

## SIT Graduate Institute/SIT Study Abroad SIT Digital Collections

---

Independent Study Project (ISP) Collection

SIT Study Abroad


---

Fall 2018

# The Influence of Habitat Preference on Longitudinal Population Composition and Distribution of Groupers (Serranidae) in Chumbe Island Coral Park, Zanzibar Tanzania

Caroline Daley  
*SIT Study Abroad*

Follow this and additional works at: [https://digitalcollections.sit.edu/isp\\_collection](https://digitalcollections.sit.edu/isp_collection)

 Part of the [African Studies Commons](#), [Aquaculture and Fisheries Commons](#), [Environmental Indicators and Impact Assessment Commons](#), [Environmental Monitoring Commons](#), [Marine Biology Commons](#), and the [Oceanography Commons](#)

---

### Recommended Citation

Daley, Caroline, "The Influence of Habitat Preference on Longitudinal Population Composition and Distribution of Groupers (Serranidae) in Chumbe Island Coral Park, Zanzibar Tanzania" (2018). *Independent Study Project (ISP) Collection*. 2915.  
[https://digitalcollections.sit.edu/isp\\_collection/2915](https://digitalcollections.sit.edu/isp_collection/2915)

This Unpublished Paper is brought to you for free and open access by the SIT Study Abroad at SIT Digital Collections. It has been accepted for inclusion in Independent Study Project (ISP) Collection by an authorized administrator of SIT Digital Collections. For more information, please contact [digitalcollections@sit.edu](mailto:digitalcollections@sit.edu).

**The Influence of Habitat Preference on Longitudinal Population Composition and Distribution of Groupers (*Serranidae*) in Chumbe Island Coral Park, Zanzibar Tanzania**

Caroline Daley

Advised by Dr. Narriman Jiddawi

December 12, 2018

The School for International Training - Zanzibar, Tanzania

Academic Director Richard Walz

Thanks are in order to Said Omar and Zuleikha Makame for their endless support and warmth; Ulli Kloiber and the Chumbe Island rangers and staff for their patience, kindness, and a forever home in the Zanzibar archipelago; to Kenna Kuhn for her honesty, humor, and friendship; and to Richard Walz for his dogged dedication to the success of his students and his inspirational commitment to knowledge, hard truths, and the beauty of the natural world.

## Table of Contents

Abstract		
Introduction	...	1
Methods and Materials		
Study Site	...	5
Focus Species	...	6
Nesbitt, 2014	...	7
Survey Methods	...	7
Results		
Population Composition and Distribution	...	10
Population Biodiversity and Evenness	...	14
Habitat Preference	...	14
Age Distribution	...	17
Comparison of Abundance, Biomass, and Biodiversity Between 2014 and 2018	...	17
Longitudinal Population Comparison Within the MPA	...	18
Longitudinal Population Comparisons Outside the MPA	...	20
Discussion		
Population Composition and Distribution	...	21
Habitat Preference and Age Distribution	...	24
Regime Shift Between 2014 and 2018	...	27
Longitudinal Changes in <i>Serranid</i> Populations	...	28
Open Access Areas and Spillover	...	30
Conclusion		
Population Instability in OAA's	...	31
Wide Range and Population Dominance	...	31
<i>Serranid</i> Population Health and Coral Reefs	...	32
Management Recommendations	...	33
Works Cited	...	34

## **ABSTRACT (English)**

A survey of six common grouper (*Serranidae*) species was conducted on both the western protected and eastern unprotected reefs around Chumbe Island. Species, estimated maturity, and fundamental niche and general habitat preference was extrapolated based on observed realized niche and qualified according to substrate, depth, slope position, and general reef region. Abundance, biomass density, and biodiversity of *Serranid* populations were compared among locations on the reef with habitat preference in mind in order to best assess how habitat influences population composition, distribution, and health. The results of this study provide depth to previous research on the protected reef and indicate noteworthy shifts in population composition between 2014 and 2018 in favor of species with less specified habitat preference and subsequently wider ranges. Thus, this study suggests that *Serranid* populations around Chumbe Island are experiencing a regime shift in response to the degradation of their coral reef habitat. Surveys of Chumbe's nearby unprotected eastern reef indicate low levels of species abundance, which are hypothesized to be the result of inappropriate habitat structure, increased fishing pressure, and decreased population health within the MPA. Ultimately, this study suggests that monitoring *Serranid* populations collectively in terms of abundance and without heed to species does not effectively measure population health. Indeed, research of reef dependent fishes that does not take habitat into consideration fail to capture, explain, and inform management of changes in marine populations and the habitats they are intrinsically linked to as a result of a threat that cannot be mitigated even by an MPA – climate change.

## **ABSTRACT (Kiswahili)**

Uchunguzi wa aina sita za kawaida za chewa (*Serranidae*) zilifanyika kwenye miamba ya magharibi iliyohifadhiwa na mashariki inayozunguka kisiwa cha Chumbe. Aina, inakadiriwa ukomavu, na upendeleo mazingira asilia ambapo aina za chewa huishi ulirekodiwa kwa kutumia vigawanyo sanifu vinavyolingana. Msingi wa viumbe kuweza kukaa katika mazingira na kupedelea kutoweka kwa mazingira ya kiikologia ya jumla ulifanywa kwa ziada kulingana kukisia na kuangalia pamoja na kutambua viumbe kuweza kukaa katika mazingira naeneo ambalo viumbe kukukua, kupata chakula na kuweza kuishi, kina, mteremko mkali, na miamba. Wengi na Uzito wa idadi jamii ya chewa walilinganishwa miongoni mwa maeneo wanayoishi kwenye miamba na ucgaguzi maeneo ya kimazingira na kuzingatia jinsi gani mazingira yanavyoathiri ueneaji na ubora wa maeneo kimazingira. Matokeo ya utafiti huu yametowa taarifa za kina juu ya utafiti uliofanywa kwenye mwamba uliohifadhiwa na zinaonyesha mabadiliko muhimu kati ya mwaka 2014 na 2018 inazifanya aina chache zinazoishi kwenye maeneo maalum Utafiti wa miamba ya karibu isiyohifadhiwa ya mashariki ya Chumbe inaonyesha kiwango cha chini aina za viumbe, utafiti huu huthibitishan matokeo ya muundo kimazingira usiofaa, kuongezeka kwa shughuli za uvuvi, na kupungua kwa ubora wa kimazingira kwa eneo hifadhi ya bahari. Hatimaye, utafiti huu unashauri ufuatiliaji wa aina za viumbe wengi haziwezi kupima ubora wa idadi ya viumbe na kushindwa, kufafanua, mabadiliko katika katika bahari yanaohusishwa kwa sababu ya tishio ambayo hawezi kushughulikiwa hata na MPA - mabadiliko ya tabia nchi.

## INTRODUCTION

Coral reefs offer innumerable ecosystem services, many of which operate both synergistically and, unfortunately, self-destructively. In Zanzibar, the most troublesome example of this instability between services stems from the rapidly growing coastal population's unsustainable exploitation of the productive fishing grounds offered by nearby coral reefs. Coral reefs are incredibly sensitive ecosystems, and many of the services they offer and much of the marine life that occupy them are contingent on a high standard of health (Richmond 2011). Groupers (*Serranidae*) are apex predators that exhibit strong habitat preferences to structurally complex and healthy reefs, and are thus often regarded as an indicator of overall reef health (Hackradt et al. 2014; Pinca et al. 2011). The presence of groupers on a reef indicates (1) that the reef is not overexploited, (2) that the coral is healthy and complex, (3) that lower trophic levels are being balanced by natural predation (Hackradt et al. 2014; Kelly and Ruhl, 2011), and (4) that the reef likely supports high abundances and biodiversity of marine life and offers noteworthy, stable ecosystem services to the surrounding area as a result of the aforementioned three characteristics (Hackradt et al. 2014; Myers and Worm 2003, Myers et al. 2007, and Worm et al. 2006, as cited in Russ and Alaca 2011). However, *Serranids* are especially vulnerable to overfishing and ecosystem degradation due to their site fidelity and highly specific habitat preferences (Chiappone et al. 2000; Exton, as cited by Kelly and Ruhl 2011; Chapman and Kramer 2000, Sale 1991, Samoily 1997, and Zeller 1997, 2002 as cited in Zeller et al. 2003); tendency to form spawning aggregates (Sadovy 1994, as cited in Chiappone et al 2000); long life, slow growth rate, and delayed sexual maturity (Hackradt et al. 2014; Sadovy 1994, as cited in Chiappone et al. 2000); and resultantly low resilience to disturbances in population and habitat (Sadovy de Mitcheson et al. 2012). Groupers often generate a high market price, especially when

sold into a burgeoning tourism economy like that of Zanzibar, and their populations have suffered as a result. Moreover, in a reality in which comprehensive studies of grouper spawning aggregations, larval export, and population dynamics are lacking worldwide, longitudinal research into the persistence of grouper populations in the West Indian Ocean has fallen relatively by the wayside. While these factors contribute to groupers' vulnerability, they also render groupers an ideal case study for comprehensively assessing the effectiveness of Chumbe Island Coral Park Limited (CHICOP) at protecting the species, promoting spillover into unprotected areas, and thereby supplementing the health of neighboring reef ecosystems.

In order to best account for the rapid changes occurring on coral reefs in the face of climate change, this study aims to identify habitat preferences of six common species of grouper in order to inform best management strategies in the face of external pressures that cannot be eliminated by the boundaries of a no-take area (NTA). Habitat health and type have been shown to significantly influence not only the distribution, but also abundance and biomass of groupers (Hackradt et al. 2014). Thus, defining the habitat preferences of these apex predators is of the utmost importance in order to appropriately attune management strategies in response to environmental change in order to best ensure continued conservation of serranids in the face of present and future threats (Berger and Possingham 2008; Friedlander et al. 2003). The comparison of fundamental niche, or the habitat that a species is expected to occupy based on its known preferences, and realized niche, the habitat that a species actually occupies, enables a discussion of the other variables at play that might cause these two areas to be different (Buxton et al. 2014). Accurate definitions of a species' fundamental niche allow for efficient and effective conservation of said habitat, if the population of that species is found to be in decline. Likewise, by methodically observing changes in a species realized range, one is able to extrapolate changes

in overall ecosystem and reef health and better understand phenomena such as regime shifts and spillover effect (Rowly 1994, as cited in Hackradt et al. 2014). Thus, a sound understanding of the relationship between a species and the habitat it occupies is foundational to the effective and long-term conservation in the context of the worlds coral reef ecosystems.

CHICOP - a privately-owned marine protected area (MPA) off the western coast of central Unguja, Zanzibar - safeguards ecological ecosystem services offered by coral reefs, which include buffering coastlines from wave action, sequestering carbon dioxide, and supporting the biodiversity of marine species that depend upon them (Richmond 2011). Indeed, even small scale MPA's like Chumbe have been shown to consistently support higher abundance, biodiversity, and biomass of groupers and other predatory and commercially fished species than surrounding unprotected areas (Edgar et al. 2014; Fenberg et al. 2012; Hackradt et al. 2014; Sterner and Anderson 1998). While the implications of partitioning off an economically and socially valuable resource in the name of conservation are contentious, MPA's are often argued to benefit local fisher people by promoting the larval export and spillover of mature individuals into fishable areas, otherwise known as spillover effect (Hackradt et al. 2014). Oftentimes, however, unsustainable fishing practices outside park bounds increase in order to compensate for restricted fishing grounds (Skoglund 2014). This is not to say, however, that equilibrium between fishing and reef health cannot be achieved, and CHICOP's educational outreach program, relatively small NTA, and eastern open access area constitute steps toward appropriate mediation of the needs of both parties (Unsworth et al. 2007). Indeed, in 2005, 94% of artisanal fisher-people around Chumbe Island reported that they believed that fish populations migrate outside the NTA, thereby increasing their yield on the eastern reef (Tyler 2006, as cited in Nordlund et al. 2012). In order to better understand the effectiveness of CHICOP in



adequately meeting the needs of the reef – both in terms of ecological health and the aesthetics necessary to generate income from tourism to fuel continued management and research - and those of local fishermen, this study aims to systematically assess grouper (*Serranidae*) populations on the protected and unprotected areas and serves as an initial foray into an study of localized population dynamics around Chumbe Island (Francis et al. 2002, as cited in Skoglund 2014; Sterner and Anderson 1998).

This report utilizes longitudinal abundance and biomass data collected annually by CHICOP, as well as specific comparisons of population composition and biodiversity both before and after a significant disturbance in coral reef health (2016 mass coral bleaching event) in order to contextualize the findings of this study and anticipate responses to future threats. It is important to consider that this study draws its analytical power from the fact that the data is ultimately analyzed spatially and takes habitat appropriateness into consideration in discussions of current species abundance and biomass density. Capacity for spillover is assessed with population health within the NTA and habitat appropriateness of the surrounding OAA in mind. A comparison of populations on protected and unprotected reefs both quantifies CHICOP's success at conserving grouper populations and achieving spillover, as well as provides examples of habitat and circumstances that are inappropriate for the persistence of certain species. Moreover, focused investigation into realized niche offers amendment to current understanding of each species' fundamental niche, as well as a platform for extrapolating the overall health of the reef as a function of the amount of groupers it currently supports and both the quality and type of habitat they occupy. By conducting research within an NTA that adheres to four out of the five features shown by Edgar et al. 2014 to exponentially benefit conservation success (no-take, effective enforcement, isolation by deep water or sand, and more than 10 years of

existence) and boasts longitudinal increases in grouper biomass and abundance, changes in *Serranid* population may largely be attributed to the anthropogenic degradation of coral reefs via sea level and temperature rise, which unfortunately cannot be kept at bay by the boundaries of an MPA (Edgar et al. 2014). Ultimately, this study intends to lay a foundation for continued monitoring and research on population dynamics on and between protected and unprotected reefs and to generate an understanding of how grouper habitat might be better managed to maximize the benefit of the reef, local fisher-people, and CHICOP itself in the face of changes in environment that cannot be mitigated by stagnant boundaries and policy strategies.

## **MATERIALS AND METHODS**

### **Study Site**

Chumbe Island is located 6 kilometers off the western coast of Zanzibar and 33 kilometers off the eastern coast of Tanzania in the Zanzibar Channel. It measures a maximum of 1 kilometer running north to south and lays claim to fringing coral reefs on both sides. In accordance to Tanzania's commitment to protect 10% of its marine ecosystems by 2012, Chumbe Island Coral Park Limited - which includes mangrove forests and other terrestrial ecosystems as well as 55 hectares of the western fringing reef and associated backreef, seagrass beds, and coast – was established in 1994 by the semi-autonomous government of Zanzibar (Nordlund et al. 2012). CHICOP is the first privately-owned MPA in East Africa and the first self-sustaining MPA in the world, funding itself through educational ecotourism and high-end bungalow-style accommodation. Chumbe's western fringing reef and abutting backreef and seagrass beds fall within the NTA, granting them extensive research and vigilant protection by CHICOP, and, subsequently, a grouper population that was 300% larger than that of the

unprotected reef, even at its minimum at the park’s inception in 2006 (CHICOP 2017).

Chumbe’s eastern fringing reef, however, enjoys no protection, and, as a result, is vulnerable to the over-exploitive and sometimes destructive fishing practices. Fishing is extremely important to Zanzibar’s informal economy and is the means by which most coastal communities feed themselves, so the designation of MPA’s is complicated and nuanced even for a park like CHICOP, which fosters an impressively strong relationship with community stakeholders through on-site environmental education (Horrill et al. 1996; Unsworth et al. 2007).

### Focus Species

Figure 1 includes brief descriptions of the six *Serranid* species included in this study. These species are informally regarded as the most commonly observed within CHICOP. Fundamental niche and general habitat preference are informed both by external species profiles and Nesbitt’s survey of these same species in MPA in 2014, thereby attuning the descriptions to the populations specific to Chumbe’s western reef. Other species

Species	Description	Distinction of Maturity	Substrate	Depth	Reef Slope	IUCN Status	Notes
<i>Aethaloperca rogae</i> (Redmouth Grouper)	Dark body, red inside mouth; juveniles distinguished by white margin at end of tail and variable white bar on side	Reaches 34 cm Maximum length: 60 cm	Sparse coral Deep coral Deep sand	1 – 54 m	On and around reef slope and backreef	Data Deficient (Unknown trend)	Uncommon; not caught by fishermen; wide range
<i>Anyperodon leucogrammius</i> (Slender Grouper)	Elongated body with flat, long snout and round tailfin; pink-brown with pale stripes; juveniles distinguished by white and yellow stripes	Reaches 30 cm and/or Color change Maximum length: 65 cm	Sparse coral Dense coral	1 – 50 m	Top of reef slope and backreef	Least Concern (Unknown trend)	Associates with table corals in shallow reefs; uncommon with generally low abundance
<i>Cephalopholis argus</i> (Peacock Grouper)	Dark brown or red with blue rimmed black spot and lighter bands toward tail	Reaches 22 cm Maximum length: 60 cm	Dense coral Deep sand	< 6 m	On and around reef slope	Least Concern (Stable)	Common on coral reefs
<i>Cephalopholis miniata</i> (Coral Grouper)	Orange-red body with small, blue spots with brown borders; juveniles distinguished by orange coloration with widely scattered blue spots	Reaches 26 cm Maximum length: 50 cm	Dense coral Deep sand	4 – 150 m	On and around reef slope; concentrated where steepest	Least Concern (Decreasing)	Common; caught in artisanal fisheries
<i>Epinephelus fuscoguttatus</i> (Brown Marbled Grouper)	Dark brown with light brown mottling	Reaches 50 cm Maximum length: 120 cm	Dense coral Deep sand	1 – 60 m	On and around reef slope	Near Threatened (Unknown trend)	Uncommon and wary; caught in artisanal fisheries
<i>Plectropomus laevis</i> (Black Saddled Grouper)	Red-brown, dark spots and white belly; five light bands on back and flanks; juveniles distinguished by yellow fins and five black bands across back	Color change Maximum length: 125 cm	Sparse coral Dense coral Deep sand	4 – 90 m	Bottom of reef slope	Vulnerable (Decreasing)	Strong habitat preference; wary

Figure 1. Description of focus species and respective fundamental niche (Debelius 1999; Hiatt and Strasburg 1960; Lieske and Myers 1996; Kelly and Ruhl 2011; Nesbit 2014; Nesbit and Richmond 2015; Unsworth et al. 2007, IUCN.org)

were observed within the MPA, but were not included in this survey for the sake of continuity between this and Nesbitt's study and a more focused and precise survey. An understanding of general fundamental niche contextualizes and corroborates the validity of the realized niches of each species observed in this study.

### **Nesbitt, 2014**

In 2014, Kimberly Nesbitt conducted a foundational *Serranid* survey within the MPA in order to establish long term monitoring efforts for these important species (Nesbitt 2015). This study adopts her six species of focus and modifies and expands her methods slightly in order to more comprehensively study realized niche in conjunction with population composition.

Generally, Nesbitt concluded that most mature individuals and individuals with the potential to grow large dwell primarily in deep water associated with reef slope, and that smaller species and juveniles dwell primarily in the shallower backreef area (Nesbitt and Richmond 2015). No juvenile *E. fuscoguttatus* or *C. miniata* were observed, though the population of *P. laevis* was divided evenly between juvenile and mature individuals and juveniles composed 90% of the population of *A. rogae* (Nesbitt 2015). *C. argus*, *A. rogae*, and juvenile *P. laevis* exhibited wide ranges and low site fidelity, while *E. fuscoguttatus*, *C. miniata*, and *A. leucogrammicus* were concentrated at highly specific areas of the reef that adhere to the parameters listed in Figure 1 (Nesbitt 2015).

### **Survey Methods**

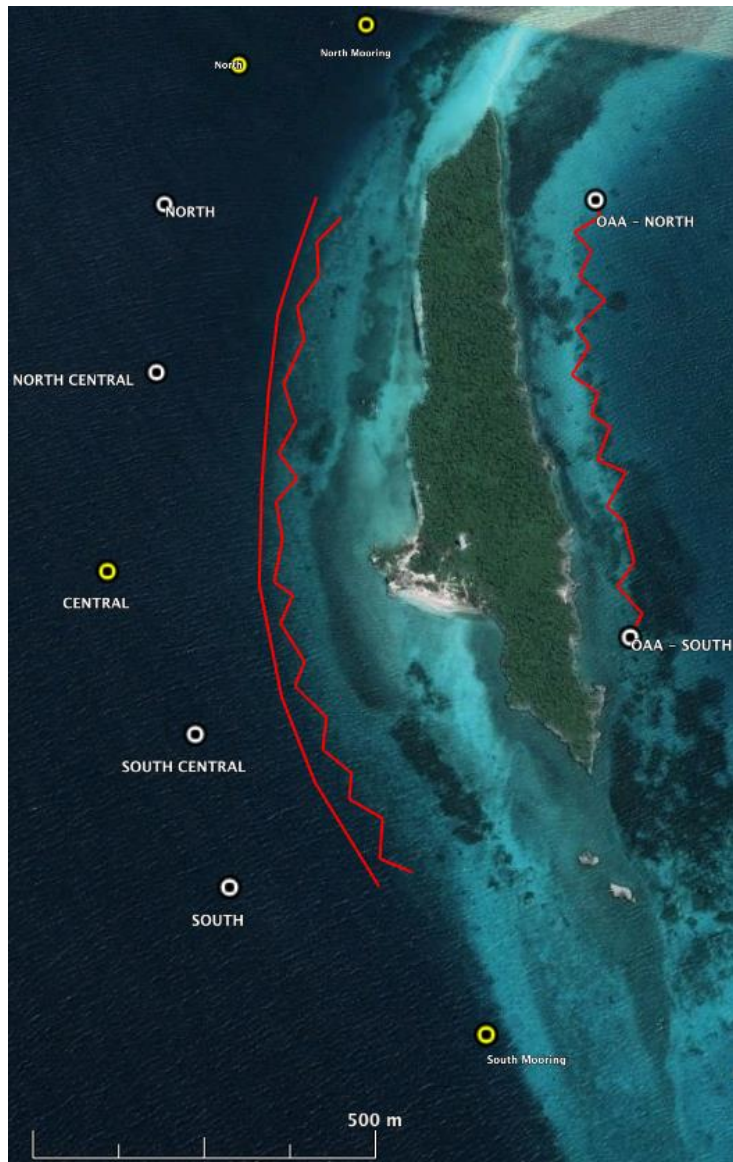
Visual under-water censuses were conducted on both the slope and backreef of the western no-take zone and the reef of the eastern open access area on either side of Chumbe Island, Zanzibar during the month of November, 2018. The western reef was surveyed within the MPA between points at which coral becomes notably sparse and the slope disappears. Start and end locations in the southern and northern most reaches of the MPA were replicated relative to

landmarks on the island and were approximated at 6degrees 17.096'S, 39degrees 10.571'E and 6degrees 16.509'S, 39degrees 10.483'E, respectively. Both the slope and the backreef were surveyed between these two points from south to north within prescribed zones approximated by visual landmarks on the island (Figure 2). The slope was surveyed linearly from south to north, thereby representing an informal transect. The reef slope was defined as the area of steepest bathymetric decline between dense coral and deep sand and was characterized by dense coral cover. The backreef was surveyed in a serpentine swim parallel to the slope at a minimum perpendicular distance of approximately 10 meters (English et al. 1997). Backreef was defined as the area adjacent to the slope with no significant incline and was characterized by sparse to dense coral cover. The eastern reef was surveyed north to south in a serpentine swim parallel to Chumbe's coast and the area surveyed was bounded by landmarks on the island that correspond to where coral begins and ends at the northern and southern ends of the informal transect and were approximated at 6degrees 16.505'S, 39degrees 10.730'E and 6degrees 16.892'S, 39degrees 10.771'E, respectively. The western slope and backreef (hitherto, in addition to the east reef, referred to as 'regions') were divided into four 'zones' (north, north central, south central, and south) according to landmarks in order to compare *Serranid* populations between eight distinct 'locations' (e.g. south central backreef). Southern zones were surveyed at low to mid-tide, northern zones were surveyed at mid to high tide, and the eastern reef was surveyed exclusively at low tide.

Differentiation of 'zones' is explained in greater detail in Figure 2. Yellow markers represent physical buoys that were present at the time of survey, and white markers represent markers that were approximated based on position relative to specified on land markers. Markers with capitalized labels indicate differentiations between zones. The red lines represent

approximate transects, and the straight line represents slope surveys while the serpentine lines represent backreef swims.

The entire slope, backreef, and eastern slope were surveyed a total of three times, and the north and south-central zones were surveyed an additional three and two times respectively due to the importance of slope to *Serranid* habitat. All individuals within 5 meters of the transect were included in the survey. Species and estimated length and/or maturity for each individual as well as habitat parameters such as depth, substrate, position on slope, and general notes for each sighting were recorded using a waterproof audio recorder attached to a floating ring. In addition to the time at which each species was sighted, time at which each zone was entered and exited, region surveyed, and ambient weather conditions were recorded. Maturity was determined post-survey based on the information in Figure 1, unless species maturity is indicated color change (e.g. *P. laevis*), in which case it was determined in-field (Debelius, 1999; Fishbase.org, as cited in Nesbitt 2014).



	Zone	Latitude	Longitude
MPA	NORTH	6° 16.509'S	39° 10.483'E
	NORTH CENTRAL	6° 16.664'S	39° 10.453'E
	CENTRAL	6° 16.837'S	39° 10.456'E
	SOUTH CENTRAL	6° 16.971'S	39° 10.494'E
	SOUTH	6° 17.096'S	39° 10.571'E
OAA	NORTH	6° 16.505'S	39° 10.730'E
	SOUTH	6° 16.892'S	39° 10.771'E

Figure 2. Map of Chumbe Island and estimated transects and zones. Red lines represent estimated transects. Yellow markers indicate buoys present at time of survey, white markers indicate imaginary points of differentiations. Capitalized labels indicate differentiation between zones, estimated latitude and longitude included in above table. Estimations of area surveyed calculated based on these coordinates.

## RESULTS

### Population Composition and Distribution

A total of 362 individuals were observed around Chumbe Island, the vast majority of which were recorded within the MPA, and nearly twice as many individuals were observed on the slope than the backreef. *Serranid* populations on the protected backreef alone boasted 700%

more individuals than the unprotected reef, and the biomass density per hectare likewise differs notably between the eastern reef (2.3 kg/ha) and structurally comparable western backreef (93.43 kg/ha) (Figure 4a). slope and backreef regions were dominated by *A. rogaea*, both in terms of relative species abundance and biomass density (figures 3a and 4a), which is noteworthy considering that *A. rogaea* has only the second largest maximum length (60 cm) of the six focus species (Figure 1). Moreover, *A. rogaea* held the largest relative abundance across all locations within the MPA and the largest biomass density in all locations, except in the north slope where it is surpassed only by *E. fuscoguttatus* (figures 3b and 4b). With a relative abundance that was still less than half that of *A. rogaea*, *C. argus* was observed to have the second highest relative abundance in both protected regions, though its biomass density also fell behind that of *E. fuscoguttatus* (Figure 4a). Similar to the increase in total population between backreef and slope, biomass density likewise increased between backreef and slope for all species, which emphasizes Nesbitt's observation that larger individuals prefer the reef drop-off (Nesbitt and Richmond, 2015). High relative abundances and biomass densities were shown on both south and north central slopes across all species (Figure 3b and 4b). In keeping with their distribution across regions, relative species abundances of *P. laevis*, *E. fuscoguttatus*, *C. miniata*, and *A. leucogrammicus* were consistently lower than those of *A. rogaea* and *C. argus* across locations (Figure 3b).



Figure 3a.

	Total Abundance (Relative Abundance)			East Reef
	Slope	Backreef	TOTAL	
<i>P. laevis</i>	16 (0.07)	2 (0.02)	<b>18 (0.05)</b>	0 (0)
<i>E. fuscoguttatus</i>	7 (0.03)	1 (0.01)	<b>8 (0.02)</b>	0 (0)
<i>C. miniata</i>	10 (0.04)	2(0.02)	<b>12 (0.03)</b>	1 (0.06)
<i>C. argus</i>	46 (0.20)	33 (0.28)	<b>79 (0.23)</b>	13 (0.81)
<i>A. rogaea</i>	143 (0.63)	76 (0.63)	<b>219 (0.63)</b>	1 (0.06)
<i>A. leucogrammicus</i>	6 (0.03)	4 (0.03)	<b>10 (0.03)</b>	1 (0.06)
<b>TOTAL</b>	<b>228</b>	<b>118</b>	<b>346</b>	<b>16</b>

Figure 3b.

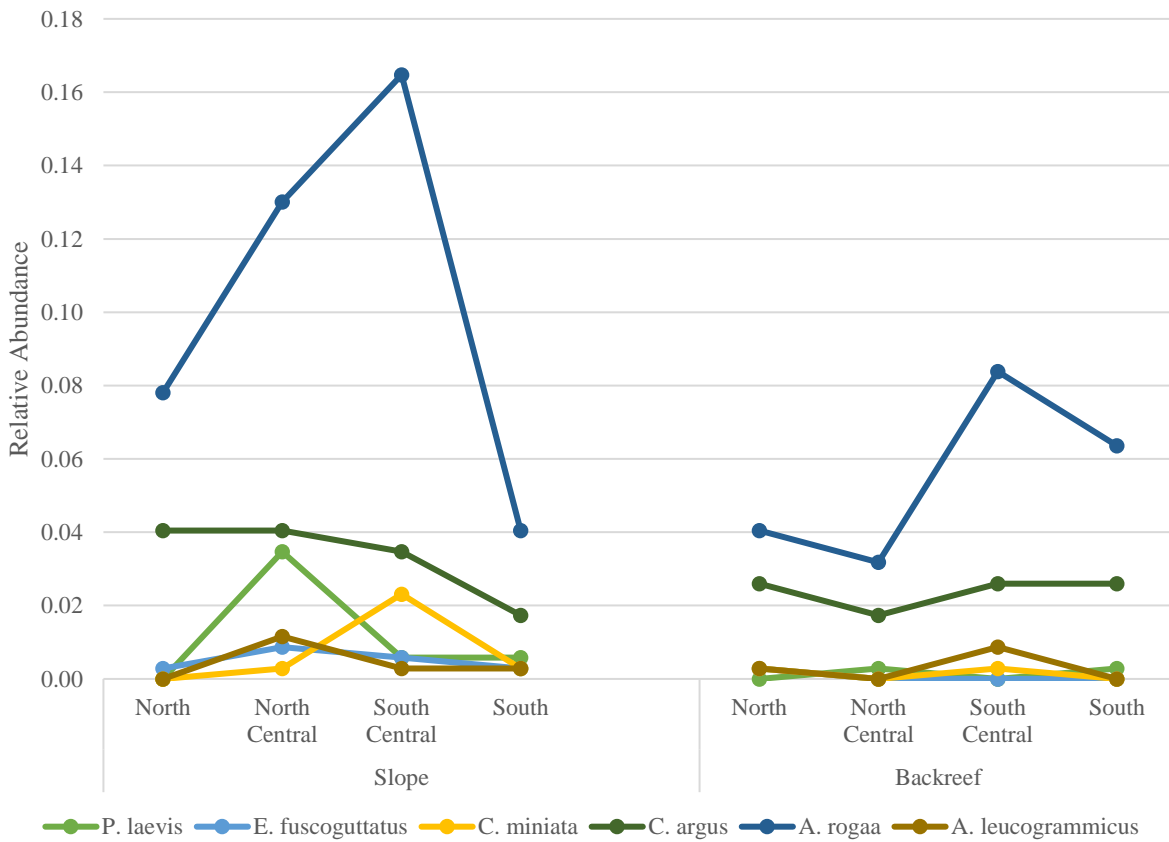


Figure 3. Total species abundance and relative abundance of six focus *Serranidae* between regions and locations in Chumbe Island's MPA. Figure 3a. Relative species abundance calculated between regions out of region total population counts. East reef not included in "TOTAL" MPA species abundance and relative species abundance. 3b. Relative species abundance calculated between 'locations' out of total reef population count. East reef not included.

Figure 4a.

	Biomass Density (kg/ha)			East Reef
	Slope	Backreef	TOTAL	
<i>P. laevis</i>	54.09	3.17	<b>27.29</b>	0.00
<i>E. fuscoguttatus</i>	128.01	4.68	<b>63.10</b>	0.00
<i>C. miniata</i>	12.57	1.10	<b>6.55</b>	0.05
<i>C. argus</i>	88.38	17.51	<b>51.83</b>	1.94
<i>A. rogae</i>	196.18	63.42	<b>126.37</b>	0.17
<i>A. leucogrammicus</i>	14.09	3.54	<b>8.59</b>	0.14
<b>TOTAL</b>	<b>493.31</b>	<b>93.43</b>	<b>283.74</b>	<b>2.30</b>

Figure 4b.

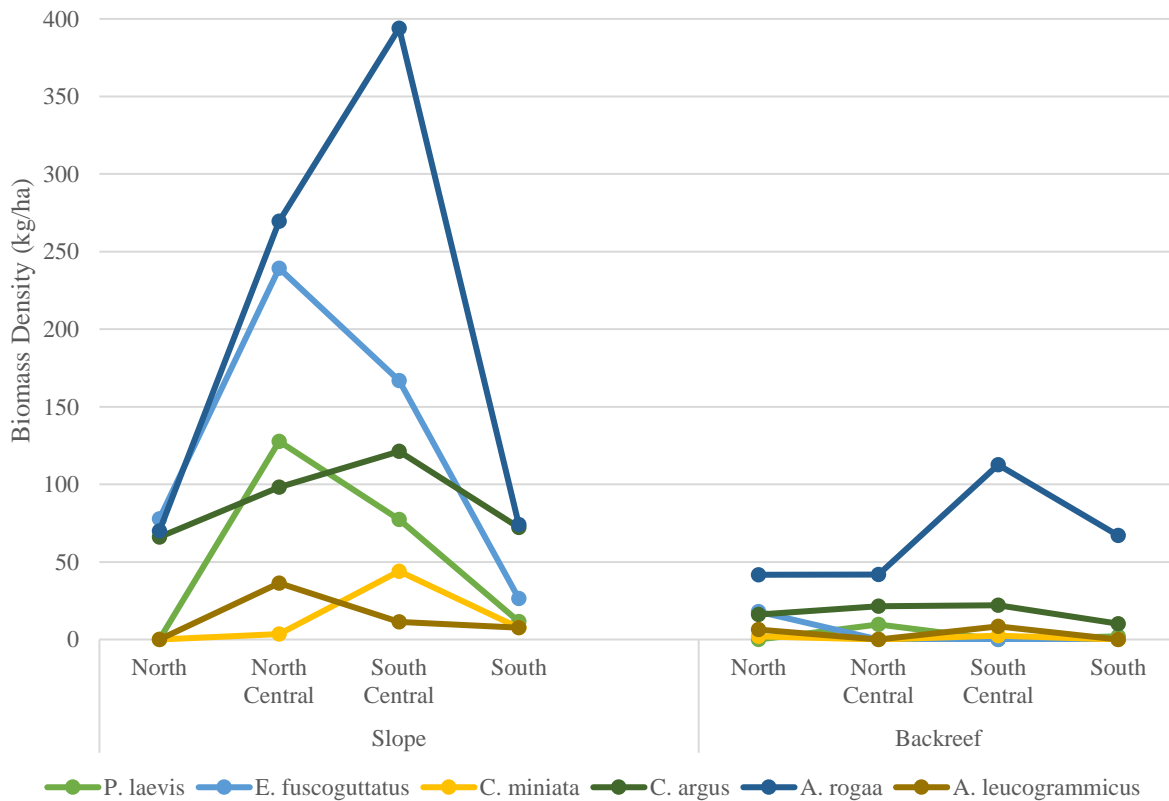


Figure 4. Total biomass density (kg/ha) of six focus *Serranidae* between regions and locations in Chumbe Island’s MPA. Total hectares surveyed estimated by multiplying total transect length for each region by perpendicular width of area surveyed. Individual fish masses calculated according to length-weight relationships offered in “Biomass Calculator” Excel sheet available at Chumbe Office, Stonetown, Zanzibar. Figure 4a. Species biomass density calculated between regions out of total region hectareage. East reef not included in “TOTAL” MPA biomass density. Figure 4b. Species biomass density calculated between ‘locations’ out of total reef hectareage.

## Population Biodiversity and Evenness

According to both the Shannon-Wiener Index, which quantifies both richness and evenness, and simple species richness, the slope exhibited higher biodiversity than the backreef within the MPA, except in the northern zone (Figure 4). When viewed on a larger scale, the two regions exhibited comparable levels of biodiversity, but the division of each region into zones and locations allows the distinct differences between locations to be observed. The north central zones exhibited the highest biodiversity according to the Shannon-Weiner Index, and the other three zones displayed decreased levels of biodiversity comparable to one another. In terms of both the Shannon-Weiner Index and general species richness, the lowest biodiversity occurred in the southern backreef and northern slope (Figure 5). Numerical measurements of biodiversity in the eastern OAA were comparable to the aforementioned protected locations, despite the fact that the total abundance and biomass density of the eastern reef were significantly lower than those of the southern backreef and northern slope. Overall, the western NTA exhibits a Shannon-Weiner Index of 1.09 and a species richness of 6.

Shannon Weiner Index (Species Richness)					
MPA - West Reef	North	N. Central	S. Central	South	
Backreef	1.08 (5)	0.83 (3)	0.86 (4)	0.72 (3)	0.93 (6)
Slope	0.65 (3)	1.24 (6)	1.00 (6)	1.26 (6)	1.14 (6)
	0.90 (4)	1.20 (6)	0.99 (6)	1.01 (6)	
<b>OAA - East Reef</b>	0.69 (4)				

Figure 5. Shannon-Wiener Index of biodiversity and species richness by location on both protected and unprotected reefs around Chumbe Island.

## Habitat Preference

By comparing each species' realized niches, a better understanding of fundamental niche and habitat preferences of each species can be reached. Most species displayed discernable preference to specific habitats, and Chi-Squared Test of Independence indicated that significant relationships existed between maturity and habitat preference in *P. laevis*, *C. argus*, and *A. rogae*. Higher abundances of all species were observed on the slope, though *C. argus* and *A.*

*leucogrammicus* were present in almost equal abundances between the slope and non-sloping environments (the western backreef and eastern OAA). Large species and species with the potential to grow large (*P. laevis* and *E. fuscoguttatus*) and *C. miniata* were seen more commonly on dense coral cover, and *C. argus*, *A. rogae*, and *A. leucogrammicus* exhibited no preference between substrates (Figure 6). Preference to depth was less apparent, though all species except *C. miniata* were most commonly seen in less than 10 meters of water. Only *A. rogae* and *C. miniata* were observed at depths greater than 12 feet. *P. laevis*, *C. miniata*, and *E. fuscoguttatus* frequented the middle slope, *A. rogae* and *A. leucogrammicus* were observed in equal abundances in sloping and no-sloping environments, and *C. argus* heavily favored non-sloping reefs (Figure 6). *A. rogae*, *C. argus*, and *P. laevis* were observed in every habitat category on the western reef (except at depths greater than 12 feet) in relatively even distribution.

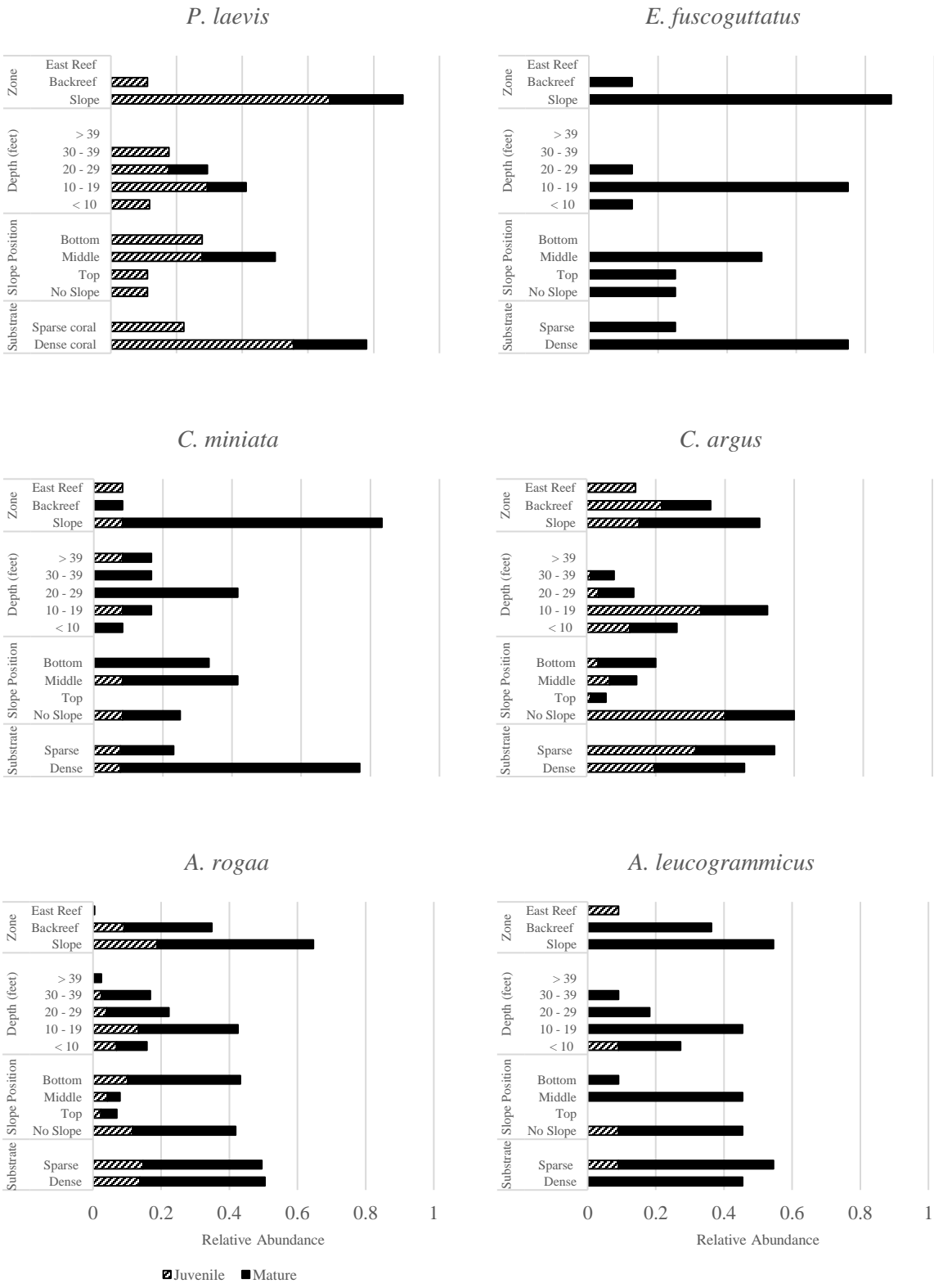


Figure 6. Habitat preferences of juvenile and mature individuals of each species according to the relative abundance of each age class observed in each qualifier. X-axis represents abundance relative to total population count on both the western and eastern reef. Distinctions between juvenile and mature individuals made according to parameters listed in Figure 1.

## Age Distribution

Distribution of mature and juvenile individuals differed significantly between species. Very few mature *P. laevis* and very few juvenile *A. leucogrammicus* and *C. miniata* were recorded, and no juvenile *E. fuscoguttatus* were observed, so it is impossible to determine whether differences in habitat preference exist between age groups. Comparatively, populations of *A. rogaea* and *C. argus* were more evenly distributed across maturities, and juvenile habitat preference mirrored that of the adult individuals. More juvenile *P. laevis* were observed than mature individuals, which is an age distribution unique to this species.

## Comparison of Abundance, Biomass, and Biodiversity Between 2014 and 2018

A comparison of abundance, biomass density, and biodiversity between 2014 and 2018 indicated a change in population composition over the past four years. Relative species abundance has decreased for all species, except *A. rogaea*, which exhibits an almost 100% increase in abundance between 2014 and 2018 (Figure 7). In conjunction with a spike in relative abundance, *A. rogaea* experienced a significant increase in biomass density. Relative abundance of *C. miniata*, *A. leucogrammicus*, and *E. fuscoguttatus* all decreased minimally and stayed

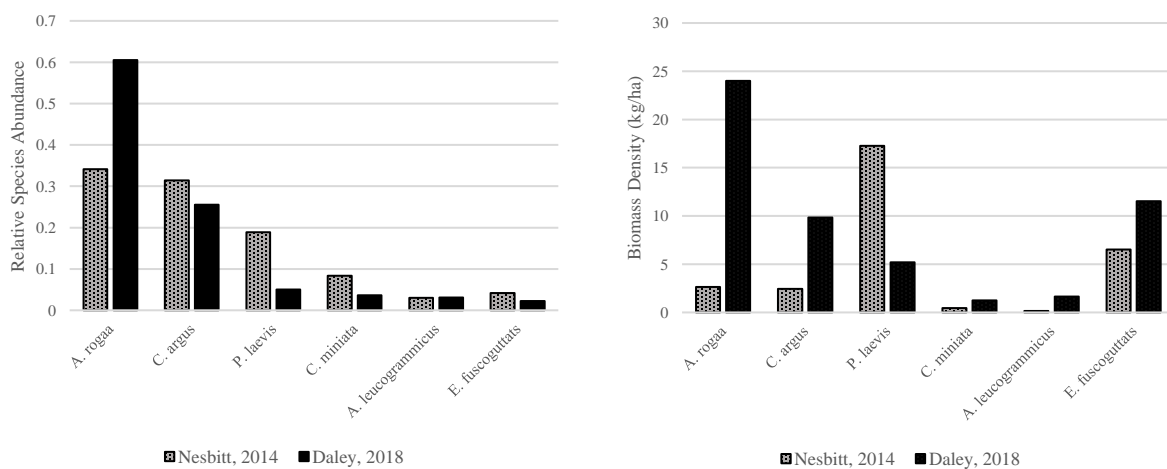


Figure 7. Comparison of relative species abundance and biomass density between *Serranid* surveys conducted in 2014 and 2018 around Chumbe Island. Biomass density calculated over 12.5 hectares of coral reef within the NTA. Individual fish masses calculated according to length-weight relationships offered in “Biomass Calculator” Excel sheet available at Chumbe Office, Stonetown, Zanzibar. 2014 biomass calculated based on averaged weight categories.

below 0.1, but biomass density of all three species has increased since 2014. While populations of *C. argus* experienced minimal decreases in relative abundance and managed to generate an increase in biomass, the noticeable declines observed in already low abundance of *P. laevis* resulted in a steep decrease in biomass density.

These shifts in abundance are reflected in a decrease in biodiversity of *Serranid* populations from 1.49 in 2014 to 1.09 in 2018, according to the Shannon-Wiener Index. All species except *A. rogae* experienced a decrease in relative abundance, and therefore the population is less even and biodiverse. Though all species were represented in both years, evenness decreased significantly, as indicated by the comparatively steep and concave appearance of the Whittaker plot in 2018 (Figure 8).

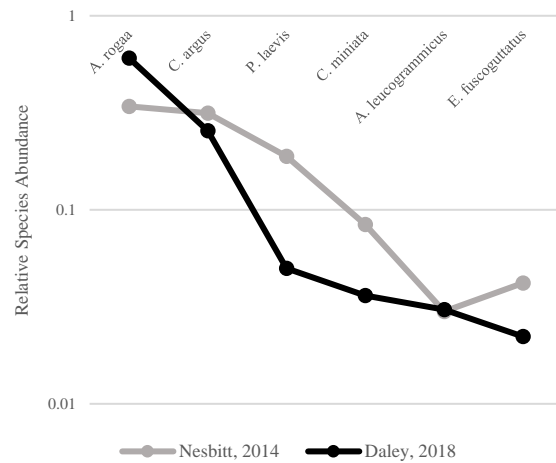


Figure 8. Whittaker plot of relative species abundance between 2014 and 2018.

### Longitudinal Population Comparison within MPA

According to data gathered by CHICOP, both population and biomass density longitudinally increased from 2006 when monitoring began, though densities fluctuated over time, which is to be expected in a natural system. Values calculated for Nesbitt and Daley differ noticeably from those calculated for CHICOP, yet the two focused surveys are consistent to one another and exhibit increases in population and biomass density between 2014 and 2018, in keeping with the general trend captured by CHICOP. Moreover, the increase in population and biomass density between Nesbitt and Daley’s data is consistent, while CHICOP’s data exhibit an increase in population density and a decrease in biomass density between 2014 and 2018 (Figure

9). CHICOP conducts its *Serranid* surveys in the same place every year on five transects in between the zones this study defines as ‘north central’ and ‘south central.’ The disparity between the densities based on CHICOP’s data and those based on Nesbitt and Daley’s data are likely due to this difference in survey methods, as CHICOP’s data only captures the population density in the central regions, which have been shown to be inhabited by larger individuals (Figure 4b) while maintaining relative abundances that are comparable to other zones (Figure 3b). Thus, the high population density and low average biomass density calculated based on Nesbitt and Daley’s surveys are accounted for by differences in survey scale and location.

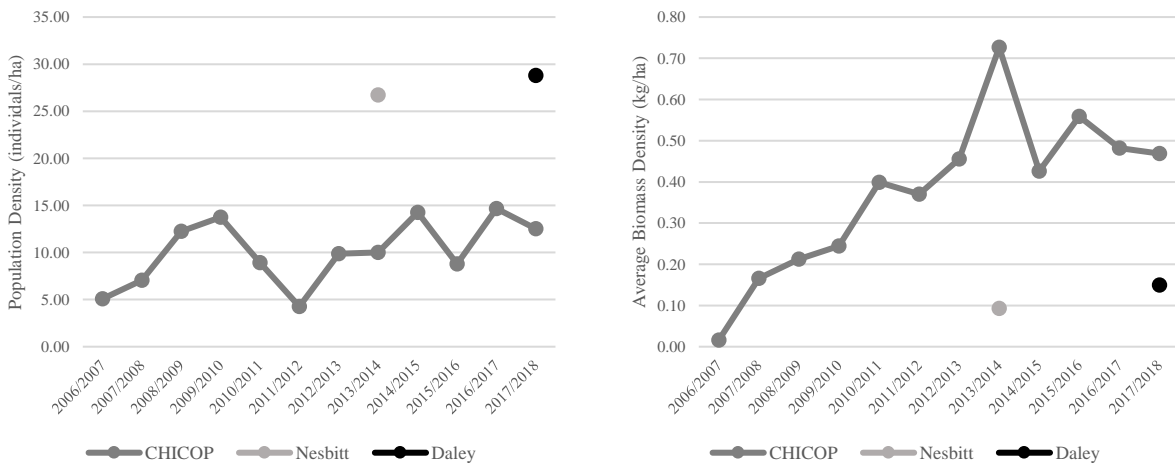


Figure 9. Comparison of population density and average biomass density within the MPA between CHICOP’s general long-term monitoring program and Nesbitt and Daley’s focused surveys. Densities calculated over 12.5 hectares (the total area of coral reef within the MPA), and CHICOP’s data calculated out of 7.5 hectares (total area surveyed). Individual fish masses calculated according to length-weight relationships offered in “Biomass Calculator” Excel sheet available at Chumbe Office, Stonetown, Zanzibar.

Average biomass per individual, which effectively combines measurements of population and biomass density, corroborated the relationship between increased population and biomass density. Biomass per individual increased consistently until 2013/2014 and then fluctuated (Figure 10). Similar to patterns observed in population and average biomass density, values for average biomass per individual calculated for Nesbitt and Daley were lower than those calculated for CHICOP in 2014 and 2018, but they were consistent to one another and indicate



an increase in average biomass per individual which is in keeping with the general trend exhibited by CHICOP's data (Figure 10).

CHICOP's data, however, displayed a decrease in average biomass per individual between 2014 and 2018 and did not corroborate the

increase suggested by Nesbitt and Daley.

This incongruency of data was likely due, again, to the difference in survey methods. It is possible, due to CHICOP's smaller survey

area, that changes in average biomass per individual were not representative of the

entire reef and therefore did not exhibit the same trends as Nesbitt and Daley.

same trends as Nesbitt and Daley.

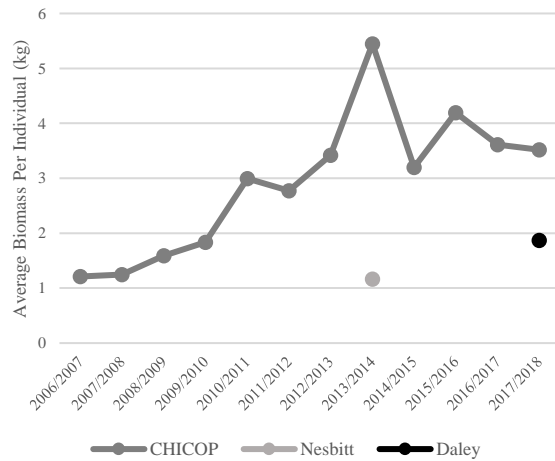


Figure 10. Comparison of average biomass per individual (kg) within the MPA between CHICOP's general long-term monitoring program and Nesbitt and Daley's focused surveys.

### Longitudinal Population Comparison outside MPA

Though Nesbitt did not survey outside the MPA, CHICOP conducts long-term monitoring outside the NTA on neighboring Tele reef, allowing for an assessment of *Serranid* populations in OAA's over time and a comparison of populations between sites. Tele exhibited a decrease in abundance between 2008 and 2018 and reached a minimum in 2017/2018, but average biomass density remained relatively high and decreased only slightly between 2016/2017 and 2017/2018 (Figure 11). Chumbe's eastern reef exhibited a total population density higher than was ever observed on Tele, but supported an average biomass density that exceeded Tele only during the first two monitoring seasons (2008/2009 and 2009/2010).

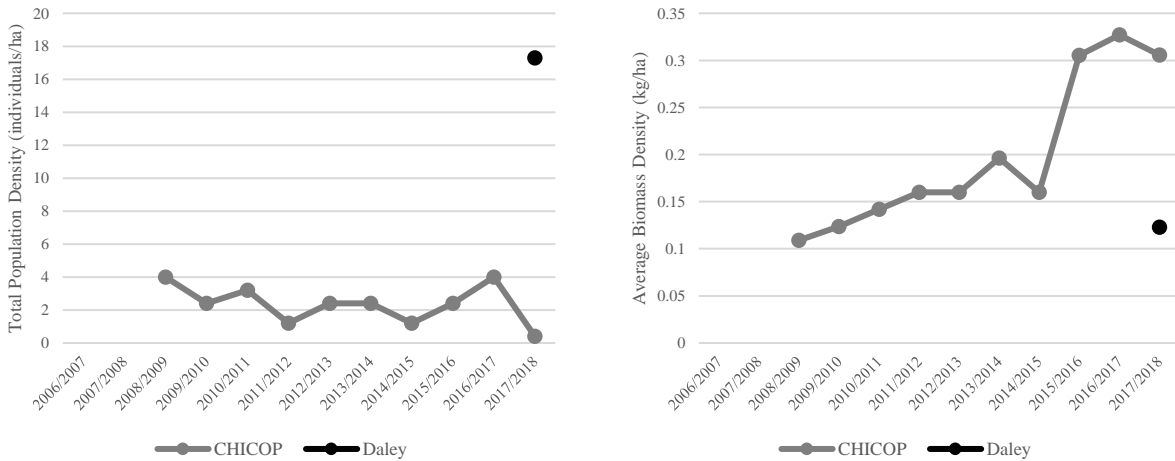


Figure 11. Comparison of population density and average biomass density in fished areas near Chumbe Island Coral Park. Data from CHICOP’s general long-term monitoring of Tele reef and Daley’s focused surveys of the reef immediately east of Chumbe Island are assessed. Densities calculated over 2.5 and 0.925 hectares, respectively. Individual fish masses calculated according to length-weight relationships offered in “Biomass Calculator” Excel sheet available at Chumbe Office, Stonetown, Zanzibar.

Indeed, this inverse relationship between population and biomass density indicated that though the *Serranid* population on Tele was decreasing, it still maintained a large biomass because the average biomass per individual was consistently high (Figure 12). Similarly, though Chumbe’s eastern reef exhibited a higher population density per hectare, it supported a biomass that is small compared to Tele’s because the average biomass per individual was low (Figure 12).

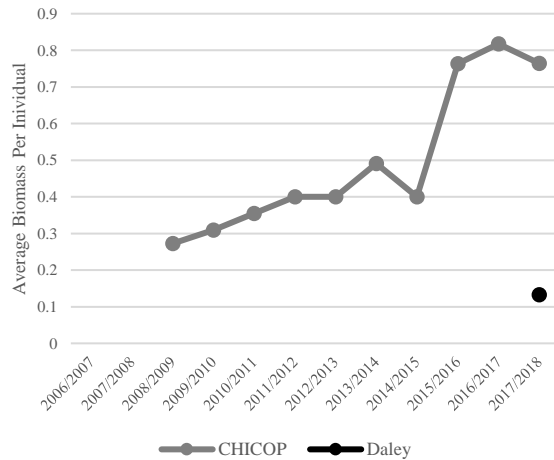


Figure 12. Comparison of average biomass per individual (kg) in OAA’s between CHICOP’s general long-term monitoring on Tele reef and Daley’s surveys of Chumbe’s eastern reef.

## DISCUSSION

### Population Composition and Distribution

All six species exhibited consistently lower relative abundance and biomass density on the backreef than the western slope. This phenomenon was also observed by Nesbitt in 2014 and

suggests that most *Serranid* species prefer deeper reef slopes to shallower, non-sloping environments (Chiappone et al. 2000; Nesbitt and Richmond 2015). More variation in abundance and biomass density existed between zones on the slope, while *Serranid* populations remained continuously low across the backreef, indicating that no preference is given to specific backreef locations, which is likely due to the fact that the backreef is structurally homogenous across zones. Relative abundance and biomass density generally increased for all species on the north and south central slope, indicating that the continuity and complex reef structure of the central slopes attract more and larger individuals than other locations (figures 3 and 4) (García-Charton et al. 2001).

As a region, the backreef supported a lower level of biodiversity than the slope according to the Shannon-Wiener Index. This fact was congruent with the decreased biomass density and relative abundance of all species in that region. The north was the only zone in which the biodiversity of the slope exceeded that of the backreef, and this discrepancy was likely due to the fact that the northern backreef extends further north than the slope, thereby providing larger areas of suitable habitat. Aside from the northern backreef, the central zones of each region demonstrated higher levels of biodiversity according to the Shannon-Wiener Index than adjacent locations in the same region, which substantiates the hypothesis that all six *Serranid* species favor the central slope (García-Charton et al. 2001). Interestingly, though measurements of total abundance and biomass density on the eastern OAA were far below those of the western NTA, the biodiversity of the OAA exceeded that of the northern slope and rivaled those of the southern and northern central and southern backreef. The similarity between the composition of these populations and those on the eastern reef and the stark difference in total biomass density and abundance brings effectiveness of spillover into question.

Perhaps abundance and density are not enough within the MPA to achieve significant spillover into abutting OAA's (Hackradt et al. 2014), or the population within the NTA are not stable or complex enough to support sustainable spillover (Perez-Ruzafa et al. 2008, as cited in Hackradt et al. 2014; Russ and Alaca 2011). Based on the abundance of *A. rogae* and *C. argus*, one might expect these populations have approached carrying capacity and would be most commonly observed outside the bounds of the NTA (Perez-Ruzafa et al. 2008). This is true of *C. argus* because of the similarity of reef structure between the eastern OAA to the NTA backreef, but only one *A. rogae* was observed on the eastern open access reef. This is likely due to the shallowness and discontinuity of the habitat and to the fact that *A. rogae* is especially vulnerable to overfishing because of its tendency to swim away from reef shelter and freely in the water column. Thus, not only the habitat structure, but also the distribution and intensity of fishing efforts significantly impact manifestations of spillover (Hackradt et al. 2014). Accordingly, the decreased abundance and biomass density observed in the zones adjacent to the edge of the MPA can be attributed simply to lower levels of habitat continuity, complexity, and appropriateness rather than a gradient of spillover (Goñi et al. 2008, Stenzenmüller et al. 2008, and Forcada et al. 2009, as cited in Hackradt et al. 2014).

The low relative abundance and high biomass density of *E. fuscoguttatus* and *P. laevis* across all locations can be explained by the rarity and large maximum size of these species. These species exhibited specific preference to the central slope, and *E. fuscoguttatus* displayed particular preference to the north central slope where coral begins to become sparse (Nesbitt 2015). Thus, the fact that the biomass of *A. rogae* exceeded that of both *P. laevis* and *E. fuscoguttatus* (except on the northern slope) despite its relatively small maximum length speaks to the scale of its relative abundance (63%) across all eight locations (figures 3a and 4a). The low

abundances and biomass densities of *E. fuscoguttatus*, *P. laevis*, *C. miniata*, and *A. leucogrammicus* suggested a patchy distribution and highly specified fundamental niche that was likely not adequately assessed by the survey methods employed by this study (Unsworth et al. 2007). Similarly, the biomass density of *C. argus* was surprisingly high given its small maximum length, which is likely attributable to the fact that its relative abundance is consistently second to that of *A. rogaea*. Despite this, the relative abundance of *C. argus* was only about a third that of *A. rogaea*, and the remaining four species failed to approach even half of the relative abundance of *C. argus* (Figure 3a). The abundance of *A. rogaea* in all locations indicated that the species has little to no habitat preference and implies a broad fundamental niche and unique willingness to venture away from the structure of the reef (Nesbitt 2015). It is apparent that *A. rogaea* dominated both Chumbe's western backreef and slope, followed at a considerable distance by *C. argus* and that the distribution of these six species was not even (figures 3 and 4), which is attributable overarchingly to the fact that small MPA's do not protect all species equally. Although Chumbe meets four of the five qualifications for successful conservation via an MPA as listed by Edgar et al., it does not meet the minimum size (100 km<sup>2</sup>) cited to maximize marine park benefits (Edgar et al. 2014). Small NTA's fail to adequately protect large *Serranid* species and species that participate in spawning aggregations (Unsworth et al. 2007) and render rare species with specific habitat preferences especially vulnerable to density dependent intra and interspecific competition compared to more robust species that are able to thrive in more than one habitat or microhabitat (Donaldson 2000).

### **Habitat Preference and Age Distribution**

The distribution of *A. rogaea*, *C. argus*, and *P. laevis* revealed significant specific habitat preferences between species. A significant relationship between maturity and slope and depth of observed *A. rogaea* was determined according to Chi-Squared Independence Tests. While *A.*

*roga* was observed in all habitat categories, the species indicated preference to the bottom of the slope and non-sloping environments and depths between 0 and 29 feet. Juveniles were observed in all habitat categories (except at depths greater than 12 meters) in relative abundance proportionate to those exhibited by mature individuals, indicating that the reef within the NTA was suitable to this species at all life stages and that the age distribution of this species was healthy (Figure 6). The only other species that exhibited a healthy age distribution is *C. argus*, though there was a more distinct difference in preferred habitat between juvenile and mature individuals. A significant relationship between maturity of *C. argus* and depth, slope, and region was observed, according to Chi-Squared Independence Tests. Juvenile *C. argus* were more frequently observed on the backreef, non-sloping environments, and mid slope. No significant relationship between age and substrate or apparent preference for substrate type existed for either *A. roga* and *C. argus* (Figure 6). The apparent lack of preference for substrate, minimal observed preference to region, and noticeable preference to depths less than 10 meters speaks to Chumbe Island Coral Park's ability to support high abundances and biomass densities of these species. *P. laevis*, *E. fuscoguttatus*, and *C. miniata* displayed high relative abundances on the slope and areas of dense coral cover, which corroborates Nesbitt's observations that their habitat and range are limited and highly specified (Nesbitt, 2015), and their preference for these qualities explains the spike in relative abundance and biomass density in central sloping regions and on the slope in general (figures 3 and 4). Indeed, the central slopes possess increased coral complexity and density as well as a wealth of vertical niches not offered by more shallow and non-sloping locations, and this richness and variety predisposes the north and south central slope to higher abundances and biodiversity, which was reflected by the more specified habitat preferences of the species that occupy it (García-Charton et al. 2001).

Few to no juvenile *E. fuscoguttatus*, *C. miniata*, and *A. leucogrammicus* were observed, and therefore, no representative conclusions regarding difference in habitat preference between maturities can be drawn. It is not surprising that few *A. leucogrammicus* were identified in survey conducted by both Nesbitt and Daley because they are notoriously furtive and generally uncommon (Hiatt and Strasburg 1960; Nesbitt 2015; Unsworth et al. 2007). However, the absence of juveniles indicated an imbalance in age distribution within these species and suggested that larval import and juvenile migration into the MPA have been compromised either by these species contribution to exploited spawning aggregations (Friedlander et al. 2003; Sadovy et al. 2005; Sadovy de Mitcheson et al. 2015), lack of connectivity between appropriate habitat (Fenberg et al. 2012), or the absence of other healthy ecosystems to contribute to larval export and from which developed individuals might migrate (Leis et al. 1991, as cited in García-Charton et al. 2000). Such imbalances in maturity have the potential to negatively impact reproductive health and generate a positive feedback loop that ultimately results in population collapse (Hackradt et al. 2014).

Conversely, populations of *P. laevis* were dominated by juveniles, which exhibit a broad realized niche. Too few mature individuals were observed to determine representative differences in habitat preference, but the fact that *P. laevis* was the only species whose population was dominated by juveniles indicates that it is being impacted by different variables or that the same variables effect this species in a different way. While the habitat preference of juvenile *P. laevis* was apparently broad, mature individuals most likely favor more specific habitats due to their large maximum size (Nesbitt 2015), and their scarcity, as well as that of *E. fuscoguttatus*, may be attributed to the slow growth rate and limited spawning period of large species (Sadovy 1994, as cited in Chiappone et al. 2000). Moreover, it is important to note that

while the population of *P. laevis* was dominated by juveniles, the population as a whole was still relatively small compared to those of *A. rogaea* and *C. argus* and exhibited a startling decrease in relative abundance and biomass densities since 2014 (Figure 7). The scarcity of mature *P. laevis* and the general decline in population health was especially significant considering the species' status as "vulnerable" according to the IUCN (Figure 1) and warrants further attention.

The relationship between wide habitat range, relatively small maximum size, and high relative abundance and biomass density of *A. rogaea* and *C. argus* further emphasizes the inequity in protection generated by small MPA's. These findings suggest that populations of species with restricted habitat preferences benefit minimally from small protected areas, and this unfortunate reality is compounded by the fact that many rare species must compete not only amongst each other for resources and habitat, but also with dominant species that are able to inhabit less specialized niches.

### **Regime Shift Between 2014 and 2018**

With this in mind, the increase in biomass density within the MPA for all species except *P. laevis* emphasizes further the need to specifically investigate population composition and distribution of this species both around Chumbe Island in order to best attune management toward conserving this vulnerable species and on other reefs in the Zanzibar archipelago and to develop best management practices going forward (Figure 7). While the biomass density generally increased between 2014 and 2018 in keeping with the trend extrapolated from CHICOP's long term management research (Figure 9), relative abundance of all species except *A. rogaea* decreased in the same time interval (Figure 7). *A. rogaea* held the highest relative abundance in 2014 by only 0.03 and supported only the third highest biomass density. Moreover, the intense decrease both in biodiversity and in evenness as articulated by the Whittaker plot in conjunction with shocking increase in relative abundance and biomass density suggested that an



ecological regime shift is occurring on Chumbe's western reef. A mass coral bleaching event occurred in 2016 between the two surveys and likely caused a disturbance shocking enough to alter not only the health of the coral, but the populations of grouper that depend heavily on specific coral habitats (Cheal et al. 2008; Hackradt et al. 2014). Thus, *Serranid* species that exhibited broader fundamental niches and less specific habitat preferences (*A. rogae* and *C. argus*) flourished and experienced rapid surges in abundance that caused the ecosystem to lose biodiversity and become even more unstable (Myers et al. 2007 and Myers and Worm 2003, as cited in Russ and Alaca 2011). In the face of global climate change, even populations of coral dwelling groupers protected within MPA's are vulnerable to decline as their highly specialized and delicate habitat collapse (Berger and Possingham 2008; Hackradt et al. 2014). Thus, a comprehensive understanding of each species fundamental niche is paramount to successful management of *Serranids* and other reef dwelling species as the static protection of even immensely successful marine protected areas like CHICOP proves insufficient (Berger and Possingham 2008; Friedlander et al. 2003).

### **Longitudinal Changes in *Serranid* Populations**

Population and biomass density and average biomass per individual calculated for Nesbitt and Daley diverged from those calculated by CHICOP because of the disparity in survey methods - CHICOP surveys 15 transects in five groups of three transects surveyed end to end parallel to the slope in the central area of the MPA, while Nesbitt and Daley conducted surveys of the entire length of the slope and backreef. Population density calculated by Nesbitt and Daley is higher than that based on CHICOP's data because more and smaller individuals were observed over numerous surveys of the entire reef than were observed in 15 transects, but the individuals observed by CHICOP possessed a higher average biomass than those observed by Nesbitt and Daley because the surveys were conducted in only center of the reef, which this study indicates

to have the highest biomass density and relative species abundance of the entire reef (figures 3 and 4). Comparison between these points is valuable, none the less, in contextualizing the trends suggested by CHICOP's data in comparison to values calculated for the year using a different method in a larger study site. CHICOP, Nesbitt, and Daley all report an increase in total population density, but only CHICOP reports a diminished biomass density and average biomass per individual between 2014 and 2018, which suggests that the decline in *Serranid* size is localized to the central regions of the reef (figures 9 and 10).

The hypothesis that Chumbe Island Coral Park is experiencing a regime shift is corroborated by the fact that grouper biomass and population density has increased since monitoring began in 2006 (Figure 9). This increase suggests that the ecosystem is not at a point of explicit decline and that it is rather at an intermediate point of degradation of biodiversity that will ultimately result in complete ecosystem collapse (Hackrad et al. 2014). These increases in both biomass and population density as well as average individual biomass also speak to CHICOP's successful management of a highly vulnerable and valuable ecosystem. Population density appears to increase minimally compared to biomass density, which is attributable to the increase in average biomass per individual since 2006 and the apparent longevity of individuals that reside within the NTA.

Increases in population density and biomass per individual of the whole reef (as calculated according to Nesbitt and Daley) indicated that in the past four years, the grouper population within Chumbe's MPA has increased by a total of approximately 2 individuals per hectare and individual biomass has increased by an average of nearly 1 kilogram per individual (figures 9 and 10). These metrics are underwhelming and, based on the difference in population

composition between 2014 and 2018, are likely only accentuating the spike in the abundance and biomass density of *A. rogae* than increases in collective *Serranid* populations (Figure 7).

### **Open Access Areas and Spillover**

In keeping with studies worldwide, both open access areas supported lower densities than the NTA (Hackradt et al. 2014; Unsworth et al. 2007; Fenberg et al. 2012; Edgar et al. 2014). Tele supported a high biomass density and low total population density compared to Chumbe's eastern reef, which was potentially owing to the eastern reef's proximity to the MPA (Perez-Ruzafa et al. 2008; Chapman et al. 1999, as cited in Hackradt et al. 2014). Though Tele was not surveyed for the sake of this study, the decreased biomass observed on the east reef is likely attributable to its shallowness, structural simplicity, patchiness, and general small scale (Goñi et al. 2008, Stenzenmüller et al. 2008, and Forcada et al. 2009, as cited in Hackradt et al. 2014). While less than 1 hectare of Chumbe's eastern reef was surveyed, Chumbe's study site on Tele includes approximately 2.5 hectares, which speaks to the reefs scale and, as a result, the larger quantities of biomass it was able to support compared to Chumbe's eastern reef. Both reefs, however, are most likely experiencing overfishing, as the population density of the OAA was only 60% of that in the NTA and the average individual biomass within the NTA was nearly 6 times that of the eastern reef (Ferry and Kohler 1987, PDT 1990, and Beets and Friedlander 1992, as cited in Chiappone et al. 2000; Hackradt et al. 2014). Fishing is not the only factor that is influencing populations outside the NTA, and based on brief visual assessments while surveying, the aforementioned inappropriateness of the habitat also contributed to the small population and individual size of groupers on Chumbe's eastern reef (García-Charton et al. 2001; Hackradt et al. 2014).

## CONCLUSION

### Population Imbalance in OAA's

Assessment of grouper population within the context of their preferred habitat allows more detailed insight into the localized reasons behind population composition and distribution. Interestingly, many of the backreef locations resemble the eastern open access area with regard to biodiversity, but the OAA's comparatively low population and biomass density indicates that the shallow, discontinuous, and fished reef exhibits poor health of grouper populations compared to MPA. Thus, the relatively small *Serranid* populations on two nearby open access reefs suggest that the ecosystems are unable to sustain healthy populations due to the stress of extractive fishing practices, the unsuitable coral reef structure, or to the fact the MPA does not support a healthy enough population to result in spillover into adjacent open access fishing areas.

### Wide Range and Dominance

This hypothesis is corroborated by the decline in health exhibited by *Serranid* populations within the MPA. The dominance of *A. rogae* and *C. argus* was attributable to the fact that their fundamental niche was less specific than that of the other four species. Moreover, the age distribution of these two species was balanced and indicated healthy reproductive capacity, while populations of *C. miniata*, *A. fuscoguttatus*, and *A. leucogrammicus* consisted of mostly adults and those of *P. laevis* were composed primarily of juvenile individuals (Claudet et al. 2008; Fenberg et al. 2012; Garcia-Charton et al. 2008; Lester et al. 2009 as cited in Hackradt et al. 2014). Both this study and that conducted by Nesbitt noted that *C. miniata*, *A. fuscoguttatus*, *P. laevis*, and *A. leucogrammicus* exhibited highly specific habitat preferences (Nesbitt 2015). Overarchingly, in keeping with Nesbitt's findings, all species exhibited preference to the slope where it is most steep and complex in the central zones (Richmond and

Nesbitt 2015). High abundance and biomass across locations, wide range and unspecified realized niche, and balanced age composition suggest that populations of *A. rogae* and *C. argus* are healthy and thriving. Decreased abundance and biomass, high site fidelity and specified habitat, and unstable age composition of the remaining four species indicate that these populations are in decline.

### ***Serranid* Population Health and Coral Reefs**

*Serranids* are considered an indicator species for a reason, and the overall health of the reef within CHICOP can be extrapolated based on the composition and distribution of groupers on the reef. Similarly, it can be deduced that declines in coral health will result in declines in the health of grouper populations. With this relationship in mind, the immensely degrading impact of the 2016 mass bleaching event in addition to consistent, more gradual destruction of coral ecosystems via rising sea levels and temperatures, it should not be surprising that compositions of *Serranid* populations are experiencing regime shifts in favor of species that are able to adapt and accommodate intense habitat disturbances.

Though the imbalance in biodiversity and evenness between locations and relationship between coral reef health and *Serranid* populations was evident when the population is assessed spatially and with habitat appropriateness in mind, these insights were not reflected by rapid assessments of total abundance and biomass. Assessments of abundance and biomass are easy, quick, and generally suggest population growth and health within MPA's (Claudet et al. 2008, Fenberg et al. 2012, Garcia-Charton et al. 2008, and Lester et al. 2009, as cited in Hackradt et al. 2014; Fenburg et al. 2012; Hackradt et al. 2014; Russ and Alaca 2003; Unsworth et al. 2007). However, the results of this study indicated that these measurements did not appropriately capture population health. This study brings to the forefront the impending threats that climate

change poses to Chumbe's *Serranid* populations, coral reef ecosystems, and other marine ecosystems and communities that depend upon them. Moreover, it becomes abundantly clear that effective management strategies must do more than impose stagnant boundaries on already immensely dynamic marine environments that are only changing more rapidly.

### **Management Recommendations**

Increased monitoring efforts should be made in order to better understand already threatened species, such as *P. laevis*, that are especially vulnerable to the impacts of climate change in order to best amend management strategies to support their continued persistence and eventual recovery. Little is known about larval export dynamics and spawning aggregations of groupers, and more studies and increased understanding of these phenomena would greatly benefit large scale conservation of spatially isolated but ecologically connected areas (Fenberg et al. 2012; Sadovy et al. 2005; Unsworth et al. 2007). Additionally, increased small-scale protection of specific, significant, and spatially proximal ecosystems might compound the benefits generated by randomly aggregated and similarly sized MPA's. Alternately, limitations on fishing effort or season may prove effective in meeting the needs of both local fisher people and the impacted coral reef ecosystem (Sadovy et al. 2005). These management changes of this scale prove difficult to achieve in a region of the world that benefits from relatively little research and whose economies depend so heavily on the accessibility of marine resources. However, compromises and decisions must be made in order to conserve marine ecosystems, protect the ecosystem services they offer coastal communities, and safeguard biodiversity.

## WORKS CITED

- Berger, M. and Possingham H. P. (2008). Environmental factors that influence the distribution of coral reef fishes:: modeling occurrence data for broad-scale conservation and management. *Marine Ecology Progress Series*. 361, 1-13.
- Buxton, C. D., Kharmann, K., Kearney, R., and Gardner, C. (2014). When Is Spillover from Marine Reserves Likely to Benefit Fisheries? *PLoS ONE*. 9(9).
- Cabanban, A.S., Kulbicki, M., Fennessy, S., Heemstra, P.C., and Yeeting, B. (2008). *Cephalopholis miniata*. *The IUCN Red List of Threatened Species*: e.T132732A3435490. Downloaded on 31 October 2018.
- Cheal, A. J., Shaun, K. W., Emslie, M. J., Dolman, A. M., and Sweatman, H. (2008). Responses of reef fish communities to coral declines on the Great Barrier Reef. *Marine Ecology Progress Series*. 372, 211-223.
- Chiappone, M., Sluka, R., and Sullivan Sealy, K. (2000). Groupers (Pisces: Serranidae) in fished and protected areas of the Florida Keys, Bahamas and northern Caribbean. *Marine Ecology Progress Series*, 198: 261-272.
- CHICOP (2017). 3rd Ten Year Management Plan for Chumbe Island Coral Park.
- Choat, J.H., Liu, M., Craig, M.T., Yeeting, B., and Robinson, J. (2008). *Plectropomus laevis*. *The IUCN Red List of Threatened Species*: e.T64412A12779966. Downloaded on 31 October 2018.
- Chumbe Island Coral Park Limited. <http://www.chumbeisland.com/nature-reserve/>. Accessed November 6 2018. “Project History” and “Educational Resources.”
- Claudet, J. , Osenberg, C. W., Benedetti-Cecchi, L. , Domenici, P. , García-Charton, J. , Pérez-Ruzafa, Á. , Badalamenti, F. , Bayle-Sempere, J. , Brito, A. , Bulleri, F. , Culioli, J. , Dimech, M. , Falcón, J. M., Guala, I. , Milazzo, M. , Sánchez-Meca, J. , Somerfield, P. J., Stobart, B. , Vandeperre, F. , Valle, C. and Planes, S. (2008). Marine reserves: size and age do matter. *Ecology Letters*, 11: 481-489.
- Cornish, A. (Grouper & Wrasse Specialist Group) (2004). *Epinephelus fuscoguttatus*. *The IUCN Red List of Threatened Species*. Downloaded on 31 October 2018.
- Debelius, H. (1999). *Indian Ocean reef guide: Maldives, Sri Lanka, Thailand, South Africa, Mauritius, Madagascar, East Africa, Seychelles*. Frankfurt: IKAN-Unterwasserearchiv.
- Donaldson, T. J. (2002). Habitat association and depth distribution of two sympatric groupers of the genus *Cephalopholis* (Serranidae: Epinephelinae). *Ichthyological Research*. 49: 191-193.
- Edgar, G. J., Stuart-Smith, R. D., Willis, T. J., Kininmonth, S., Baker, S. C., Banks, S., Barrett, N. S., Becerro, M. A., Bernard, A. T. F., Berkhout, J., Buxton, C. D., Campbell, S. J., Cooper, A.

T., Davey, M., Edgar, S. C., Günter, F., Galván, D. E., Irigoyen, A. J., Kushner, D. J., Moura, R., Parnell, P. E., Shears, N. T., Soler, G., Strain, E. M. A., and Thomson, R. J. (2014). *Nature* 506: 216-220.

English, S., Wilkinson, C., and Baker, V. (Eds.) (1997). Survey Manual for Tropical Marine Resources (68-80). Australian Institute of Marine Science.

Fenberg PB, Caselle JE, Claudet J, Clemence M, Gaines SD, et al. (2012). The science of European marine reserves: Status, efficacy, and future needs. *Marine Policy* 36(5): 1012–1021.

Friedlander, A., Sladek Nowlis, J., Sanchez, J. A., Appeldoorn, R., Usseglio, P., McCormick, C., Bejarano, S., and Mitchel-Chui, A. (2003). Designing Effective Marine Protected Areas in Seaflower Biosphere Reserve, Colombia Based on Biological and Sociological Information. *Conservation Biology* 17(6): 1769-1784.

García-Charton, J. & Pérez-Ruzafa, Á. Marine Biology (2001). Spatial pattern and the habitat structure of a Mediterranean rocky reef fish local assemblage. *Marine Biology* 138(5) 917-934.

Hackradt CW, García-Charton JA, Harmelin-Vivien M, Pérez-Ruzafa Á, Le Diréach L, Bayle-Sempere J, et al. (2014). Response of Rocky Reef Top Predators (Serranidae: Epinephelinae) in and Around Marine Protected Areas in the Western Mediterranean Sea. *PLoS ONE* 9(6): e98206.

Heemstra, P.C., Pollard, D., Samoilys, M., Yeeting, B., and Choat, J.H. (2008). *Anyperodon leucogrammicus*. *The IUCN Red List of Threatened Species*: e.T132787A3451337. Downloaded on 31 October 2018.

Heemstra, P.C., Samoilys, M., Cornish, A., and Cabanban, A.S. (2008). *Aethaloperca rogaa*. *The IUCN Red List of Threatened Species*: e.T132814A3458443. Downloaded on 31 October 2018.

Hiatt, R. W. and Strasburg, D. W. (1960). Ecological Relationships of the Fish Fauna on Coral Reefs of the Marshall Islands. *Ecological Monographs* 30(1), 65-127.

Horrill, J. C., Darwall, W. R. T., and Ngolie, M. (1996). Development of a Marine Protected Area: Mafia Island, Tanzania. *Royal Swedish Academy of Sciences*. 25(1), 50-57.

Kelly, J. and Ruhl, E. (2011). Are Marine Reserves Effective in Preserving Coral Reef Ecosystems? School for International Training, Zanzibar, Tanzania.

Knudby, A., LeDrew, E., and Brenning A. (2010). Predictive mapping of reef fish species richness, diversity and biomass in Zanzibar using IKONOS imagery and machine-learning techniques. *Remote Sensing of Environment*. 114(6), 1230-1241.

Knudby, A. and Nordlund, L. (2009). Remote sensing of seagrasses in a patchy multi-species environment. *International Journal of Remote Sensing*. 32(8), 2227-2224.



Levin, P. S. and Grimes, B. C. (2002). Coral Reef Fishes: Dynamics and Diversity in a Complex Ecosystem. In Sale, P. F. (Ed), *Reef Fish Ecology and Grouper Conservation and Management* (377-389). San Diego, CA: Academic Press.

Leyendecker, H. (2017). Chumbe Island Coral Park, Zanzibar, Tanzania Underwater Photo-Guide Volume 1 - Reef Fish, Edition 2017.

Lieske, E. and Myers, R. (1996). Coral Reef Fishes: Caribbean, Indian Ocean, and Pacific Ocean, Including the Red Sea. (24-30). Princeton, NJ: Princeton University Press.

Liu, M. and Choat J. H. (2008). *Cephalopholis argus*. *The IUCN Red List of Threatened Species*: e.T132781A3449833. Downloaded on 31 October 2018.

McClanahan TR, Graham NAJ, Calnan JM, MacNeil MA (2007) .Toward pristine biomass: Reef fish recovery in coral reef marine protected areas in Kenya. *Ecological Applications* 17: 1055–1067.

Nesbitt, K. D. (2014). A Survey of Serranidae Species of Genus *Aethaloperca*, *Anyperodon*, *Cephalopholis*, *Epinephelus*, and *Plectropomus* Chumbe Island. School for International Training, Zanzibar, Tanzania.

Nesbitt, K. D. and Richmond, M. D. (2015). A preliminary assessment of the status and habitat preference of the grouper (Serranidae) population of Chumbe Island Coral Park, Zanzibar, Tanzania. *West Indian Ocean Journal of Marine Science*. 14(1 and 2), 113-116.

Nordlund, L. M., Kloiber, U., Carter, E., and Riedmiller S. (2012). *Chumbe Island Coral Park – governance analysis*. *Marine Policy*. 41, 110-117.

Richmond, M. D. (Ed). (2011). A Field Guide to the Seashores of Eastern Africa and the Western Indian Ocean Islands. (358-361). Sida and WIOMSA.

Russ, G. R. and Alaca, A. C. (2011). Enhanced biodiversity beyond marine resource boundaries: The cup spillith over. *Ecological Applications*. 21(1), 241-250.

Sadovy de Mitcheson, Y. , Craig, M. T., Bertocini, A. A., Carpenter, K. E., Cheung, W. W., Choat, J. H., Cornish, A. S., Fennessy, S. T., Ferreira, B. P., Heemstra, P. C., Liu, M. , Myers, R. F., Pollard, D. A., Rhodes, K. L., Rocha, L. A., Russell, B. C., Samoily, M. A. and Sanciangco, J. (2013). Fishing groupers towards extinction: a global assessment of threats and extinction risks in a billion dollar fishery. *Fish and Fisheries*, 14: 119-136.

Skoglund, S. (2014). Effects of different marine protection levels on fish communities in tropical seagrass beds and coral reefs. Unpublished master's thesis, Stockholms Universitet, Stockholm, Sweden.

Unsworth, Richard K. F., Abigail Powell, Femmy Hukom, and David J. Smith. (2007). The ecology of indo-pacific grouper (serranidae) species and the effects of a small scale no take area

on grouper assemblage, abundance and size frequency distribution. *Marine Biology* 152, no. 2: 243-254

Williamson, D. H., Russ, G. R., and Ayling, A. M. (2004). No-take marine reserves increase abundance and biomass of reef fish on inshore fringing reefs of the Great Barrier Reef. *Environmental Conservation* 31(2): 149-159.

Zeller, D., Stoute, S. L., and Russ, G. R. (2003). Movements of reef fishes across marine reserve boundaries: effects of manipulating density gradient. *Marine Ecology Progress Series*. 254, 269-280.