Coral Reefs under Threat: Could Repopulating the West Indian Spider Crab Help?

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Abstract

Marine Ecosystems in the Caribbean have been actively shifting from an ecological state of coral reefs to macroalgal dominated ecosystems which grow on stony coral skeletons. This shift in stable states has been expedited by the effects of anthropogenic climate change. Coral reefs and macroalgae are rival species that will compete for space in order to obtain nutrients, sunlight, and space to grow. Thus, since current conditions for coral growth are becoming more unfavorable due to climate change (increasing sea temperatures) macroalgae is becoming dominant on reefs in the Caribbean. In order to assist the restoration of Caribbean coral reefs, researchers have proposed reintroducing *Minthrax spinosissimus*, the West Indian Spider Crab, to the Florida Keys in order to limit competition between new coral recruitment and macroalgae growth. This paper works to create a management report for key components that must be necessary to ensure a successful reintroduction, including (1) pre-reintroduction laboratory and field experiments, (2) specific goals outlined in detail to analyze success of the reintroduction at different intervals after reintroduction. And (3) long term monitoring practices to analyze coral growth and species populations of *spinosissimus*.

Introduction

Coral Reef Ecosystems are one of the most biodiverse ecosystems on the planet and have huge ecological importance and human benefit. These ecosystems are home to about 25% of all known marine fish species, and provide crucial habitat, breeding grounds, and food for marine species. (Environmental Protection Agency, 2021). Not only are coral reefs critical for the maintained health of the oceans, they also play important roles for humans by providing ecosystem goods and services. Moberg & Folke listed these goods and services in their 1999 paper as follows; "renewable resources, mining of reefs, physical structure services (coastline protection from hurricanes), biotic services (maintenance of ecosystems, Export of organic production, and plankton to pelagic food webs), biogeochemical services, (nitrogen fixation, CO_2/Ca budget control), Information services (climate and pollution records), and social and cultural services (Recreation, fishing, ecotourism)." It is estimated that coral reefs bring in $36 billion a year in economic value to the world through activities such as fishing, scuba diving, and off-reef tourism such as eating local seafood, vacationing on beaches adjacent, paddleboarding, etc. (Brumbaugh, 2017). However, anthropogenic climate change is causing coral reef coverage to decline globally, by as much as 80% in certain areas of the world such as the Caribbean (Gardner et al., 2003). The need to protect these invaluable ecosystems is at an all-time high, and thus new innovative management techniques are being introduced in the hope to maintain coral reef health. One such management technique is the reintroduction of *Minthrax spinosissimus,* the West Indian Spider Crab, to the Florida Keys in hopes of encouraging new coral recruitment. A 2021 study by Spadaro and Butler documented a field experiment using *M. spinosissimus* in controlled environments. The authors designated 12 reef patches in the middle of the Florida Keys reef tract for use in the experiment and implemented three treatments (a replicate of 4 reefs per treatment) to test the effectiveness of *spinosissimus*'s removal of macroalgae on coral reefs. The three treatments were: unmanipulated coral reefs, reefs stocked with crabs, and reefs on which divers manually removed seaweeds and added crabs. The results were striking, showing that macroalgae coverage on each patch stocked with the crabs was 50% less than on unmanipulated reefs, and on patches where the seaweed was manually removed and crabs were added the coverage was approximately 80% less than that of unmanipulated reefs. This study was repeated a second time the next year with nearly identical results, *M. spinosissimus* worked to clear about 50% of the seaweed from the substrate on coral reefs in the Florida Keys. Two years after each experiment, divers surveyed the area for new coral recruitment to allow for visible coral growth on the patch sites. The results showed 131 living juvenile corals on the first experiment, and 830 juveniles on both sites combined. This study also showed that the removal of macroalgae on the patch sites caused an indirect effect on the abundance of reef fish species, as the sites that were scrubbed and had crabs showed a 3-5 fold increase in fish density (Spadaro & Butler, Mark, 2021). This study has major ecological implications to the management of coral reefs, and the use of reintroduction biology to change the ecological state of the coral reef ecosystem. By using the results from Spadaro and Butler's research as a baseline, this paper identifies key management practices that must be in place in order to ensure a successful reintroduction of *spinosissimus* to the Keys and potentially to the greater Caribbean.

There has been extensive research published on the impacts of climate change and coral reefs, beginning in the 1980s and continuing into the present. According to Gardner et al., "the average hard coral cover on reefs has reduced by 80%, from about 50% to 10% cover, in three decades" (2003). This striking statistic analyzed coral coverage from 1973-2003, and recent studies have shown that coverage is still declining. According to Hoegh-Guldberg et al., even if the goals of the Paris Climate Agreement are achieved, coral reefs are likely to decline by 70–90% relative to their current abundance by midcentury" (2018). One of the main drivers of coral reef decline via anthropogenic climate change is global rising sea temperatures. (Hoegh-Guldberg, 2010; Hughes et al., 2003; Brown & Cossins, 2010). As more greenhouse gasses are emitted into the atmosphere, this creates a blanketing effect over the earth that traps energy from the sun in the atmosphere. Some of this energy is absorbed by the oceans, causing rising sea temperatures. Anthropogenic climate change has been documented since the late 1800s, and since then there has been no collective effort to slow the rate of emissions of harmful greenhouse gases that work to catalyze the effects of global warming. Using proxy data measurements from the Vostok ice cores, data can be reconstructed dating back 160,000 years to show that human impacts have altered the composition of carbon dioxide in the atmosphere, as time goes on the level of CO_2 in the atmosphere rises to new levels that had not been reached in the past 400,000 years. (Blackburn, 2011).

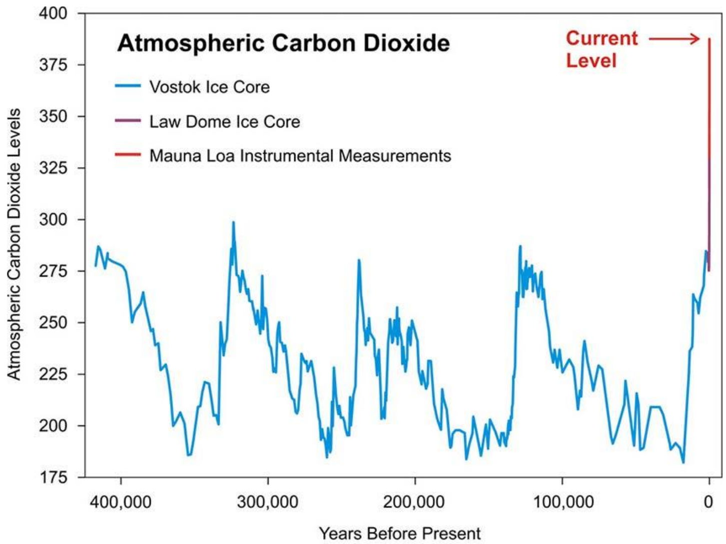

Figure 1: Past and present climate data showing rising atmospheric carbon dioxide levels globally.

The global average sea temperature is rising at a rate that is too fast for coral reefs to adapt to. Corals are animals that evolved millions of years ago, and thus their tolerance to rapidly changing sea temperatures are extremely low. Corals are classified into the phylum cnidaria, and further broken into classes; Hexacorallia and Octocorallia. For the purpose of this study, the main corals being referenced for restoration by *spinosissimus* are within the Hexacorallia class, Order Scleractinia, otherwise known as stony corals (Digital Atlas of Ancient Life). These corals are comprised by one large colony with many identical polyps that extract Calcium Carbonate out of the water and use it to grow their stony skeleton. Each polyp has a unique symbiotic relationship with marine algae called zooxanthellae, which are vital for coral's survival. The zooxanthellae photosynthetically provide the coral polyp with glucose for food and oxygen. In return, the coral provides zooxanthellae with a protected environment and the compounds needed for photosynthesis. Increasing water temperatures from global warming are causing corals to expel the zooxanthellae that live symbiotically within the corals calcium carbonate structure due to being in a high stress environment outside of the coral's temperature tolerance zone. (Brown & Cossins, 2010; Hughes et al., 2003). It is projected that within the next 20 years, sea temperatures globally could surpass the threshold for corals to survive, as these animals are not likely to genetically adapt to higher temperatures quickly enough (Hughes et al., 2003). Since coral species will not be able to adapt to these new temperatures and acidity levels on their own, the question for their survival becomes what can be done from a human standpoint to save these keystone species.

As corals are bleaching more frequently and undergoing more mortality events, there has been a shift in the ecological state of coral reef ecosystems from that of coral dominated benthic landscape to that dominated by macroalgae. Macroalgae in this paper is defined as any species that is benthic (is rooted to the sea floor) and classified into three different types: red, brown, and green algae. Two of the most common algal species on coral reefs in the Caribbean are Sea Lettuce (*Ulva lactuca*), and Sea Grapes (*Caulerpa lentillifera*) (Dell et al., 2020). Corals and macroalgae share the same tropic level as primary producers, and thus they are competitor species that will fight for the same resources such as light, nutrients, and space to grow (Smith,

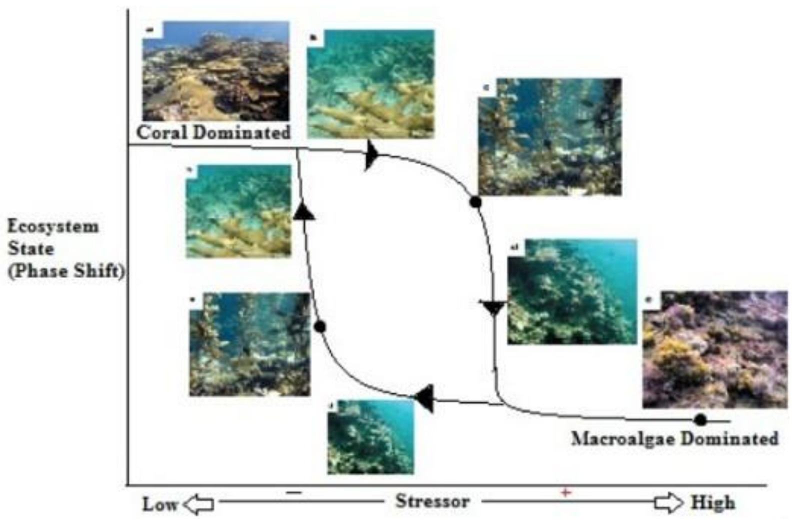

Figure 2: Diagram showing the ecosystem state and stressor relationship of a coral reef and macroalgal community. (image curtesy of Project Coral Online)

2015). The phase shift from coral reefs to macroalgae would be detrimental to the health of oceans globally, as coral reefs support an extremely high amount of biodiversity compared to their land coverage, as only about 1% of the ocean is coral reefs (Office of Habitat Conservation, 2022). A macroalgae dominated ecosystem does not support this high amount of diversity, and thus the shift from coral reefs to macroalgae could cause a full ecosystem collapse. Both coral reefs and macroalgal communities have bottom up ecosystem controls, meaning the primary producers control the subsequent trophic level populations. Corals provide a habitat that many species are endemic to and cannot live without, thus this phase shift to macroalgae is creating a completely different ecosystem with different trophic levels. This phase shift of stony coral coverage to macroalgal dominance has been documented since the 1970's as Dell et al., states “coral cover has declined to a regional average of 13%, while macroalgal cover is now ~ 40% of the forereef (between 28% and 45% by ecoregion” (2020). It has even been shown that macroalgae will secrete a chemical potent to corals called allelochemicals, further catalyzing the shift from corals to macroalgae. (Morrow et al., 2011). Therefore, in the bleached state that many corals are in, their sensitivity to allelochemicals, and macroalgae’s rapid growth rate, corals alone stand hardly a chance at recolonizing Caribbean reefs by themselves.

In an effort to combat the phase shift of coral reefs to macroalgal ecosystems, reintroductions of herbivorous species that graze on macroalgae have been conducted with various native species. Along with the crab, there are other guilds of herbivores that would fulfil the proposed role of grazing macroalgae from coral reefs. One reintroduction experiment that is of particular interest is the restocking of the Spiny Sea Urchin, *Diadema antillarum.* This species was a highly mobile herbivore that was abundant on reefs throughout the Caribbean, but due to a suspected water borne pathogen it experienced 93-100% mortality throughout the Caribbean over the span of 13 months, starting in January of 1983 (Lessios, 2016). The die from *D. antillarum* contributed to the ecological phase shift of coral reef dominated ecosystems to seagrass ecosystems, as this herbivore was responsible for clearing rocky substrate of algae for coral recruitment. Subsequent proposed reintroductions of *D. antillarum* were not successful over a large scale, and populations are not likely to recover to pre-1980 levels (Lessios, 2016). This was due in large part to increased predation on the herbivore and the effects of the disease still being prevalent. Lessios does however state that in small cohorts where *D. antillarum* has increased in population show greater levels of coral recruitment, survivorship, and growth (2016). Another reintroduction of marine herbivores has been restocking parrotfish on reefs, as these fishes are one of the most common herbivore presently found on reefs. (Lewis & Wainwright, 1985) However, this method of coral restoration via parrotfish could provide negative results, as parrotfish also exhibit corallivory, the act of grazing on coral polyps. If the population of parrotfishes on a reef is too high, or if there are multiple herbivores on the reef, parrotfishes could resort to corallivory in an effort to lower competition between other species, effectively undermining the goal of increased coral growth (Williams et al., 2019).

Many marine reef species provide relief to corals by grazing on their macroalgae competitors, including The West Indian Spider Crab, *M. spinosissimus*. The Crab is the largest species of herbivorous crab found in the Caribbean. Its habitat and range is documented in the book *Decapoda (Crustacea) of the Gulf of Mexico, with Comments on the Amphionidacea*, and the following information about its ecology is as follows. Its native range spans from North Carolina to South Florida, Cuba, and within the Caribbean Sea to Venezuela. Felder et al. classifies its habitat in four different zones; benthic, hard substances, loose rubble or coral fragments, associated with aquatic vegetation, and its native depth range is from the surface down to 179 meters (2009).

Figure 3: Native Range of Mithrax spinosissimus, courtesy of Felder et al., 2009

Studies conducted on the crab shows that it is highly mobile within their home ranges, and daily movement was inversely correlated with the density of the species in an area (Hazlett & Rittschof, 1975). Therefore, in a day this species would be able to cover a large amount of ground (approximately 1.5km/day) to feed on algae and clean substrate for coral growth, however from a reintroduction standpoint there would be a balance of the number of species to introduce without crowding the species, and potentially causing the crabs to be less mobile. This theory of less mobility with increased density is supported by Wilber and Wilber Jr.'s article in which they analyze the death rates of *spinosissimus* in culture and found that aggression-related mortality was more common at higher densities, and when clumps of macroalgae were introduced to the cultures to entice mobility and feeding, aggression mortality percentages rose to the highest percentage at 61% of deaths (1991). There are many articles relating to the genetic connectivity of the Crab throughout its native range in the Caribbean, which will be helpful when reintroducing the crab, as different regions of the Caribbean have genetically different populations of the Crab. The ecology and genetics of this species are very typical for the behavior that we would see for a marine herbivore and could make an ideal candidate for a top herbivore within its trophic class, aiding in the restoration of coral via herbivory of macroalgae on substrate. Another experiment that reinforces the idea that *M. spinosissimus* could be used as a key herbivore for the removal of macroalgae was a study conducted by Zeinert et al. using the crab for biofouling removal of marine aquaculture cages. The study concluded that the removal of macroalgae on the aquaculture cages was significant and the long term survival of the crab was high, over 80% of crabs in outside enclosures survived after the four trials, lasting from 11 days to 31 days. This study is also instrumental in obtaining rates of herbivory for the species of crab, as they concluded it's grazing rates were 3.3% - 4.16% bodyweight of algae in 22–24 °C water, 5.61% - 8.55% BW in 26–28 °C water. (Zeinert et al., 2021).

Other reintroduction experiments of terrestrial amphibians give insight to the feasibility of introducing a crustacean to a marine environment. According to nunez et al, "it is clear that exotic herbivores can play a fundamental role in re- structuring communities and drastically altering native ecosystems" (2010). This article was written in a mainly negative connotation, showing that introducing various herbivores (deer, beaver, lagomorphs, and insects) to an ecosystem can drastically shift the stable state of the terrestrial environment. However, since that would be the goal of an introduction of *M. spinosissimus,* these documentations provide a set of successful experiments that could be emulated in the marine realm. Specifically, one introduction experiment of Apple Snails (*Pomacea canaliculate*) in Asian wetland environments has been shown to help targeted species of macrophytes grow in the wetland ecosystem, as the snails were introduced specifically to target and consume a competitor of the favored macrophyte (Yam et al., 2016). Given the past studies done for herbivory management for coral regrowth, there must be a set criterion present for the herbivore species being introduced to be able to perform successfully, which can be applied to the Florida Keys and subsequently the greater Caribbean, where *M. spinosissimus* plans to be reintroduced to. Using the other herbivory experiments in the terrestrial environment, it has been shown that a "bottom up" trophic cascade within an ecosystem is possible given the type of herbivore introduced. The snail *P. canaliculate* is an excellent example of this bottom up management of Asian Wetlands, and this snail exhibits ecological behavior similar to that of *M. spinosissimus*, therefore this reintroduction experiment could be used as a baseline for the creation of a management strategy for the introduction of *M. spinosissimus.*

Reintroduction biology is typically met with skepticism by other researchers due to the conventional reasons for the reintroduction of a species. Reintroductions have historically been conducted by large nonprofit organizations such as zoos, which have the goal of restoring biodiversity most efficiently, without understanding the mechanisms of population growth and extinction (Sarrazin & Barbault, 1996). Limitations of the field itself are generally the result of lack of post-reintroduction monitoring of the species and ecosystem. Specifically within the marine science field, herbivory reintroductions are limited in success by the general lack of understanding of what limits the continued growth of adult coral colonies and how diversity within the herbivorous trophic level of a reef impacts algal accumulation (Adam et al., 2015). The objective of this paper is to create a comprehensive management strategy for the best practice to introduce the crab, if the study is found to be feasible, and a larger scope of where *spinosissimus* could be introduced given the current ecological state of the reefs in the Caribbean.

<u>Methods</u>

For the first component of this paper, suggesting the best management practice for the reintroduction of *M. spinosissimus*, a comprehensive search of applicable peer reviewed papers was conducted that was classified into two separate groups: (1) past reintroduction projects that are similar to *spinosissimus* in terms of trophic level and ecological role, and (2) management practices for marine ecosystems, specifically coral reefs. For the first group, a set of criteria was determined in order to ensure that previous reintroduction experiments were as applicable as possible to the proposed introduction of *M. spinosissimus.* These criteria included: trophic level of the species being reintroduced, type of habitat introduced, as some habitats operate on a top down ecosystem control vs a bottom up ecosystem control. The coral reef habitat that *spinosissimus* would be introduced to is a bottom up ecosystem control, and thus the examples that are pulled for analyzation would be more beneficial if the ecosystem was a bottom up control. Lastly, if the authors classified this study as a success or not. It would be beneficial to have multiple studies that have been classified as both a failure and a success in order to remain unbiased towards the outcome and to aid in the understanding of particular events or characteristics that make a reintroduction study unsuccessful. It is preferred to have six case studies in total that meet the criteria, 3 that were classified as successes and three that are classified as failures.

The second group of literature that was compiled for this project is a set of terrestrial and aquatic reintroduction goals and best management practices, which have been used to create a management practice and best way to introduce *spinosissimus* to the Florida Keys region and, long term, throughout the Caribbean. These articles were chosen from a different set of criteria, as I wanted to create a set of metrics for reintroduction that has been proven to aid in the success of a reintroduction. Therefore, the metrics that were chosen for these studies were: (1) year published, as the longer the publication remained in circulation, the more reintroduction studies could use the criteria highlighted in the original publication and there would be more evidence for the correctness (or failure) of the criteria set in place for reintroduction studies. The other piece of criteria was (2) how many times this article was cited in other pieces of literature. In keeping with the points from the last set of criteria, the metric of citation number further solidifies the point that the set of practices listed in the publication are successful due to the amount of studies that used this publication for their own reintroduction studies, or vice versa, depending on the results of the studies that have cited the original publication, and I will be checking for success or failure of the reintroduction studies that have cited the original management practice in order to only find articles that have management practices that have been tested and proven to be successful many times.

The second component of this study is providing a map of the future places that *spinosissimus* could be reintroduced beyond the Florida Keys, if the proposed reintroduction study is conducted and shows promising results for the regrowth of coral reefs within the Florida Keys Reef Tract, this species could be reintroduced to the larger Caribbean. In order to create a functional map of habitable areas where *spinosissimus* could be reintroduced, literature will be compiled that outlines the specific habitat types of several parts of the Caribbean, broken into different ecoregions as outlined in Wilkinson et al's book *Marine Ecoregions of North America*. For each ecoregion, specific metrics such as temperature, depth, benthic substrate, species of algae, and other herbivores present will be analyzed and checked for compatibility with the ecology and physiology of *M. spinosissimus*. Then, a map will be created with the use of GIS software that will show the previous historical range of the crab, where it is found now, and the proposed areas where it could be reintroduced given the current state of each ecoregion, in order to show applicability that this study can be expanded outside of a small sample range such as the Florida Keys.

Results

Analyzation of six papers for the past reintroduction experiment component of the first goal of this project, creation of a management report, yielded relatively redundant information regarding reintroductions. Of the 6 papers, three reported negative results, while three reported positive results. Reintroductions based on species tropic level included one producer, three herbivores, one omnivore and one carnivore. The single most suggested management practice was the implementation of post reintroduction long term management of the ecosystem the species was reintroduced to. In one study the lack of long term monitoring was considered a reason for the failure of the project (Bennett et al., 2016). Other popular reasons for the success or failure of the reintroduction project included: if the ecosystem was protected by a government agency or not, lack of understanding the initial decline in the species being reintroduced, poorly defined objectives and criterion for success, interactions with competitor species and the rest of the trophic levels in the ecosystem, lack of understanding about the ecological function of the ecosystem prior to reintroduction, and foundational understanding of the proposed reintroduced species ecology and environmental needs.

For the existing management practices section of the literature, many overlaps were present between existing reintroduction experiments in terms of moving forward with new best practices. However, of the five articles used for the creation of a management report, two were focused on management practices of herbivory on coral reef sites, one highlighted the pros and cons of the most popular current coral restoration techniques (as of 2020), one was a general outline of current challenges regarding reintroductions, and the last was an example management report for the reintroduction of Sockeye into Skaha lake (2004). Of these five papers, general themes became apparent for the necessary components of a reintroduction experiment before the reintroduction itself. These components include: (1) identifying and clearly defining the goals and metrics for success for a restoration project. (2) Creation of a spatial management plan that has detailed knowledge on the distribution of suitable habitat for the reintroduced species. (3) Identification of other factors that are limiting the growth of corals other than competition of macroalgae in order to better predict the sites that would most benefit from the reintroduction of *spinosissimus* (Adam et al., 2015; Boström-Einarsson et al., 2020; Sarrazin & Barbault, 1996). There were also other key factors that were highlighted post-reintroduction, the factor that was most common was increased post-reintroduction monitoring of the sites to evaluate the success of the reintroduction experiment.

Determining the range of reintroduction of *spinosissimus* was done so by comparing the average annual water temperature, benthic substrate type, species of macroalgae present, and existing competitor herbivore species present. By using the book *Marine Ecoregions of North America* four different regions were identified and used to show feasibility of reintroducing *spinosissimus* to four different regions within the Caribbean. These regions were as follows: South Florida/Bahamian Atlantic, Northern Gulf of Mexico, Southern Gulf of Mexico, and Caribbean Sea. (T.A.C et al., 2009) The following table shows the habitat types of each ecoregion.

	Average low and high temperature	Benthic Substrate Type	Species of Macroalgae Present	Existing competitor herbivore species present
South Florida/Bahamian Atlantic	22.5 - 28°C	Seagrasses, coral reefs, sand banks, caves and crevices, mangroves	*Dictyota menstrualis, Dictyota pulchella, Halimeda opuntia (Smith, 2015)*	Parrotfishes (Smith, 2015)
Northern Gulf of Mexico	14 - 30°C	sand barriers; silt and mud, with clays in central Gulf coast; sandy muds in Texas; and sand and carbonate muds in Florida	Red, brown, green algae (Wynne, 2008)	Surgeonfish (Smith, 2015)
Southern Gulf of Mexico	24 – 28.5°C	Seagrasses, coral reefs, mangroves, estuaries, lagoons, deltaic systems	corticated foliose algae (Favoretto et al., 2020)	Parrotfish, surgeonfish, urchins accounted for only 9% of herbivory. (Favoretto et al., 2020)
Caribbean Sea	25.5 - 28°C	coral reefs, mangroves, seagrass beds, deepsea communities	*Galaxaura rugosa, Dictyopteris delicatula, Wrangelia argus* (Ballantine & Aponte, 1997)	*Diadema antillarum,* parrotfishes, surgeonfishes (Gonzalez, 2020)

<u>Table 3:</u> comparing key environmental needs of *M. spinosissimus* across different ecoregions within the Caribbean

Each of the key components of an ecosystem were ranked by importance based on the most basic ecological needs of a species. The ranking is as follows: (1) species of macroalgae present. Arguably the most important aspect of reintroduction is ensuring the survival of the species, which would not be possible if the preferred type of algae the *spinosissimus* consumes is not present. The results from Zeinert et al (2021) concluded that the crabs have a high preference for turf algae, which is comprised of many different genera, however their study on biofouling removal of cages concluded that the crabs were not specific in their eating choices, and cleared macroalgae from 95 ± 3% to 58 ± 9% during the 20 day trial. Therefore, all of the genera noted to be most prevalent in all of the ecoregions would be sufficient food for the crab. Component (2) is Benthic Substrate Type. *Spinosissimus* was noted to have habitat preferences of "benthic, hard substances, loose rubble or coral fragments, associated with aquatic vegetation" (Felder et al., 2009). Using this metric to determine suitable habitat, the ecoregion "Northern Gulf of Mexico" was eliminated due to a lack of benthic structure that the crab prefers. This species uses crevices and caves that naturally occur on coral reef and other rock substrate that this ecoregion does not have, therefore it can be deduced that the Northern Gulf region would not be suitable for reintroduction. Component (3) is temperature, as noted in Felder et al., 2009 and Zeinert et al. 2021, the crabs have a temperature range of approximately 22°C - 28°C, however the crabs were shown to have a statistically significant higher rate of grazing at higher temperatures, indicating their preference for warmer waters. Therefore none of the existing ecoregions are eliminated, but should be noted when reintroducing the species to areas with lower winter temperatures. Component (4) of existing competitor species is the least important component due to the understanding that if *spinosissimus* is reintroduced to the ecosystem, it will create a shift in herbivore populations, and the goal is that it would outcompete other herbivores who are currently residing in the ecosystem. Therefore no ecoregions will be eliminated via this component, but will be interesting to note how different herbivorous functional feeding groups will respond to the grazing *spinosissimus*. Given the hierarchy of ecological components of the species, it is determined that *spinosissimus* could be reintroduced to three of four ecoregions, those being the South Florida/Bahamian Atlantic, Southern Gulf of Mexico, and Caribbean Sea. A map created with the use of GIS outlining potential areas of reintroduction is below. It should be noted that the reasoning for the absence of *spinosissimus* to the middle Caribbean Sea is due to the depth range of the animal, as this species cannot tolerate depths greater than 179 meters.

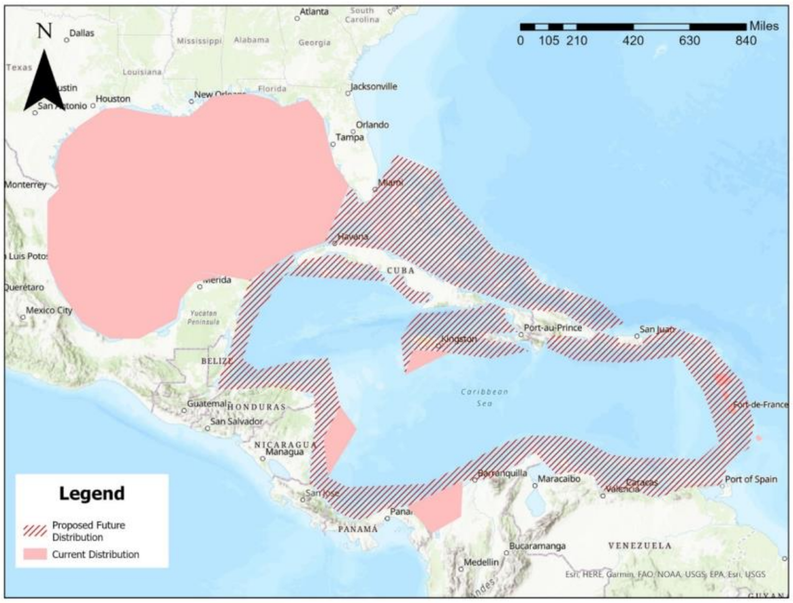

Figure 2: Current and Proposed Distributions of *M. spinosissimus.*

Discussion

Given all of the published materials regarding reintroduction experiments and management practices, a clear management report can be created that takes the necessary steps to ensure that reintroduction of *M. spinosissimus* is done in the most responsible way in order to assist the adaptation of Caribbean coral species to the changing climate. Recommendations follow key components of past reintroduction experiments, as well as recommendations that each experiment and management report highlight as downfalls of past experiments. In order to have a successful reintroduction, a thorough review of how *Minthrax spinosissimus* will behave under different environments should be conducted. This paper serves to be a baseline for the literature review component of the review, analyzing the feasibility of reintroducing the crab within the Florida Keys, and subsequently the larger Caribbean. Through review of published peer reviewed studies, key ecosystem components were analyzed with the habitat needs of *spinosissimus* to determine suitable ecoregions for it's survival and population growth. Of the four ecoregions in the Caribbean, three of them have proven to be suitable environments for the survival and growth of the crab. These ecoregions are: (1) South Florida/Bahamian Atlantic, (2) Southern Gulf of Mexico, and (3) Caribbean Sea. It would be suggested that in addition to this paper, researchers conduct their own literature review to further solidify the understanding of the ecology of the crab and how it will interact with smaller microhabitats within ecoregions. In addition to the literature review conducted in this paper, a discussion of the existing management of the sites that the crab would be reintroduced to would be extremely beneficial in ensuring the success of the reintroduction. Results from (Williams et al., 2019)) showed that coral coverage before effectively managing herbivores (most notedly parrotfishes) coral coverage in both Marine Protected Areas (MPAs) was around 7%, while macroalgae coverage was approximately 35-45%. However, after 10 years of management (reduced fishing in MPAs) coral coverage within MPA's was estimated at 16–23, 38–56, or 36–75%, but had barely recovered (approximately 10%) in non-protected areas. This significant increase in MPAs shows that the governance of sites where *spinosissimus* would be reintroduced matters greatly in terms of promoting coral recovery, and it is suggested that the crab be reintroduced in MPAs.

Given the themes present in past reintroductions and coral reef management reports, I recommend that the Spadaro & Butler experiment (2021) conducted within the Florida Keys be ran again in each of the ecoregions to show that the crab can not only survive but thrive in different ecoregions on a small scale before reintroducing a larger population to the reef. This helps to prevent a failed restoration experiment, as defined in Bennett et al. (2016) that a partial reason for the failed introduction of the Brown Treecreeper bird species was a lack of understanding of the environment and predation. While *spinosissimus* has lower predation rates when they reach their adult sizes, juveniles are at a higher risk of predation, and it would be wise to examine their native predators and abundance within each ecoregion to ensure populations could grow. Along with repeating the assisted restoration experiment that Spadaro and Butler conducted in 2021, it is suggested that a laboratory experiment be conducted that identifies the preferred genera of macroalgae that the crab eats. Like previously mentioned in the Zeinert et al article, the crabs removed a significant amount of biofouling algae on cages and only showed a distaste for organisms that they could not reach within the holes of the cage. However, in order to ensure a successful reintroduction, a controlled experiment that yields statistical results of the preference of macroalgae eaten by the crabs would be hugely beneficial in order to create confidence that the species will be able to survive in each ecoregion where different genera of macroalgae dominate. Another downfall of past reintroduction experiments is the lack of a clear set of goals and criteria for meeting goals for the experiment (Godefroid et al., 2010; Sarrazin & Barbault, 1996). These goals must be feasible and follow an appropriate timeline, as coral recruitment can be a lengthy process that is not seen in just a few months. Example goals for this reintroduction experiment should target the survival of the crab, setting goals for short term survival (no more than 15% of the population lost within 4 weeks of reintroduction), mid term health (are crabs clearing substrate noticeably, what percentage of algal decline would be a suitable target goal after 6 months post reintroduction? Are crabs also sustaining their populations, should we expect to see population growth by now?). Long term goals should be at least one year post reintroduction, with the hopes that analysis continues regularly for five years post reintroduction. These goals would target coral growth of recruits identified in the short and mid term goals section, while also monitoring new recruitment rate as well. The suggestion of short, mid, and long term goals was modeled after (Bennett et al., 2016).

Possibly the number one suggestion from the literature reviewed for the analysis of the feasibility of reintroducing *spiniosissimus* was the need for more regular long term management post-reintroduction. As documented in Boström-Einarsson et al., the majority of coral restoration projects (60%) reported less than 18 months of monitoring. The reasoning for the reintroduction of the crab would be to assist in restoring coral coverage in the Caribbean to historic baselines via the shifting of states of macroalgae back to coral coverage. Therefore, not only is long term management needed to ensure that the crab populations are being sustained (more importantly growing), but also to ensure that new coral recruitment is happening, as this is the ultimate goal of the reintroduction. Like previously discussed, the need for a clear set of goals with understanding of the criterion to meet these goals is imperative for a successful experiment, regardless of the success of the reintroduction. Therefore, long term management can be more beneficial to the understanding of how *spinosissimus* altered the state of the ecosystem and individual trophic levels.

<u>Conclusion</u>

The main goal for the proposed reintroduction of *Minthrax spinosissimus* is the assisted restoration of dominant reef building corals to the Caribbean. This can be achieved through the depletion of macroalgae, a direct competitor of coral for substrate to grow, nutrients in the water column, and sunlight. The goal is that *M. spinosissimus* will be a better grazer of large macroalgae that now dominates most Caribbean coral reefs than other herbivores that are present, or in areas with little herbivory, it can fill the niche and become the primary herbivore. Thus, by reducing macroalgae coverage on coral reef sites, the availability of substrate for new coral recruits to land and settle will be greatly increased. This indirect effect of the reintroduction of *spinosissimus* was documented in a 2021 study by Spadaro and Butler, which showed that coral coverage increased five fold over two years. The introduction of the crab could also potentially help to restore the natural community structure of coral reefs, as the study documented a 3 to 5 fold increase in reef fishes on sites where crabs were reintroduced. The return of reef fishes helps to strengthen biodiversity on reef sites, which will in turn help to make the reefs more resilient to climate change.

Minthrax spinosissimus has been shown to be a good candidate for reintroduction due to it's role and functional feeding group as a grazer, feeding mainly of turf macroalgae. Unlike parrotfish, the common herbivore used in management practices to help restore coral reefs, *spinosissimus* has no mention of feeding on coral polyps such as parrotfish who will use their beak like jaws to take bites out of corals. However, future research is suggested to determine if *spinosissimus* is capable of corallivory and at what frequency they would eat corals over macroalgae. Many studies have looked into restoring populations of the long spiny sea urchin, *Diadema antillarum* to the Caribbean, however these reintroductions do not look feasible over such a large scale due to the presence of the disease that nearly wiped them out of the Caribbean in the 1980's. While it would be worthwhile to try and restore urchin populations on a reef by reef basis, *spinosissimus* could be used on a much broader scale due to it's lack of disease susceptibility and large ecological range.

However, as with all reintroduction proposals, there are potential downfalls to this project, despite best management practices and proper research done prior to the reintroduction. The main concerns for this project would be increased corallivory due to increased coral coverage. Parrotfish in particular are notorious for killing whole coral colonies with grazing, and a balance between coral growth and corallivory must be found, however it is nearly impossible for researchers to manually create this balance, as once the crabs are reintroduced, a trophic cascade could occur that would be nearly impossible to reverse. Therefore, the potential negative effects of this reintroduction could work to be detrimental and undermine the original goals of the reintroduction. It should also be noted that this reintroduction should only be used to slow the extinction of Caribbean coral species, not to help adaptation, as the only way to prevent the extinction of corals in the Caribbean and worldwide is to slow the effects of climate change at the source, including stopping pollution, eutrophication, rising sea temperatures, and ocean acidification. Unfortunately, the growth of new coral recruits on a reef will not matter if the conditions are unfavorable for the juvenile recruits to grow into adulthood. Therefore, the main focus for the restoration of coral reefs should be management of factors that are hindering the health of adult coral colonies.

Future recommendations for this project include a stringent set of goals and criteria to be created in order to successfully track the success of the reintroduction in terms of crab population as well as coral health. Identification of different marine protected areas, as MPAs have been shown to have a higher success rate for herbivory management of coral reef environments. Experiments regarding grazing rates of *spinosissimus* in a controlled laboratory setting to identify different genera of macroalgae that the crab will and will not eat to better understand the limitations of its proposed spatial distribution. As well as field experiments that show that in different ecoregions the crab will still be able to successfully do its job of clearing macroalgae for the indirect effect of increasing coral recruitment of juveniles. Post reintroduction monitoring is necessary in alignment with the outlined goals that would be created, it is recommended to have a set of goals for short, mid and long term post-reintroduction monitoring to be able to better understand how *Minthrax spinosissimus* has altered the ecological state of Coral Reefs in the Caribbean.

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