Synthesis of Invasive Lionfish Management Best Practices in the Atlantic, South Pacific, and Other Oceanic Environments and the Applicability of Such Practices to the Great Barrier Reef

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The Politics of Protecting the Great Barrier Reef

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Introduction to the Issue of Invasive Lionfish Proliferation in Coral Reef Ecosystems

In recent years there has been an alarming trend of lionfish (*Pterois miles)* invasion throughout the Mediterranean Sea, Atlantic Ocean, and South Pacific Ocean. Lionfish are voracious predators that can rapidly outcompete rivals and exhaust prey species native to the respective regions. Even in their native habitat of the Indo-Pacific, lionfish can become a problem for ecosystems if their numbers are not monitored. Over thirty-seven years, lionfish have spread down the eastern coast of North America, wreaking havoc on ecosystems, human economics, and human health. As invasive predators with the capacity to produce up to thirty-thousand eggs every four days, lionfish have had the greatest negative impact on oceanic ecosystems since the advent of industrial fishing (Birch 2022, par. 4). These rising lionfish populations add stress on coral reefs, primarily because lionfish prey on herbivores and herbivores consume the algae from coral reefs. Thus, herbivores help maintain a more stable algal growth rate and without them, reefs can experience algae overpopulation, harming the health of the reefs (NOAA Fisheries 2020, par. 6). Effective, sustained efforts to control lionfish numbers are a necessity to prevent further spread of lionfish populations and to reduce the stress on coral reefs worldwide. The Great Barrier Reef has experienced a similar proliferation of harmful species, including crown-of-thorns starfish and lionfish, and could benefit from utilizing some of the strategies employed in the Atlantic and Mediterranean to address the invasion (Kletou 2016, par. 1). There are a variety of proposed solutions and control strategies that have been created to address this problem. These solutions focus on an outreach approach as well as, more recently, a biological approach. In this paper, we will seek to both synthesize the current literature on lionfish management and establish best practices for how to deal with invasive species of this type in Australia's Great Barrier Reef in the South Pacific. In particular, we will do this through presenting educational and biological angles regarding lionfish management as well as by examining the economic incentives of lionfish control. We will explore potential, future avenues for combating invasive species and how Australia's government and federal agencies can apply them to the Great Barrier Reef's invasive lionfish population.

Utilizing Education and Outreach to Control the Great Barrier Reef's Lionfish Invasion

Policy centered around prevention through education and outreach against invasive species is crucial to controlling invasive species in reef ecosystems. While lionfish were likely introduced to the Atlantic through the exotic pet trade, many of the invasive species that threaten the Great Barrier Reef arrived via biofouling ("Controlling the Northern Pacific Seastar (Asterias Amurensis) in Australia - DAWE" n.d.). When flora and fauna proliferate on the hull of vessels, they are inadvertently transported from one location to another. Australia relies on the Marine Arrivals Reporting System (MARS) as well as the National Taskforce on the Prevention and Management of Marine Pest Incursions established in 1999 to prevent the introduction of invasive species into Australian waters ("Managing Biofouling in Australia - DAWE" n.d.). Vessels are encouraged to have a biofouling plan in place that incorporates management of possible species growth and regular removal of buildup on the vessel. This policy was implemented following the Review of National Marine Pest Biosecurity (Arthur et al. 2015, 4). Creating policy, education, and outreach programs that address invasive species before they are introduced into the natural environment is the best way to limit damage to the coral reef's ecosystem and control invasive lionfish populations before they experience an exponential surge. Communities in the Atlantic that have undertaken preventative measures against lionfish, such as Bonaire Marine Park and Florida Keys National Marine Sanctuary, have succeeded in protecting native ecosystems and controlling lionfish numbers (Morris and Gulf And Caribbean Fisheries

Institute 2012, 15). These efforts have been successful largely due to the involvement of citizen scientists, which is akin to the practices employed in Australia as there are similar biofouling laws in place However, these measures have had no effect on lionfish proliferation as lionfish can spread without vessels as a conduit. Early involvement leads to increased awareness, prevents misconceptions in the community, and creates greater overall support. Education and outreach measures aim to minimize the impact of invasive species upon the reef. There are three main areas of concern in regards to invasive aquatic species: environment (e.g., ecological disruption), economics (e.g., tourism and fishing), and human safety (e.g., proper catching and handling practices). In addressing these areas of concern, it is essential to emphasize that invasive species impact many interlinked sectors and stakeholders and, thus, only through collaboration can the threat be appropriately handled. When establishing an education and outreach program, experts must work with locals and create a community of citizen scientists, who can provide a constant source of monitoring and management. Current literature on the control and management of invasive species highlights the importance of transparent and credible messaging tailored to the audience, as different interest groups will be more concerned about certain consequences of marine pest invasion over other aspects. One of the most influential groups to engage with is the local diver population (Morris and Gulf And Caribbean Fisheries Institute 2012, 31). These individuals spend substantial amounts of time interacting with the reef and are an essential asset when monitoring and physically removing invasive species as well as when creating economic plans for their use.

Economic Incentives Supporting Lionfish Population Management

Economic policies developed in the Atlantic and Caribbean, including the creation of bounties, fishing derbies, and a tourist industry based on lionfish hunting, provide solutions that when applied to the Great Barrier Reef, can similarly create financial motivation for individuals to remove invasive species from the reef (Ulman et al. 2022). As an invasive species, lionfish disrupt the regular fishing practices of an area, posing an economic threat to communities that sustain themselves through fishing and tourism. However, local economies can be geared towards incentivizing lionfish capture. Hunting lionfish can serve as an economically beneficial method for locations suffering from lionfish invasion. Removal and extermination are the primary means of controlling lionfish numbers. As such, economic incentives and educational platforms furthering these agendas will likely prove fruitful for lionfish population management. Due to the sheer fecundity and aggressive nature of lionfish, large numbers must be consistently removed to see a benefit to the reef. Current recommendations for removal sit at between fifteen to sixty-five percent of the adult population per annum to prevent rapid repopulation (Morris and Gulf And Caribbean Fisheries Institute 2012, 25). Removal plans need to be long-term in nature, as lionfish are unlikely to be entirely eradicated from an area once introduced. One aspect of removal is identifying where critical spawning and egg-laying regions are in the local environment so that the most significant numbers of lionfish can be eliminated before reaching maturity. When control programs have been initiated, there has been a marked improvement in the relative number of other species groups, allowing for a more sustainable future for the reef (Goodrich 2014, par. 6). These economic incentives, methods, and processes for controlling lionfish populations can be applied to Australian policy and catered to their environmental needs, given the Great Barrier Reef's recent experience of a proliferation of invasive lionfish.

Synthetic Biology and Genetic Techniques to Build Coral Reef Resilience

Beyond integrating educational platforms and economic incentives into Australia's best practices for managing its concerning incline in the predatory lionfish population on the Great

Barrier Reef, current research suggests that exploring a biological angle could prove fruitful. Globally, in areas like the Atlantic Ocean, Mediterranean Sea, and South Pacific Ocean, agencies and researchers are conducting efforts to manage, if not exterminate, prolific invasive marine species, such as lionfish. However, studies show that while current efforts are publicly acceptable and low risk, they have a low chance of success regarding their ability to manage lionfish and invasive species populations (Thresher and Kuris 2004, par. 2). In other words, these methods alone may not be enough in the long run, spurring the recent conversation of using more drastic, biologically-permanent methods of protecting reefs from invasive lionfish in different parts of the world. While there is currently a lack of concrete policy and efforts regarding ameliorating the lionfish invasion through biological methods and genetic modification in Australia, preliminary steps are being taken to explore this potential intervention. To explain, enhancing coral resilience through synthetic biology techniques is one of the primary genetic avenues that is presently being explored to reduce the negative effects of invasive species, like lionfish, on the biodiversity and health of reef ecosystems. For instance, coral microbiome manipulation is emerging as a potentially valuable approach for improving coral resilience and enhancing their ability to handle external stresses, ranging from marine pest species to the effects of climate change. By modifying the algal zooxanthellae that live within most types of coral polyps and altering the abundance of zooxanthellae species diversity, scientists can introduce or remove genetic material that influences the fitness of the coral reef complex (Peixoto et al. 2019, 2). Beyond genetically manipulating corals to build coral resilience against external stressors and pest species, another approach to mitigate the effects of the lionfish invasion is through the managed relocation of natural or engineered coral populations (Peixoto et al. 2019, 3). With regard to best practices of managing the Great Barrier Reef, this could include hybridizing or engineering more resilient coral species and moving them to locations with greater invasive species presence, coral bleaching, or need for reef recovery. In fact, researchers at the Australian Institute of Marine Science (AIMS) are currently examining various assisted evolution strategies, like assisted gene flow and hybridization (Australian Institute of Marine Science n.d., par. 1). Assisted evolution ecnompasses an array of approaches that actively intervene to catalyze naturally-occurring evolutionary processes. With respect to coral reef ecosystems, accelerating evolution means enhancing coral growth and reproduction, which allows reef restoration and counters the negative effects of the lionfish invasion. For assisted gene flow, AIMS scientists are examining ways to bring in more beneficial genes for adaptation and resilience into the coral gene pool. Furthermore, AIMS is conducting hybridization experiments, where they produce viable offspring from different pairs of coral species and then grow these young coral hybrids in a controlled simulator setting. They test to see if the hybrid progeny have greater growth potential and survival rates under variable conditions and threats (van Oppen et al. 2015, par. 2). With further testing, these synthetic biology and genetic techniques may be a game changer for boosting reef recovery rates and building coral reef resilience, which generally helps protect coral against harm like lionfish.

Opposingly, the primary arguments against the use of synthetic genetic techniques to enhance coral reefs is that greater understanding of the associated risks of manipulating coral microbiomes is required, since people fear that genetic altering coral may have unknown, negative consequences on the ecosystem and human affairs. Peixoto et al. (2019, 3) explains how "there still remains a lot of unanswered questions including concerns around the biosecurity of manipulating microbes in laboratory-based settings and releasing these into the reef environment." As such, risk assessments are necessary and can feasibly be conducted by laboratory and field tests. In fact, Australia's Coral Sea houses the National Sea Simulator, a twenty-five million dollar facility opened in 2013 by AIMS (Cornwall 2019, par. 4). This simulator can be used to perform field tests when genetically manipulating corals, coral microbiomes, and invasive species. Assuming successful results, genetic engineering techniques could then be incorporated into Australian best practices for managing the lionfish invasion on coral reef ecosystems. To add another regulatory layer and sense of validity, all of these tests involving genetic engineering and genetically modified organisms are regulated under the Commonwealth Gene Technology Act 2000, which came to fruition on June 21, 2001. This legislation offers a cooperative national approach, and a 2006 review found it to be an effective measure for monitoring GMOs and related activity. Under this act, "dealings involving the intentional release of a GMO into the environment are illegal in Australia unless conducted pursuant to a license from the Regulator" ("Regulatory Framework in Australia" 2019, par. 4). This applies to controlled releases, like field trials. Additionally, before issuing such a license, the Gene Technology Regulator has to create a risk assessment and risk management plan "that identifies any potential risks to the health and safety of people and the environment posed by gene technology, and the means of managing those risks" ("Regulatory Framework in Australia" 2019, par. 4). Beyond testing and regulations, public opinion on the use of genetic modification is a matter that must be taken into consideration. Although genetic engineering can be a newly emerging and controversial field, a study conducted by Australia's CSIRO found that around ninety percent of Australian respondents moderately to strongly supported the use and testing of genetic engineering to restore and enhance coral (Synthetic Biology Future Science Platform 2020, 4). This public support is an indicator that coral genetic modification will likely continue to rise as a prevalent field and potential measure for countering the harmful effects of lionfish predation on coral reefs.

Genetic Modification of Lionfish as Invasive Species Management Mechanism

Another biological angle that is being discussed regarding lionfish management best practices is aimed at modifying the lionfish themselves. Through the use of genetic engineering techniques as population control mechanisms, improved local to regional management of invasive, pest marine species like lionfish may be possible. However, due to the uncertainty of using such genetic techniques, there may be risks and unforeseen long-term consequences on the environment and biodiversity of the respective ecosystems that must be considered, which will be discussed in greater depth later (Rittermann 2016, 30). As previously explained, all efforts and tests conducted in Australia with respect to genetically modifying lionfish are subject to the rules, regulations, and guidelines of the Commonwealth Gene Technology Act 2000. Now, to delve into the various genetic approaches that can be taken to mitigate the effects of invasive lionfish on coral reef health and abundance, Adam Rittermann (2016, 31) explains how there are several methods of genetically targeting the lionfish in order to better manage their population and reproductive abilities. These methods are all autocidal techniques, which means they decrease the lionfish population's ability to produce viable offspring. Although Rittermann's paper titled *A Review of Present and Alternative Lionfish Controls in the Western Atlantic* discusses these methods with regards to the lionfish issue in the Atlantic Ocean, these tactics can similarly be explored and potentially employed in Australia's Great Barrier Reef in the South Pacific. The first transgenic option is sex or stage-specific lethality/sterility. This solution is enacted by releasing fertile lionfish that carry an artificially-produced dominant, repressible gene that is inherited by offspring.This method can induce the death or sterilization of progeny at specific life stages or of a certain sex (Rittermann 2016, 32). In the latter version, where the repressible factor sterilizes or kills progeny of one sex, males that carry the gene would kill all their female progeny, leading to gradual species population reduction (Rittermann 2016, 32). If translated to managing the lionfish invasion in the Great Barrier Reef, this technique could become an extremely effective way to eradicate, or at least reduce, lionfish populations in the South Pacific and beyond.

Another technique, patented in 2001, called gender distortion works by inserting an artificially-designed genetic construct into the target organism's genome at the respective locus. This construct is then activated and functional during the sex-determination developmental stages, inhibiting the targeted gene responsible for sex differentiation; this hindrance allows for more male progeny. Resembling the previous technique of sex or stage-specific lethality/sterility, this gender modifcation technique is passed down to progeny, meaning that the resulting male populations continue to carry the gender-distorting construct to subsequent generations of offspring (Rittermann 2016, 33). If AIMS and other relevant authorities were to introduce and monitor this technique with the lionfish population in the Great Barrier Reef, in the long term, this could lead to an exponentially greater number of males and an overall declining population of lionfish due to the lesser number of females. Rittermann (2016, 33) goes on to explain how this gender distortion technique is safe, cost-effective, ethical, and specifically aimed at effectively reducing established invasive species populations. In fact, the gender distortion construct is species-specific and, thus, does not pose a threat to native or other species beyond the targeted invasive species. As such, this technique has immense potential and feasibility for incorporation into Australia's best practices for managing the lionfish invasion on the Great Barrier Reef.

Furthermore, a transgenic method known as inducible mortality is yet another potential autocidal technique for reducing lionfish numbers on the Great Barrier Reef. Inducible mortality refers to the process of inserting heritable fatality genes that cause the death of a species when the genes are activated by external factors, whether that be exposure to extreme environmental variability or an artificial trigger (Ritterman 2016, 34). In fact, this method was already proposed as a solution to combat the invasive carp population in Australia (Grewe 1997, 122). Thus, using it to manage lionfish on the Great Barrier Reef may be an option employed in the near future in Australia. Rittermann (2016, 34) goes on to say that the utilization of this technique can perhaps lead to local or even regional lionfish removal. Although these transgenic interventions hold immense potential to combat the lionfish invasion in coral reefs in different parts of the world, there are some points of concern and uncertainty regarding using genetic engineering as a management mechanism. Genetically modified organisms (GMOs) can be difficult to extensively test and can have unpredictable consequences on human health and the environment. For instance, the transgenic lionfish with modified genes may have greater fitness and create unexpected alterations to their respective ecosystems, shifting the local biome and food web (Rittermann 2016, 30). Alternatively, these genetically modified lionfish may undesirably spread their modified traits to other reef native species via either breeding with sexually compatible relatives or horizontal gene transfer (i.e., transferring genes to different organisms or species other than transmission from parent to offspring). If these engineered traits are transferable to other marine species and aim to reduce lionfish viability, then the release of these GMOs may harm native species populations. Another risk is that these GMOs, unless eliminated from natural causes and lesser survival fitness, are difficult to exterminate once released into the open, marine environment (Rittermann 2016, 31). As such, any issues related to the genetic modifications implemented on the released lionfish would persist through the wild-type lionfish population. However, although there is a level of uncertainty when utilizing genetic engineering and GMOs, it seems this may be a scenario where the benefits outweigh the risks. Applying this discussion to the Great Barrier Reef, the Center for Research on Introduced Marine Pests at CSIRO, a governmental scientific research agency, held workshops regarding finding more effective alternatives for controlling marine invaders instead of the current publicly acceptable and low-risk yet unsuccessful controls being used in Australia. These workshops included relevant stakeholders, like local conservation groups, marine authorities, fishing industries, multilevel managers, and international scientists (Thresher and Kuris 2004, par. 7). At these workshops, the general consensus was that genetically modifying marine pests, like lionfish, to reduce their invasiveness and viability had the most potential for success against invasive species while also gaining public acceptance (Thresher and Kuris 2004, par. 8). Therefore, in coming years, genetic engineering techniques may be at the forefront of lionfish management in Australia's Great Barrier Reef as well as in other reefs in the Western Atlantic and Mediterranean Sea, provided that there is support from relevant stakeholders and the general public.

Conclusion

Ultimately, the most effective measures for best practices against invasive lionfish found in the Great Barrier Reef consist of education and outreach, economic incentivization, and potentially synthetic biology and genetic engineering techniques. Drawing from methods and processes used to manage lionfish proliferation in reefs found in the Atlantic, Mediterranean, and South Pacific, it seems this three-pronged approach touching upon educational, economic, and biological platforms is crucial for mitigating lionfish numbers in Australia. Education and outreach can prevent invasive marine species from establishing themselves and play an important role in maintaining community investment in reducing lionfish numbers. Economic development works in tandem with outreach as it incorporates the concerns and motivations of the local population and commercial industries and, subsequently, allows them to fiscally benefit from the removal of lionfish. All of these measures are encompassed in the process of removal and destruction, which ultimately is the most important measure to take for restoring the health of coral reefs. As for the use of synthetic biology and transgenic techniques, the two primary avenues here for combating the negative effects of invasive lionfish include genetically modifying lionfish themselves or synthetically building coral reef resilience. Within these two categories, there are several approaches that can be taken and with further testing and the continual advancement of modern science, this biological angle may be the future of lionfish population management. Overall, the issue of lionfish management and coral reef protection from invasive marine species is a complex, multifaceted pursuit – one whose success will require interagency, general public, and stakeholder support and active cooperation.

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