friedlander et al., 2013b; Yates et al., 2014; Legare et al., 2015). The reefs and other habitats of the Coral Bay portion of VICRNM are home to a wide diversity of reef fish, corals, invertebrates, seagrass, and algal communities (Friedlander et al., 2013b; Costa et al., 2013). Humans use the area for recreation such as kayaking, snorkeling, mooring of boats, and also in times of hazardous weather as a refuge for boats, a practice which has given the Hurricane Hole portion of the area its name. Apart from permitted gathering of bait fish from the Hurricane Hole portion of VICRNM, all forms of extractive use as well as anchoring and tying to mangroves were prohibited with establishment of the Monument (Presidential Proclamation 7399). Despite the added protections of these ecosystems, reef fish populations have continued an overall decline (Rogers and Beets, 2001; Pittman et al., 2014b).

The boundary of the VICRNM in Coral Bay is based on the Territorial Submerged Lands Act (1974) which transferred submerged areas within 3 n mi of the shore from federal to territorial control. Specifically, the Act states that “all submerged lands adjacent to property owned by the United States” were excluded from such transfer. In the case of the Coral Bay area, a search of land records placed the boundary separating federal versus territorial control along the midline of Hurricane Hole and Round Bay (Johnson and Thormahlen, 2002) (Figure 1.1). This federal ownership of submerged parts of Coral Bay made it possible to convert them to National Monument status as part of VICRNM. Therefore, although created to protect a marine ecosystem, ecology was never actually considered when the geographic boundaries were established (Devillers et al., 2015). The Proclamation (7399) further states that the boundaries are “the smallest area compatible with the proper care and management of the objects to be protected”. This study investigates the movements of reef fish relative to the boundary of the Coral Bay portion of the Monument and its potential for reef fish protection.

1.2. Reef Fish In Coral Reef Ecosystems

Many species of reef fish present in Coral Bay move among habitats during various phases of their life history. Many Lutjanidae (snappers) and other species are known to utilize seagrass and mangroves as juveniles but then shift to coral reefs once they grow larger (de la Moriniere et al., 2002; Christensen et al., 2003; Gratwicke et al., 2006; Huijbers et al., 2015). Several Lutjanidae and Haemulidae (grunts) species are known to reside at reefs and other structurally complex hard bottom habitats during the day but then undergo nightly foraging migrations of several hundred meters into adjacent sand and mud habitats (Ogden and Ehrlich,

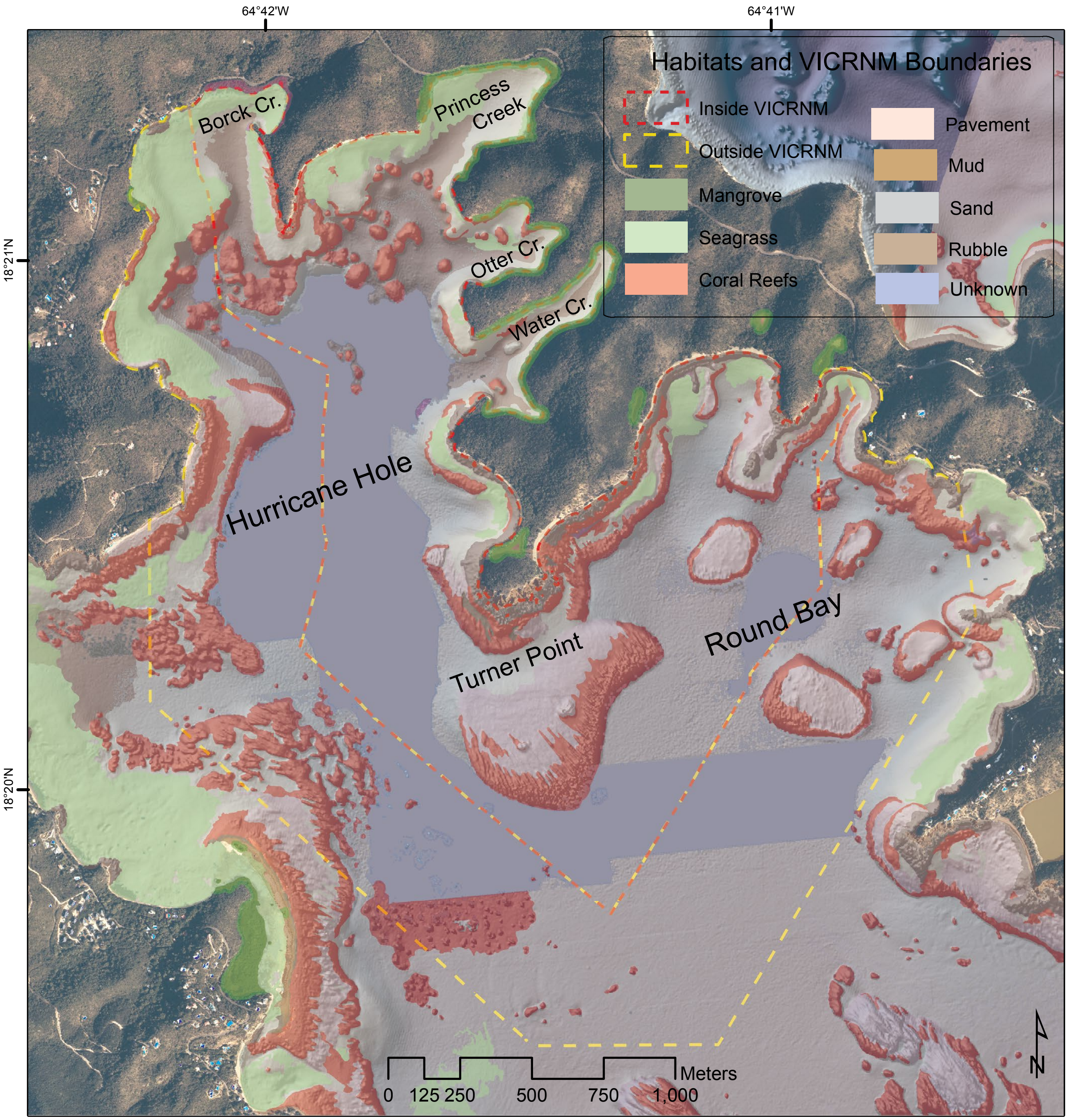


Figure 1.1. Study area within Coral Bay, St. John. Geographic places noted in the text are labelled. VICRNM boundaries (red) and outer edge of study area (yellow) are also shown. Bottom types adapted from Costa et al. (2013).

1977; Beets et al., 2003; Kendall et al., 2003; Nagelkerken et al., 2008; Hitt et al., 2011). Reef fish species have a diversity of home range size requirements that may take them across 10-100s of m of continuous reef habitat (Kramer and Chapman, 1999; Semmens et al., 2005; Pittman et al., 2014a). Other species including many Carangidae (jacks) range even more widely among habitats on a daily basis (Wetherbee et al., 2004; Brown et al., 2010; Friedlander et al., 2013a). Less frequent lunar-cycle or seasonal-based migrations also take place by reef fish for reproduction or foraging. Spawning aggregations are perhaps the best example of this and can result in considerable fish movements either to local congregation spots on nearby reef promontories, or more widely to shelf edge sites that are considerable distances away from their regular territories (Randall and Randall, 1963; Nemeth et al., 2007; Afonso et al., 2009; Pittman et al., 2014a). Each of these movement patterns has the potential to temporarily or permanently relocate fish outside of the protected confines of the VICRNM boundaries. Although studied in other geographies (e.g., Egli and Babcock, 2004; Nemeth, 2005; Meyer et al., 2007; Brown et al., 2010; Friedlander et al., 2013a; Pittman et al., 2014a), the timing and frequency of these behaviors and migrations relative to the local landscape, dimensions, and configuration of the VICRNM boundary in Coral Bay are unknown.

1.3. Acoustic Telemetry

Acoustic telemetry is an effective tool for quantifying habitat utilization patterns, home range size, site fidelity, migration, MPA boundary crossing, and the timing of such movements for marine fish (e.g., Wetherbee et al., 2004; Heupel et al., 2006; Fairchild et al., 2013; Pittman et al., 2014a). In this approach, an acoustic transmitter that emits a unique identification code is implanted into a fish of interest. The fish's movements are logged on an array of battery-powered acoustic receivers that are strategically positioned throughout the fish's ecosystem to track the location and timing of the fish's activity. There are now many studies with suggestions for optimizing the design and deployment of acoustic telemetry arrays for many fish types in various environments (Heupel et al., 2006; Hobday and Pincock, 2012; How and de Lestang, 2012; Mathies et al., 2014).

1.4. Objectives

Our overall goal was to monitor reef fish movements in the Coral Bay area of the VICRNM for 1 year. Because the National Park Service is responsible for managing the entire reef fish community within Monument boundaries, we took a broad approach encompassing a diversity of fish species and habitats. Specifically we sought to quantify residence time of reef fish within the Monument, the frequency of fish movements across the VICRNM boundary, and identify hotspots of concentrated fish activity within the study area.

Data recording. Photo credit: M. Kendall, Biogeography Branch, NOAA

2.0. METHODS

2.1. Study Area

The Coral Bay, St. John study area consists of many small, mangrove lined bays with scattered seagrass beds, sand and mud bottoms, fringing and patch reefs, rocky promontories, gorgonian pavements, and spur and groove reefs (Costa et al., 2013) (Figure 1.1). Diversity and biomass of reef fish in this area have among the highest values among reefs throughout St. John and especially large numbers of several Lutjanidae and Haemulidae species reside there (Friedlander et al., 2013b). Terrestrial runoff from the largest watershed in the area is from residential development, is concentrated in the inner reaches of Coral Harbor to the west, and has little impact on outer parts of the Bay and Hurricane Hole. The water column is well mixed, wave energy is low, tidal range is small, and currents are minimal. These uniform water characteristics are not believed to be a major source of spatial variability on transmitter detections (Heupel et al., 2006; Hobday and Pincock, 2012; How and de Lestang, 2012; Mathies et al., 2014). Noise from boats is highest near Coral Harbor in the western portion of the study area but vessel traffic is never heavy, with only a few small boats transiting each hour during daylight (M. Kendall, pers. obs.). As with most coral reef ecosystems, biotic sounds peak at dawn and dusk (Kaplan et al., 2015). Unfortunately, there is a lack of seafloor imagery for the deepest main stem areas of Hurricane Hole and Round Bay due to turbidity (see ‘unknown’ area in Figure 1.1), however, reconnaissance dives suggest those areas may primarily be comprised of sand and mud bottom.

Acoustic receivers were placed strategically throughout the study area to address the objective of understanding movements of reef fish within and across the VICRNM boundary. Based on prior experience and the theoretical detection range of transmitters published by the manufacturer, receivers were positioned to monitor fish inside VICRNM (receiver numbers I1-15) within small bays, at bay mouths, along the VICRNM border (B1-11), and in adjacent areas outside the VICRNM border (O1-12) (Figure 2.1, Table 2.1). The receivers along the boundary were each covered by a foam shroud on one side to make them hemi-directional and only able to detect fish presence within VICRNM (Kendall et al., 2016). All receivers were secured to the seafloor using sand screws, attached to steel cables ~2 meters off the bottom, and held vertical in the water column using 2 floats (15 cm diameter). All receivers were deployed in August and September 2013.

Fish trap. Photo credit: M. Kendall, Biogeography Branch, NOAA

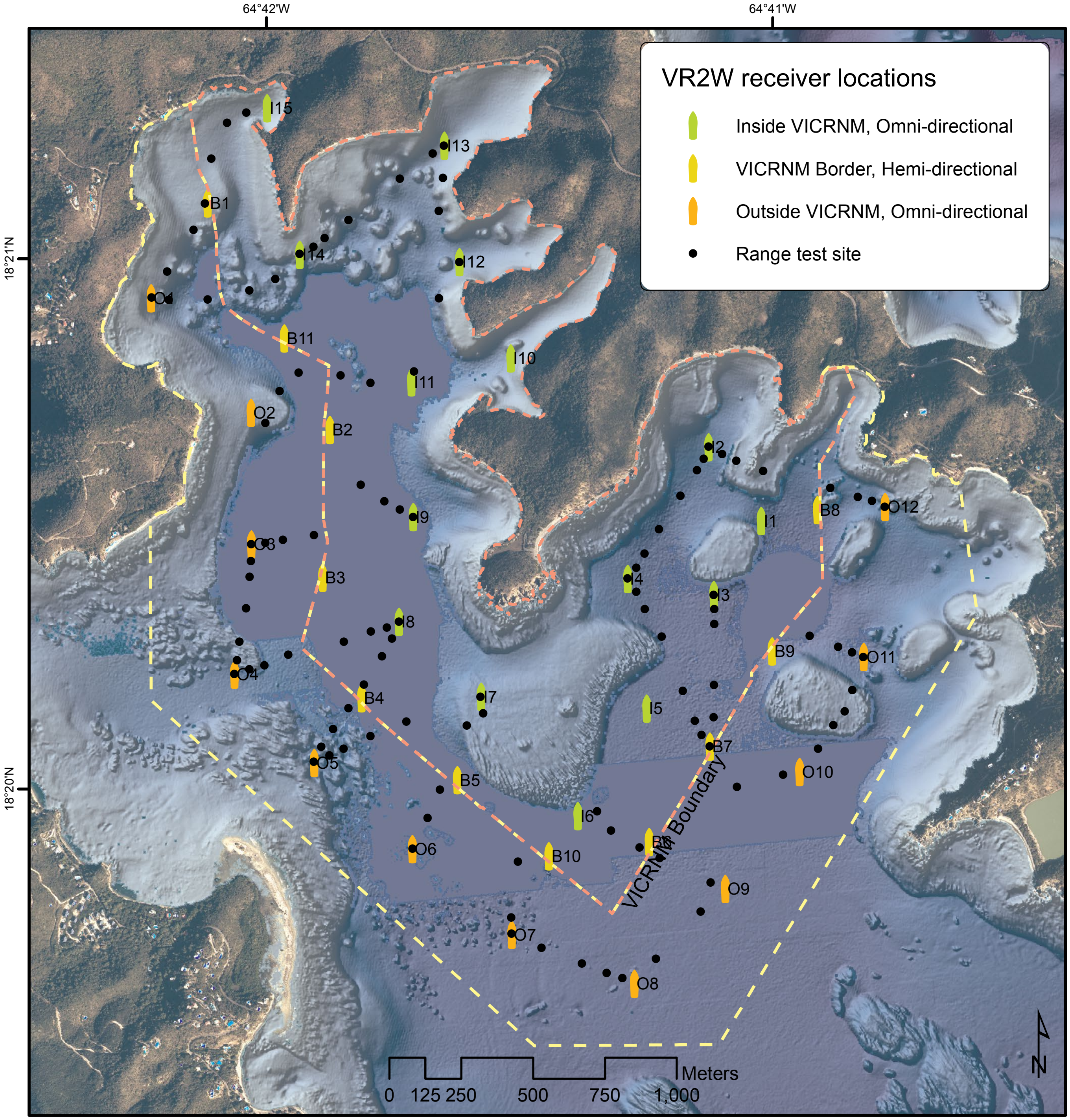


Figure 2.1. Locations of VR2W acoustic receivers and range test sites. Seafloor topography is shown in blue. VICRNM boundaries (red) and outer edge (yellow) of study area are also shown.

2.2. Fish Capture and Tagging

A wide variety of reef fish are vulnerable to capture using fish traps (Robichaud et al., 2000). Baited (e.g., dead fish, vegetable matter, canned mackerel) and un-baited fish traps were set for 2-3 days in various habitats and depths throughout the Coral Bay portion of VICRNM with approximately equal effort in the Hurricane Hole and Round Bay areas (Figure 2.2). Capturing fish from throughout VICRNM maximized the scope of inference and minimized the likelihood of transmitter code-collisions and false detections from too many transmitters in any one area (Pincock, 2012). Catch composition was similar to other studies using fish traps in the area (Beets et al., 2003; Friedlander et al., 2013a) and was dominated by Lutjanidae and Haemulidae but also included a diversity of other reef fishes including Serranidae (groupers), Scaridae

Table 2.1. Coordinates and depth of acoustic receivers.

Receiver	Location Description	UTM 20 N Easting	UTM 20 N Northing	Depth (m)
B1	Borck Creek	320174	2029949	6
B2	Hurricane Hole	320600	2029161	20
B3	Hurricane Hole	320574	2028647	20
B4	Coral Bay	320710	2028228	22
B5	Coral Bay	321043	2027943	17
B6	Coral Bay	321711	2027727	24
B7	Coral Bay	321922	2028059	24
B8	Limetree Cove	322296	2028882	23
B9	Round Bay	322138	2028390	24
B10	Coral Bay	321362	2027678	23
B11	Hurricane Hole	320441	2029479	20
O1	Hurricane Hole	319977	2029619	8
O2	Hurricane Hole	320325	2029221	8
O3	Hurricane Hole	320326	2028763	20
O4	Coral Bay	320267	2028310	16
O5	Coral Bay	320545	2028003	17
O6	Coral Bay	320887	2027703	23
O7	Coral Bay	321232	2027405	24
O8	Coral Bay	321659	2027234	25
O9	Coral Bay	321976	2027564	24
O10	Coral Bay	322234	2027971	24
O11	Round Bay	322457	2028371	23
O12	Round Bay	322531	2028893	18
I1	Round Bay	322101	2028844	22
I2	Elk Bay	321918	2029101	17
I3	Round Bay	321936	2028587	25
I4	Round Bay	321636	2028643	22
I5	Coral Bay	321702	2028192	23
I6	Coral Bay	321463	2027818	20
I7	Coral Bay	321126	2028233	14
I8	Coral Bay	320840	2028493	22
I9	Hurricane Hole	320890	2028858	18
I10	Water Creek	321229	2029410	11
I11	Hurricane Hole	320883	2029327	20
I12	Otter Creek	321051	2029745	15
I13	Princess Bay	320998	2030150	8
I14	Hurricane Hole	320495	2029770	6
I15	Borck Creek	320381	2030280	4

(parrotfish), Holocentridae (squirrelfish), Sparidae (porgies), Carangidae, and several other taxa that were too small to accommodate transmitters. Minimum fish size in this study was 19 cm to ensure that tag size and weight would not adversely affect fish behavior. Sexual maturity was estimated for tagged fish using size at maturity data from FishBase.org (Froese and Pauly, 2016). After capture, fish were treated for barotrauma if needed using a hypodermic needle and then taken to a nearby wet lab.

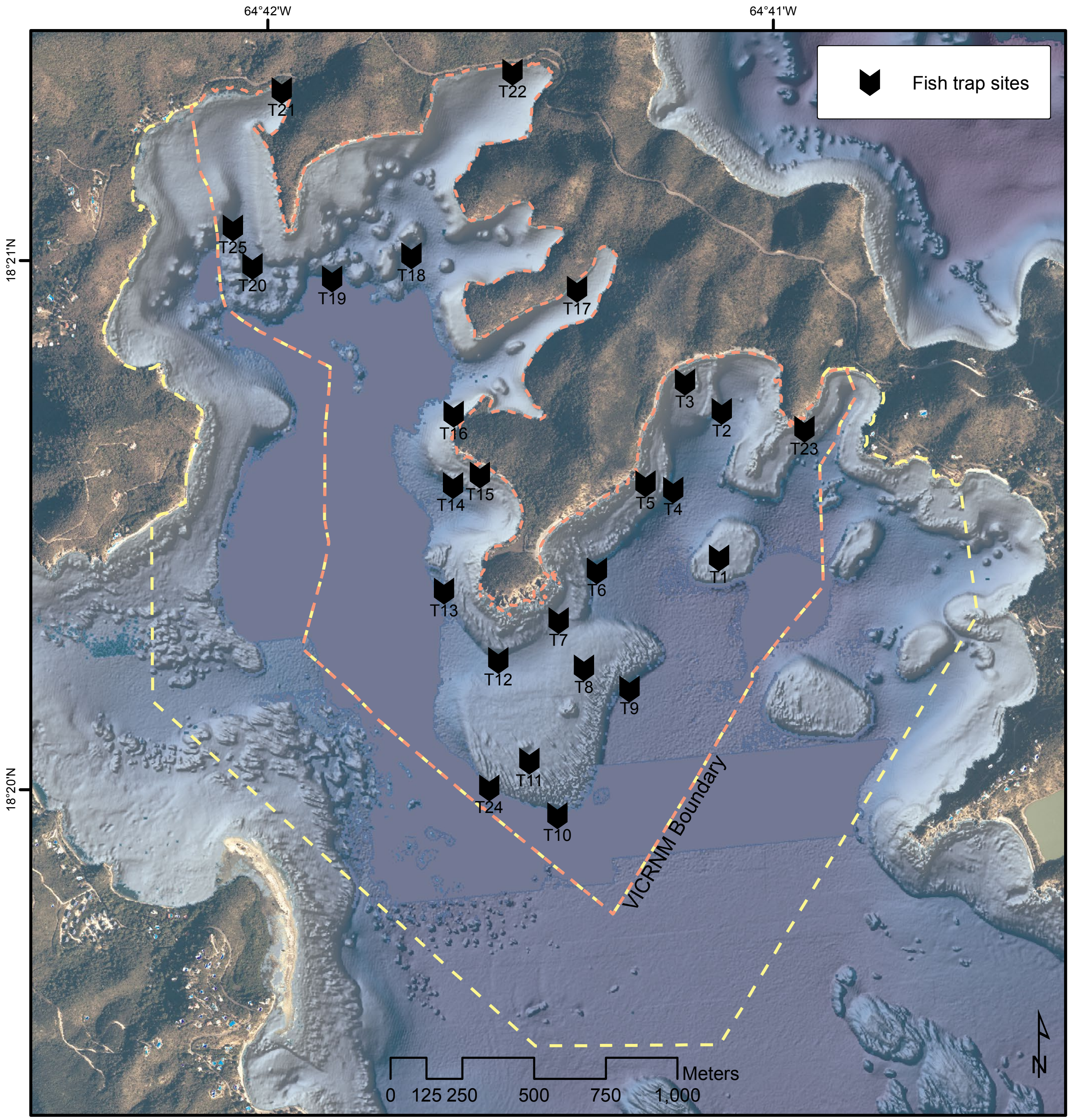


Figure 2.2. Fish trap locations. Seafloor topography is shown in blue. VICRNM boundaries (red) and outer edge of study area (yellow) are also shown.

At the wet lab, uniquely coded transmitters (VEMCO model V7-4L, 7 by 18 mm, with enhanced coding and a ~376 day battery life) were implanted into fish using recently evaluated best-practices for surgical procedures that minimize stress and mortality (Friedlander et al., 2013a; Reese Robillard et al., 2015). Transmitters were implanted into the body cavity through a ~1.5 cm incision made abdominally off the ventral midline approximately halfway between the pelvic and anal fins. This was closed with a single suture. After the ~2 minute surgical procedure, fish were held in large seawater tanks over-night for recovery, and then released at their capture locations. Survivorship was 96% following the surgery and recovery periods.

To understand how the suite of species that we tagged compares to the overall fish community in Coral Bay, we compared our list of tagged fish to those seen on recent diver-based surveys in the same area. From 2001-2011, NOAA/NPS have conducted ~1,700 visual counts of fish on hard and soft bottom habitats within VICRNM (Friedlander et al., 2013b). Based on the minimum size limit for tagging of ~20 cm, we summarized all the fish were greater than 20 cm long that were seen during surveys. Relative abundance was compared at the family level using pie charts for: 1) fish tagged in this telemetry study, and 2) those seen on visual surveys.

2.3. Range Testing of the Receiver Array

Effective range of the receivers for detecting transmitter signals was determined in December 2013 by deploying special range-test transmitters in a diversity of locations around both the omni- and hemi-directional receivers throughout the study area. In this analysis, a range-test transmitter of the same size and strength as the transmitters implanted in fish but with a ~15 second ping rate was deployed ~0.5 m off the bottom for a minimum of ten minutes at each range-test site. This distance off the bottom simulated the near benthic position typical of the reef fish that we tagged. This transmitter was deployed repeatedly in various directions, distances, and landscape settings relative to each receiver (Figure 2.1).

For the omni-directional receivers, the percentage of transmitter pings actually detected out of pings emitted at each deployment site was plotted against distance from each receiver. A smoothed curve was fit to the distance by detection percentages for each receiver using the spline smoother in Excel 2010. The shape of this curve matches the typical sigmoid or logistic shape seen in coral reef environments (Hobday and Pincock, 2012; How and de Lestang, 2012; Farmer et al., 2013; Selby et al., 2016). Inflection points of the curves (~50% probability of detection) were used to identify the typical detection range experienced by each omni-directional receiver. The uni-directional receivers were evaluated using a similar process but analysis focused instead on the ability of the receivers to monitor transmissions along the VICRNM boundary (see Kendall et al., 2016 for description).

A map of VICRNM's boundary overlaid with estimated ranges for each receiver was used to calculate the proportion of the study area actually monitored by receivers. This is needed to correct for bias in monitoring area during data interpretation and statistical tests. The offshore edge of the study area was defined using a line drawn beyond the detection range of outside receivers such that receivers were equidistant from the drawn line and the VICRNM boundary. Total area of the study was calculated as the area between this line and the shoreline within VICRNM. This was subdivided into the areas inside and outside of VICRNM. These were further subdivided into areas inside and outside of the detection range of receivers. If fish movements are random, the proportion of fish detections inside versus outside VICRNM should be similar to the proportion of area monitored inside versus outside of VICRNM.

2.4. Data Download and Analysis

Deployment of 68 transmitters was conducted in August and September of 2013, with an additional seven transmitters deployed in December 2013. All receivers were recovered and downloaded in March 2015. Recovery was 18 months after initial deployment and ensured that all transmitter batteries had expired and no additional data on fish movements could be obtained.

The acoustic data for each fish detected on a minimum of three different days was subjected to several analyses. This three day cut-off prevented analyses from being influenced by those fish that may have quickly died or emigrated from the study area due to capture and handling. Data were processed into individual detection profiles that conveyed basic information about their movements. This included the calculations described in Table 2.2: the time-span of detections, number of detections, percent of days detected, number of receivers visited, number and frequency of VICRNM boundary crossing events, proportion of detections inside versus outside VICRNM, and location of day versus night activities. Values for individual fish were then summarized for those species with ≥ 5 fish included in the analysis (i.e., *Haemulon plumierii* (white grunt), *Haemulon sciurus* (blue striped grunt), *Lutjanus griseus* (gray snapper), *Lutjanus synagris* (lane snapper), *and Ocyurus chrysurus* (yellowtail snapper)). Tests among species were only conducted when significant values for overall ANOVA (parametric) or Wilcoxan tests (non-parametric) were found. Differences among species for these variables were tested using a Tukey type multiple-means comparison test when parametric assumptions of normality and homogeneity of variance were met. For those species, mean and standard error (SE) values are plotted. Dunn's test for multiple group comparisons based on ranked values was used when parametric assumptions could not be met through transformation. For those species, median and interquartile-range are plotted. There were too few fish within even these species and too small of a range in sizes to enable analysis of the influence of fish length on detection patterns.

Note that individual detections for each fish cannot be considered independent observations for statistical analysis. It is reasonable to assume, however, that summary values for each fish are independent given the diversity of fish and widespread locations from which they were sampled. Consequently, most statistical tests are based on summary values for each fish as replicates. This meets the statistical assumption of independent observations and has the added benefit of weighting each fish equally in identifying movement patterns rather than having those fish with many detections dominate the results.

Detections inside versus outside of VICRNM for each fish were evaluated against the null hypothesis that fish are randomly moving throughout the study area. If each fish is randomly using the area, their observed proportion of detections inside versus outside VICRNM should be approximately the same as the proportion of the study area within detection range of receivers that is inside (69% of the detection area) versus outside of VICRNM (31%, see Results). Although ~69% of observed detections should be inside VICRNM, ~50% of the fish should have observed values above and below this value due to random variability. This was evaluated by scoring each fish as having greater than, or less than, the expected proportion of detections. A G-test with Williams' correction for low sample size (Sokal and Rohlf, eds., 1981) was then used to determine if the observed results differed from the expected ratio of 50:50.

Table 2.2. Description of variables used to summarize detection data for each fish.

Variable	Description
Detection timespan	Number of days between fish release and last detection
Number of detections	Total number of detections across all receivers
Percent of days detected	(Number of days with ≥1 detection)/(Detection timespan)
Number of receivers	Number of receivers at which a fish was detected
Number of boundary crossings	Number of times a fish crossed the VICRNM boundary (in or out)
Boundary crossings per week	(Number of boundary crossings)/(Number detection days/7)
Percent of detections inside versus outside VICRNM	Percentage of all detections inside (B or I receivers) versus outside (O receivers) of VICRNM boundary. Expected value if fish movements were random are shown for reference.
Percent of inside detections during day versus night	Percentage of all detections inside VICRNM that occurred during day versus night (based on time of sunrise and sunset). Expected value if fish movements were random are shown for reference.
Percent of outside detections during day versus night	Percentage of all detections outside VICRNM that occurred during day versus night (based on time of sunrise and sunset). Expected value if fish movements were random are shown for reference.

A similar approach was used to test if the observed detections during the day versus night were different than expected at random. This was done to determine if fish were more likely to be detected inside VICRNM during the day and outside VICRNM at night, as may be expected for fish that undergo nocturnal foraging migrations. In day versus night tests, random movements and therefore number of detections, could be expected to split roughly evenly between day and night since the length of day and night are approximately equal at this latitude. In this case, each fish was scored as having greater than, or less than, the expected proportion of detections inside the Monument during the day. A separate test scored each fish as having greater than or less than the expected proportion of detections outside VICRNM at night.

Next, maps depicting spatial aspects of fish activity were created. Data from all species were combined into plots depicting the total number of fish, as well as total detections recorded at each receiver. Because receivers with larger detection range will be more likely to record greater numbers of fish and detections, these values were standardized by dividing them by the detection area (m^2) of each receiver. Last, to investigate whether the spatial patterns of fish movement varied by time of day, detections were divided into diurnal (sunrise to sunset) and nocturnal (sunset to sunrise) time periods. The number of detections per hour within each of these time categories was depicted at each receiver in bar graph format.

3.0. RESULTS

3.1. Range Test

The plot of distance to transmitter by detection percentage revealed differences in the typical detection range experienced by receivers in the study area (Figure 3.1). Most receivers experienced good detection (i.e. >50% of possible detections as recommended by manufacturer, VEMCO, 2015) of transmitter pings up to 75 m away but a significant drop-off in detection by 100 m. Four receivers experienced shorter detection ranges with few ping detections beyond 50 m. These were located along steep slopes or among patch reef habitats (Selby et al., 2016). Another group of receivers detected an adequate number of pings to indicate fish

French grunt, Haemulon flavolineatum. *Photo credit: M. Kendall, Biogeography Branch, NOAA* presence as far away as 175-200 m. These were typically in deep, flat, quiet parts of the study area. There were very few detections beyond 250 m. These values were used to plot the detection range for each receiver and for analysis of fish detection data (Figure 3.2). This pattern in size of detection range with environmental setting is consistent with a recent study on shark movements using the same telemetry equipment manufacturer in a partially overlapping study area (Legare et al., 2015). A few receivers were not evaluated at enough distances in the range test to calculate the 50% detection rate (e.g., I1 and I10). These were assigned an assumed detection range based on measured performance of more thoroughly evaluated receivers in similar environmental settings. For hemi-directional receivers, detection range was calculated to be ~175 m facing inside the Monument boundary. Based on these detection patterns, if tagged fish were detected on an I or B receiver, they were

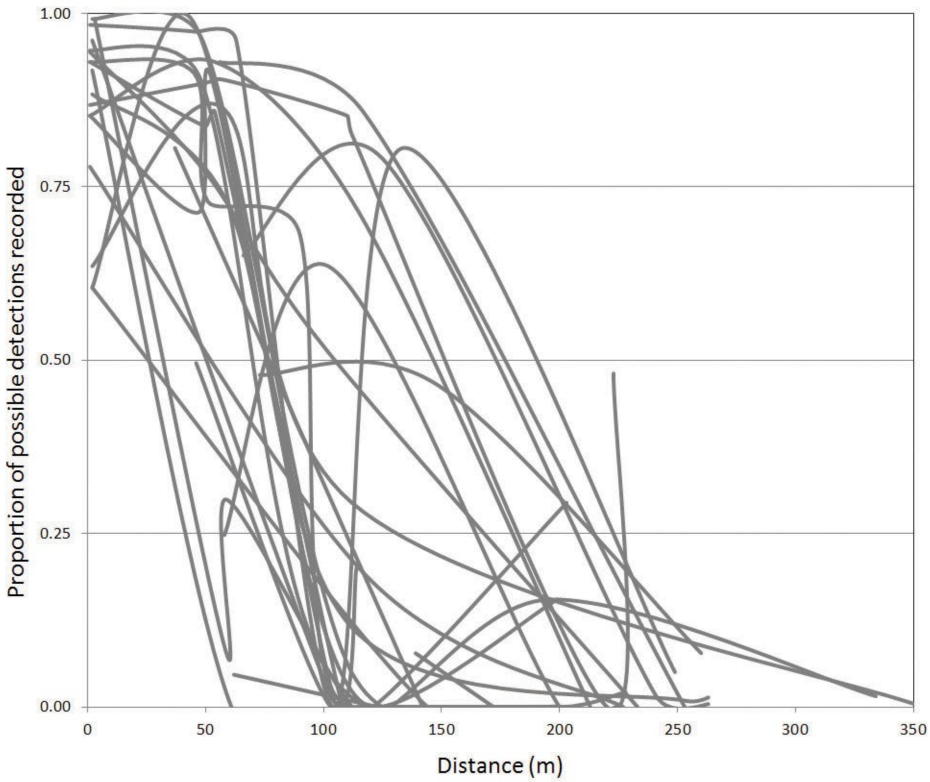
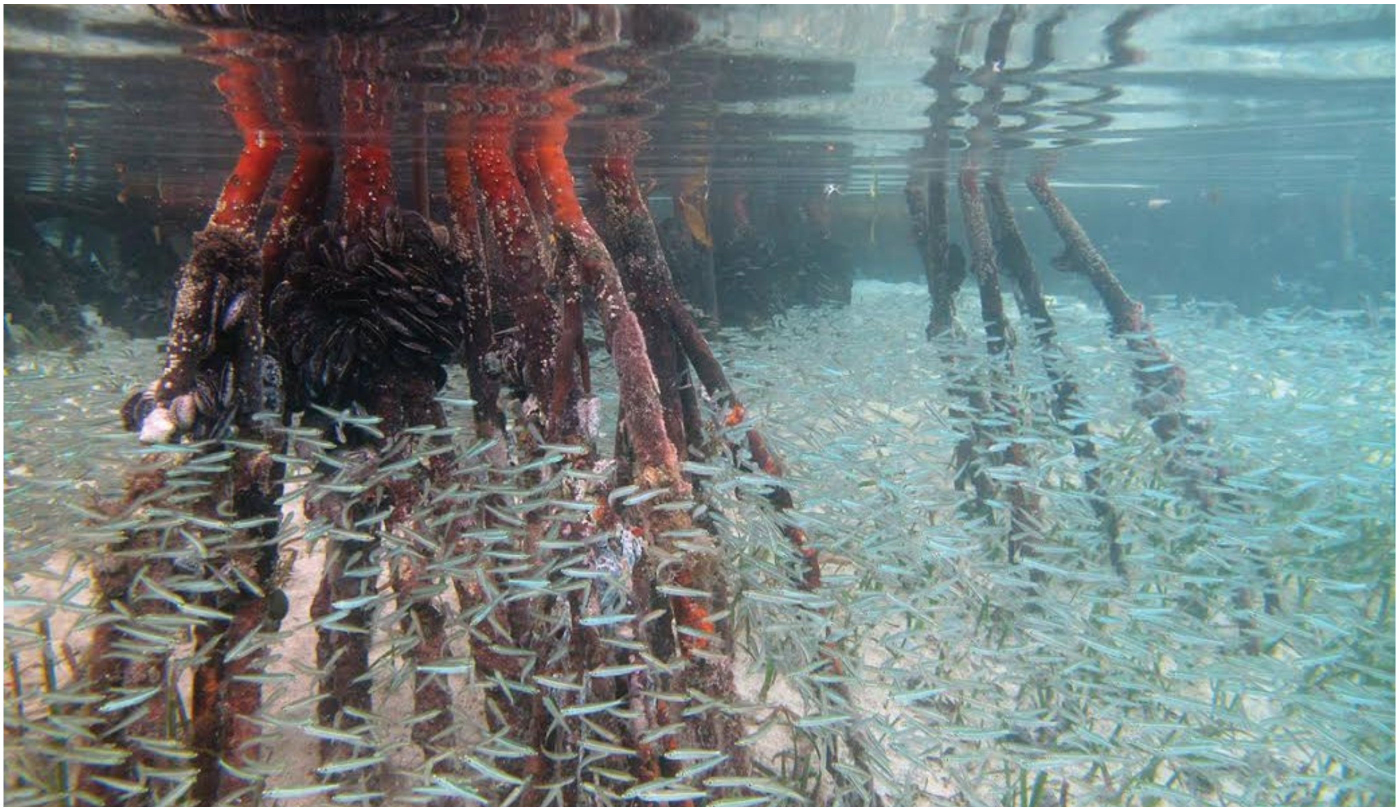


Figure 3.1. Detection range results for omni-directional receivers. Curves based on each receiver represent the proportion of possible pings detected as a function of distance from the receiver.



Mangrove roots teeming with fish. Photo credit: C.S. Rogers assumed to be inside the Monument boundary. If they were on an O receiver, they were assumed to be outside the Monument boundary.

Total area of the study was 601 hectares with 24% of that covered by the detection range of receivers. Specifically, of the 308 HA comprising VICRNM in Coral Bay, 102 HA (33%) were within detection range of the receivers. Of the 293 HA in the study area outside of VICRNM, 45 HA (15%) were within detection range of receivers. The ratio of these two values was used as a null hypothesis for testing fish distributions. If fish were randomly distributed in the study area, 69% of detections should occur inside VICRNM and 31% should occur outside.

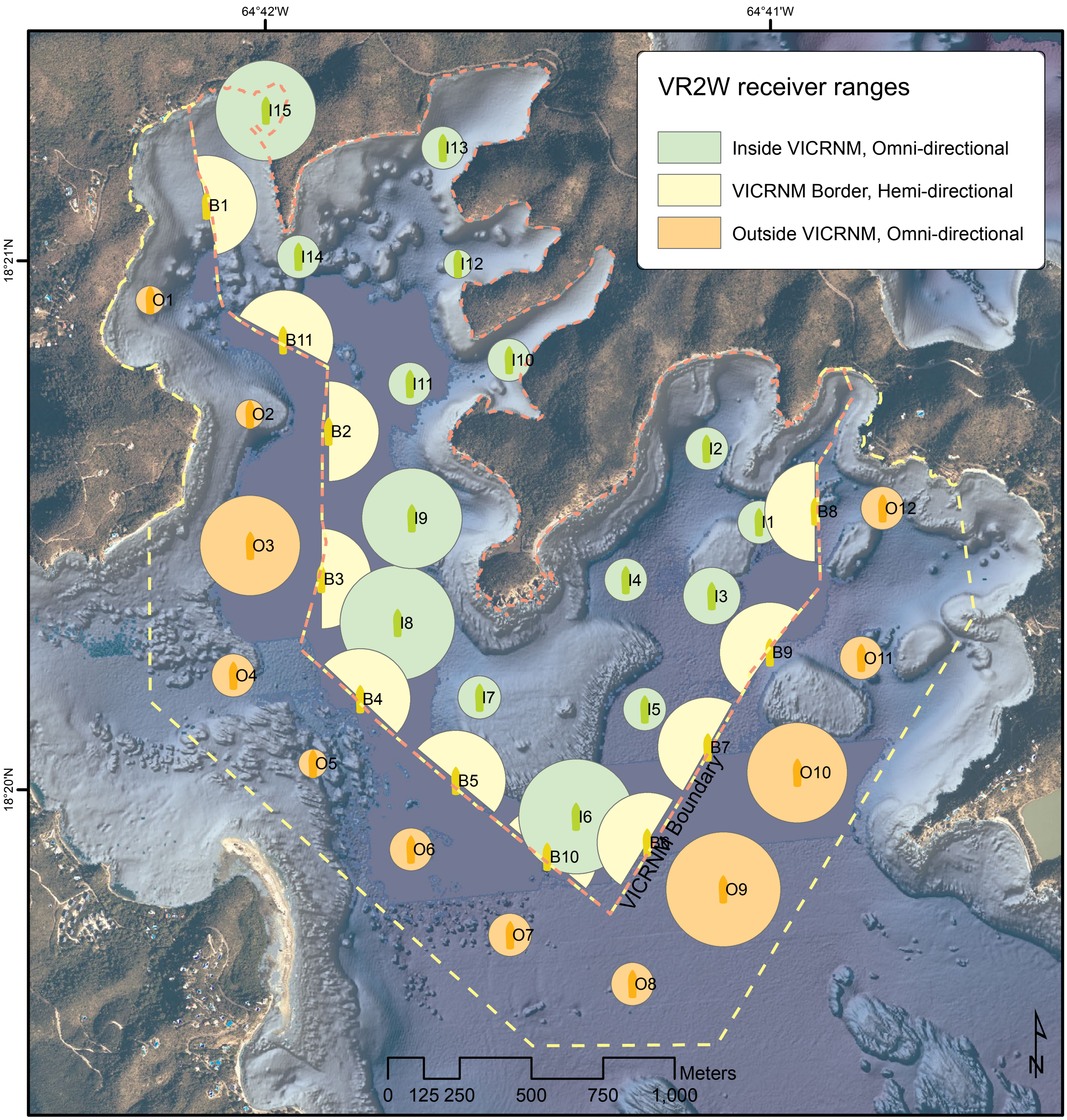


Figure 3.2. Detection ranges of omni- and hemi-directional receivers. Seafloor topography is shown in blue. VICRNM boundaries (red) and outer edge of study area (yellow) are also shown.

3.2. Fish Tagged

The 75 fish tagged in this study included seven families and 17 species. Fish from the Lutjanidae (n = 38 fish) and Haemulidae (n = 24) families were the most common. *L. synagris* (n = 16) and *H. sciurus* (n = 11) were the most commonly tagged species. Roughly equal numbers of fish were tagged from the Hurricane Hole (n = 38) and Round Bay (n = 37) sides of the Monument (Figure 3.3).

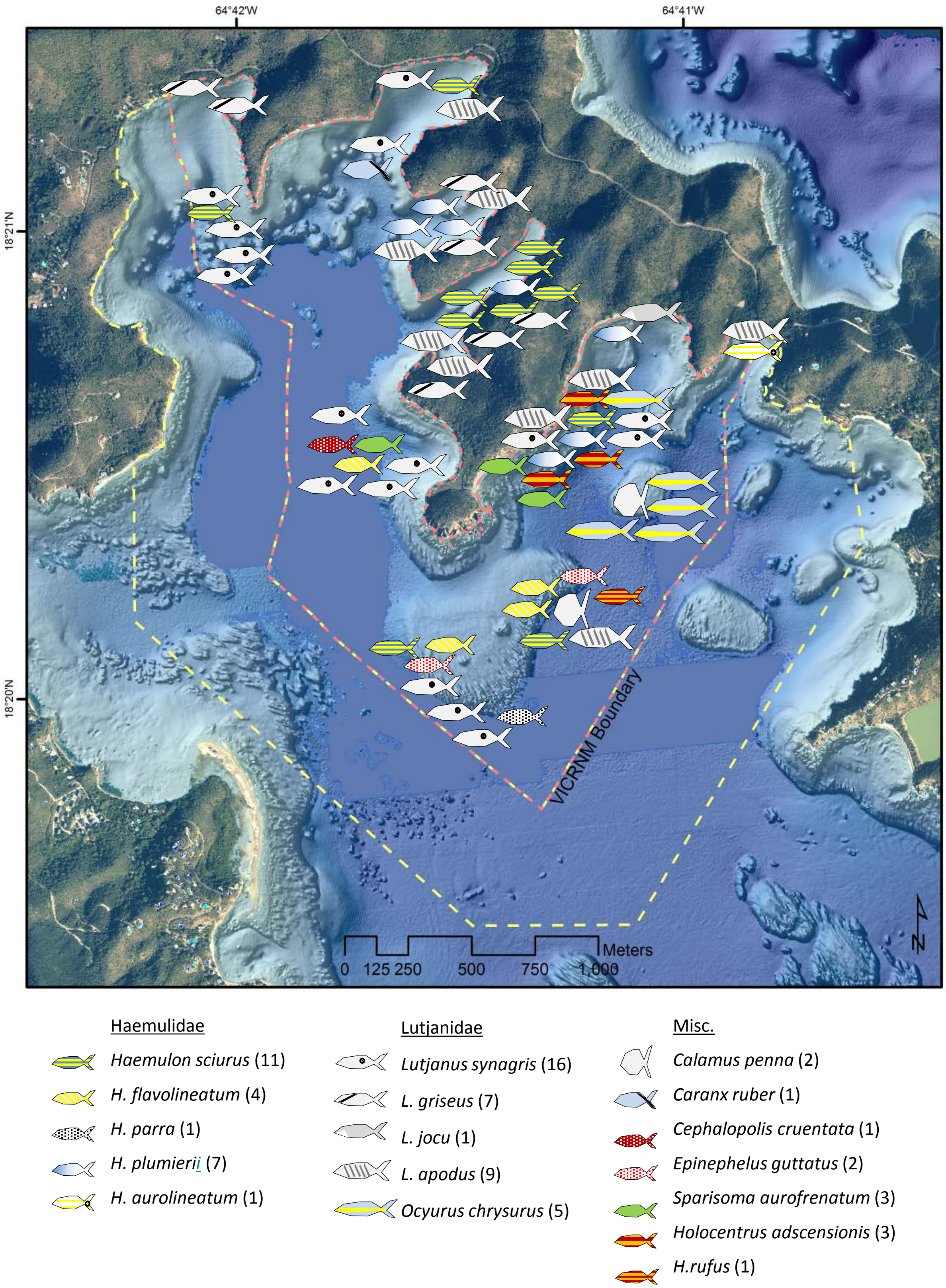


Figure 3.3. Locations where fish were captured and released. Seafloor topography is shown in blue. VICRNM boundaries (red) and outer edge of study area (yellow) are also shown.

Comparison of the relative abundance of fish tagged in this study to those seen on visual surveys in the same area were broadly similar (Figures 3.4a-b). At the family level, approximately half of the fish tagged were Lutjanidae, another approximately one third were Haemulidae, and the remaining approximately one sixth were from five other fish families. In visual counts by divers, Lutjanidae were also the most abundant family (approximately one fourth of fish seen were over 20 cm) and the other six families in the suite of tagged species comprised over approximately one half of the other fish seen. An additional approximately one fifth of the fish seen during diver-surveys were from 21 families not included in the tagging study due to body cavity size that was too small to accommodate transmitters (e.g., Acanthuridae) or lack of trapping them.

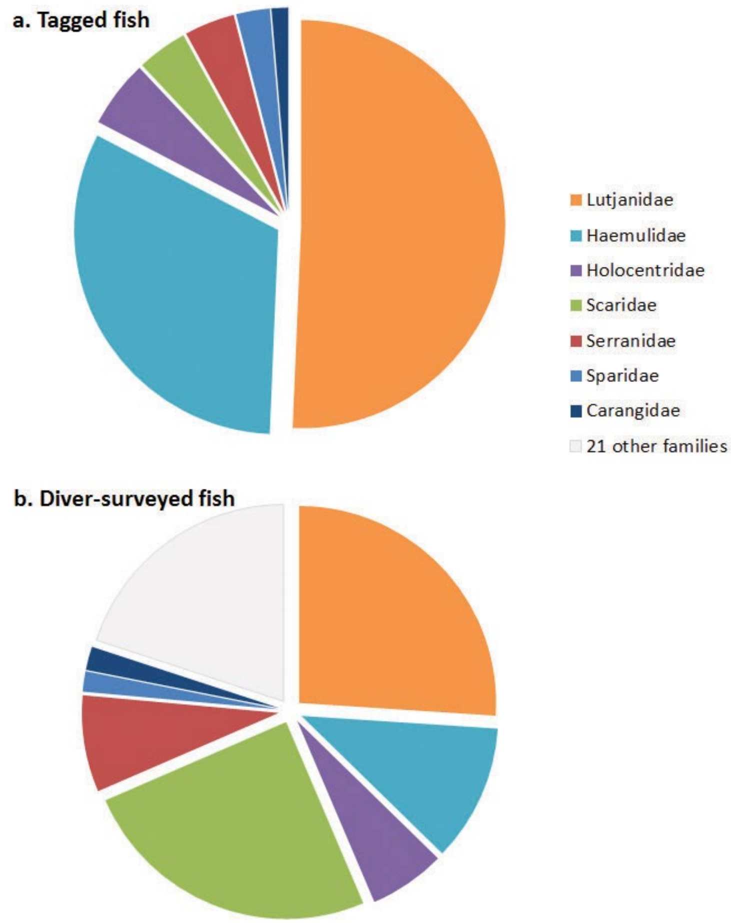


Figure 3.4. a-b Comparison of fish families tagged in this telemetry project to those seen on recent diver-based surveys in the Coral Bay area.

3.3. Movement Data For Individual Fish

Of the 75 fish tagged, 18 were detected on less than three distinct days after release or never detected at all, and were excluded from further analysis. Detection results for each remaining fish show large differences among and within species (Figure 3.5a-c). Some fish had only a few dozen detections spanning just a few days. Others were consistently detected for over a year and had more than 15,000 detections.

Tag implantation. Photo credit: M. Kendall, Biogeography Branch, NOAA

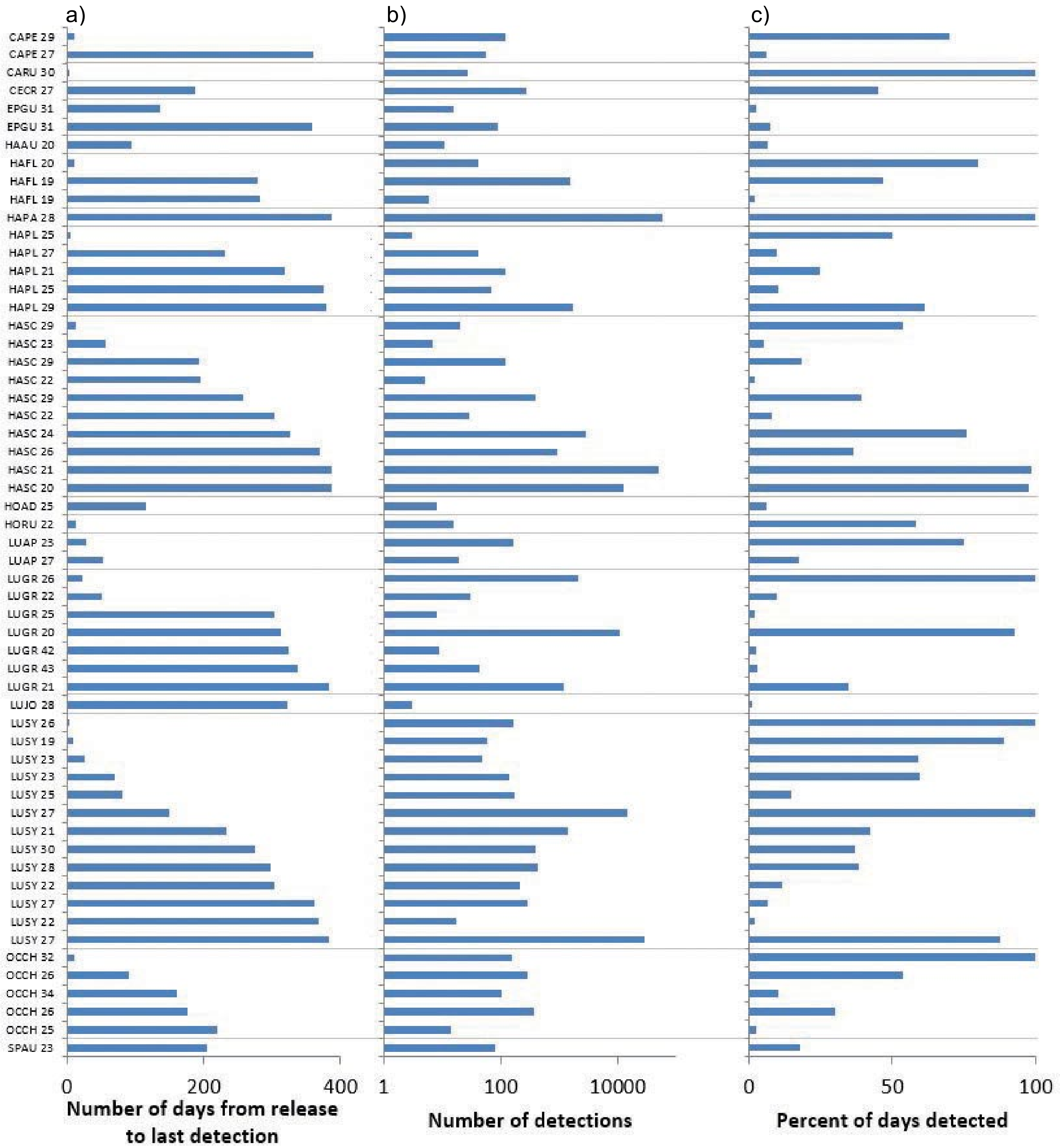


Figure 3.5. Detection patterns for each fish (4 letter species codes and length in cm from Table 3.1): a) detection time-span expressed as the number of days from release to last detection, b) total number of detections, and c) percentage of days with detections during the detection timespan. Species are separated by horizontal lines.

Over half of the fish were detected on just four or fewer of the 38 receivers in the study area (Figure 3.6a). One fish, a *L. synagris*, was detected on 14 different receivers. A majority of the fish (34 or 60%) were never detected outside of the VICRNM boundary (Figure 3.6b), and only one, a *L. synagris*, was detected crossing the VICRNM boundary on a regular basis over consecutive days (Figure 3.6c).

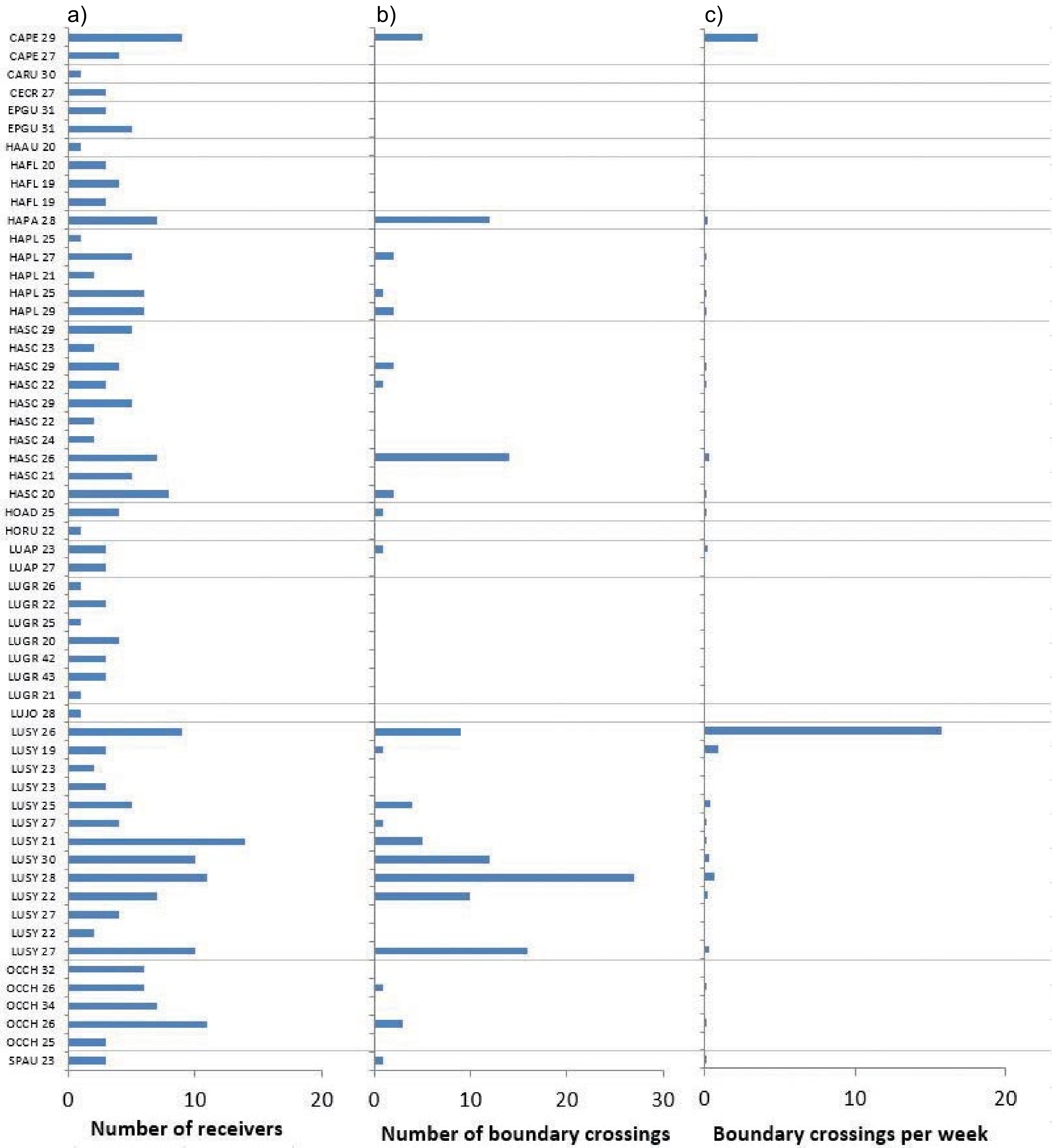


Figure 3.6. Detection patterns for each fish continued (4 letter species codes and length in cm from Table 3.1): a) number of receivers visited for each fish, b) number of times the VICRNM was crossed, and c) frequency of boundary crossings expressed as number of times per week. Species are separated by horizontal lines.

Of the 57 fish with sufficient data, 55 (96%) had a greater proportion of their detections inside VICRNM than expected if they were moving randomly (Figure 3.7a). Only two fish, both *L. synagris*, had more detections outside VICRNM than expected. This was a significant departure from the expected ratio if fish were utilizing the study area at random [null hypothesis of 50:50, $G_{adj} = 61.1 > \chi^2(0.001, 1)$].

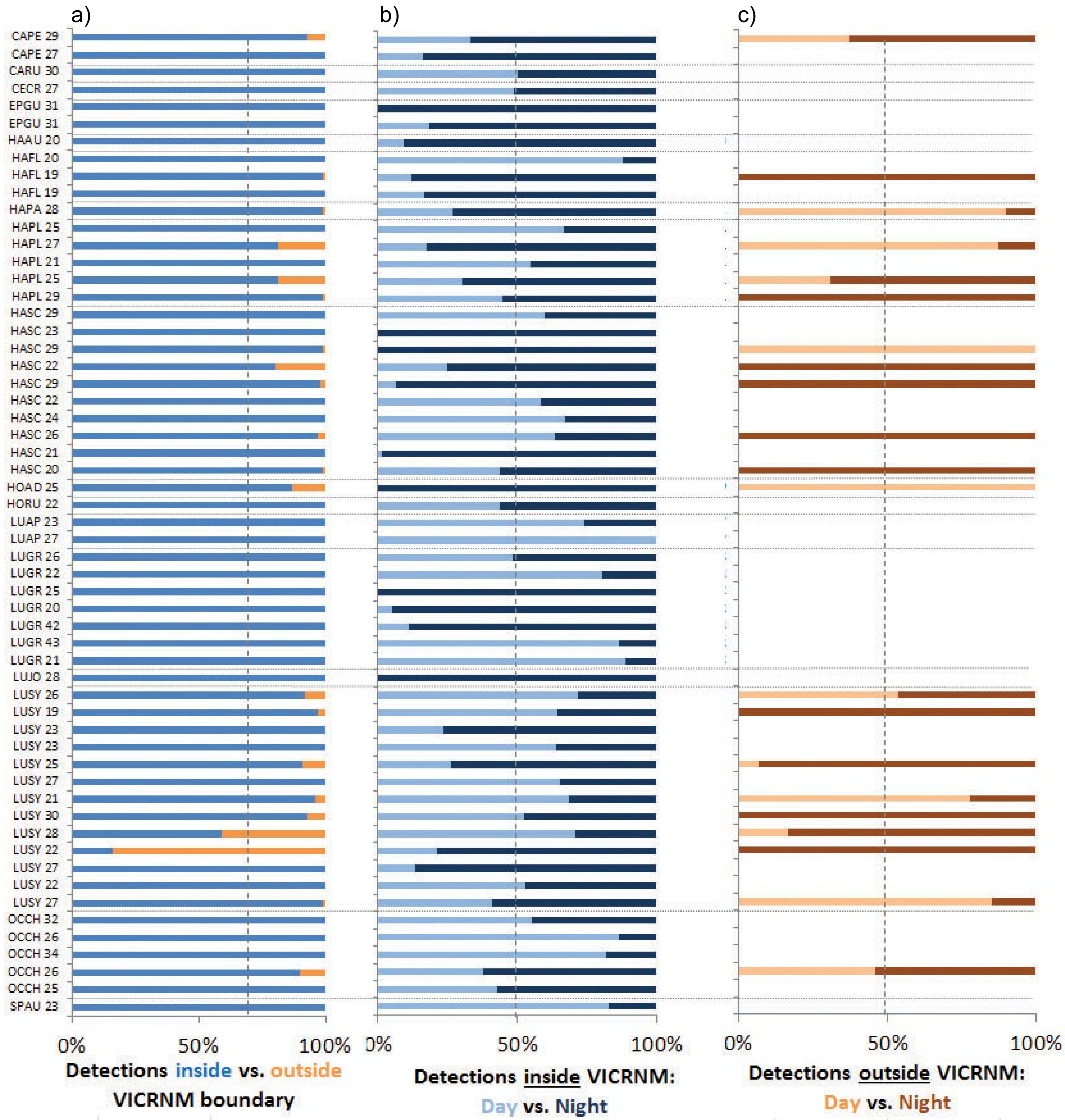


Figure 3.7 Detection patterns for each fish continued (4 letter species codes and length in cm from Table 3.1): a) percentage of detections inside vs. outside VICRNM, b) percentage of day vs. night detections for each fish while inside VICRNM, and c) percentage of day versus night detections for each fish while outside VICRNM. Species are separated by horizontal lines. Dashed vertical lines denote the expected position of bar transitions if detections were randomly distributed.

Of the 57 fish with sufficient data that were detected inside VICRNM, 33 had a majority of detections during the night, whereas 24 had more detections during the day (Figure 3.7b). This was not significantly different from the expected ratio based on random fish activity and the length of day at this latitude [null hypothesis 50:50, G_{adj} = 1.4, NS]. Outside VICRNM, only 21 fish were detected (Figure 3.7c). Of those, twice as many (14) had more nighttime detections than daytime detections (7). However, this was not significantly different from the expected ratio based on random fish activity [null hypothesis 50:50, G_{adj} = 2.3, NS].

Table 3.1. Location, date, and size of individual fish tagged. Letters following fish size denote whether the value is greater than the published length at maturity where m = mature, i = immature, and u = unknown (based on length at 50% maturity values in www.fishbase.org). Name codes are first two letters of the genus and species. Trophic groups are P = piscivore, MI = mobile invertivore, SI = sessile invertivore, H= herbivore, Z = planktivore

Transmitter ID	Family	Scientific Name	Name Code	Common Name	Trophic Group	Total Length (cm)	Release Date 2013	Trap/Release Site
11971 1167180	Sparidae	*Calamus penna*	CAPE	Sheepshead Porgy	MI/SI	27 u	26-Aug	Round Bay- T1
11967 1167176						29 u	26-Aug	Round Bay- T8
11926 1167135	Carangidae	*Carangoides ruber*	CARU	Bar Jack	P	30 i	30-Aug	HurricaneHole- T22
11952 1167161	Serranidae	*Cephalopholis cruentatus*	CECR	Graysby	MI/P	27 m	28-Aug	Hurricane Hole- T14
11984 1167193	Serranidae	*Epinephelus guttatus*	EPGU	Red Hind	MI/P	31 m	22-Aug	Round Bay- T8
11977 1167186						31 m	26-Aug	Round Bay- T11
11914 1167123	Haemulidae	*Haemulon aurolineatum*	HAAU	Tomtate	MI	20 m	6-Dec	Round Bay- T23
11947 1167156	Haemulidae	*Haemulon flavolineatum*	HAFL	French Grunt	MI/SI	19 m	28-Aug	Hurricane Hole- T14
11978 1167187						19 m	26-Aug	Round Bay- T11
11982 1167191						19 m	23-Aug	Round Bay- T8
11983 1167192						20 m	22-Aug	Round Bay- T8
11965 1167174	Haemulidae	*Haemulon parra*	HAPA	Sailor's Choice	MI	28 u	23-Aug	Round Bay- T10
11957 1167166	Haemulidae	*Haemulon plumierii*	HAPL	White Grunt	MI	20 m	27-Aug	Round Bay- T5
11932 1167141						21 m	30-Aug	Hurricane Hole- T26
11931 1167140						25 m	30-Aug	Hurricane Hole- T26
11921 1167130						25 m	30-Aug	Hurricane Hole- T26
11976 1167185						26 m	26-Aug	Round Bay- T3
11934 1167143						27 m	29-Aug	Hurricane Hole-T17
11960 1167169						29 m	27-Aug	Round Bay- T5
11937 1167146	Haemulidae	*Haemulon sciurus*	HASC	Bluestriped Grunt	MI	20 m	29-Aug	Hurricane Hole-T17
11941 1167150						21 m	29-Aug	Hurricane Hole-T17
11966 1167175						22 m	26-Aug	Round Bay- T11
11936 1167145						22 m	29-Aug	Hurricane Hole-T17
11959 1167168						23 m	27-Aug	Round Bay- T5
11940 1167149						24 m	29-Aug	Hurricane Hole-T17
11911 1167120						26 m	6-Dec	Hurricane Hole- T25
11945 1167154						29 m	29-Aug	Hurricane Hole-T17
11943 1167152						29 m	29-Aug	Hurricane Hole-T17
11973 1167182						29 m	26-Aug	Round Bay- T8
11925 1167134						30 m	30-Aug	Hurricane Hole-T22
11954 1167163	Holocentridae	*Holocentrus adscensionis*	HOAD	Squirrelfish	MI	25 m	28-Aug	Round Bay- T5
11955 1167164						26 m	27-Aug	Round Bay- T5
11953 1167162						26 m	28-Aug	Round Bay- T5
11980 1167189	Holocentridae	*Holocentrus rufus*	HORU	Longspine Squirrelfish	MI	22 m	22-Aug	Round Bay- T8
11939 1167148	Lutjanidae	*Lutjanus apodus*	LUAP	Schoolmaster Snapper	MI/P	19 i	29-Aug	Hurricane Hole-T17
11910 1167119						23 i	30-Aug	Hurricane Hole-T22
11933 1167142						24 i	30-Aug	Hurricane Hole- T26
11962 1167171						24 i	27-Aug	Round Bay- T5

Table 3.1. cont. Location, date, and size of individual fish tagged.

Transmitter ID	Family	Scientific Name	Name Code	Common Name	Trophic Group	Total Length (cm)	Release Date 2013	Trap/Release Site
11942 1167151	Lutjanidae cont. from previous page	*Lutjanus apodus*	LUAP	Schoolmaster Snapper	MI/P	25 m	29-Aug	Hurricane Hole-T17
11913 1167122						25 m	6-Dec	Round Bay- T23
11981 1167190						27 m	23-Aug	Round Bay- T8
11919 1167128						28 m	30-Aug	Hurricane Hole- T26
11963 1167172						36 m	27-Aug	Round Bay- T5
11929 1167138	Lutjanidae	*Lutjanus griseus*	LUGR	Gray Snapper	MI/P	20 i	30-Aug	Hurricane Hole-T21
11944 1167153						21 i	29-Aug	Hurricane Hole-T17
11938 1167147						22 i	29-Aug	Hurricane Hole-T17
11935 1167144						25 i	29-Aug	Hurricane Hole-T17
11930 1167139						26 i	30-Aug	Hurricane Hole-T21
11918 1167127						42 m	30-Aug	Hurricane Hole- T26
11920 1167129						43 m	30-Aug	Hurricane Hole- T26
11975 1167184	Lutjanidae	*Lutjanus jocu*	LUJO	Dog Snapper	MI/P	28 i	26-Aug	Round Bay- T3
11949 1167158	Lutjanidae	*Lutjanus synagris*	LUSY	Lane Snapper	MI/P	19 i	28-Aug	Hurricane Hole- T14
11923 1167132						21 i	30-Aug	Hurricane Hole-T20
11950 1167159						21 i	28-Aug	Hurricane Hole- T14
11924 1167133						22 i	30-Aug	Hurricane Hole-T20
11979 1167188						22 i	26-Aug	Round Bay- T5
11958 1167167						22 i	27-Aug	Round Bay- T5
11951 1167160						23 m	28-Aug	Hurricane Hole- T14
11948 1167157						23 m	28-Aug	Hurricane Hole- T14
11922 1167131						25 m	30-Aug	Hurricane Hole-T20
11927 1167136						26 m	30-Aug	Hurricane Hole-T22
11958 1167167						22 i	27-Aug	Round Bay- T5
11951 1167160						23 m	28-Aug	Hurricane Hole- T14
11948 1167157						23 m	28-Aug	Hurricane Hole- T14
11922 1167131						25 m	30-Aug	Hurricane Hole-T20
11927 1167136						26 m	30-Aug	Hurricane Hole-T22
11916 1167125						26 m	6-Dec	Round Bay- T24
11974 1167183						27 m	26-Aug	Round Bay- T5
11915 1167124						27 m	6-Dec	Round Bay- T24
11917 1167126						27 m	6-Dec	Round Bay- T24
11912 1167121						28 m	6-Dec	Hurricane Hole- T25
11928 1167137						30 m	30-Aug	Hurricane Hole-T22
11961 1167170	Lutjanidae	*Ocyurus chrysurus*	OCCH	Yellowtail Snapper	MI/Z	25 m	27-Aug	Round Bay- T5
11968 1167177						26 m	26-Aug	Round Bay- T1
11970 1167179						26 m	26-Aug	Round Bay- T1
11969 1167178						32 m	26-Aug	Round Bay- T1
11972 1167181						34 m	26-Aug	Round Bay- T1
11956 1167165	Scaridae	*Sparisoma aurofrenatum*	SPAU	Redband Parrotfish	H	21 u	27-Aug	Round Bay- T5
11946 1167155						23 u	28-Aug	Hurricane Hole- T14
11964 1167173						23 u	27-Aug	Round Bay- T5

3.4. Species Summaries

The five species with sufficient sample size (n ≥ 5 fish) showed relatively consistent values for percent of days detected, percent detections inside VICRNM, and percent of days detected inside VICRNM. Significant differences were found between *L. synagris* and *L. griseus* for several variables. *L. synagris* were detected at significantly more receivers and crossing the VICRNM boundary more often and regularly than *L. griseus* (Figure 3.8). In the case of *L. griseus*, tagged fish were never detected outside VICRNM. Both species of Haemulidae showed similar patterns for these variables. All other species and variables showed no significant differences in statistical tests, however, sample size was low which limited the statistical power, and multiple-comparison tests are conservative. For example, average number of days detected for *O. chrysurus* was less than half of the days detected for all other species but no significant differences was found at $p < 0.05$. Similarly, *O. chrysurus* was detected at the highest median number of receivers among all species but, due to the conservative multiple comparison test, low sample size, high variability, and rank-based test, was not significantly different than other species.

Queen angelfish, Holacanthus ciliaris*, among mangrove prop roots. Photo credit: C.S. Rogers*

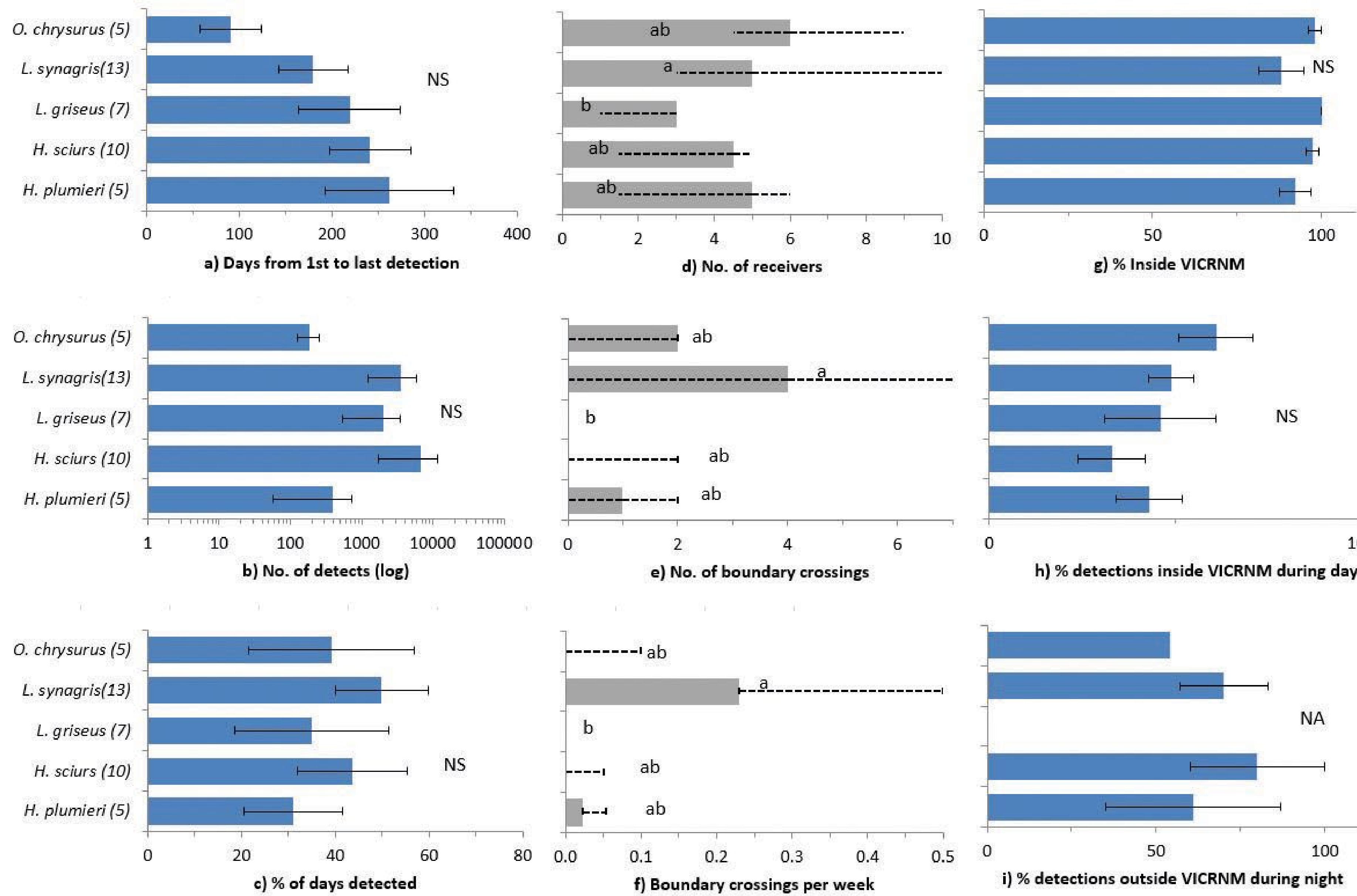


Figure 3.8. Summarized detection patterns for species (n) with at least 5 individuals tracked. When parametric tests were used to evaluate differences among species, the mean (blue bars) and SE (solid lines) are shown. When non-parametric tests were used to evaluate differences among species, the median (grey) and interquartile range (dashed lines) are shown. NS denotes a non-significant result within each variable. NA denotes too few values for any statistical comparison. Lower case letters denote significant differences in group membership at α = 0.05. Graphs show: a) mean detection time-span expressed as the number of days from release to last detection, b) mean number of detections, c) mean percentage of days with detections during the detection timespan, d) median number of receivers visited for each fish, e) median number of times the VICRNM was crossed, f) median frequency of boundary crossings expressed as number of times per week, g) mean percentage of detections inside VICRNM, h) while inside VICRNM, mean percentage of detections during daytime, and i) while outside VICRNM, mean percentage of nighttime detections.

3.5. Hotspots of Fish Activity

Receivers inside VICRNM typically detected more fish than those outside or on the border (Figure 3.9). Receivers detecting the most fish were those at the mouths of Otter and Water Creeks, the northern extremity of Round Bay, and off the high-relief reef area southeast of Turner Point. One location outside VICRNM also detected many fish. The boundary receivers (B5, B10), and especially receiver O7 along the southern edge of the study area detected many fish despite having a relatively short detection range.

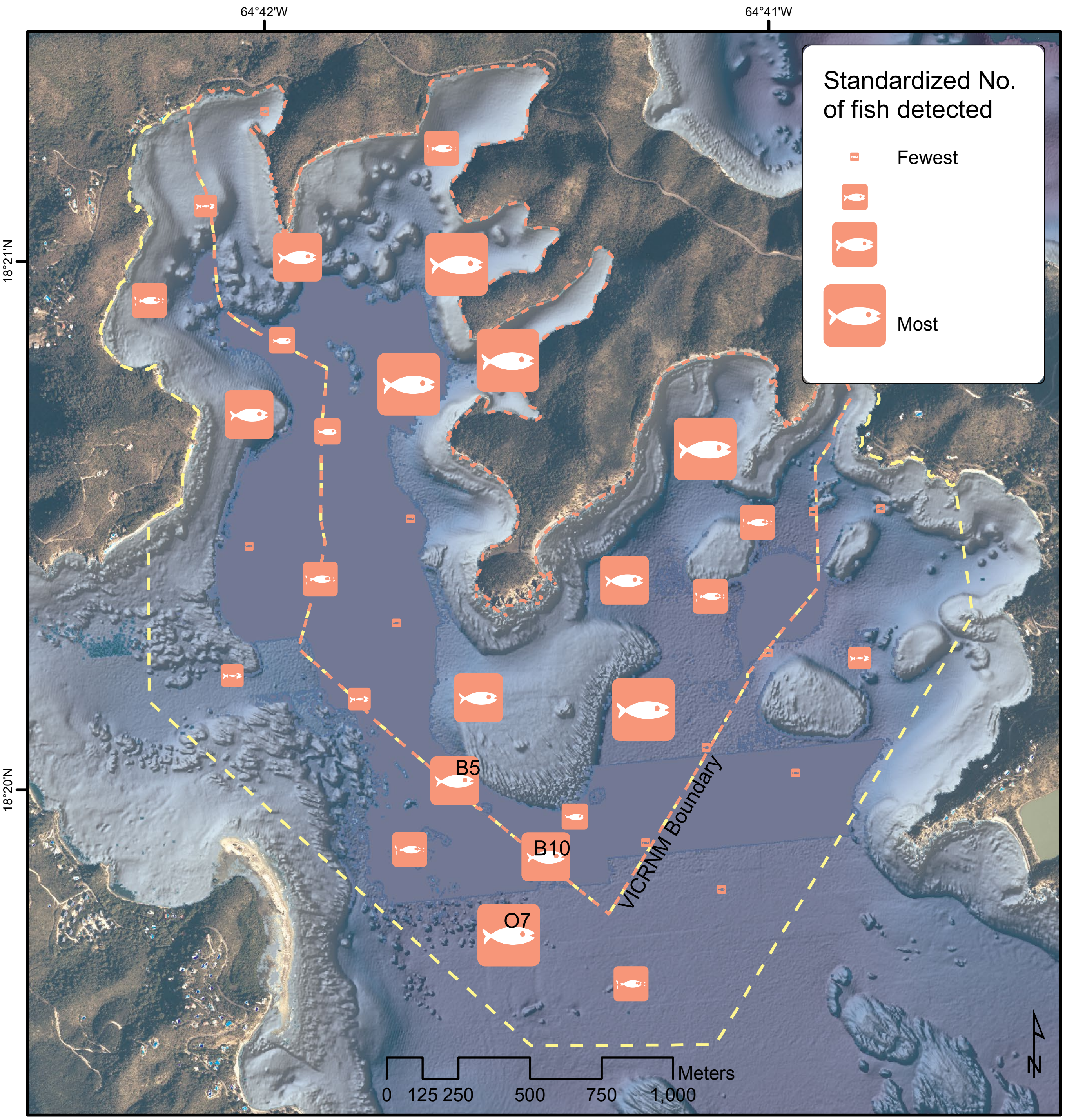


Figure 3.9. Standardized number of fish detected at each receiver. Symbol size is scaled to the number of unique transmitters (fish) detected at each receiver divided by the detection area for each receiver. Larger symbols represent a relatively greater number of fish in the area of a receiver. Seafloor topography is shown in blue. VICRNM boundaries (red) and outer edge of study area (yellow) are also shown.

A similar spatial pattern was observed based on the standardized number of detections at each receiver, only more concentrated in just two areas (Figure 3.10). These were the mouths of Otter and Water Creeks as well as the boundary receivers off the southern edge of the reef at Turner Point.

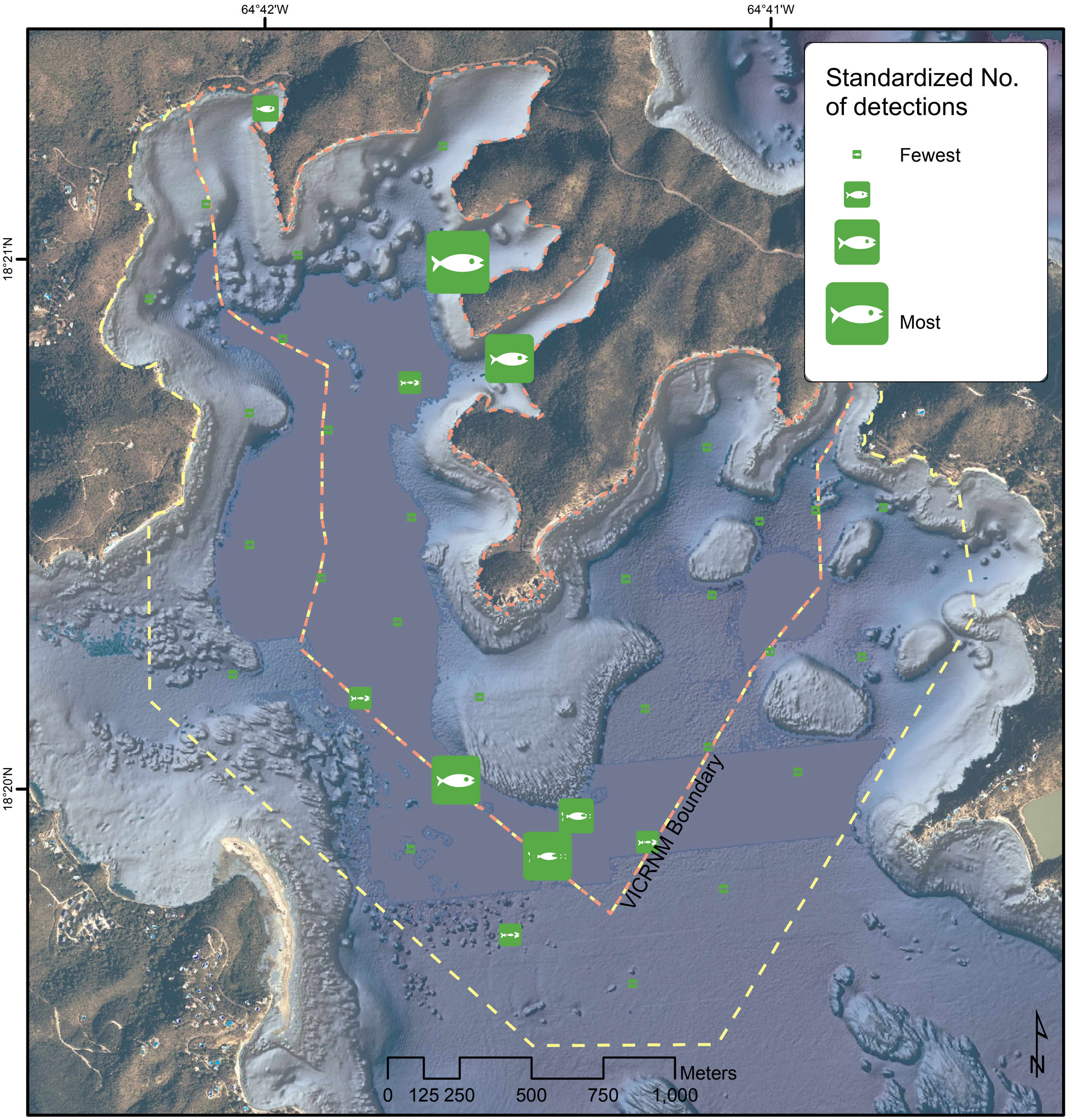


Figure 3.10. Standardized number of detections at each receiver. Symbol size is scaled to the number of detections at each receiver divided by the detection area for each receiver. Larger symbols represent a relatively greater number of detections in the area of a receiver. Seafloor topography is shown in blue. VICRNM boundaries (red) and outer edge of study area (yellow) are also shown.

Examining the number of fish detected during the day versus night at each receiver revealed a generally even spilt at most locations although often slightly skewed toward more fish being detected during the day (Figure 3.11). In a few locations, nearly two thirds or more of the fish detected occurred during the day. These included sites near the mouth of Borck Creek, receivers at the southern end of the reef off Turner Point, and the receiver in the patch reef area farther south (O7).

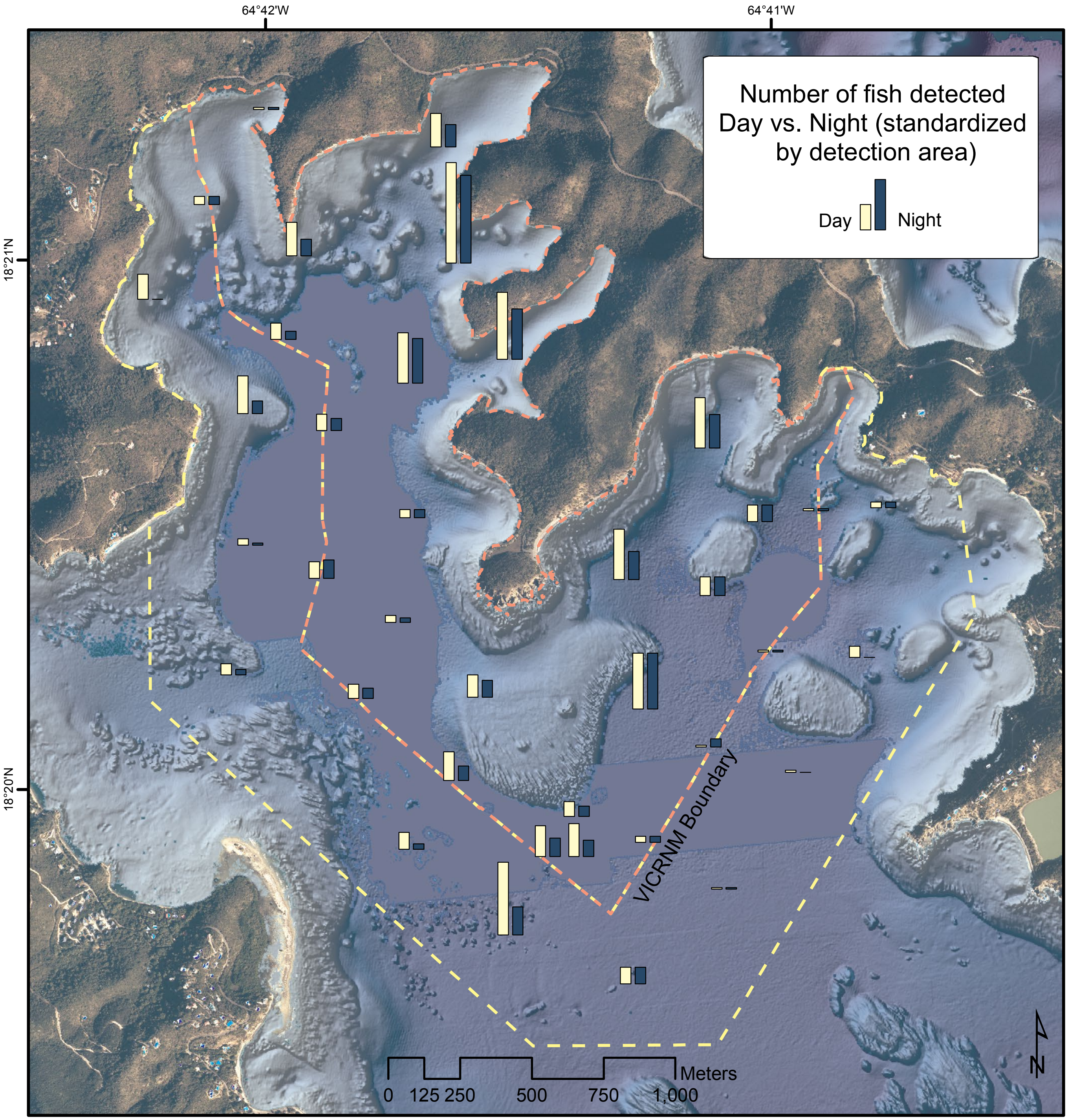


Figure 3.11. Standardized number of fish detected at each receiver during the day versus night. Number of fish detected during the day versus night divided by the detection area of each receiver. VICRNM boundaries (red) and outer edge of study area (yellow) are also shown. Seafloor topography is shown in blue.

The number of detections at each receiver during the day versus night showed a somewhat different pattern (Figure 3.12). Only seven out of the thirty-eight receivers had a greater proportion of detection during the day. Most receivers had the bulk of their detections at night. There was also a difference apparent at inside versus outside VICRNM receivers. Those outside the Monument had a much greater proportion of their detections during the night.

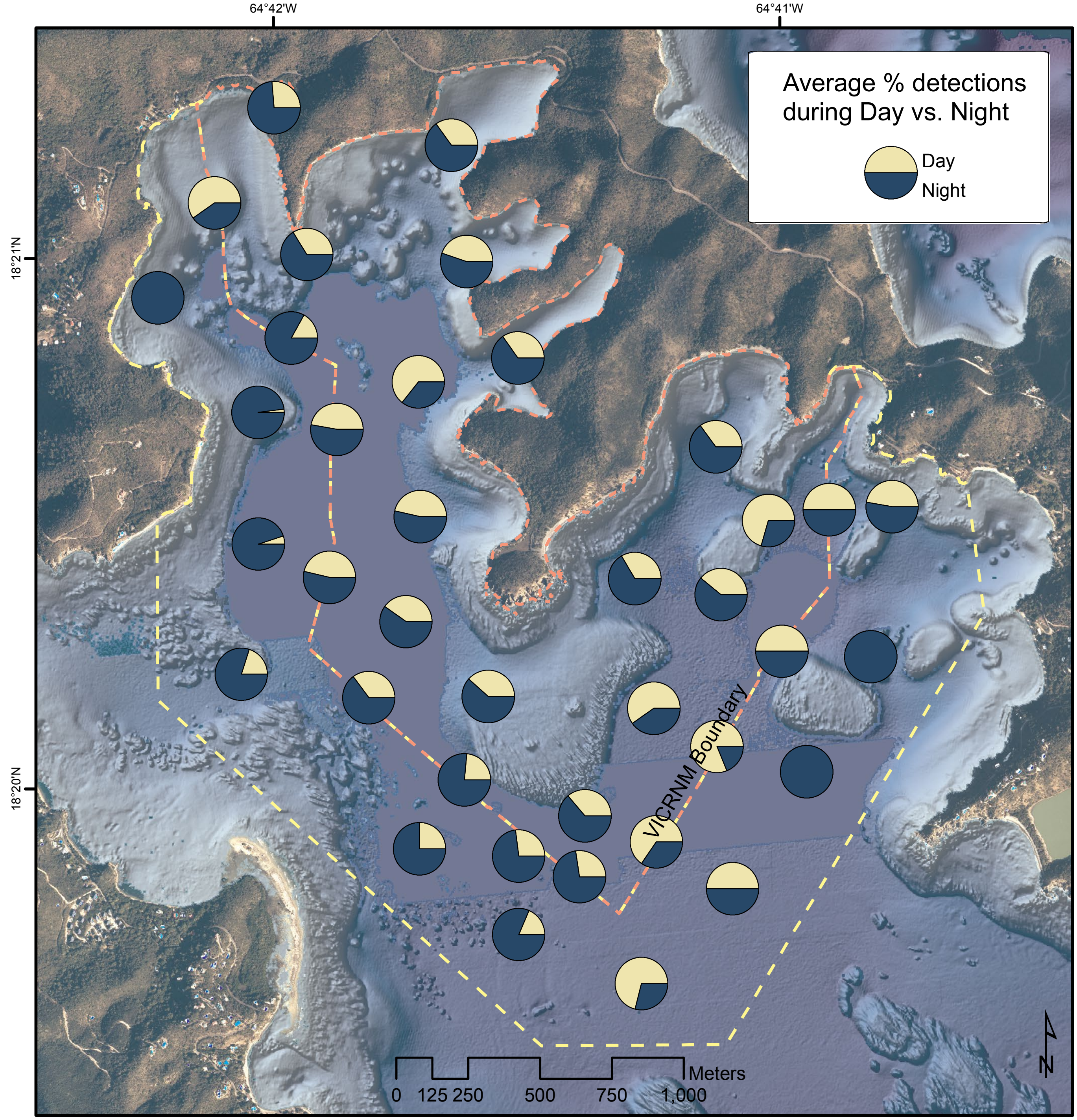
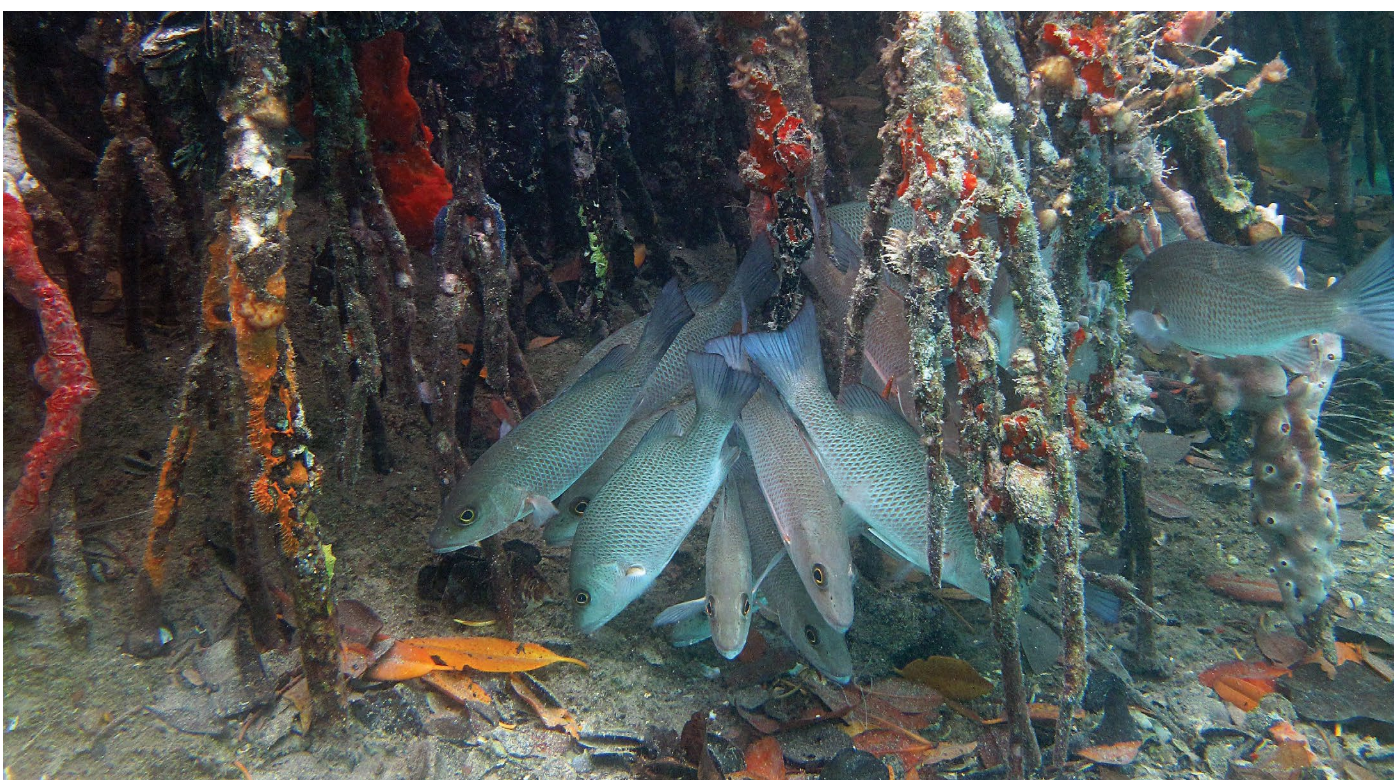


Figure 3.12. Average proportion of detections during the day versus night for fish detected at each receiver. Detections for each fish were converted to proportions from day versus night. These values were averaged for all the fish detected at a given receiver. VICRNM boundaries (red) and outer edge of study area (yellow) are also shown. Seafloor topography is shown in blue.

4.0. DISCUSSION

Presidential Proclamation 7399 (2001) that created the Monument emphasizes that its biological communities live in an interdependent relationship and include habitats essential for sustaining and enhancing the tropical marine ecosystem. The Proclamation goes on to assert that the boundaries encompass the smallest area compatible with the proper care and management of the objects to be protected. For the reef fish in the Coral Bay segment of the Monument, this telemetry study provides evidence both for and against this claim. Overall, it appears that the Monument offers potential protection to a majority of the fish community studied here. Receivers inside VICRNM typically detected more fish than those outside or on the border, over half of the fish were never detected outside of the VICRNM boundary, and a large majority of the fish had a significantly greater proportion of their detections inside the Monument than could be expected if they were moving randomly. In contrast to these apparently encouraging statistics however, are several other variables that must also be considered to get a more complete understanding of protection. First, while some fish were potentially resident within the monitoring area for the whole duration of the study, most were not based on their detection period and presumably emigrated from the detection area or were removed via natural or fisheries based mortality. Fish that emigrated beyond the outer receivers in the study area of course leave no record and therefore statistics such as “percent of detections inside the Monument” must be interpreted cautiously. The maximum duration of any inference must also be limited to approximately one year given the expected battery life of the transmitters.

Telemetry data is often used to make recommendations for the design of MPAs to best protect areas of core activity or ecological significance (Alfonso et al., 2009; Heupel and Simpfendorfer, 2005; Meyer et al., 2007). Tracking data has also demonstrated that protection within a reserve hinges on correct placement and coverage of critical habitat areas (Eristee and Oxenford, 2001). Although the VICRNM boundary in Coral Bay was not designed with ecological criteria in mind, like many other MPAs (Devillers et al., 2015), it appears to have aligned coincidentally with an important ecological principle of MPA design for reef fish; the boundary does not cross through continuous reef habitat. Land ownership and the configuration of the bays in this area resulted in the boundary being placed roughly along the centers and deepest parts of Hurricane Hole and Round Bay. This put the boundary in the sand or mud habitat that separates the reef and mangrove habitats that fringe both sides of the bays (see Costa et al., 2013). The boundary therefore rests on a physical feature that acts as a natural barrier to movements of many reef fish (Beets et al., 2003; Eristhee and Oxenford, 2001;



Snappers among mangrove prop roots. Photo credit: C.S. Rogers

Popple and Hunt, 2005; Farmer and Ault , 2011). Even those species that periodically move away from the reef do so over regular routes, across predictable distances, and have high site fidelity when returning to the reef (Ogden and Ehrlich, 1977; Holland et al., 1993; Meyer et al., 2000; Beets et al., 2003; Hitt et al., 2011). The VICRNM boundary also happens to completely encompass the deep, spur and groove reef that extends southward from Turner Point (see Costa et al., 2013). This reef has among the highest values of diversity and abundance for reef fish around St. John (Friedlander et al., 2013b).

Schoolmaster snapper, Lutjanus apodus.
Photo credit: M. Kendall, Biogeography Branch, NOAA

Several previous studies have used telemetry to investigate the movements of marine fish relative to MPA boundaries. In many studies spanning various species and families, the majority of fish tagged within MPAs exhibit strong site fidelity, relatively small home ranges, and spend most of the study period within protected areas (Holland et al., 1996; Meyer et al., 2000; Lowe et al., 2003; Popple and Hunte, 2005; Lindholm et al., 2005; Meyer and Holland, 2005; Marshell et al., 2011; Bond et al., 2012; Pittman et al., 2014a). Others show only temporary residence of weeks to a few months and a gradual disappearance of fish from the MPA/ study area over time, likely due to emigration, premature tag failure, or exploitation (Chateau and Wantiez, 2009; Meyer et al., 2010). Some studies find multiple behavioral modes for one species, with one group resident and another moving in and out with less site fidelity (Egli and Babcock, 2004). A variety of behaviors were observed in our study, with some fish displaying residency and strong site fidelity for the majority of the study period, while a few resided in the MPA from a few days to a few months after release before leaving and never returning. The majority (56%, n=32), were detected too sporadically over the study period to judge their residency with high confidence, and either slipped in and out of the Monument throughout the year, or partially resided in gaps in the array or used high relief spots that interfered with acoustic signals (e.g., Lindhom et al., 2005, and possible for the serranids, holocentrids, and *Lutjanus apodus* (schoolmaster snapper) in this study).

It is clear that some fish species have the potential to be better protected by the Monument boundaries than others. Eighteen tagged fish were excluded from analysis due to insufficient detection data (fewer than three days). These fish may have a home range primarily outside of the detection area or may have relocated following the trauma of capture and tagging.

There are also general patterns of protection-likelihood that can be inferred for some species. For example, detection data suggest that *L. griseus* were among the least mobile fish in the study. They were never detected outside VICRNM, and rarely moved beyond the confines of the mangrove-lined bays from which they were tagged. At the other end of the spectrum, all five *O. chrysurus* were detected on many receivers and frequently crossed the VICRNM boundary but were detected for an average span of only 100 days, less than a third of the study duration. This short time and likely emigration is similar to the tracking period observed for this species in the Dry Tortugas (Farmer and Ault, 2011) but is in contrast with evidence suggesting higher site fidelity in the northern Florida Keys (Lindholm et al., 2005). It is most likely that in the case of VICRNM, these fish emigrated from the area and left no detection record for the majority of the study. Few detections and varied locations for *L. apodus* likewise suggest these fish did not remain in the study area.

In fact, of the nine *L. apodus* tagged, only two were detected for more than three days. Detection patterns suggest that *L. synagris* are also among the more mobile species. They were detected at more receivers and crossing the VICRNM boundary more often and regularly than species such as *L. griseus*. In the middle of this spectrum were fishes such as those in the family Haemulidae which were detected at an intermediate number of receivers and crossed the Monument boundary a moderate number of times compared to other species. The boundary along sand and mud bottom approximately equidistant from the fringing reefs and mangroves along the eastern and western shorelines may protect fish that are generally full time residents on those fringing habitats. This includes *L. griseus, Epinephelus guttatus* (red hind)*, Cephalopholis cruentatus* (graysby)*, Holocentrus rufus* (longspine squirrelfish), and *Sparisoma aurofrenatum* (redband parrotfish) tracked in this and other studies (Beets et al., 2003; Popple and Hunte, 2005; Pittman et al., 2014a). Less protected will be those that regularly migrate out large distances into sand areas or range even more widely (Meyer et al., 2007; Afonso et al., 2009; Pittman et al., 2014a; Legare et al., 2015).

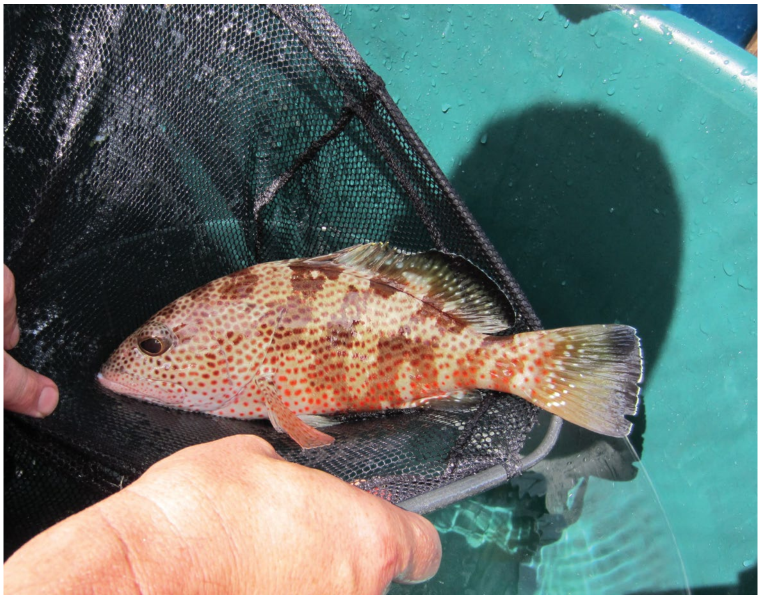
Most of the fish tracked in this study were sexually mature based on length data. Some species known to undertake spring/summer spawning migrations (Luo et al., 2009; Nemeth et al., 2007) potentially include both *E. guttatus* and the two largest *L. griseus* tracked here. The limited amount of detections for these particular individuals and the timing of their absences from our array may represent spawning migrations beyond the confines of the Monument at certain times of the year. Some species show ontogenic shifts into other habitats or a broader home range with maturity (Garla et al., 2006; Wetherbee et al., 2004), however the present study was focused primarily on adults and ontogenic patterns could not be examined.

In addition to the general spatial patterns related to the Monument boundary, there were a few specific locations where fish activity was concentrated. Telemetry has effectively identified sites in other systems where multiple individuals regularly converged either at shared refuges, for social schooling behavior, or along a common movement pathway (e.g., Holland et al., 1996; Eristhee and Oxenford, 2001). In VICRNM, both the number of fish and number of detections were highest at receivers at the mouths of Otter and Water Creeks and off the high-relief reef area south of Turner Point including boundary receivers and one location outside the Monument. In the case of Otter and Water creeks, the high values are likely due to a combination of the resident fish in those bays such as *L. griseus* and *H. sciurus*, and also the fish that were moving in and out or passing in front of those bays along the reef-lined promontories that separate them (i.e., *H. sciurus, H. plumierii, L. synagris*, and *Haemulon flavolineatum* (French grunt)). In the case of the area south of Turner Point, several factors may be contributing. This rock and submerged reef promontory is the most seaward extension of reefs connected to the inshore bays and other habitats inside the Monument (Costa et al., 2013). It may be a staging or spawning locale for those species known to seek such features (Randall and Randall, 1963; Sadovy de Mitcheson et al., 2008; Karnauskas et al., 2011). It also may be a migration pathway/departure point towards deeper waters farther south. Rather than more directly leaving their inshore residence areas through open bottom areas during departure, fish could at least be protected for as long as possible by travelling close to the structural refuge of the reef (Pittman et al., 2014a) until leaving the area via this promontory. The patch reefs farther offshore of the area also recorded many fish, but few detections, potentially indicating that fish were moving relatively quickly through this area. Tracks of several fish suggested their departure via this route, including *L. synagris, O. chrysurus, L. apodus, H. plumierii*, and *Calamus penna* (sheepshead porgy). Although fish tended to stay within

Hurricane Hole mangroves.
Photo credit: C.S. Rogers

the side of the Monument in which they were trapped, it could also be a simple pinch-point for fish transiting between Hurricane Hole and Round Bay as in the case of an *L. apodus* released in Princess Bay and tracked moving around Turner Point into Round Bay.

Overall, the differences in day versus nighttime detection patterns lacked statistical significance. Disproportionate movements of fish beyond the outer edge of the study area during the day versus night may have partly biased the detection values and therefore made general patterns difficult to detect. Despite this concern, a few important contrasts were evident. First, a much greater proportion of detections were during the night on most receivers outside the Monument. This pattern could result from fish that undergo nocturnal migrations away from reefs to forage in adjacent habitats (Meyer et al., 2000; Beets et al., 2003; Kendall et al., 2003; Hitt et al., 2011). The typical scales of those foraging migrations could easily take fish outside the Monument at night on a regular basis, not only increasing detections there but also making them more exposed to fishing. This movement pattern was clearly observed in several *H. sciurus* and *L. synagris* in this study which were found in the bays of Hurricane Hole during the day, but at night were tracked moving south to the border receivers off Turner Point and occasionally outside the Monument boundary.



Red hind, Epinephelus guttatus.
Photo credit: M. Kendall, Biogeography Branch, NOAA

Also of note, in a few locations many more individual fish were detected during the daytime than nighttime, but those sites did not have a greater number of detections. These included the northwestern parts of Hurricane Hole, receivers at the southern end of the reef off Turner Point, and the patch reef area farther south. Given the strong site fidelity of some fish to daytime resting locations (e.g., as documented for Haemulids by Beets et al., 2003; Hitt et al., 2011), it was somewhat surprising that more receivers were not dominated by daytime detections as these were. This could be the result of fish occupying daytime resting sites within rugose reef or mangrove habitat that enable a few detectable transmissions but are generally hidden due to acoustic shadows compared to those foraging at night over less-complex sand or mud habitat (Lindholm et al., 2005; Hitt et al., 2011; Selby et al., 2016). Utilizing those sites as daytime refuges, may result in just a few detections. The southernmost site was puzzling however, since it was dominated by daytime detections but, based on benthic maps (Costa et al., 2013), has virtually no reef where fish could rest during the day.

A large majority of receivers (31 out of the 38) had a greater proportion of their detections at night. Although noise from biotic interference shows crepuscular peaks, it is relatively consistent in the study area during the core hours of the day and night (Kaplan et al., 2015) and is therefore not suspected to have biased the detection results in those time periods. Day versus night differences could have been somewhat masked by the difference in environmental noise or sound transmission among habitats. Detection ranges were generally farther for receivers deployed on soft bottom, however, range tests were all conducted during the day in this study. Use of long-term, stationary-control tags could better quantify daily variability (Mathies et al., 2014).

Although only 75 fish were tagged in this study, they were broadly representative of the overall reef fish community seen in Coral Bay. Over 75% of the fish over 20 cm that have been seen on visual surveys in the area were from the same 7 families that comprised the tagged fish in this study. In both cases, Lutjanidae were the most abundant family represented. Differences were that relative abundance of tagged versus visually-surveyed fish varied at the family level and more importantly, ~20% of the fish visually documented by divers were comprised of 21 additional families not included in the group of tagged fish. Some of these differences are due to the biases associated with trapping versus visual censuses. Traps may catch more mobile fish attracted to structure (Robichaud et al., 2000), whereas visual censuses often miss species that are cryptic or reclusive in response to divers. Another key cause of differences is the habitat types in which the two sampling techniques were used. Trapping for the telemetry study was focused on reef edges and mangrove areas. In contrast, visual surveys excluded mangroves and were instead focused on hard and soft bottom habitats. Despite the bias toward more mobile fish that are subject to capture in traps, the fish tagged in the present study broadly represent the fish found in Coral Bay at the family level and in composite, provide a reasonable scope-of-inference on fish movements overall.

It is crucial to note that even for fish which have a robust record of residence inside the Monument, their actual protection generously assumes compliance with no-take regulations. Data on number and frequency of no-take violations or enforcement in this area are largely lacking and beyond the scope of this study. Hence, it must be acknowledged that discussion of protection of fish within the Monument really refers to potential-protection, pending adequate enforcement. Results of this study can be used to justify investment in enforcement of existing rules and even prioritize species or locations within VICRNM in Coral Bay that may be more important or responsive to management actions than others.

Important next steps in this investigation include further analysis of the existing data from Coral Bay as well as collection of additional field data. Recent applications of graph theory and network analysis on fish telemetry data have proven insightful (reviewed in Jacoby and Freeman, 2016). These analysis techniques can identify groups of fish and the receivers or locations that they are regularly associated with. Corridors of movement and important clusters or crucial nodes of activity can be statistically quantified. The sensitivity of those associations and spatial patterns to various timescales (e.g., daily, lunar, seasonal) and divisions of the fish community can be contrasted (e.g., juveniles vs. adults or among species, families, or guilds). Additional field studies could be prioritized toward common species with fewer individuals tracked (e.g., parrotfish), multi-year studies to track inter-annual or seasonal patterns (Egli and Babcock, 2004; Knip et al., 2012), species of concern for conservation (Chateau and Wantiez, 2007), or tracking a similar suite of species in a new geography (e.g., Meyer and Holland, 2005; Marshell et al., 2011). Comparing results among locations is critical to develop a general understanding of the processes governing movement networks and how other landscape settings may result in broader inferences on fish movements and implications for design of MPA boundaries.

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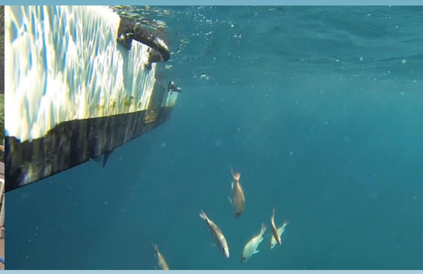

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