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Evaluating the Potential Use of Saltwater Quarries in the Florida Keys for the Semi-Wild Mariculture of Caribbean King Crab (*Maguimithrax spinosissimus*)

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EVALUATING THE POTENTIAL USE OF SALTWATER QUARRIES IN THE FLORIDA KEYS FOR THE SEMI-WILD MARICULTURE OF CARIBBEAN KING CRAB (*MAGUIMITHRAX SPINOSISSIMUS*)

by

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ABSTRACT

EVALUATING THE POTENTIAL USE OF SALTWATER QUARRIES IN THE FLORIDA KEYS FOR THE SEMI-WILD MARICULTURE OF CARIBBEAN KING CRAB (*MAGUIMITHRAX SPINOSISSIMUS*)

Samantha Glover
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Advisor: Dr. Mark J. Butler

Coral reef degradation, resulting from anthropogenic factors and natural change, has resulted in drastically reduced coral cover causing a phase shift from coral-dominated to macroalgae-dominated reefs, especially in the Caribbean. An important contributor to this shift is the loss of herbivores due to overfishing and the disease-related reduction of the long-spined sea urchin (*Diadema antillarum*) population during the 1980s. However, recent studies conducted in the Florida Keys have shown that increasing the abundance of herbivorous, native Caribbean king crabs (*Maguimithrax spinosissimus*) on reefs, can reduce the cover of nuisance algae and improve coral recruitment. *Maguimithrax spinosissimus* grazing rates surpass all grazers except the stoplight parrotfish (*Sparisoma viride*) and they consume some types of algae that possess physical and chemical defenses and are avoided by most fish grazers. These characteristics make *M. spinosissimus* an excellent candidate for coral reef restoration, but their low natural density poses a bottleneck to their widespread use. Because of their year-round reproduction, brief larval period, and quick growth, I hypothesize that cultivating *M. spinosissimus* in saltwater quarries would be an economically efficient method for generating sufficient numbers of crabs for coral reef restoration. I surveyed 16 land-locked saltwater quarries in the Florida Keys where *M. spinosissimus* already occurs or could potentially be introduced and compared those data to those of nearshore reefs. The majority of quarries displayed stratification of the water column, with dissolved oxygen and pH decreasing with depth whereas temperature and salinity increased with depth. Structural complexity was greater in coral reef environments, but percent algal cover was higher in quarries presumably due to low abundance of herbivores. There was no difference in the population size structure, fecundity, relative predatory mortality, and relative health (hemolymph protein index) of crabs in quarries when compared to those living on coral reefs. These results indicate that mariculture of *M. spinosissimus* is likely feasible in saltwater quarries.

This thesis is dedicated to my family, friends, and my partner, Joshua McGilly for continuously supporting my dreams in the field of marine science and providing me with unconditional love.

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INTRODUCTION

The Caribbean King Crab *Maguimithrax spinosissimus* (Lamarck 1818) (Crustacea; Decapoda; Majidae), also known as the West Indian Spider Crab, is the largest brachyuran crab in the Western Atlantic (Winfree and Weinstein 1989). It ranges from the Carolinas, throughout the Caribbean, and as far south as Venezuela (Rathbun 1925; Provenzano and Brownell 1977; Williams 1984). It is a sexually dimorphic species with adult males larger than females, reaching over 180 mm carapace width (CW) and weighing more than 3 kg (Rathbun 1925; Creswell et al. 1989; Baeza et al. 2012; Spadaro & Butler 2021). They are found on coral reefs and other crevice-rich habitats from 1 m to 200 m depth (Colin 1978). Juvenile *M. spinosissimus* are predominantly herbivorous and graze primarily on algal turfs and macroalgae (Adey 1987a,b). As adults, they opportunistically include more protein in their diet by consuming benthic epifauna in addition to algae (Wilber & Wilber 1989; Creswell 2011), which improves their growth when compared to diets only consisting of algae (Wilber and Wilber 1989, 1991).

The species is reproductively active year-round (Munro 1974; Craig et al. 1989; Iglehart et al. 1989; Spadaro & Butler 2021), and roughly every six weeks, a mature female produces consecutive clutches from a single mating (Adey 1987a,b; Creswell 2011) that are fertilized by stored sperm in the spermatheca (Tunberg & Creswell 1988). Female fecundity estimates range from tens of thousands (Brownell et al. 1977, Creswell et al. 1989) to 100,000 eggs per clutch (Creswell 2011). Larval development is very short for a decapod crustacean, with pre-nauplius larvae spending <12 hours in the coastal plankton before molting (Brownell et al. 1977) into the first of two zoeal larval stages and then a megalopa stage (Creswell 2011). Megalopae are benthic and molt to the first crab stage within 4–6 days post-hatch (Brownell et al. 1977; Provenzano & Brownell 1977). There are only a few small artisanal fisheries for *M.*

spinosissimus due to a lack of organized markets and the low density of natural crab stocks (Creswell et al. 1989). However, *M. spinosissimus* is an ideal candidate for mariculture because of their largely herbivorous diet, reproductive frequency, large size, and short larval duration.

PREVIOUS *M. SPINOSISSIMUS* MARICULTURE EFFORTS IN THE CARIBBEAN

Previous attempts to rear *M. spinosissimus* larvae in tank systems and floating cages has been successful, but proved non-viable for the commercial market due to high infrastructural and labor costs as well as the lack of a robust market for the crabs (Brownell et al. 1977, Adey 1987a,b, Ryther et al. 1987, Creswell et al. 1989, Wilber et al. 1992). With larvae reared in laboratory grow-out tanks with filtered seawater and floating cages in lagoons, high larval mortality was reported during the second zoea stage; only 200–500 reached crab stage from an initial hatch of "tens of thousands" of larvae (Brownell et al. 1977). An alternative larviculture system utilizing screens floating in shallow water tables (Creswell et al. 1989, Tunberg and Creswell 1991) resulted in 90% of the zoea larvae molting to megalopa and 30–50% survival through the first crab stage (Creswell et al. 1989). A rearing method using "hatch boxes" (floating cages) in protected lagoons was developed by Adey (1985). The cages were anchored for three weeks to accumulate algal turf on the mesh, then egg-bearing females were placed inside. Once the eggs hatched, females were removed and 2–3 algal-covered screens were placed inside each cage. The screens were replaced every 4 days after the first 20–30 days (Adey 1985).

The use of floating cages for *M. spinosissimus* aquaculture had advantages: it precluded the need for laboratory grow-out or the building of artificial ponds and resulted in a higher-yielding culture method (Chen et al. 2007). However, this method had some drawbacks. For example, production of algal turf on the floating screens was insufficient to maintain the biomass of crabs (Creswell & Tunberg 2000) and survival of *M. spinosissimus* larvae and juveniles in floating cages was low (mean survivorship of 0.06% after 131 days; Idyll & Caperon 1986), due to predators that inhabited the turf screens within the cages (Creswell et al. 1989). Another limitation to *M. spinosissimus* mariculture is that postlarval and juvenile crabs are cannibalistic and aggressive (Creswell & Tunberg 2000). High mortalities (60%) were reported due to aggressive interactions between crabs stocked at high densities, suggesting that provisioning of adequate space and protective cover could help alleviate cannibalistic encounters (Wilber & Wilber 1991). A novel but untested alternative to labor-intensive aquaculture methods for *M. spinosissimus* that avoids the use of laboratory tanks or floating cages, is the use of largely abandoned saltwater quarries for semi-wild mariculture and large-scale production of *M. spinosissimus* for use in coral reef restoration and, perhaps, development of a commercial crab market for human consumption.

POTENTIAL OF *M. SPINOSISSIMUS* MARICULTURE FOR CORAL REEF RESTORATION

Coral disease, low coral recruitment, climate change, and the absence of herbivores has resulted in a phase shift on many coral reefs to macroalgae-dominated reefs that has weakened their resilience and persistence (Mumby 2006; Arnold & Steneck 2011). The problem is especially dire in the Caribbean where managers are trying to reduce overfishing, increase coral cover through transplantation, and promote the recovery of the long-spined sea urchin (*Diadema antillarum)* whose populations were decimated by disease in the 1980s (Lessios et al. 1984). In the Florida Keys, Florida, coral cover has declined to <5% of historical levels and restoration efforts utilizing herbivores to stock reefs have largely focused on reintroduction of *D. antillarum*, with mixed results (Nedimeyer & Moe 2006; Macía et al. 2007; Myhre & Acevedo-Gutiérrez 2007; Burdick 2008).

However, a recent experimental study (Spadaro & Butler 2021) conducted in the Florida Keys documented that the stocking of *M. spinosissimus* on coral reefs dramatically decreased and maintained algal cover at low levels resulting in a 3–5-fold increase in coral and fish recruitment. *Maguimithrax* *spinosissimus* grazing rates surpass all grazers except the stoplight parrotfish (*Sparisoma viride*) (Butler & Mojica 2012) and they consume some types of algae that possess physical and chemical defenses avoided by most fish grazers (Paddack et al. 2006). Their densities are typically low on coral reefs, likely because of high predation pressure (Butler and Mojica 2012); but stocking them on reefs at higher densities yields remarkable progress toward coral reef recovery (Spadaro & Butler 2021).

In addition to being used in coral reef restoration efforts, *M. spinosissimus* is of possible commercial value because it is similar in morphology, texture, and taste to existing crab products (e.g. snow crab; *Chionoecetes opilio*). Currently, there are only a few small artisanal fisheries for *M. spinosissimus* in the Caribbean (Guzman & Tewfik 2004), mainly because of their scarcity and the ineffectiveness of traps for their capture (Creswell 2011). Given the potential benefits of *M. spinosissimus* for coral reef restoration and market, I hypothesized that *M. spinosissimus* mariculture within saltwater quarries may be economically efficient and offer a novel, sustainable source of crabs for large-scale coral reef restoration and human seafood consumption. More than 150 saltwater quarries exist throughout the Florida Keys, but their environmental conditions are unknown. Most of these quarries are land-locked, with a few connected to the Atlantic Ocean or Florida Bay. There is no information available on the current distribution, abundance, or life cycle of *M. spinosissimus* in the quarries although hundreds of crabs have been collected from a few of the quarries (pers obs).

SEMI-WILD MARICULTURE USING SALINE LAKES AND PONDS

Marine shrimp farming currently dominates global crustacean aquaculture practices and contributes substantially to the world's shrimp demand. Production is primarily concentrated in Asia and Latin America, but it is practiced in over 60 countries (Jory & Cabrera 2003) and represents a multibillion-dollar industry (Moss 2002). Despite its high profitability, shrimp farming has resulted in negative environmental effects, the most evident being the destruction of wetlands. It is estimated that about 1–1.5 million ha of coastal lowlands in Asia and Latin America have been converted into shrimp farms (Paez-osuna 2001). Shrimp-pond effluents are often discharged into estuarine environments where they deleteriously affect water quality through eutrophication (Paez-osuna 2001). Such negative effects could be mitigated through aquaculture in land-locked saline lakes or ponds and by innovative polyculture methods that decrease nutrient loading into local environments (Anufriieva 2018). For example, coastal and inland salt ponds, especially in Asia and Latin America, are used for the semi-intensive aquaculture of brine shrimp (*Artemia* sp.) that are grown as food for other aquaculture organisms and rely on algae-rich "green water" from shrimp ponds that drain into *Artemia* ponds to supply *Artemia* with food and replace evaporated water (Le et al. 2018; Van Stappen et al. 2020).

Fish have also been reared in saltwater ponds. For example, one study focused on large-scale production of juvenile Atlantic cod (*Gadus morhua*) in a dammed estuarine pond. Instead of rearing and feeding larvae in the laboratory as is common practice, larvae were released into a saltwater basin to feed naturally on zooplankton (Oiestad et al. 1985). A portion of one dam was replaced with screen to allow for tidal flow into the pond, which increased the supply of zooplankton. High mortality was reported from cannibalism and predation from birds, but 75,000 fish were captured alive from the pond and 20,000 tagged juveniles were released into the wild (Oiestad et al. 1985). These and other studies have shown that predator abundance and food availability are some of the key factors that limit survival of species in open mariculture systems. I hypothesize that open systems, like saltwater quarries, could be ideal for semi-wild mariculture of *M. spinosissimus* for several reasons. First, using existing quarries for crab mariculture avoids the high build-out and labor costs of aquaculture facilities. Quarries also contain natural food sources (e.g., algae) and ample crevice-shelters for crabs (e.g., holes in the limestone walls, rocky ledges, and sponges). Finally, the density of natural predators is likely to be less in saltwater quarries than in the open sea.

IMPORTANT CONSIDERATIONS FOR WATER QUALITY IN QUARRY MARICULTURE

Another potentially important factor limiting the utility of quarries for mariculture of *M. spinosissimus* is water quality. The environmental conditions in saltwater quarries in the Florida Keys are unknown and likely to vary depending on season, weather, basin size, depth, runoff, and connectivity with the sea. Small, shallow quarries (e.g., 6 m depth) may exhibit higher water temperatures because sunlight penetrates through the water column to the bottom. In contrast, deep quarries (e.g., 20 m depth) may possess a thermocline due to the differential warming of surface waters by sunlight. Salinity may also vary between summer and winter because terrestrial runoff from heavy rainfalls could depress quarry salinity, whereas evaporation during dry weather periods may increase salinity. There is also a risk that heavy rainfalls could fill quarries with effluent, pathogens like *E. coli*, polychlorinated biphenyls (PCBs), and other toxins. The tolerance of *M. spinosissimus* to water quality parameters is limited to laboratory studies of salinity and temperature (Creswell & Tunberg 2000). *Maguimithrax spinosissimus* tolerate hypersaline conditions up to 40 ppt, become stressed at 25 ppt, and die if salinity drops below 20 ppt (Creswell and Tunberg 2000). The optimal temperature range for culture of *M. spinosissimus* is 28–29^{o}C. Their growth and activity decrease below 25^{o}C and abnormal shell development, anorexia, and lethargy ensue above 30^{o}C (Creswell & Tunberg 2000). Dissolved oxygen (DO) is likely a limiting factor for crab survival in stratified quarries although there are no published reports on the DO thresholds for *M. spinosissimus* as there are for other crabs of commercial value like the southern king crab (*Lithodes santolla*) (between 4-9 kPa) and larval blue crabs (*Callinectes sapidus*) (3.86 mg/L) (Paschke et al. 2010; Tomasetti et al. 2018).

Excess ammonia and nitrate are common problems in aquaculture systems. Ammonia is a waste product of aquatic organisms and is toxic to decapod crustaceans (Romano and Zeng 2013). The toxic un-ionized form of ammonia (NH_3) affects aquatic organism growth, central nervous system function, energy metabolism, ionic balance, and survival (Heath 1995; Wicks et al. 2002; Foss et al. 2003). Nitrite is formed from ammonia as a product of the nitrification process and usually accumulates in aquatic systems when there is an imbalance of nitrifying bacteria. In crustaceans, nitrate reduces thermal tolerance, induces hypoxia in tissues, hinders respiration, and stimulates methaemocyanin formation (Chen & Chen 1992; Alcaraz et al. 1997). One study tested the effects of ammonia and nitrite on tiger crab (*Orithyia sinica*) growth, survival, and molting (Koo et al. 2005). They found that juvenile tiger crabs exposed to ammonia (50, 100, and 150 mg/L) and nitrite (150, 200, and 250 mg/L) had reduced survival and growth and a shortened intermolt period (Koo et al. 2005). The tolerance of *M. spinosissimus* to ammonia and nitrite is unknown.

Given the previous success in rearing *M. spinosissimus* in the laboratory and the use of saline lakes and ponds for aquaculture of other marine species (e.g., *Artemia* sp., *Gadus morhua*), semi-wild mariculture in saltwater quarries may become a novel practice. I hypothesized that quarries would have greater variability in water quality parameters, greater algal cover, and similar benthic structural complexity to that of nearby coral reefs. I also hypothesized that the abundance of predator and competitor species in quarries would be less than that on coral reefs. To test this, the first objective of my project was to evaluate environmental conditions (e.g., water quality, benthic structural complexity, algal cover) and ascertain the abundance of predator and competitor species to assess potential suitability for *M. spinosissimus* mariculture in quarries in comparison to data collected from nearby coral reefs. I hypothesized that populations of *M. spinosissimus* in quarries would have similar size and sex structure, nutritional condition, and fecundity as their coral reef counterparts. Therefore, my second objective was to determine which quarries contained populations of *M. spinosissimus* and estimate their abundance, population structure, fecundity, and nutritional condition.

METHODS

STUDY AREA

This study was conducted in the Florida Keys, Florida (USA), which contains 150+ abandoned saltwater quarries that were formerly used as limestone borrow pits. They are spread throughout the upper, middle, and lower keys (Fig. 1) and vary considerably in size, depth, and biological and environmental characteristics. Some are close to the shore, while others are farther inland, but all are saltwater and show evidence of tidal fluctuations. My field studies were carried out in 16 saltwater quarries for which I was able to obtain permission to conduct this research from the owners. Portions of the study were also conducted in nearshore hard bottom and coral-reef habitats (see appendix). I will be referring to crabs collected from reef and hard-bottom sites as “reef” crabs throughout this thesis. The fieldwork was conducted November-December of 2020 and June- July of 2021.

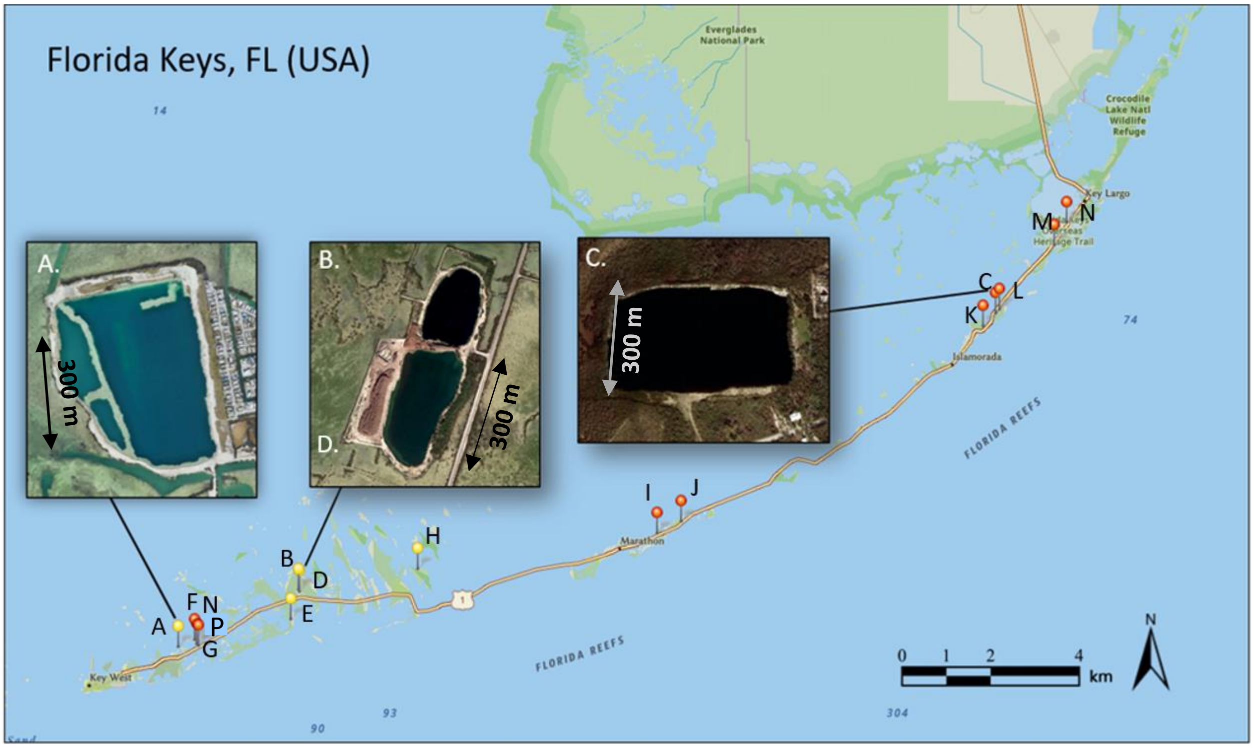

Figure 1. Map of the Florida Keys retrieved from ArcGIS online with locations of the 16 quarry sites. Yellow pins denote quarries (N = 4) containing crab populations, and red pins denote quarries (N = 12) without crab populations. Satellite photograph of quarries (A) of Big Coppitt, (B) Cudjoe west (C) Tavernier 2 and (D) Cudjoe east. Other quarries are as follows: (E) Sugarloaf, (F) Shark key 9, (G) Shark key 6, (H) No name, (I) Squirrel key camp, (J) Grassy Key, (K) Tavernier 10, (L) Tavernier 3, (M) Key Largo 24, (N) Key Largo 25, (O) Shark key 8 (P) Shark key 7.

WATER QUALITY

Water quality can significantly alter the health, survival, and growth of aquatic organisms so understanding the vertical profile of water quality in quarries can help inform decisions as to which location(s) would be the most successful for *M. spinosissimus* mariculture. Environmental sensors (YSI temp/salinity/O2 meter/pH) were deployed from a kayak at the deepest point of the quarry every 1 m depth starting from the surface and continuing to the bottom of each quarry, or to the maximum depth of the YSI (11 m), to determine the vertical profile of temperature, salinity, and dissolved oxygen). In addition, 150 ml water samples were collected in acid-washed polyethelene bottles from the surface and bottom of the water column using a Van Dorn water sampler. Water sample bottles were placed on ice upon collection, and then frozen at 0^{o}C upon returning from field sampling. Nutrient water samples, also collected using the Van Dorn water sampler, were frozen at 0^{o}C upon return from sampling. Then they were thawed and filtered through a 25-micron filter to remove suspended solids. After filtering, the samples were placed back into the freezer before being sent to the Florida International University CAChE Nutrient Analysis Core Facility, a NELAC-accredited nutrient analysis laboratory, and analyzed for NO_2^-, $+NO_3^-$, NH_4^+, and PO_4^{3-} as well as for 25 trace metals.

These data were compared to Florida Keys water quality data from surrounding sample locations recorded by the Southeast Environmental Research Center (SERC) Water Quality Monitoring Network (Briceño & Boyer 2020). Water quality data from the Florida Keys National Marine Sanctuary is sampled quarterly each year by this network. Field samples and grab samples were collected from 112 fixed stations within the Florida Keys National Marine Sanctuary boundary. Seabird SB19 casts were measured for depth profiles of temperature, salinity, dissolved oxygen, photosynthetically active radiation, turbidity, and depth. Ambient water samples were collected from 0.25 m below the water surface and 1 m from the bottom with a Niskin bottle (General Oceanics). Samples were analyzed by the Florida International University SERC Nutrient Laboratory.

RUGOSITY

Benthic structural complexity was estimated in each quarry using a diver-based rugosity chain method. The rugosity index is calculated as the ratio of the overall chain length to the actual linear distance covered (Risk 1972). Divers laid a measuring tape vertically along the slope of the quarry wall starting 1 m below the surface and moved toward the lower ledge of the quarry shelf, or bottom of the slope in shallow quarries, and recorded the initial length (between 3-5 m depending on depth and structure). Then a diver swam the length of the transect while pushing the tape into all crevices, following the contour as closely as possible until the end of the initial length was reached; the length of the new line was then recorded. This measurement was repeated 14 times at haphazard locations within each quarry, a sample size determined by a power analysis using preliminary quarry rugosity data with a power level of 0.80.

ALGAL COVER

Determining the percent cover and composition of macroalgae in each quarry provides one with important information regarding food availability for *M. spinosissimus*. Macroalgal cover was determined in each quarry using 0.25 m^2 photo quadrats taken every 0.5 m down to a depth of 4 m haphazardly. In each quarry, seven vertical transects were completed with nine photo quadrats per transect at haphazard locations. The number of transects and photos per transect were determined by using preliminary photo quadrat data collected at Cudjoe west quarry to conduct a power analysis yielding a power of 0.80. Percent cover and the broad taxonomic composition (Chlorophyta – green algae; Rhodophyta – red algae; Phaeophyta – brown algae) of algae were determined from the photo quadrats using the program Coral Point Count with Excel Extensions (Kohler & Gill 2006). For each photo, 25 random points were overlaid on the image, and overall percent cover was calculated by the program after each point was identified as green algae, brown algae, red algae, substrate (rocky or sandy bottom), or “unknown” if it was not clear. Green algae were further categorized into filamentous, fleshy, turf, and calcareous. A MANOVA was used to compare percent cover of green algae types in quarries versus coral patch reefs.

PREDATOR AND COMPETITOR SURVEYS

To estimate the abundance of potential predators (known to feed on crustaceans) and competitors (other herbivores) of *M. spinosissimus* in quarries, a GoPro HERO7 (Woodman Labs, Inc) camera was attached to a 2.2-kg dive weight and placed on the quarry edge at 2-m depth haphazardly and left to film. Films were made once at each quarry during the daytime. The battery life of the GoPro HERO7 is limited in video mode, therefore recordings were made for 30-minutes. Filming was conducted at 2- m depth where *M. spinosissimus* is abundant and during the day because the GoPro HERO7 does not contain night vision settings. The first and last five minutes of each 30-minute video were not included in the analysis to account for possible bias caused by the placement and removal of the camera by divers. Crustacean predators and competitors captured in each video were identified and counted in a random subsample of 50 video frames from the middle 20 minutes of recording. Due to the frequent absence and low numbers of predators and competitors captured on video in these quarries, the resultant data were insufficient for statistical analysis.

CRAB POPULATION STRUCTURE AND DYNAMICS

After determining that only four out of 16 quarries contained populations of *M. spinosissimus*, population structure (i.e., size and sex structure), and dynamics (i.e., relative mortality, fecundity) of *M. spinosissimus* in quarries was estimated and compared with similar measures in nearby nearshore hard-bottom and patch reef habitats where crabs occur. I grouped crabs collected from hardbottom and reef habitats together for analyses because individually, their sample sizes were smaller than that of the quarry crabs. Crabs were counted in each quarry at night (when they are most active) by divers who surveyed crabs within one 2 m wide by 100 m long belt transects at each of three depths: 0–2m, 2–4m, and 4–6m. Crabs observed at each depth stratum were captured and upon return to the surface their sex, size, and reproductive status were recorded. Crabs from hard-bottom and patch reefs were collected by divers deployed from a boat during the day who recorded their size, sex, and reproductive status. A Kolmogorov-Smirnov test was used to determine if the size distributions of quarry and reef crabs were similar. Two-sample t-tests were used to compare the proportion of males and females between quarry populations and reef populations. A two-factor ANOVA was used to determine if sex and depth affected the density of crabs in each quarry.

CRAB REPRODUCTION

The fecundity of female crabs from quarry and reef crab populations was estimated using the total number of eggs and average mass per egg from a single clutch per female. Gravid females of various sizes were collected from quarry and hard-bottom habitats, and their carapace width was recorded. Eggs were scraped off the abdomen of each female into a small collection dish and the total wet mass (g) of each clutch was measured using an analytical balance and recorded. Each clutch was then divided into 5 subsamples and weighed as described above, and the number of eggs per subsample counted under a dissecting microscope. Each subsample weight (g) was divided by the number of eggs in that subsample to obtain the mass per egg. Total egg number for each female was calculated by taking the total egg mass (g) and dividing by the average mass per egg of the subsamples (5). Data collected by Baeza et al. (2015) on the fecundity of crabs, predominantly collected from hard bottom and reef sites, were compared to data that I collected on crabs from quarries. Egg bearing females in the Florida Keys were collected by hand during June 25 – July 22, 2015, from a quarry, shallow subtidal hard bottom communities, and coral reefs on the ocean side of Long Key (Baeza et al. 2015). Fecundity in Baeza et al. 2015 was calculated with the equation F = EmMass/(Ess1 + Ess2 + Ess3 + Ess4) X 400 + 400 where F = total number of eggs and EmMass = dry weight of the remaining egg mass after the four egg subsamples have been taken (Baeza and Thiel 2000). An ANCOVA was used to determine if location and carapace width had an effect on crab fecundity.

CRAB MORTALITY

A comparison of relative predatory mortality among habitats was measured by tethering crabs (N = 60 crabs for each trial) of varying sizes (<30 – 80+ mm CW) and sexes in three quarries, three hard-bottom sites, and three patch reefs. Tethering mobile prey can only provide relative estimates of predation rates because experimental artefacts can arise and have been well recognized (Baker and Waltham 2020). To tether the crabs, a 0.5 m-long monofilament (11 kg test) harness was tied and glued dorsally to the carapace of each individual, and the other end was tied to a brick to anchor the tether in place. The crabs were placed 5 m apart during the late morning or early afternoon at a depth between 1–3 m near natural shelters (e.g., crevices, sponges, corals) so they could forage and hide. Crab presence/absence was recorded by divers after 24 hrs. Missing crabs were considered victims of predation based on the condition of the tether and any remains. This method has been used successfully in previous studies of *M. spinosissimus* ecology on coral reefs (Spadaro and Butler 2021) and in predation studies focused on other marine organisms in their respective habitats (Heck & Wilson 1987; Barshaw & Able 1990; Smith & Herrnkind 1992 ; Ryer et al. 2010) The relative predator mortality rates of crab populations in each habitat were compared using a log-linear contingency analysis to determine the effects of habitat type, size, and sex on *M. spinosissimus* survival.

CRAB NUTRITIONAL CONDITION AND GROWTH

Nutritional Condition

The nutritional health of *M. spinosissimus* crabs was estimated and compared from a measurement of the concentration of protein within the hemolymph (blood) of crabs from quarries and reef populations. Hemolymph refractive index is correlated with hemolymph protein concentration and is a reliable indicator for the dilution of protein during periods of starvation (Oliver et al. 2001; Behringer & Butler 2006). Temperature, salinity, dissolved oxygen, molting and starvation can affect hemolymph protein concentrations in crustaceans (Engel et al. 1993; 2001). Blood was drawn from the tissue between the joint of one appendage with a 1 mL syringe. Two to three drops of blood were placed on the prism of a density-salinity refractometer and the refractive index as was recorded before the blood clots. The prism of the refractometer was cleaned between each sample using distilled water and a tissue. There are no published data on hemocyanin levels of *M. spinosissimus,* so I used the refractive index value that was converted to hemolymph protein concentration using the equation: $y= -0.139 + 1.203x$ (Behringer and Butler 2006). This equation was derived from a standard curve developed using bovine albumin to determine hemolymph protein level (Musgrove 2001). Molt stage identification, described in the “Relative Growth” section, was used to account for the high concentration of hemolymph protein during pre-molt and low concentration post-molt (Barlow and Ridgway 1969). Differences between quarry and reef crab hemolymph protein levels were analyzed using a two-sample t-test.

Relative Growth

The growth process of crustaceans is a discontinuous process that is described in terms of molt increment, or change in size at molt, and the intermolt period, or the duration between two successive molts (Botsford 1985). Drach (1939) classified the molting cycle into four periods: post-molt, intermolt, pre-molt, and molt. The post-molt stage is subdivided into stage A and B where cuticular formation is not completed and the carapace is soft. Intermolt is also described as stage "C" and the cuticular formation is completed, the carapace is thick and hard. Pre-molt is subdivided into three stages: D_0, D_1, and $D_{3\text{-}4}$. These stages are where the epidermis retracts from the cuticle and the new epidermis is visible under the old one when looking through a microscope. Ecdysis, or molting, is stage E of the molt cycle. The relative incidence of any molt stage in individuals that are randomly sampled would indicate the relative duration of the intermolt period under field conditions, assuming that the molt cycle of a population is asynchronous (Gorokhova 2002). Therefore, the molt cycle duration can be estimated for a population when the proportion of individuals in each stage of the molt cycle are known.

I used a snow crab molt-staging technique outlined by Moriyasu and Mallet (1986), which incorporates observations on the morphogenesis of setae on the basal endite of the maxilla to determine the intermolt stage of each crab. This appendage is relatively transparent and can be easily removed from the crab, which makes it ideal for determining setal development stages. The basal endite was removed from the maxilla using dissection scissors and placed into a vile of seawater for preservation. A wet mount was prepared by placing the basal endite on a glass slide with 1–2 drops of seawater and observed at a magnification of 63-150x under a compound microscope. Molt stages were classified into post molt (AB), intermolt (C), and premolt ($D_{0,}$ D_1 and $D_{3\text{-}4}$) based on setal development. There were no crabs sampled for reef populations during the winter sampling period.

RESULTS

WATER QUALITY

Strong vertical stratification was observed at 10 of the 16 quarries (Fig. 2–5). Some quarries (Tavernier 2, Shark key 8, Shark key 9, Cudjoe east and west, Grassy Key, No Name, and Big Coppitt) were deeper than the length of the YSI chord (see Appendix), so water quality data were limited to a depth of 12 m. Similar stratification water quality patterns were common among quarries located adjacent to one another, such as Cudjoe east and west. Unstratified quarries, such as Big Coppitt and Grassy Key were large (see Appendix) and thus subject to possible vertical mixing from wind. The quarries sampled had a mean surface temperature of 25.68˚C and a mean bottom temperature of 28.69˚C. When compared to 2020 Florida Keys reef temperatures collected by SERC Water Quality Monitoring Network (surface mean of 25.88˚C and bottom mean of 25.69˚C), quarry bottom temperatures tended to be warmer, because the majority had a reverse thermocline. The mean surface salinity of quarries was 26.5 ppt and the mean bottom salinity (either true bottom or limit of the YSI chord (12 m)) was 34.1 ppt, whereas reef surface and bottom salinities averaged around 36 ppt according to data collected by SERC Water Quality Monitoring Network. Mean bottom dissolved oxygen was lowest in quarries (mean of 1.71 mg/L), however, surface dissolved oxygen in quarries (mean of 6.41 mg/L) was comparable to mean levels of surface and bottom dissolved oxygen concentrations on reefs (mean of 6.5 mg/L). Bottom-water pH for quarries and reefs were similar (mean pH = 7.7 and mean pH = 7.8, respectively), but mean quarry surface pH was more basic (pH = 8.3) than mean reef surface pH (pH = 7.8).

The mean surface and bottom nutrient concentrations were higher in quarries than in the Florida Keys National Marine Sanctuary (Table 1). Water quality data for the Florida Keys were obtained from the Southeast Environmental Research Center (see methods) 2020 annual report of the water quality protection program of the Florida Keys National Marine Sanctuary (Briceno and Boyer 2021). Mean ammonia/ammonium (NH_3/NH_4^+) and soluble reactive phosphorous concentrations were highest in the bottom portion of the water column of quarries. Nitrate concentrations, on average, were similar at the surface and bottom for quarries, but mean nitrite surface concentrations in quarries were higher than mean bottom concentrations. Surface and bottom water samples from each quarry were also tested for concentrations of 20 trace metals (Table 2 and 3). For trace metals, selenium had the highest mean surface concentration (94.06 ppb) followed by iron (44.37 ppb) and aluminum (14.15 ppb). Trace metals with the highest mean bottom concentration were selenium (116.2 ppb), zinc (35.90 ppb) and iron (83.45 ppb). Trace amounts of lead were found in nine quarries, with Grassy Key having the highest concentration at the bottom (6.63 ppb). Mercury was detectable in four quarries, and Tavernier 3 had the highest concentration (5.15 ppb) at the surface. Low concentrations of copper were detected in seven quarries. There were some quarries where the concentrations of certain elements were below the minimum detection limit.

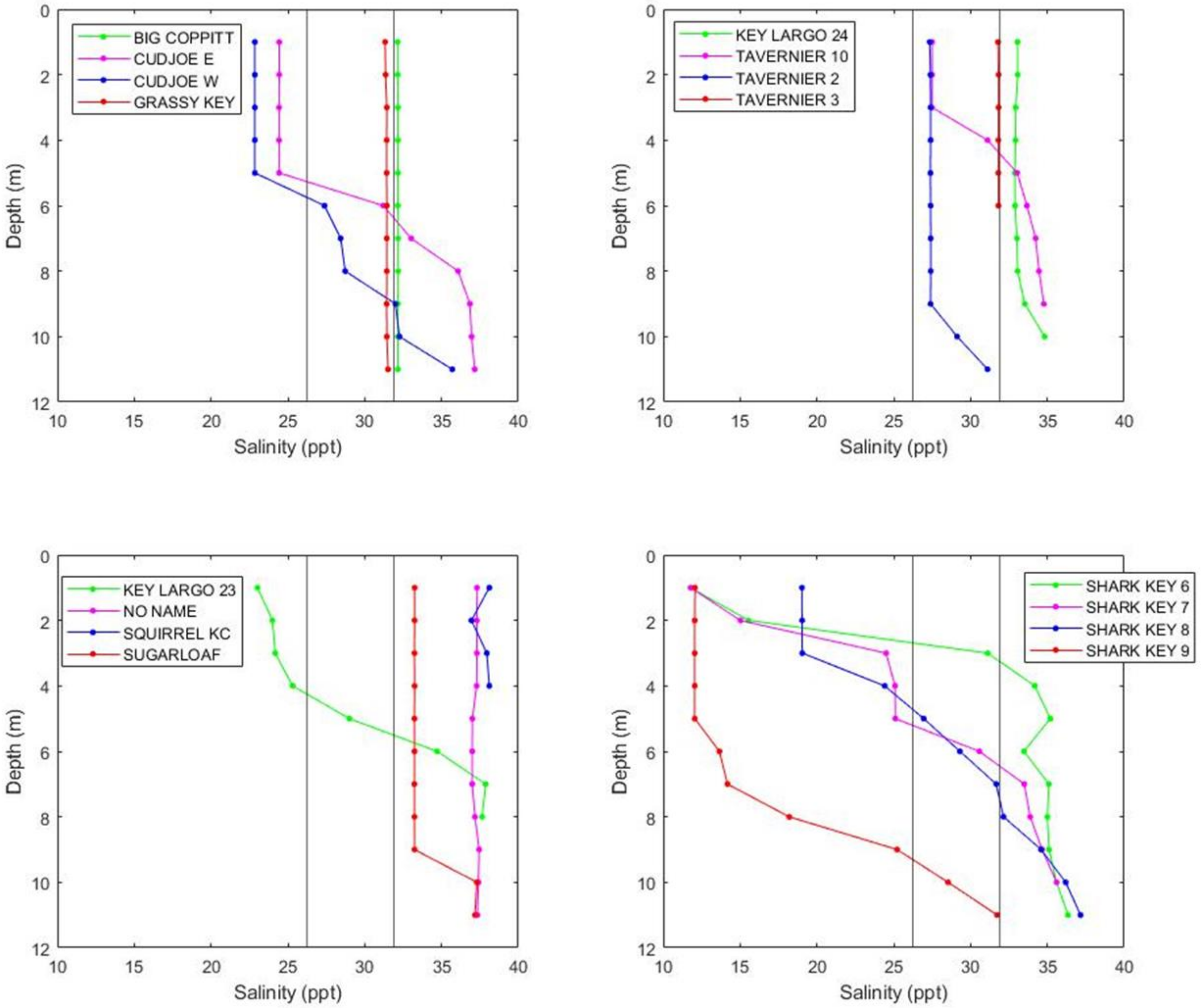

Figure 2. Vertical depth profiles of salinity for all 16 quarries. Black lines indicate mean 2020 minimum and maximum salinity for the Florida Keys National Marine Sanctuary.

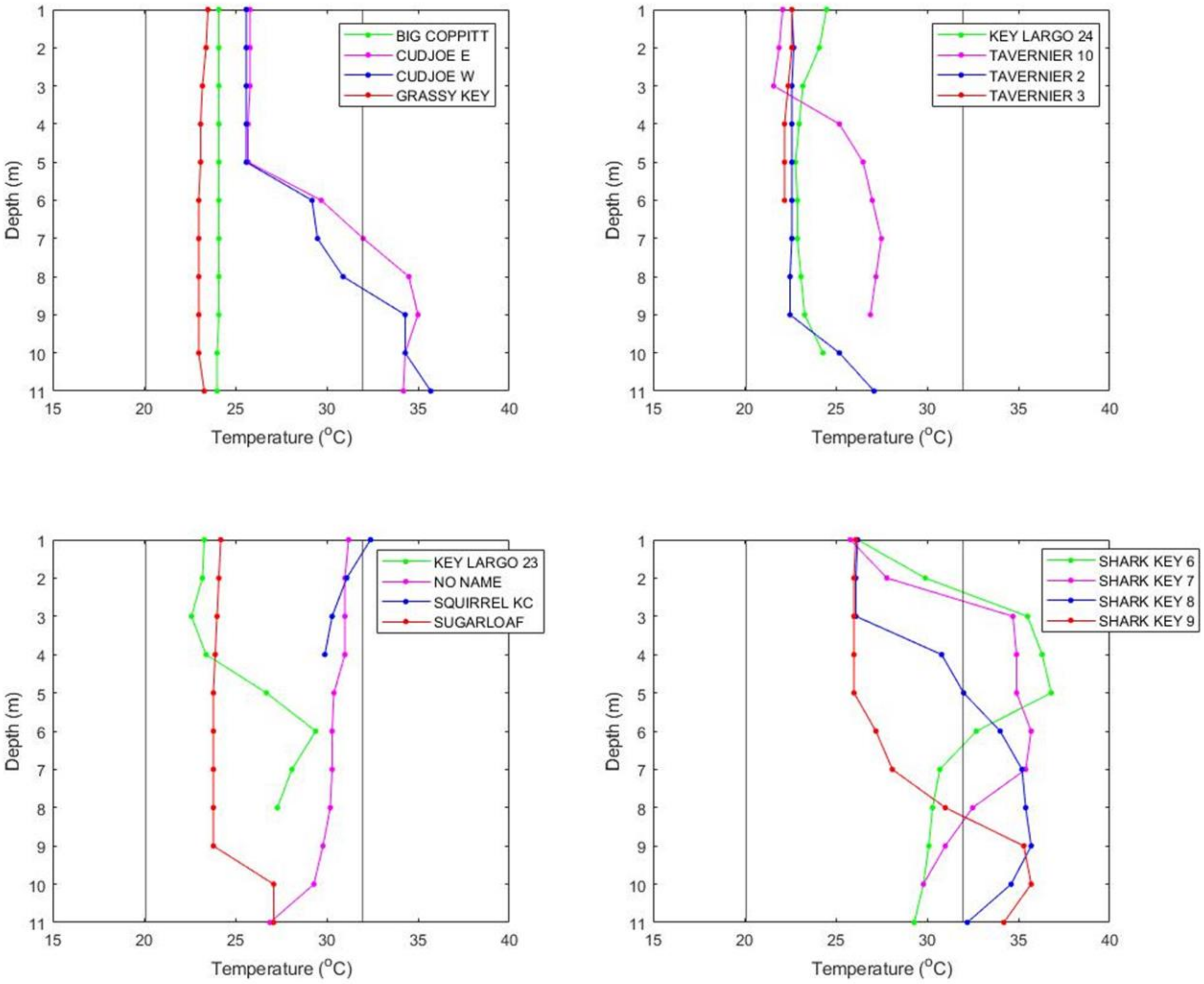

Figure 3. Vertical depth profiles of temperature for all 16 quarries. Black lines indicate mean 2020 minimum and maximum temperatures for the Florida Keys National Marine Sanctuary.

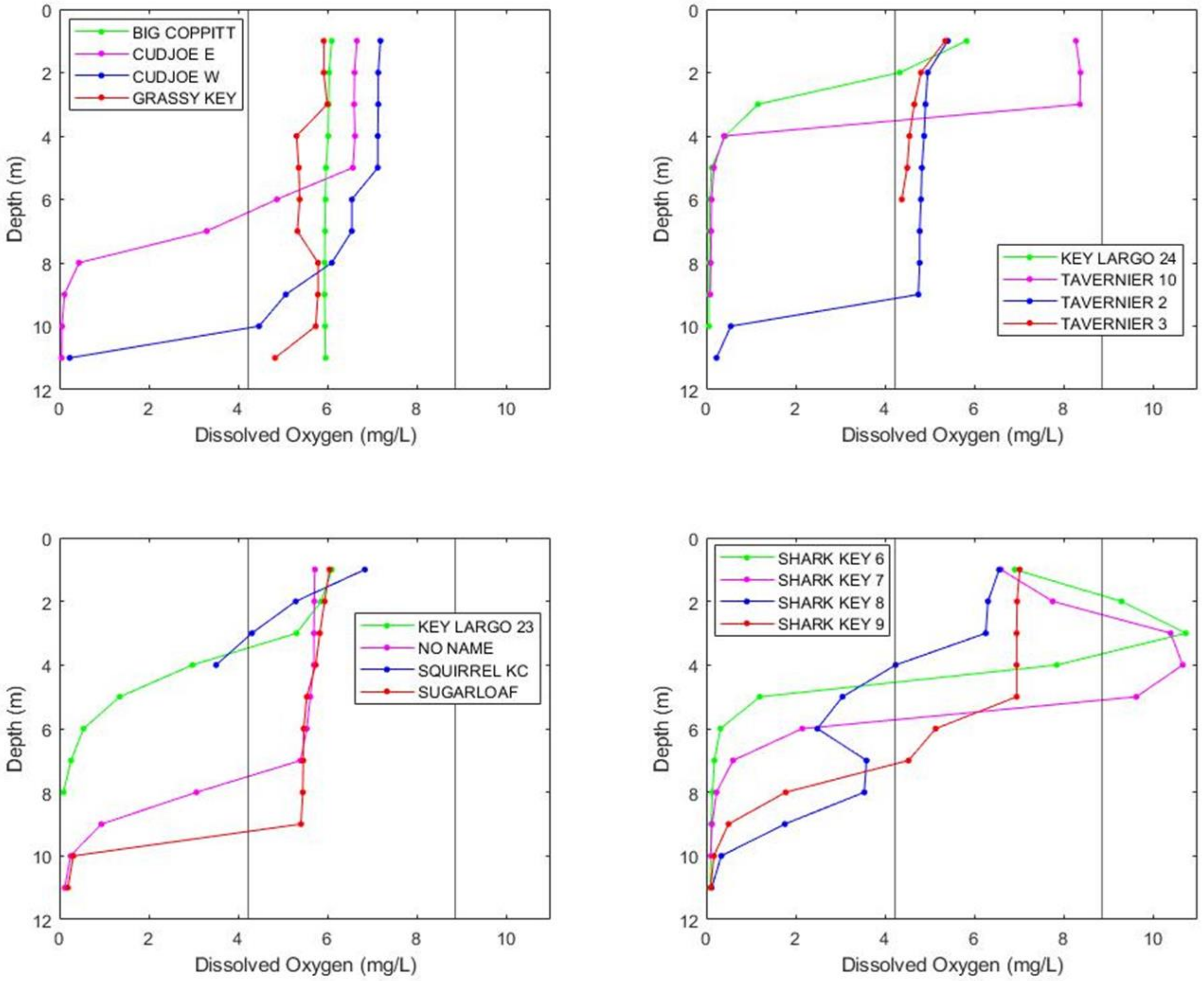

Figure 4. Vertical depth profiles of dissolved oxygen for all 16 quarries. Black lines indicate mean 2020 minimum and maximum dissolved oxygen for the Florida Keys National Marine Sanctuary.

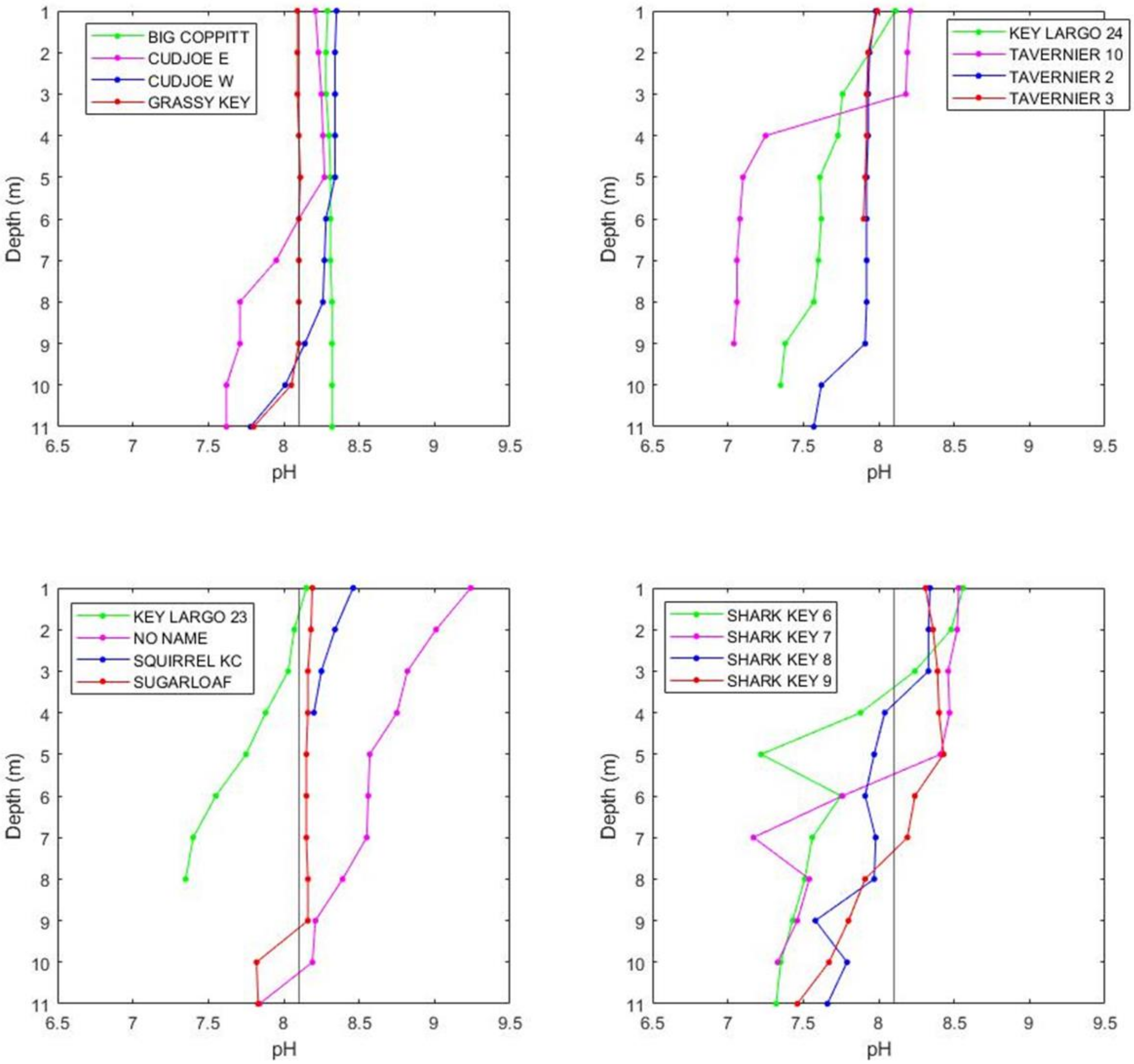

Figure 5. Vertical depth profiles of pH for all 16 quarries. Black lines indicate 2020 mean ocean pH (Garcia Soto et al. 2021).

Table 1. Quarry nutrient concentrations (nitrate and nitrite combined nitrite (NO_2^-), nitrate (NO_3^+), ammonia/ ammonium (NH_3/ NH_4^+), and soluble reactive phosphorous) collected 2 m from the surface and 2 m from the bottom at each quarry. The last row denoted in gray displays the mean 2020 surface and bottom nutrient concentrations for the Florida Keys National Marine Sanctuary provided by the Southeast Environmental Research Center, Florida International University, Miami, FL.

	Surface Nutrients (ppm)				**Bottom Nutrients (ppm)**			
Quarry	**NO2-**	**NO3-**	**NH3/NH4+**	**SRP**	**NO2-**	**NO3-**	**NH3/NH4+**	**SRP**
Cudjoe East	0.0002	0.0454	0.009786	0.000496	0.000392	0.000028	0.34804	0.002294
Cudjoe West	0.005446	ND	0.00875	0.001116	0.000322	0.00077	0.139188	0.002108
Shark Key 6	0.0002	0.0001	0.008554	0.00217	0.000084	ND	0.4109	0.001798
Shark Key 7	0.0002	0.0002	0.00812	0.00093	0.000056	ND	0.37492	0.00155
Shark Key 8	0.0006	0.0118	0.015064	0.00062	0.000042	ND	0.40866	0.005363
Shark Key 9	0.0003	0.0059	0.010024	0.001271	0.000812	0.007658	0.016324	0.000961
Big Coppitt	0.00581	0.1155	0.01442	0.002418	0.002436	0.052682	0.56182	0.03875
Tavernier 2	0.011592	0.094276	0.016016	0.001984	0.002996	0.046816	1.32048	0.099479
Tavernier 3	0.003542	0.0681	0.013482	0.002077	0.005446	0.05243	0.073724	0.006727
Florida Bay Club	0.003024	0.1576	0.012558	0.001705	0.004872	0.101262	0.014238	0.000868
Silver Shores	0.00287	0.002	0.044842	0.010912	0.00546	0.080444	0.013286	0.002542
Grassy Key	0.000504	0.4816	0.01498	0.001395	0.007196	0.073416	0.58912	0.047492
Sugarloaf	0.0011	0.0545	0.016086	0.00217	0.002772	0.043666	2.5256	0.148304
Squirrel Key Camp	0.001708	0.0402	0.01995	0.004185	0.004844	0.015386	3.2886	0.234174
No Name	0	3.07	0.05481	0.003782	0.00189	0.057722	0.023394	0.00806
Tavernier 10					0.005642	0.052276	1.03782	0.02232
Average	0.002473	0.296227	0.017829467	0.002482	0.002829	0.0449658	0.696632125	0.038924
FKNMS Average	**0.0004**	**0.001**	**0.0057**	**0.0007**	**0.0003**	**0.0015**	**0.0051**	**0.0007**

Table 2. Quarry trace metal concentrations (ppb) collected 2 m from the surface. Trace metals not detected are denoted as “ND”. The last column represents the mean concentrations for each trace metal.

Element	**SL**	**GK**	**T2**	**T3**	**SS**	**KL23**	**CJW**	**CJE**	**T10**	**SK6**	**SK7**	**SK8**	**SK9**	**SKC**	**BC**	**NN**	**Average**
Be / 9	ND	0.02	ND	ND	0.16	ND	0.09	0.11	ND	ND	0.07	0.00	ND	0.06	ND	0.03	**0.07**
Al / 27	ND	5.57	118.23	0.35	ND	ND	0.21	1.34	ND	4.97	2.73	5.38	11.84	12.72	4.66	1.78	**14.15**
V / 51	1.35	0.91	0.43		0.98	1.03	0.59	0.53	0.49	1.49	1.40	0.64	1.74	1.26	1.06	0.45	**0.96**
Cr / 52	0.25	0.10	0.28	0.58	0.38	0.14	0.17	0.11	0.32	0.99	0.75	0.81	0.63	1.12	0.49	0.76	**0.49**
Mn / 55	1.20	1.30	3.22	0.22	4.01	0.93	0.44	0.72	7.37	8.00	7.22	3.69	5.57	7.41	3.01	0.85	**3.45**
Fe / 57	30.41	39.35	45.94	2.22	54.66	28.59	25.49	26.39	34.16	72.95	68.39	35.28	47.97	75.26	37.10	85.84	**44.37**
Co / 59	0.08	0.03	ND	49.33	0.01	ND	0.03	0.05	0.00	0.10	0.06	0.02	0.06	0.04	0.02	0.05	**3.56**
Ni / 60	ND	ND	ND	0.01	ND	ND	ND	ND	ND	0.86	0.67	0.55	2.60	5.14	0.39	0.09	**1.29**
Cu / 63	1.75	ND	ND	ND	ND	ND	ND	ND	ND	1.99	2.30	0.77	1.81	0.97	0.40	ND	**1.43**
Zn / 66	2.54	ND	ND	ND	ND	11.96	ND	ND	ND	6.18	9.64	5.14	85.91	45.90	5.76	ND	**21.63**
As / 75	1.42	1.81	1.16		3.15	1.56	0.83	0.72	1.69	2.07	1.97	1.23	1.62	1.57	1.40	2.04	**1.62**
Se / 82	143.90	109.04	90.83	1.36	130.84	93.28	90.11	103.25	101.62	110.38	107.82	62.71	44.77	122.47	79.08	113.44	**94.06**
Mo / 95	7.94	8.81	6.16	105.55	8.73	7.33	3.95	5.26	4.73	7.29	6.44	2.77	5.98	9.36	7.09	2.73	**12.51**
Ag / 107	ND	ND	ND	9.35	ND	ND	ND	1.91	ND	ND	ND	ND	ND	ND	ND	ND	**5.63**
Cd / 111	0.01	ND	ND	ND	ND	ND	ND	ND	ND	0.01	ND	ND	0.01	0.01	0.02	0.00	**0.01**
Sn / 118	0.05	ND	ND	ND	ND	ND	ND	ND	ND	0.14	0.09	0.01	0.10	0.22	ND	ND	**0.10**
Sb / 121	0.17	0.18	0.07		0.14	0.09	ND	0.11	0.14	0.49	0.36	0.02	0.61	ND	ND	0.15	**0.21**
Ba / 137	8.00	6.51	4.11	0.10	6.24	5.98	8.77	9.59	7.55	18.13	17.69	9.59	13.14	10.01	7.58	16.18	**9.32**
Hg / 202	ND	0.06	ND	5.15	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	**2.61**
Pb / 208	0.86	ND	ND	ND	ND	0.36	ND	ND	ND	2.02	5.00	0.20	0.59	1.33	1.43	0.29	**1.34**

Table 3. Quarry trace metal concentrations (ppb) collected 2 m from the bottom. Trace metals not detected are denoted as “ND”. The last column represents the mean concentrations for each trace metal.

Element	**SL**	**GK**	**T2**	**T3**	**SS**	**KL23**	**CJW**	**CJE**	**T10**	**SK6**	**SK7**	**SK8**	**SK9**	**SKC**	**BC**	**NN**	**Average**
Be / 9	ND	ND	ND	ND	0.08	0.08	0.05	0.20	ND	0.10	ND	0.06	ND	0.01	ND	0.20	**0.10**
Al / 27	ND	22.31	0.40	ND	ND	0.52	8.78	22.40	5.67	5.90	14.33	7.74	23.05	10.94	6.78	1.71	**10.04**
V / 51	1.33	0.51	0.39	0.59	0.38	0.36	0.36	0.31	0.43	1.57	3.23	0.70	1.65	1.30	1.19	0.26	**0.91**
Cr / 52	0.26	1.89	0.28	0.20	0.27	0.44	0.31	0.30	0.34	0.77	0.82	0.81	0.67	3.40	0.60	1.62	**0.81**
Mn / 55	1.14	97.15	23.38	2.26	6.13	24.07	11.56	44.29	14.86	10.16	7.83	17.28	7.51	11.51	3.37	9.49	**18.25**
Fe / 57	27.84	136.42	71.79	49.25	52.09	70.94	71.48	137.95	59.90	112.69	80.09	72.55	92.79	127.74	42.43	129.19	**83.45**
Co / 59	0.04	0.06	ND	0.02	0.02	0.02	0.09	0.09	0.02	0.10	0.08	0.04	0.09	0.23	0.02	0.13	**0.07**
Ni / 60	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.74	0.62	0.55	8.21	6.98	0.30	0.12	**2.50**
Cu / 63	2.27	ND	ND	ND	ND	ND	ND	ND	ND	1.56	0.86	1.27	2.21	0.91	0.54	ND	**1.37**
Zn / 66	2.96	0.86	ND	ND	ND	ND	ND	ND	ND	6.15	4.84	5.63	194.46	58.84	13.46	ND	**35.90**
As / 75	1.46	3.93	1.88	1.36	5.28	3.83	2.80	1.88	2.40	2.12	2.71	2.28	1.64	1.99	1.55	2.53	**2.48**
Se / 82	150.32	124.66	123.14	113.39	129.00	122.21	131.50	130.34	129.36	117.13	109.18	104.11	46.16	126.32	89.38	113.00	**116.20**
Mo / 95	7.89	0.99	5.68	9.23	3.41	3.57	4.38	3.97	1.04	7.71	6.78	3.38	6.11	9.95	8.13	1.14	**5.21**
Ag / 107	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	2.41	ND	ND	0.38	ND	ND	**1.40**
Cd / 111	0.02	ND	ND	ND	ND	ND	ND	ND	ND	0.01	ND	0.00	0.01	0.02	0.00	ND	**0.01**
Sn / 118	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.07	0.01	0.01	0.68	0.21	0.01	ND	**0.16**
Sb / 121	0.15	0.29	0.03	0.11	0.12	0.09	0.07	0.05	0.08	0.40	0.39	ND	0.70	0.04	ND	0.21	**0.20**
Ba / 137	6.19	10.28	7.82	5.19	11.72	11.10	21.08	19.19	11.49	18.96	18.34	18.18	14.07	10.49	8.67	18.50	**13.21**
Hg / 202	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	0.19	ND	0.01	**0.10**
Pb / 208	0.68	6.63	ND	ND	ND	ND	ND	ND	ND	2.00	1.95	1.07	1.78	1.56	1.94	ND	**2.20**

RUGOSITY

Mean rugosity for quarries was lower ($\bar{X}$ = 1.10) when compared to mean rugosity on coral reefs, both before ($\bar{X}$= 1.4) and after algae removal ($\bar{X}$= 2.069) as measured by Spadaro (2019) (Fig. 6). Quarries on Sugarloaf and Big Coppitt Key had the lowest mean rugosity index and the highest mean rugosity indexes were recorded at Squirrel Key Camp, Shark Key 8, Tavernier 10, and Tavernier 2.

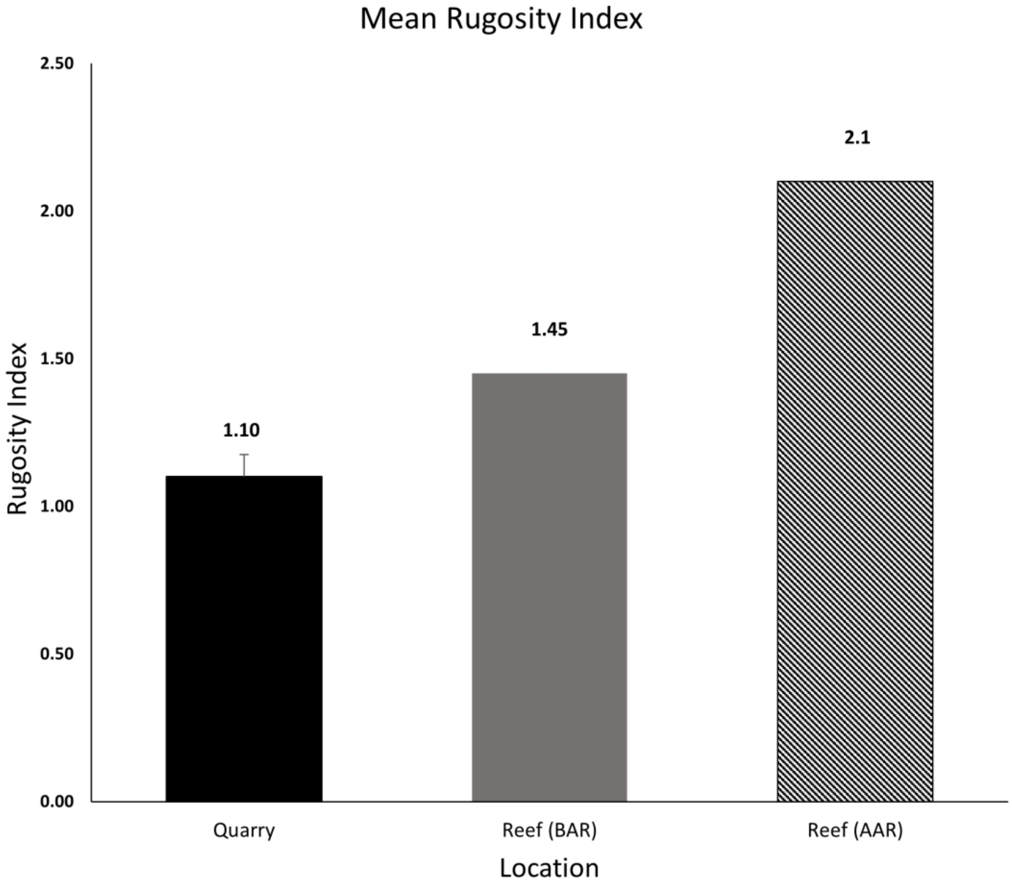

Figure 6. Mean rugosity indices for quarries (N = 16) compared to the rugosity indices for reef sites (N = 12) before (BAR) and after algae removal (AAR) from Spadaro (2019). The error bar represents the standard deviation for quarry rugosity.

ALGAL COVER

I processed a total of 720 photo quadrats (45 photos per site x 16 sites) to quantify macroalgal cover within quarries (Fig. 7). Mean percent algal cover for fleshy algae, *Halimeda*, and turf algae was significantly higher in quarries as compared to reef sites ($F = 255.29$, d$f = 3$, $p = 2.2e^{-16}$). Algal cover overall was lowest in Big Coppitt quarry (0.2) and highest in Tavernier 3 (0.99), Shark Key 8 (0.81), and Grassy Key (0.97).

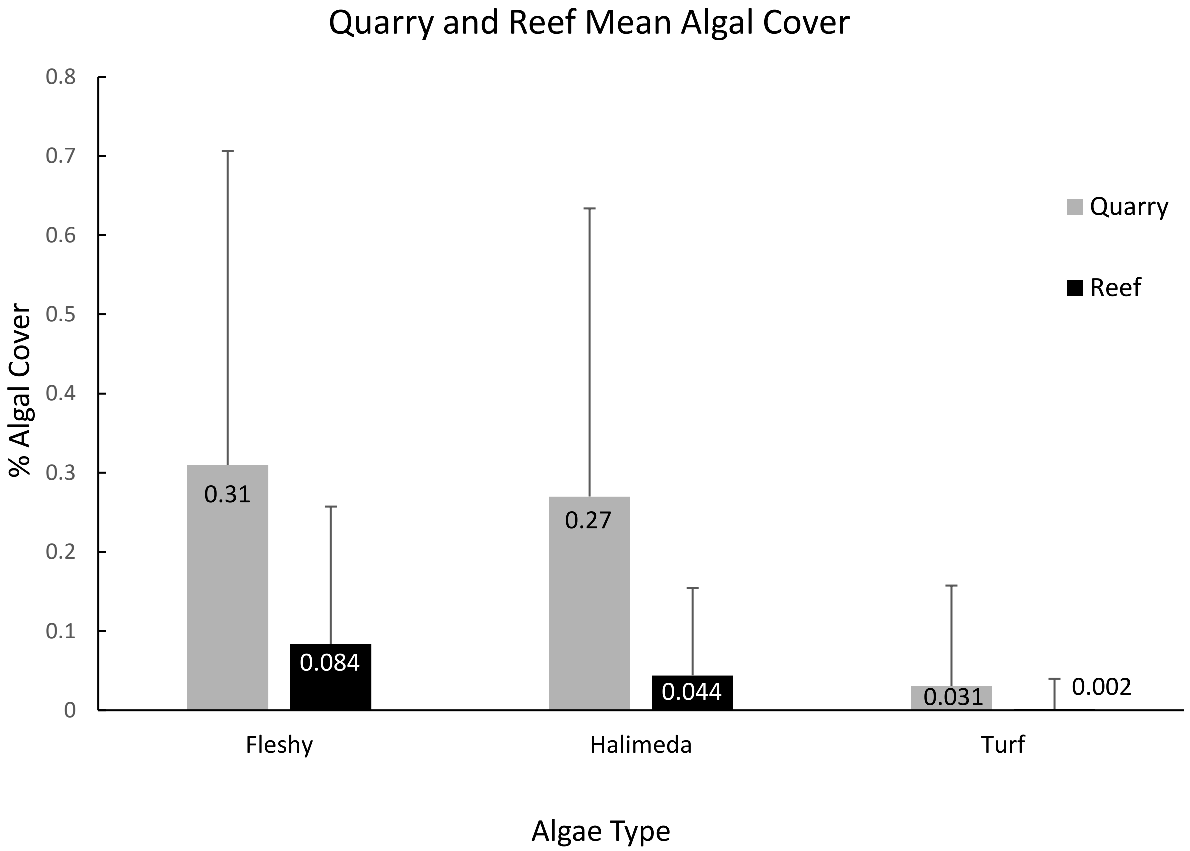

Figure 7. Bar graph showing the mean percent cover for fleshy, *Halimeda*, and turf algae at quarry and reef sites. Error bars represent the standard deviation.

PREDATOR AND COMPETITOR SURVEYS

The predator and competitor video surveys completed in each of the 16 quarries captured very few images of potential crab predators or competitors with a few exceptions (Fig. 8). The most common predators of decapod crustaceans found in the quarries were gray snapper (*Lutjanus griseus*) and schoolmaster snapper (*Lutjanus apodus*), which are predators of only small crustaceans (e.g., juvenile *M. spinosissimus*). The GoPro videography data yielded a total count of only five herbivorous fish of three species (*Scarus guacamaia, Pomocanthus arcuatus, Kyphosis secatrix*) in the four quarries harboring crabs. This confirms my *ad hoc* observations that quarries generally lack piscine competitors with *M. spinosissimus.* In one quarry (Big Coppitt) that is close to the sea and experiences periodic overflow of seawater during storms, I found one species of sea urchin (*Echinometra viridus*) to be abundant; urchins are herbivores and so potential competitors for algae. To gain a better understanding of urchin density in that single quarry, 24 random 1 m^2 photo quadrats were taken while snorkeling at 0 — 2 m depth. The mean number of urchins in Big Coppitt quarry was 56.2 per m^2.

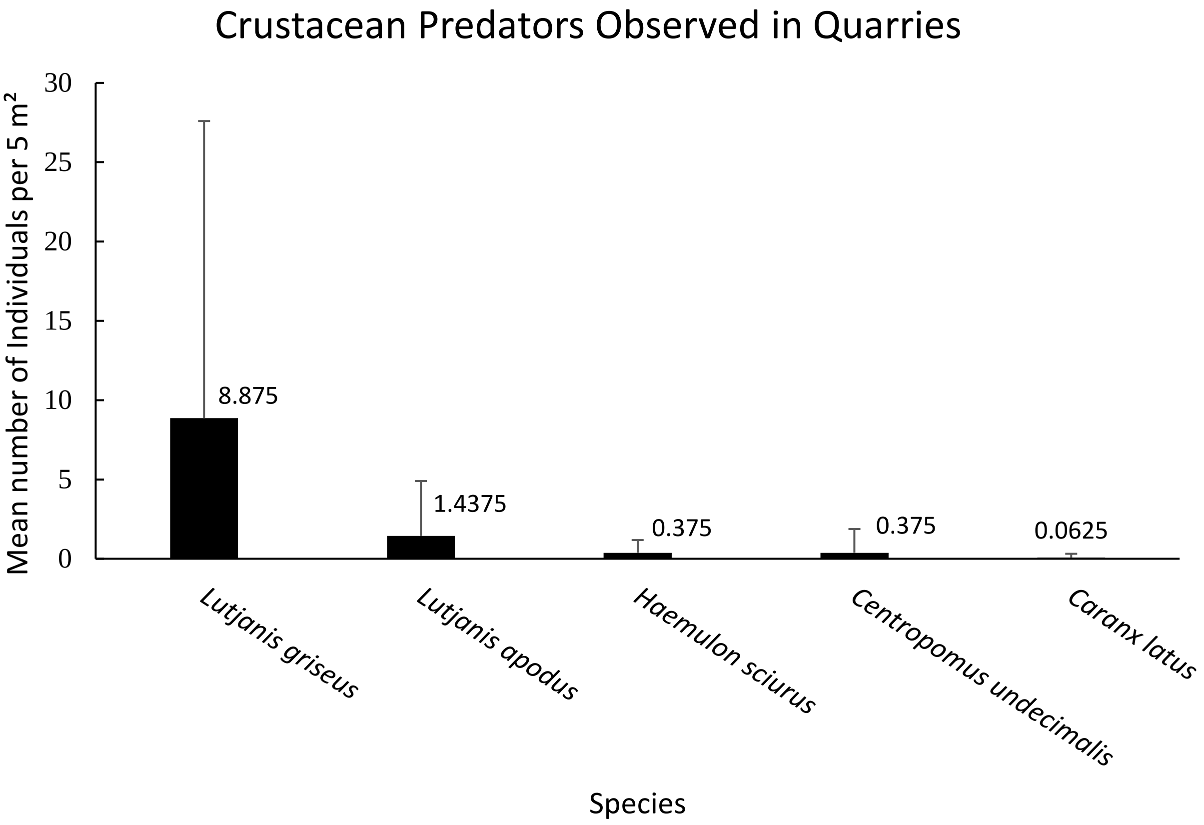

Figure 8. Mean number of individuals from each crustacean predator species observed and counted in the quarry video surveys. Error bars represent standard deviations.

CRAB POPULATION STRUCTURE AND DYNAMICS

Size Structure, Sex Structure, and Density

The size structure of crabs was similar for populations in the quarries and on the reefs (Fig. 9). In addition, the size distributions of quarry and reef crabs came from the same distribution ($D = 0.096$, $p = 0.415$). Quarry crabs ranged in size from 20 to 127.2 mm CW, while those on the reef ranged in size from 39.7 to 122.9 mm CW. Small juveniles (<20 mm CW) were absent from this dataset because they are too small and cryptic to be sampled efficiently during diving surveys. There was no difference between the proportions of female ($p = 0.2014$, $df = 1$) and male crabs ($p = 0.2014$, $df = 1$) in quarries versus those living on coral reefs (Fig. 10), and the proportion of females tended to be greater than that of males in both habitats. There is no difference between the size distributions of quarry males and reef males ($D = 0.15586$, $p = 0.5317$) (Fig. 11). However, there is a difference between the size distributions of quarry females and reef females ($D = 0.34125$, $p = 0.00186$) (Fig. 12). The surveys of the vertical density of crabs on quarry walls indicated that, while foraging at night, *M. spinosissimus* was most common on quarry walls at 0–2 m depth (Fig. 13).

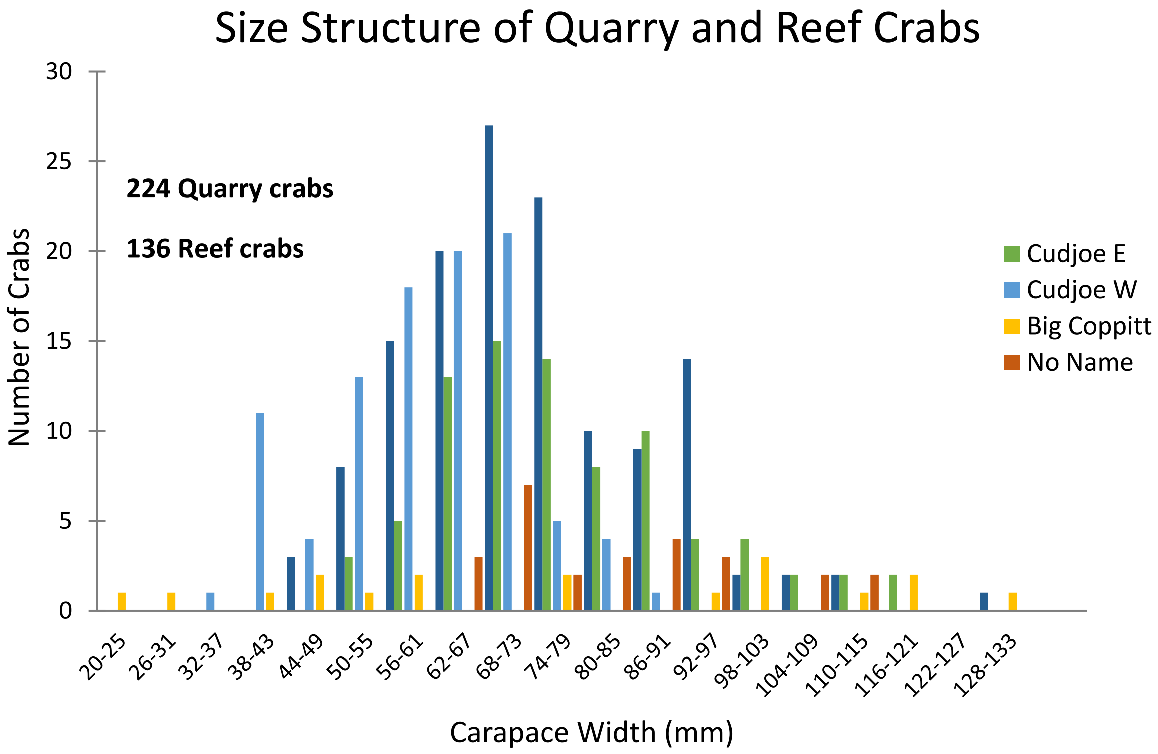

Figure 9. Size frequency histogram of *M. spinosissimus* collected from reef and quarry populations.

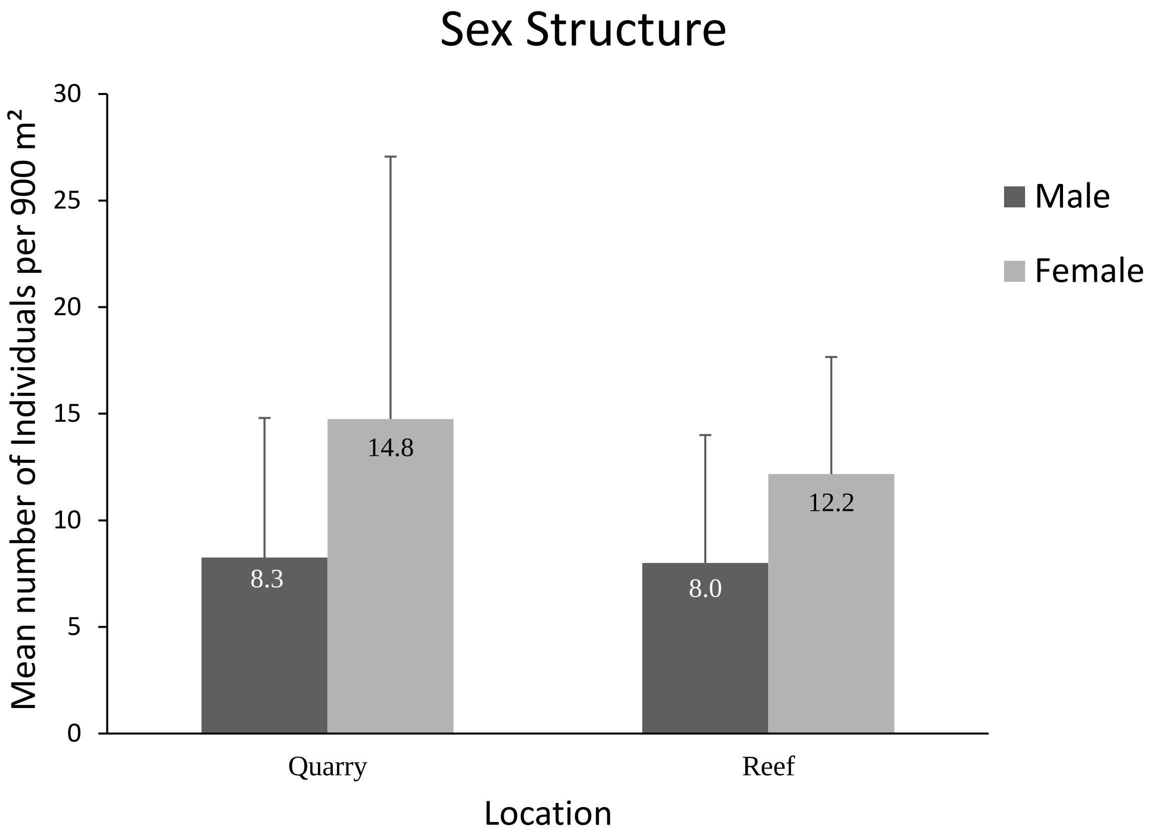

Figure 10. Mean number of males and females collected from quarry populations versus reef populations. Error bars represent standard deviations.

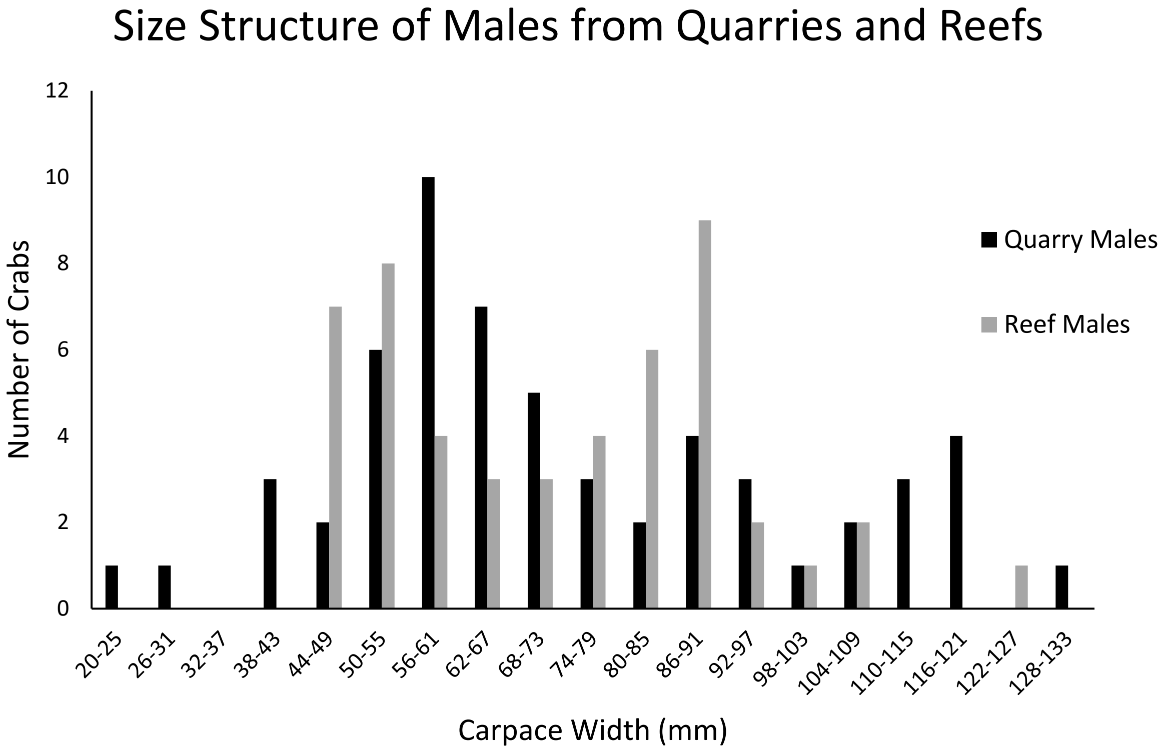

Figure 11. Size frequency histogram of male *M. spinosissimus* collected from reef and quarry populations.

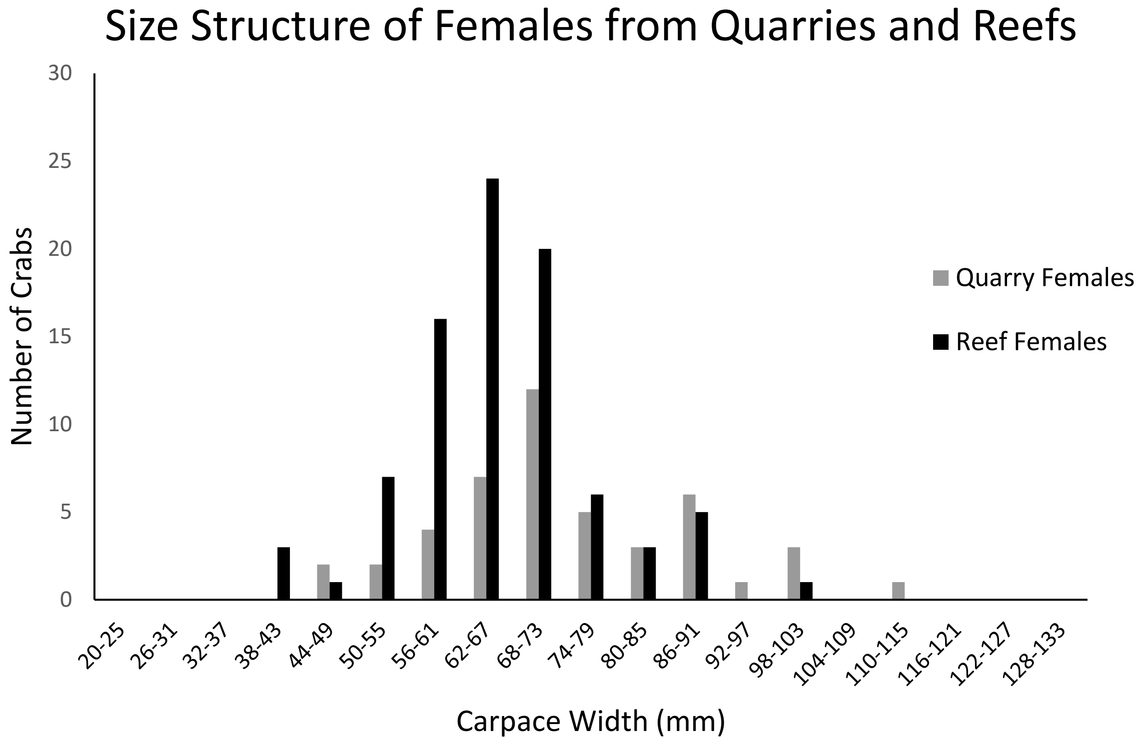

Figure 12. Size frequency histogram of female *M. spinosissimus* collected from reef and quarry populations.

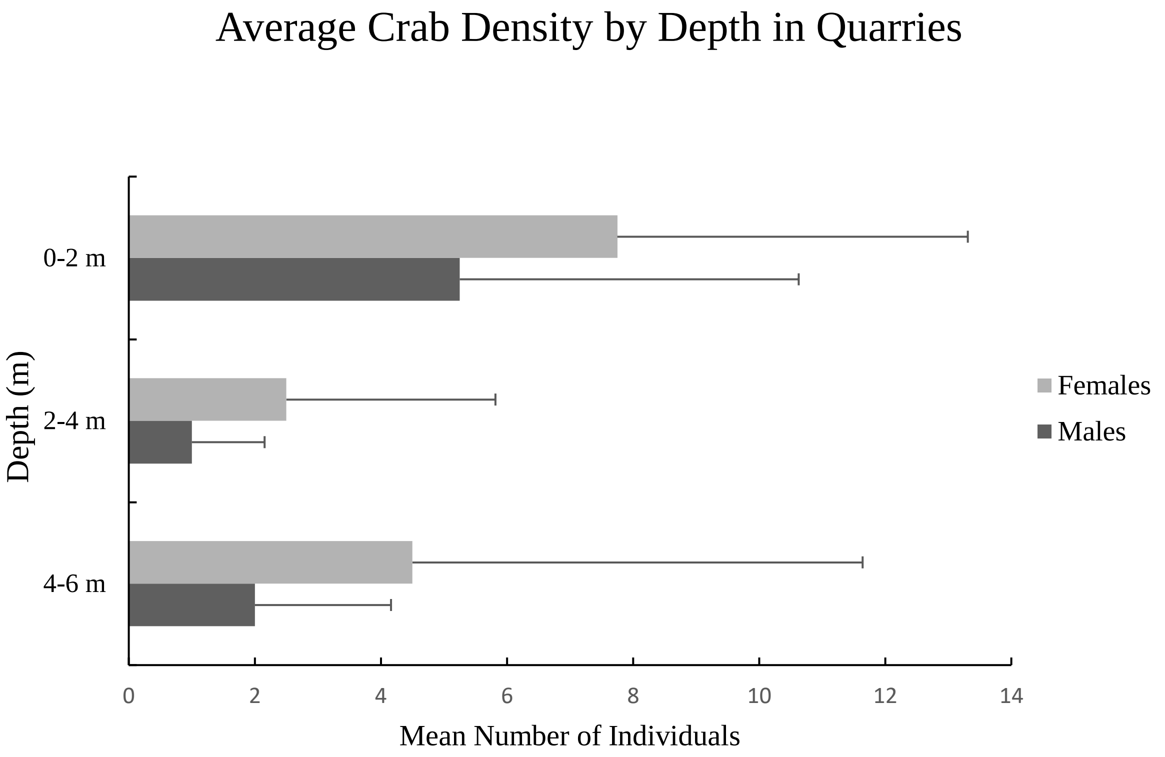

Figure 13. Mean number of males and females collected in quarries at different depths. Error bars represent standard deviations.

Fecundity

Fecundity estimates were completed for a total of 34 quarry crabs and 14 reef crabs that I collected between June and July 2021. To obtain a more robust dataset based on more replicates, fecundity estimates for *M. spinosissimus* were also obtained from Baeza et al. (2015) (see methods). Crab carapace width (mm) was a significant predictor of fecundity ($df = 1$, $F = 51.8586$, $p = 1.919e^{-10}$), but there was no significant difference in fecundity ($df = 1$, $F = 0.0254$, $p = 0.8737$) between reef and quarry locations (Fig. 14).

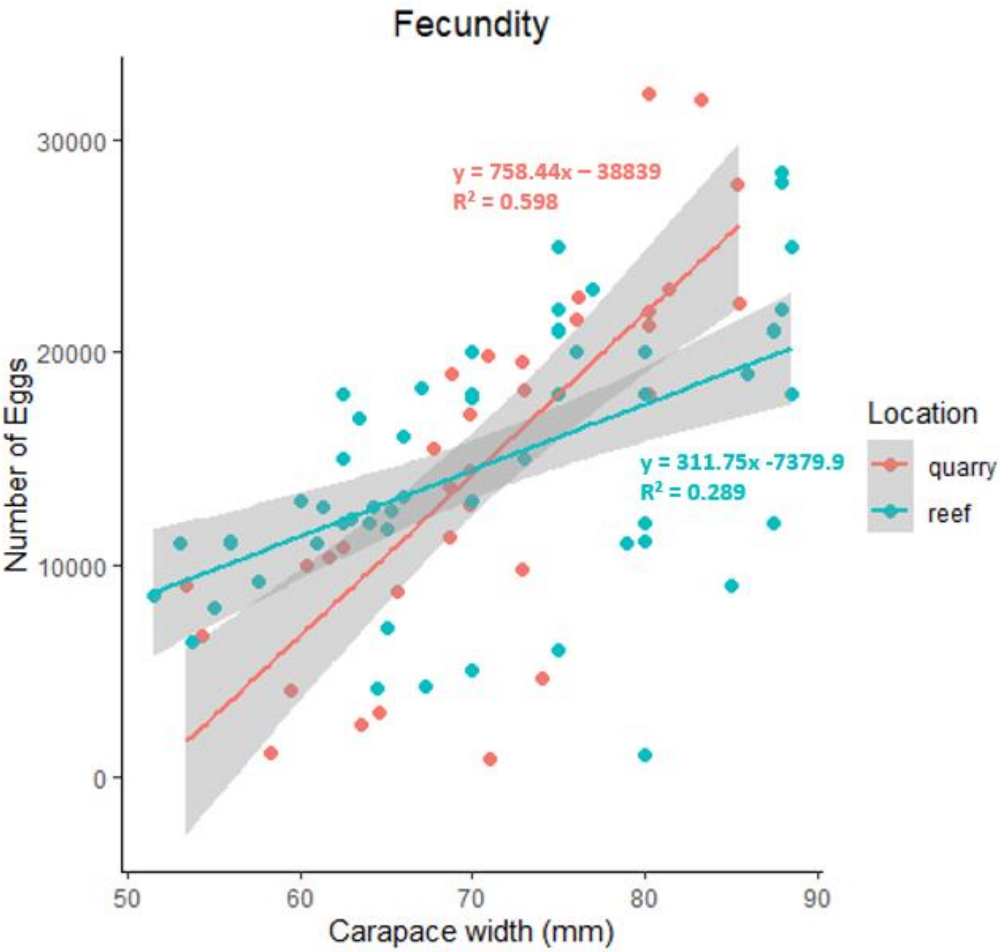

Figure 14. Relationship between female crab size and clutch size. Regression lines for size-specific fecundity estimates of crabs from quarries (red) and those collected from the reef (blue). The gray shading represents 95% confidence intervals.

Relative Mortality

Between June 2021 and August 2022, a total of 231 crabs were tethered (~ 75–80 in each of three habitat types: quarry, hard bottom, reef) (Fig. 15). There was no significant difference ($X^2 = 0.21091$, d$f = 2$, $p = 0.3484$) in predation on crabs among quarry, hard bottom, and reef habitats. In addition, sex also did not have an effect on crab predation ($X^2 = 0.1647$, d$f = 1$, $p = 0.1647$).

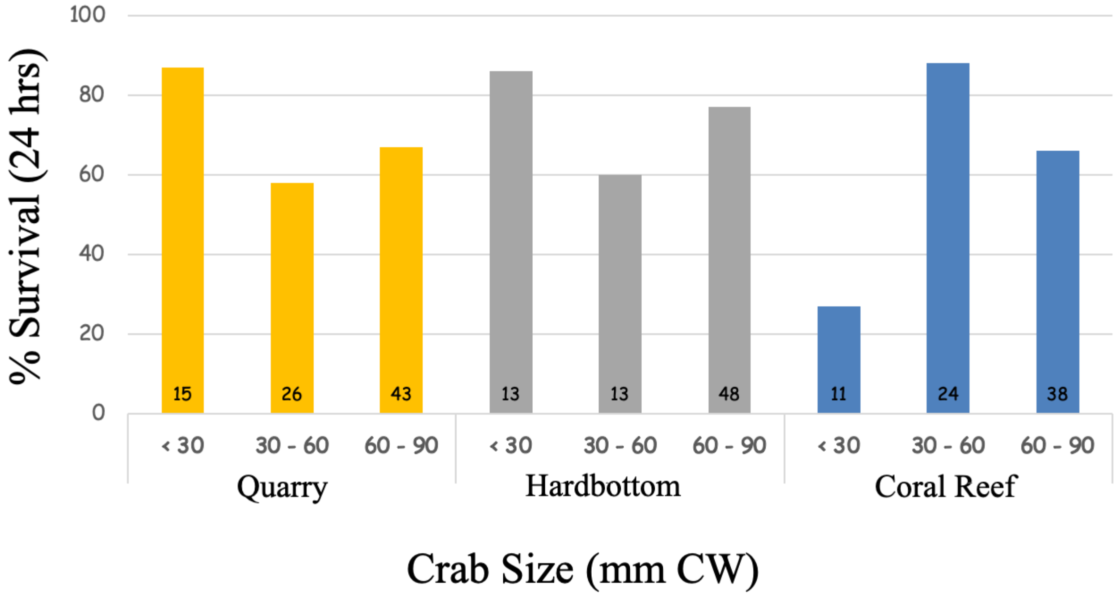

Figure 15. Survival of crabs of different size classes while tethered in three habitats.

CRAB NUTRITIONAL CONDITION AND GROWTH

Nutritional Condition

The nutritional condition of crabs expressed by the hemolymph protein index was measured for 176 quarry and 68 reef individuals (Fig. 16). Only crabs that were identified to be in molt stage "C" were included in the analysis to avoid the confounding effects of changing pre- and post-molt blood protein concentrations. There was no significant difference (t = -0.73482, df = 209, p = 0.4633) in blood protein index between quarry and reef crab populations. Quarry crabs had a mean hemolymph protein of 8.6 and a range of 3.4 – 14.8 whereas reef crabs had a mean blood protein index of 8.8 and a range of 4.6 – 14.3.

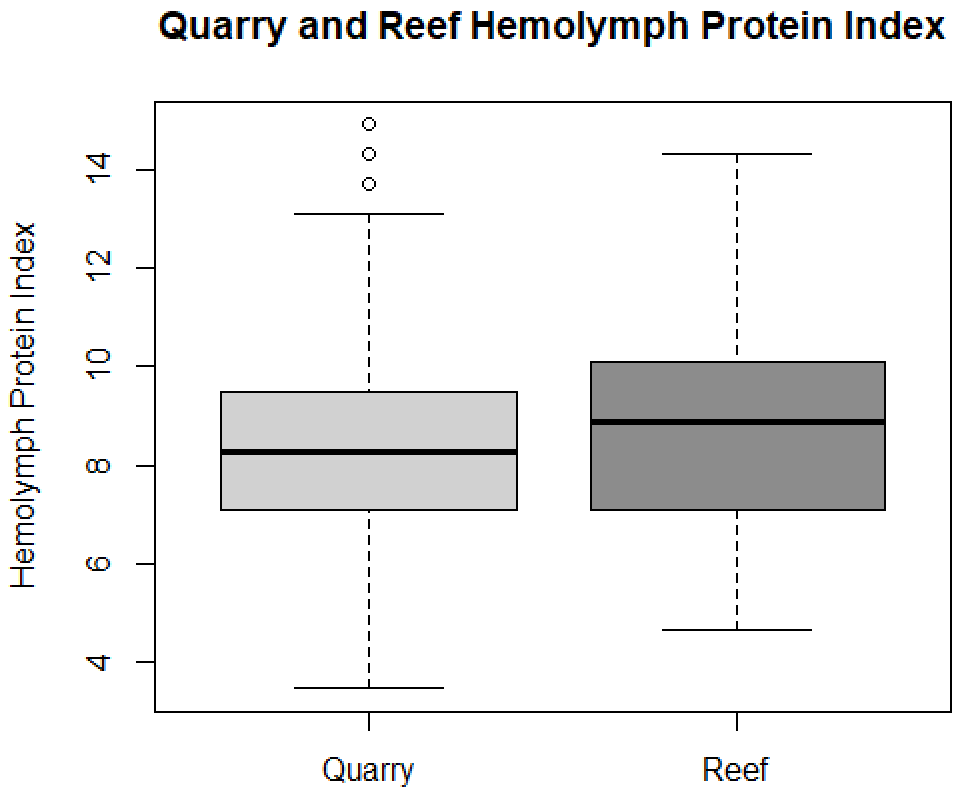

Figure 16. Boxplots showing the hemolymph protein index for quarry and reef crabs. The black line in the center of the boxes represents the median value of the dataset. The boxes represent 50% of the central data. The lower error bar is the minimum value, and the upper error bar is the maximum value, not including outliers. Outliers are represented by circles.

Relative Growth

The majority of quarry and reef crab populations were in molt stage “C” during the sampling periods in winter and spring (Fig. 17). The proportion of crabs in molt stages AB or D was 0.12 for quarry populations in the winter (N = 47). For summer, the proportion of crabs in molt stages AB or D was the same (0.25) for both quarry (N = 44) and reef populations (N = 67). However, not enough crabs in molt stage AB or D were collected to conduct a formal analysis.

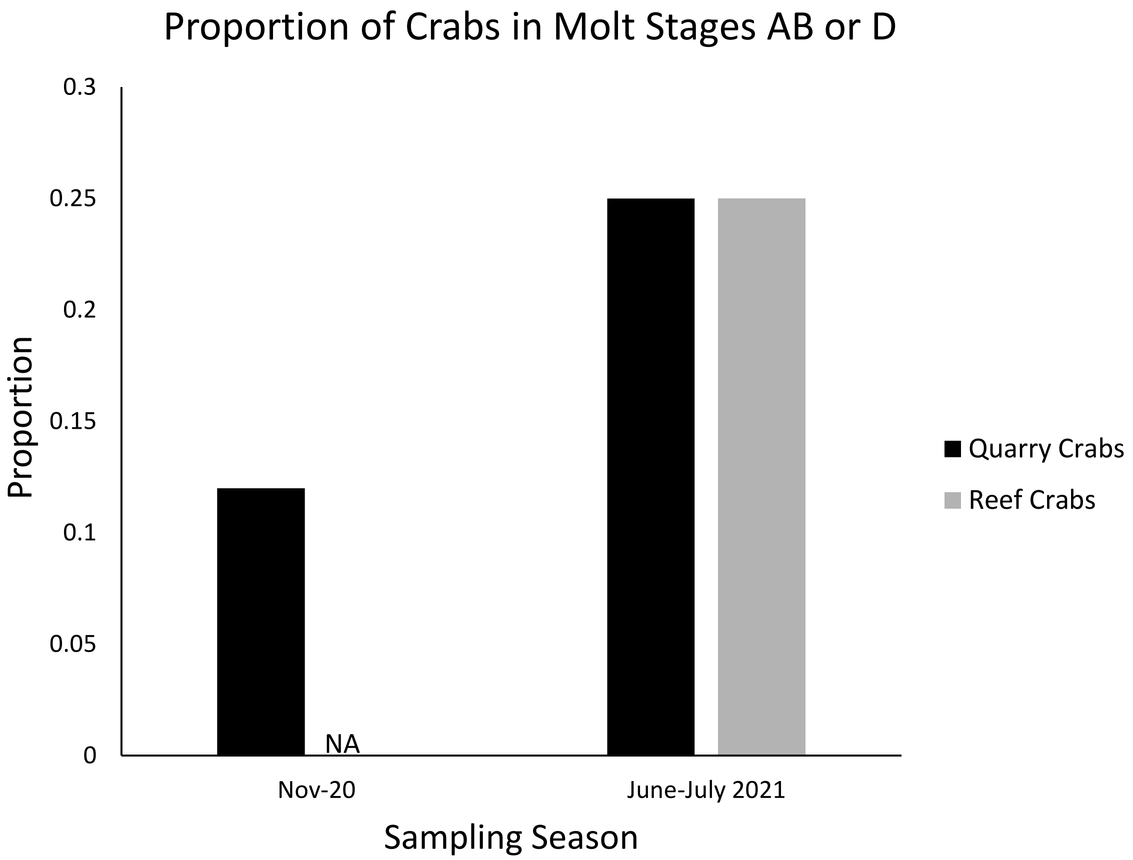

Figure 17. The proportion of crabs in molt stages AB or D during the November 2020 and June – July 2021 sampling periods.

DISCUSSION

In this study, I examined the biotic and abiotic characteristics of 16 saltwater quarries to determine if those environments are suitable for the semi-wild mariculture of *M. spinosissimus*. In addition, I also examined population structure and dynamics for quarry-dwelling populations of *M. spinosissimus* as compared to data collected for their reef counterparts. The results of this study indicate that crab populations within quarries are comparable to those in nearby wild populations in terms of population size and sex structure, fecundity, and nutritional condition. Crab populations were found in both stratified and unstratified quarries. In general, quarries had a higher percent cover of algae, lower rugosity, and lower number of predators and competitors when compared to coral reef sites.

Macroalgae is proliferating on Caribbean coral reef ecosystems due to climate change, pollution, coral disease, and loss of herbivores (Mumby 2006; Arnold & Steneck 2011; Zaneveld 2016). When *M. spinosissimus* is aggregated on coral reefs, their grazing effects on reef communities are powerful, resulting in reduced macroalgal cover, increased rugosity, increased density of juvenile corals and an increase in reef fish abundance and richness (Spadaro and Butler 2021). The primary bottleneck to the widespread use of *M. spinosissimus* in coral reef restoration is an adequate and environmentally sustainable supply of crabs for stocking. The semi-wild culture *M. spinosissimus* in Florida Keys saltwater quarries has potential to alleviate this bottleneck if conditions in quarries can sustain crab survival, growth, and fecundity.

Quarries as Habitat for *M. spinosissimus*

Physico-chemical water quality parameters are perhaps the most vital ecological factors when considering locations for crustacean aquaculture because it directly affects survival, oxygen consumption, metabolism, growth, and molting success (Chen et al. 1991; Medesani et al. 2001, Varadharajan et al. 2013). The water column was highly stratified in 10 out of 16 quarries; some quarries had up to a 6ºC temperature increase and a 20 ppt salinity increase with depth creating an inverse halocline. In the majority of the quarries I sampled, dissolved oxygen levels were at hypoxic levels (< 2 mg/L) near the bottom. Haloclines in saline or brackish water ponds and lakes obstruct vertical mixing (Ueda et al. 2005; Ozaki et al. 2021) and also affect vertical patterns in water chemistry by dissolving and reducing nutrients from the bottom sediment because of hypoxic conditions near the bottom (Ueda et al. 2005; Jeong & Kwak 2020). However, the temporal stability of the stratification in these quarries is unknown. Strong wind events or over-wash by seawater during hurricanes is likely to destabilize quarry stratification, at least temporarily.

Nitrogenous waste excreted by organisms at high density (e.g., aquaculture) damages gill tissues, affects oxygen consumption, and can lead to mortality of crustaceans (Lin & Chen 2003; Kuhn et al. 2010; Campos et al. 2012). The sensitivity of *M. spinosissimus* to toxic substances of all types is unknown, but probably varies by developmental stage and general health (de Lourdes Cobo et al. 2014; Campos et al. 2015). The toxicity of nitrogenous compounds to aquatic organisms is also highly pH-dependent (Armstrong 1979): an increase of 1 pH unit can raise ammonia concentrations 10-fold (Emerson et al. 1975). Many of the quarries sampled had decreasing pH levels with depth, and the nutrient levels were also higher at depth than that at the surface. Therefore, the effects of nitrogenous waste toxicity may be amplified in areas of low pH.

Industrialization, fossil fuel burning, mining, and urbanization are the primary causes of pollution in aquatic environments (Jan et al. 2015; Silva Pinheiro et al. 2020; Wolle et al. 2019). Among those pollutants are certain metals, such as aluminum, arsenic, cadmium, chromium, copper, nickel, lead, mercury, and silver that can bioaccumulate or biomagnifiy in aquatic animal tissues to levels that become toxic to animals and humans (de Almeida Rodrigues et al. 2021). There is enormous variability in tissue and body concentrations of accumulated trace mentals across taxa (Rainbow 1990, 1993, Phillips & Rainbow 1994). Crabs, however, display the highest metal bioaccumulation rates among crustaceans (Raknuzzamann et al. 2016; Baki et al. 2018; Ayanda et al. 2018). Levels of trace metals accumulated in the bodies of marine organisms depend on water quality, salinity, temperature, diet, reproductive cycle, and individual variation (Rajeshkumar & Li 2018). Decapod crustaceans, however, can regulate levels of certain essential metals such as: copper, chromium, manganese, zinc, and nickel (Rainbow 2007). The highest concentration of zinc was found in Shark Key 9, and both the surface (85.9 ppb) and bottom (194.5 ppb) concentrations exceeded safe chronic (81 ppb) and acute (120 ppb) limits (USEPA 2018). Cadmium and lead are common inorganic contaminants in marine and coastal sediments and are highly toxic even in low concentrations (Sokolova et al. 2004; Ivanina et al. 2008, 2010). Lead was found in 9 out of the 16 quarries, and cadmium in six quarries. Trace metal toxicity tolerance by *M. spinosissimus* is unknown, but cadmium and lead do not have physiological functions in crustaceans, and they cannot regulate these metals through normal physiological processes (Adeleke et al. 2020). Liu et al. 2016 exposed female estuarine crabs (*Chiromantes dehaani*) to 0.05, 0.1, 0.5 and 1 mg/L of cadmium chloride ($CdCl_2$) for 7, 14, and 21 days. Their results showed that lipid concentrations in the hepatopancreas and ovary of exposed crabs decreased after sustained exposure to cadmium (0.05, 0.1, 0.5, and 1 mg/L), suggesting that it decreases the lipid content by damaging the ability to digest, transport and synthase lipid (Liu et al. 2016). The cadmium concentrations reported by Liu et al. (2017) are significantly higher than that found in quarries (<0.05 mg/L), and the safe limit for saltwater determined by the EPA (7.9

ppb chronic and 33 ppb acute) (USEPA 2018), therefore suggesting that quarry concentrations have not reached toxic levels (1 ppb = 0.001 mg/L).

Lead can affect the reproductive and immune systems of crustaceans. A study exposing crabs (*Sinopotamon henanense*) to different concentrations of lead (0, 3.675, 7.35, 14.7, 29.4 and 58.8 mg/L) over 3, 5, and 7 days, higher concentrations of lead reduced the integrity of the sperm plasma membrane, the acrosomal membrane, and DNA which was attributed to increased oxidative stress (Li et al. 2017). Additionally, Xu et al. (2019) identified that crabs (*Charybdis japonica*) exposed to low concentrations of lead over long durations and high concentrations over short durations experience a reduction in enzymes in the immune system. Quarry concentrations of lead were less than the maximum limit for chronic (8.1 ppb) and acute (210 ppb) exposure provided by the EPA (USEPA 2018), and these low levels are not a concern for crab health.

When considering crab mariculture in quarries, one must be aware of the effects of heavy metals on human health and continue to monitor their concentrations present in the culture environment. Cadmium poisoning occurs from inhalation (Jaishankar et al. 2014) or ingestion of food, such as crustaceans (Baki et al. 2018). Cadmium poisoning can cause lung, liver, skeletal, reproductive, renal and cancer effects (Zhang and Reynolds 2019). Crabs (Jerome & Chukwuka 2016) and shrimp (Santos et al. 2013) have also been reported to contain lead concentrations above the limit allowed by numerous regulatory institutions. Lead poisoning can cause neurological symptoms, paralysis, gastrointestinal symptoms, anemia, and cancer (Ayanda et al. 2018). Lead can affect several tissues, making it one of the most systematic toxicants. Mercury contamination primarily happens through the consumption of seafood. Low doses throughout life can lead to chronic intoxication through bioaccumulation (de Almeida Rodrigues et al. 2021).

Fetuses are the most vulnerable to mercury poisoning and can occur without the mother showing symptoms (Brown & Austin 2012). Mercury concentration levels (5.15 ppb) in surface waters of the quarry “Tavernier 3” exceeded the United State’s EPA’s recommended water quality criteria limit (0.94 ppb chronic and 1.8 ppb acute) for aquatic life in salt water. According to the results of the trace metal analyses, and human health concerns with the concentrations of these trace metals, some quarries may not be ideal for mariculture if they are used to grow crabs for human consumption in the future.

As was expected, nutrient and trace metal concentrations were consistently higher near the bottom and below the halocline in stratified quarries. However, juvenile, and adult *M. spinosissimus* were only observed in the upper water column of both stratified and unstratified quarries. There is no documented information on *M. spinosissimus* larval movements in these quarries and how that may affect their exposure to different water quality conditions. The presence of adults and juveniles in the upper water column of quarries is most likely a result of food availability rather than water quality parameters. Winfree and Weinstein (1989) noted that *M. spinosissimus* regularly grazes on lush algal growth at night near the surface after hiding in crevices during the day, and are not commonly found along unvegetated areas, or areas shaded by tree cover. Lush algal growth was most prominent along the sides of the quarries near the surface where we observed hundreds of crabs feeding along the vertical limestone walls.

A recent study conducted by Gravinese et al. 2022 suggests that *M. spinosissimus* juveniles may also be tolerant to reduced seawater pH (7.7) and elevated temperatures (31 ºC) after their brief larval stages. Crab populations living in shallow coastal habitats, which experience more pH fluctuations from biological activity, eutrophication, and upwelling tolerate exposure to reduced pH better than their deep-sea counterparts (Pane & Barry 2007). Quarries containing crab populations did not have a seawater pH less than 7.5 or a surface temperature range greater than 30 ºC based on the measurements taken, indicating that these populations may be within their tolerance range, or may have developed tolerant genotypes (Sibert et al. 2004; Parker et al. 2012).

Population Structure and Dynamics of *M. spinosissimus* in Quarries and Reef Sites

Population size structure and dynamics of *M. spinosissimus* were similar for crabs dwelling in quarries and nearby wild habitats (e.g., reef and hard-bottom habitats). The overall size distribution of crabs in quarries and from reefs were nearly identical. Male size distribution in quarries and nearby wild habitats were similar, where small and large males were most abundant, while “medium-sized” males were less abundant. Small males are most likely abundant because of their ability to hide efficiently within structured habitats to avoid predation or aggression from other males. Large males are known to be superior fighters in most brachyuran crab species (Nakayama & Wada 2015; Tina et al. 2015), and therefore, are most likely successful when fighting with “medium-sized” males. This should be considered when determining stocking density of males, because if they are stocked too high it could lead to more frequent aggressive encounters and therefore, higher mortality rates.

Estimates of relative growth and nutritional condition of reef and quarry crabs were also similar. Concentration of protein in the haemolymph decreases in starved crustaceans (Gutzler & Butler 2017; Moore et al. 2000; Pascual et al. 2006; Wang & McGaw 2014). Therefore, measuring the protein concentration in the haemolymph of crustaceans can provide insight into their current condition (Paterson et al. 2000; Ozbay & Riley 2002; Behringer & Butler 2006; Lorenzon et al. 2013 Lopeztegui-Castillo 2021). Based on standardized comparisons among crabs while in molt cycle stage “C”, there was no difference in haemolymph protein concentration between crabs from quarries and the wild. Nutritional condition is an indicator of the quality and quantity of food sources and influences the growth rate of crustaceans (Oliver & MacDiarmid 2001; Behringer & Butler 2006; Gutzler & Butler 2017). Although the correlation between food consumption and hemolymph protein concentration has not been established for *M. spinosissimus*, these index numbers suggest that crabs in both habitats were in good nutritional condition based on studies with other crustaceans (Moore et al. 2000; Oliver & MacDiarmid 2001; Wang & Mcgaw 2014). Therefore, we can conclude that both *M. spinosissimus* populations surveyed from quarries and in the wild were in relatively good health based on high levels of haemolymph protein concentration.

The fecundity of crabs was positively correlated with carapace width for both quarry and wild populations, as documented for other decapod crustaceans (Jones et al. 1989; Bert et al. 2016; Crowley et al. 2019). However, inspection of those data suggests that smaller quarry crabs have lower fecundity than their reef counterparts of the same size, and the opposite is true for larger crabs with a break in relationship occurring around 70 mm CW such that fecundity appears higher among quarry crabs than wild crabs. Increased food constraints can cause negative allometric scaling of brood production with body size (Bolanos et al. 2012). Because quarries displayed higher percent algal cover than patch reefs, it is possible larger female crabs on reefs have increased food constraints, which can lead to lower fecundity.

Predation on Crabs in Quarries

Predators of crustaceans are abundant in Caribbean coral reef communities. Octopuses (e.g., *Octopus briareus* and *Octopus vulgaris*) are notorious predators of decapod crustaceans (Mather & O’Dor 1991; Grisley et al. 1996; Berger & Butler 2001; Anderson et al. 2008; Butler and Lear 2009). The interactions of Caribbean octopus species with *M. spinosissimus* are unknown, but it is suspected that they are a predator based on the presences of crab parts in the stomach contents of *Panulirus guttatus* (Butler & Kintzing 2016). In Big Coppitt quarry, I observed several Caribbean reef octopuses (*Octopus briareus*) during nighttime snorkel crab density surveys. In this same quarry, I also observed nurse sharks (*Ginglymostoma cirratum*), Caribbean spiny lobster (*Panulirus argus*) and numerous species of snapper (*Lutjanus* sp.), which are all known predators of crustaceans (Cox et al. 1997; Castro 2000; de la Moriniere 2003) and are evidence of the frequent connection between that particular quarry and the surrounding sea. The greater diversity of crustacean predators in Big Coppitt suggests a possible reason why the abundance of *M. spinosissimus* is lowest in this quarry compared to the other three that also contain *M. spinosissimus* populations but few if any predators. However, only daytime footage of predators was captured, and therefore, predator abundances and their activity could differ at nighttime in these quarries.

The tethering experiments indicated that predation on sub-adult and adult *M. spinosissimus* was similar across quarry, hard-bottom, and coral reef habitats. Survival of *M. spinosissimus* was particularly similar between hard-bottom and quarry habitats. In these habitats, crabs between 30 – 60 mm CW had the lowest percent survival (60%). This may indicate that there are crevices small enough in these habitats for crabs < 30 mm CW to hide in to avoid predators, and larger crabs (60 – 90+ mm CW) can avoid predation due to their size. Whereas on coral reefs, small crabs < 30 mm CW have the lowest survival, which is similar to predation rates measured by Spadaro and Butler 2021.

Crab Competitors in Quarries

Interspecific competition between *M. spinosissimus* and other herbivores in quarries appears unlikely because quarry daytime video surveys captured very few potential competitor of

M. spinosissimus, although I observed a few herbivorous fish in some quarries during my field work. In addition, nighttime video surveys could have captured activity of other nocturnal grazers, if any. *Maguimithrax spinosissimus* prefers fleshy macroalgae but will consume a variety of algae that are unpalatable to most fish grazers (Butler & Mojica 2012). Rainbow parrotfish (*Scarus guacamaia*) were observed in two of the 16 quarries, but parrotfishes in the genus *Scarus* primarily feed on turf algae (McAfee & Morgan 1996; Burkepile & Hay 2010). Due to the feeding preferences of *Scarus* and the flexible palate of *M. spinosissimus,* I suspect that there would be minimal competitive interactions between these species even when each is at high abundance. I also observed an extraordinarily high density of urchins (*Echinometra viridis*), which are nocturnally active herbivores on reefs (Ogden & Lobel 1978), in one quarry (Big Coppitt). This high density of urchins and the occurrence of parrotfish in Big Coppitt quarry explains why it also contains the lowest percent algal cover when compared to the 15 other quarries surveyed.

Genomic Considerations

Lastly, when selecting a species for aquaculture, one should consider long-term genetic adaptability to culture conditions. The most consideration should be given to the heritability of economically important traits, such as growth rate (Nelson 1977; Jung et al. 2013). Because of their large size, short larval duration, and fast growth rate, *M. spinosissimus* possesses favorable traits for aquaculture. However, only a few studies have performed genetic analyses on this species. The first to document the complete mitochondrial genome of *M. spinosissimus* was Marquez et al. (2016). Hurtado-Alarcón et al. (2018) identified two genetic stocks of *M. spinosissimus* in Colombia in an effort to improve fisheries management. Lastly, genetic data collected and analyzed by Baeza et al. (2019) suggests that there is low to moderate connectivity among populations in the wider Caribbean. There is no information regarding the genetics of *M spinosissimus* populations within quarries or the potential gene flow between quarries and nearshore sites. I collected leg samples from both quarry-dwelling and reef-dwelling *M. spinosissimus* to be used for genomic analyses conducted by the Bracken-Grissom Lab for Crustacean Genomics at Florida International University. The first round of genomic analyses has been completed for tissue samples taken from Big Coppitt, Cudjoe east, and Cudjoe west quarries. Preliminary results show that quarry populations have specific haplotypes not found in previously sequenced Florida reef populations and that quarry populations are less diverse than reef populations. A possible explanation for these results is the loss of genetic variation that occurs when a small number of individuals from a larger population establishes a new population, otherwise known as the founder effect (Mayr 1942). Future results will provide us with relevant information about the gene flow of quarry crabs and how it compares to their reef counterparts.

It is also important to consider the potential impacts of cultured organisms on natural populations. Stocks produced in hatcheries can be used to replenish or supplement recreational and commercially important stocks, rebuild populations of threatened and endangered species, or restore habitats such as coral reefs (Waples et al. 2012). Juvenile-release stock enhancement programs exist for hundreds of species (Bartley et al. 2004; Lorenzen et al. 2013) and the genetic and ecological risks that cultured stocks pose for wild populations is well documented (Waples et al. 2016). Inbreeding, selection, and genetic improvement produce new genetic characteristics among aquaculture stocks that are linked to the domestication process and these changes can occur rapidly over a few generations (Danancher & Garcia-Vazquez 2011).

When domesticated stocks are introduced to wild stocks there are three major types of genetic risks that may occur: loss of diversity within populations, loss of diversity among populations, and loss of fitness (Waples et al. 2016). Risk of low genetic variability within populations can increase when the effective population size of the captive population is lower than natural populations, and when the portion of spawners coming from captive origins is high (Waples et al. 2012). Loss of among-population diversity includes the replacement of current patterns of locally adapted populations with smaller, homogenous ones due to introduced or escaped aquaculture broodstock. Lastly, the process of domestication produces populations that are better adapted to artificial environments. Domesticated individuals are less fit when introduced into the wild, and their successful reproduction can depress fitness and compromise viability of the natural population (Waples et al. 2012).

However, Belle and Nash (2008) stated that in addition to genetic risks, escaped stocks can also cause pathogen transmission, competition for resources, colonization, predation, or damage to existing commercial or recreational fishing. In the United States, these outcomes have not occurred for most commercially cultured aquatic species because: most species are cultured within their native range; most pathogens occur naturally and are abundant; nonnative species are met with strong biological resistance; and because there are a variety of invasive-species regulations implemented by federal and state agencies to manage potential impacts (Zajicek et al. 2021). King et al. (1999) and NRC (2003) were two studies that investigated genetic impacts of farm escapes on wild Atlantic salmon populations in Maine, and both concluded that there was no evidence of genetic impact detected in wild Atlantic salmon (*Salmo salar*) populations. However, ecological consequences may be more pronounced when cultured salmon are an exotic species and not an indigenous one (Gross 1998). Therefore, I believe that with proper aquaculture management practices and the use of quarries as a natural environment to culture Caribbean king crab within their native range, the risks associated with their stock enhancement on Caribbean coral reefs should be relatively low.

This work represents the first set of biological data collected for *M. spinosissimus* populations living in Florida Keys quarries. In brief, environmental conditions in the quarries are conducive for the mariculture of *M. spinosissimus*, with the possible exception of unsafe trace metal concentrations in some quarries, and adequate shelter, which is reflected in the low rugosity scores in quarries. Still, hatchery-reared crabs have not been released in quarries and their survival and growth compared with crabs from the reef has not been evaluated. This is a logical next step to testing the efficacy of mariculture in these environments. Based on the data collected, I believe mariculture would be most efficient in the larger quarries with high algal cover and low numbers of predators and competitors. Increasing shelter availability for crabs may additionally enhance their production in quarries.

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APPENDIX

Information for each quarry where data was collected.

Quarry ID	Quarry Location	Latitude	Longitude	Area (m)	Area (ha)	Depth (m)	Distance from coast (m)
SL	Sugarloaf Key	24 37' 13.4"	-81 31' 29.8"	23193.44	2.319344	11.6	170.4
T2	Tavernier	25 1' 23.12"	-80 30' 19.11"	78287.24	7.828724	13.3	502.3
T3	Tavernier	25 1' 41.82"	-80 30' 16.81"	22103.59	2.210359	7.0	312.9
SK6	Shark Key	24 36' 11.9"	-81 38' 42.1"	3683.28	0.368328	11.6	59.4
SK7	Shark Key	24 36' 15.0"	-81 38' 44.2"	1603.674	0.160367	10.0	64.9
SK8	Shark Key	24 36' 19.0"	-81 38' 48.8"	13116.22	1.311622	18.7	70.0
SK9	Shark Key	24 36' 37.5"	-81 39' 01.3"	5162.576	0.516258	16.7	70.1
T10	Tavernier	25 0’ 23.18”	-80 31’ 25.17”	16327.6	1.63276	9.1	434.9
GK	Grassy Key	24 46' 14.83"	-80 56' 17.17"	35654.76	3.565476	19.8	155.2
CJE	Cudjoe Key	24 40' 15.9"	-81 30' 04.1"	51856	5.1856	15.2	586.3
CJW	Cudjoe Key	24 40' 24.90"	-81 30' 05.60"	35335.63	3.533563	13.8	977.9
BC	Big Coppitt Key	24 36' 04.3"	-81 40' 20.4"	222172.4	22.21724	16.9	61 .5
KL23	Key Largo	25 8' 17.16"	-80 24' 15.31"	2927.285	0.292729	8.3	25.7
KL24	Key Largo	25 03 17.2"	-80 28' 38.1"	3855.901	0.38559	10.6	17.7
SKC	Marathon	24 44' 57.36"	-80 58' 39.87"	27211.7	2.72117	5.0	56.2
NN	No Name Key	24 42' 8.154"	-81 19'54.56"	8985.86	0.89859	15.2	192.7

Coordinates for hard bottom and reef sites.

Location	Latitude	Longitude
Sugarloaf Lodge	24.6466686	-81.5656389
Twin Keys - Casitas	24.95277778	-80.74638889
Arsnicker Keys	25.9125	-80.8425
Long Key - Mayors	24.831381	-80.811842
Rachel Key	24.738036	-81.049631

VITA

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EDUCATION

M.S. (expected May 2023) – Biology, Old Dominion University, Department of Biological Sciences, Norfolk, VA
B.S. (May 2018) – Marine Science, Concentration: Marine Biology, Stockton University, School of Natural Sciences and Mathematics, Galloway, NJ
A.S. (May 2016) – Environmental Science, Brookdale Community College, Lincroft, NJ

PROFESSIONAL EXPERIENCE

2021-Present	Research and Development Manager, Oyster Seed Holdings, INC., Hudgins, Virginia
2019-2021	Graduate Teaching Assistant, Old Dominion University, Norfolk, Virginia
2019	Aquarist/ Environmental Educator, The Wetlands Institute, Stone Harbor, NJ
2018	Lead Scientist/ Support Staff, New Logic Marine Science Camp, NJ
2017-2019	Marine Fisheries Technician, New Jersey Department of Fish and Wildlife: Bureau of Marine Fisheries, Port Republic, NJ
2017	Fish Tagging Intern, American Littoral Society, Highlands, NJ

VOLUNTEER EXPERIENCE

2018	Fall Bottom Trawl Survey, NOAA Ship Henry Bigelow, Georges Bank
2018	Volunteer horseshoe crab tagger, American Littoral Society, Highlands, NJ
2018	Shark tagging, Guy Harvey Research Institute, Ft. Lauderdale, FL
2018	Invertebrate zoology undergraduate teaching assistant, Stockton University, NJ
2016	Shark tagging, Glover's Reef Marine Field Station, Belize

HONORS AND AWARDS

Biology Graduate Student Organization Travel Award, Old Dominion University, VA
Stacy Moore Hagan Estuarine Science Scholarship, Stockton University, NJ

CERTIFICATIONS

AAUS First Aid, CPR, Emergency Oxygen Administration, Old Dominion University, VA
PADI Open water Diver, Divers Two, Avon-By-The-Sea, NJ