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Artificial Reefs: a History, a Science, a Technology

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Artificial Reefs: A History, A Science, A Technology

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Signature Page:

Abstract:

Over the past 60 years, artificial reefs have expanded beyond the definition of a technology, and in turn have developed into a unique branch of marine science. To better emphasize this growth and separation, a brief history of artificial reef development and usage in chapter two shows some of the key shifts over time in this technology's purpose and the materials used to achieve that goal. Likewise, to indicate the scientific development of artificial reefs as a branch of marine science, their usage for discovery and research is recorded in chapter three, along with the exponential increase in published scientific materials that relate to artificial reefs. With the increasing popularity of these reefs, monitoring the artificial systems became essential, and added to the separation of artificial reef science as a unique branch of marine science, as described in chapter four. Lastly, chapter five articulates that artificial reefs as a system have distinguished themselves from natural coral reefs, despite the heavy overlap in benefits. This separation, as explained by the issues that are entirely unique to artificial reefs, has resulted in more support for the idea that the science of artificial reefs is indeed its own branch of marine science.

Outline of Chapter Breakdown:

Chapter 1: Introduction

Artificial reefs, a technology that has been used for centuries, has drastically shifted with regards to purpose, materials, and usage over time. While natural coral reefs provide a place for fish to live and grow, limit wave damage on shores, produce large amounts of oxygen, and act as a carbon sink, artificial reefs are able to achieve a multitude of functions including many of those achieved by natural reefs. Despite their humble beginnings as fish aggregation devices made from leaves and sticks, artificial reefs have become a unique and separate component of marine science and research.

Artificial reefs, as defined by a founding member of Fisheries and Aquatic Sciences department at the University of Florida, Willian Seaman Jr., are “one or more objects of natural or human origin deployed purposefully on the seafloor to influence physical, biological or socioeconomic processes related to living marine resources” (2000, Page 5). This means that artificial reefs are created to alter the marine environment, either so that it will be more useful to human populations or to benefit the organisms who live on the seafloor.

Artificial reefs are in no way recent inventions. Created from materials such as terracotta, sunken ships, human ashes, wood, and statues, they have existed for centuries all around the world, but only became relatively commonplace in the late 1900s. While their materials and their intended purpose were initially quite simple, artificial reefs have increased in complexity, both by way of components and usage. This shift towards complexity has resulted in extremely successful artificial reef projects, as well as reef disasters. The challenges that stem from creating successful reefs have led to a new development in the marine science world: a subfield of marine science dedicated to the study of artificial reefs. Work in this subfield entails learning about the

variety and quality of materials common in reef-building, evaluating various functions of artificial reefs, and monitoring whether the reef served its intended purpose or resulted in unintended consequences, good or bad.

The new science of artificial reefs has provided great insight into what these structures can achieve. Artificial reefs now provide unique benefits in addition to some of the functions that natural reefs possess. These artificial reefs, like their natural counterparts, still provide habitat for marine life, act as wave-breakers, and help to increase fish populations in and around the reef. Artificial reefs can also be clean and green ways to recycle materials, provide an alternative location for tourists and divers, serve as political statements, and result in many other desirable outcomes.

As an up-and-coming object for scientific learning and technological intervention, artificial reefs require stringent monitoring and care. This movement towards monitoring and studying artificial reefs, as well as the practices surrounding them is a new phenomenon. Learning how the construction, evaluation and monitoring processes of these reefs have changed and developed over time will provide crucial insights into how the subfield emerged over time, and may provide glimpses into the future of these reefs.

Despite being designed to mimic natural reefs, artificial reefs are not the same as their natural counterparts. In fact, there are many areas of scholarly debate surrounding the unique nature of artificial reefs. While some researchers believe that artificial reefs increase habitat for organisms, others argue that any increase in population seen as a result of artificial reefs is simply due to aggregation. Additionally, some scholars argue that changing the environment like an artificial reef does will cause more harm than good as it can have unintended consequences on

local communities. For instance, in some circumstances, artificial reefs have provided habitat for invasive species to take over a system. These heavily debated concepts, while related to natural reefs, are connected to some of the key questions that artificial reef science works to answer

The history and use of artificial reefs may be particularly interesting when these reefs are thought of as tools for research, tourism, fisheries, and economic gain. While there are ample resources that describe artificial reefs in varying aspects (i.e. economically, scientifically, historically), there has yet to be a comprehensive document detailing the transition artificial reefs underwent to become such a strong presence in marine science. As a tool with a rich history, stringent monitoring regulations, and deep connections to marine science, artificial reefs have arguably become their own distinct sect of marine science separate from natural reefs and natural reef science.

Chapter 2: Artificial Reefs: A Brief History

The use of artificial reefs for anthropocentric purposes has occurred throughout much of human history. From branches and leaves to concrete and metal, the materials have developed with our understanding of these reefs. Artificial reefs have also expanded their utility beyond increasing fish populations; they have become a form of art, a mode of recycling, and a research tool.

2.1) Early History of the Artificial Reef

During the Neolithic time period, it is very likely that individuals would create what is now referred to as “artificial habitat” to attract fish to one central location, making them easier to catch. These habitats were submerged solely for the purpose of collecting and killing fish (Lima et al., 2019). Artificial reefs are a subset of artificial habitat that involve the full submersion of the habitat. Thus, it makes sense that non-submersible artificial habitat would be used and connected to artificial reefs. This type of artificial habitat, often called FADs, or Fish Aggregating Devices, bring in fish, thus allowing smaller fishing vessels or a small group of fishers to get a larger catch (Polovina 1991). Artificial reefs and FADs provide solid substrate for marine life to inhabit, thus attracting fish that can consume the algae and other organisms that colonize the man-made substrate (Pickering and Whitmarsh 1997).

Like those during the Neolithic period, in the 17th century, South Americans were also found using natural materials to lure fish. They created artificial habitats from stones, branches, and leaves. Again, these devices succeeded in attracting fish, making fishing a simpler task (Lima et al., 2019).

The earliest report of the intentional creation of an artificial reef, as opposed to an artificial habitat, is from the 1700s in Japan. Again, the reef-builders used natural materials to build their creation, making multiple sunken reefs from bamboo and leaves. The first intentional artificial reef in the US, however, was on record in a book published in 1860. Made in Charleston, South Carolina, this reef was used to get more fish while fishing (D’Itri, 1986). Similarly, this reef was created using natural materials found in the surrounding area, such as leaves and large branches.

While the US, and other countries, may not have intentionally sunk ships with a biocentric focus in mind, many shipwrecks have provided sufficient materials for corals and other marine organisms to grow. Blockships, for instance, have been used for centuries on a global scale (Tucker, 2020). Blockships are vessels intentionally sunk to prevent enemy ships from entering certain channels or harbors (Tucker, 2020). Unlike the structures created from all-natural materials like bamboo and branches, blockships were not made to increase fish population or help the environment in any way, but rather with an anthropocentric and military-focused purpose in mind.

Obviously not all artificial reefs that stem from shipwrecks have been created intentionally, however; over the years, many ships have sunk accidentally, rather than with the intention of blocking others' passage into an area. The two World Wars, as well as many smaller wars, resulted in many unintentional shipwrecks, and thus accidental artificial reefs, both in regards to their origin and their benefit to the ecosystem.

2.2) Modern Artificial Reef Materials

Only within the past 60 years have artificial reefs become popular worldwide for their connections to marine life; this makes sense, as it marks the beginning of the environmental and marine science movement (Lima et al. 2019). The overall newfound interest in marine science included an interest in artificial reef practices, meaning that both reef building techniques and reef uses evolved and diversified, as explained in the introduction of Lima et al.'s "Overview and trends of ecological and socioeconomic research on artificial reefs":

It was not until the 1960s that this practice spread worldwide, through the creation of different artificial reefs related to fishing, scuba diving and coastal recreation. Materials used in their creation included rocks, tires, wood, concrete and/or metal structures, obsolete industrial material and even oil and natural gas platforms (2019).

While many of these artificial reef practices were a success, some attempts actually proved to be tremendous failures.

2.2.1) Unsuccessful Material

In the 1960s there was an initiative in Florida to dispose of at least one million car and truck tires by creating a structure and attaching said tires to that structure to form artificial reefs (Sherman and Spieler, 2006). The tires, over the past 40+ years have been separating from the structure they were bound to, and moving freely in the ocean. This new motility has caused ample destruction of natural reefs as well as caused tires to wash ashore in Florida, a problem still existing as of 2006 (Sherman and Spieler, 2006). Another component of this poor plan includes tires' inability to support high levels of coral recruitment, thus making them even worse reef-building material (Fitzhardinge and Bailey-Brock, 1989). As shown in Figure 1, the Osborn reef predominantly resulted in mobile, algae-covered tires, rather than stable coral reef structures that are healthy and diverse in marine life.

While an attempt to give a purpose to waste from landfills, this initiative caused far more harm than good, and still requires the tires to be put in a landfill as an end result. After this disaster, it is clear that it is essential to fully analyze the potential impacts, both positive and negative, of any idea that may drastically impact an ecosystem (Sherman and Spieler, 2006). Likewise, Sherman and Spieler, two professors at Halmos College of Natural Sciences and

Oceanography, use the poor example of Florida's artificial reef made of tires to explain the importance of stable and biodegradable reef-building materials to avoid similar incidents (2006). If a reef is created from biodegradable materials, it will not linger in the ecosystem like the tires, nor will it risk decaying and leaving behind toxic components. Additionally, stable reef structures are essential for the protection of surrounding habitat, as any unstable structures could topple over and destroy themselves as well as anything living in its path.

2.2.2) Successful Materials

Unlike tires, concrete has been found to be an excellent, environmentally-friendly material for the creation of artificial reefs. Its texture and chemical composition reflects that of coral rock, and has been reported to be as good of an area as coral rock for coral recruitment, or the process in which baby corals attach themselves to a solid substrate and begin to grow (Fitzhardinge and Bailey-Brock, 1989). In comparison to coral rock, and with respect to recruitment rate (of coral and other reef-builders), concrete is an overall great material to use when wanting to create an artificial reef with the intent of creating a space for marine life to grow and thrive.

While not found to have the highest recruitment rate in Fitzhardinge and Bailey-Brock's study, the concrete most closely mimicked the natural environment and was easily molded into any desired shape. Likewise, In "Artificial Reefs: The Importance of Comparisons with Natural Reefs," Hixon and Carr briefly state that, based on their research, artificial reefs perform better when they physically mimic the look and style of a natural reef (1997).

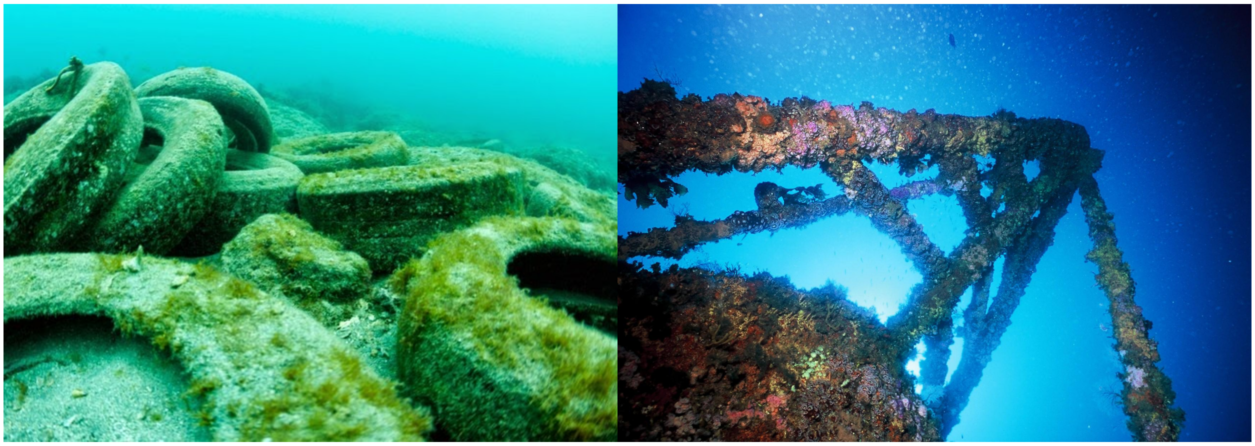

Figure 1. *This figure shows the failed Osborne Tire Reef (left) and a successful oil rig transformed into a reef (right). The Osborne reef is sandy and covered predominantly in a green algae, while the rig is covered in various materials and is very colorful. The diversity shown on the rig is a sign of a healthy reef, whereas the uniform look of the tires does not suggest a healthy reef. Additional indicators of health include diverse fish populations, presence of macro-invertebrates, and high rugosity (bumpy, varied height). Images taken from the websites amusingplanet.com and missionblue.org, respectively.*

2.2.2.A) Use of Successful Materials

Similarly, sculpture gardens created to become artificial reefs are often made using non-toxic cement, one of the ingredients in concrete. One sculptor, Jason deCaires Taylor, is a prolific creator who has over 800 underwater sculptures around the world. His sculptures provide an ecosystem for marine life, and have increased biomass by over 200 percent in previously empty seabeds (Konior 2019). Taylor's sculptures have become tourist attractions all over the world, even expanding outside of the water in museums and film. His work often degrades over time, leaving behind only pieces of his human and non-human sculptures. As such, his work successfully forces people to think about climate change and the impact we all have on the environment (Konior 2019). It also draws people away from natural reefs that often suffer at the hands, or flippers, of inexperienced tourists. One of his works, "Ocean Atlas," even led to the discovery of an oil leak in an oil refinery near the Bahamas (Konior 2019). Created with one goal

in mind, these sculptures have become ambassadors of artificial reefs, climate issues, and human rights.

Material	Number of Citations
Concrete	79
Rock, Stone, Boulders, Gravel, etc.	29
FADs	17
Offshore Platforms	16
Tires	15
Plastic, PVC, etc.	12
Breakwaters, Coastal Structures	12
Vessels, Barges, Shipwrecks	11
Wood, Trees, etc.	11
Steel, Metal	10

Figure 2. *This table shows a breakdown of some of the more commonly recorded reef-building materials, as found in Baine 2001's review of artificial reefs. Based on the chart above, the most common materials used for artificial reefs that were described in scientific papers were concrete and stones (Baine 2001). While this data is from about two decades ago, concrete is still one of the most common building materials for artificial reefs. Additionally, not all building materials on this list were recorded as successful, suggesting that some materials above, like tires, are not ideal building material for artificial reefs.*

2.2.3) Purpose-based Materials

As seen with the tire example, artificial reefs are sometimes created with the intention of eliminating waste. For example, the US Navy often repurpose old materials such as ships and platforms into artificial reefs as a cost-effective disposal method. As detailed by Hynes et al. 's work that compiles information about Rand National Defense Research, sinking large metal structures is far cheaper than recycling the material, whether domestically or internationally (2004). While similar to the Florida tire reef in its anthropocentric benefits, metal ships and platforms perform far better than tires as artificial reefs, particularly when properly prepped. According to the same study that recommended concrete as a building material for artificial reefs, metal is also an excellent substrate for coral recruitment, granted it would eventually disintegrate (Fitzhardinge and Bailey-Brock, 1989).

Additionally, Booth, Macreadie, and Fowler suggest that the “Rigs-to-Reef” program, a program that supports the sinking of oil rigs to create artificial reefs, would be beneficial for the deep sea; it would “enhance biological productivity, improve ecological connectivity, and facilitate conservation/restoration of deep-sea benthos (i.e. cold-water corals) by restricting access to fishing trawlers” (2011). Booth et al. also indicates that, as of 2011, there have been positive results from the Rigs-to-Reefs program in shallower waters, as they have increased fish stocks. Additionally, according to the Bureau of Safety and Environmental Enforcement, as of April in 2018, “532 platforms previously installed on the U.S. Outer Continental Shelf have been reefed in the Gulf of Mexico,” meaning there have been over 500 rigs that have been recycled into artificial reefs (2018).

While the governmental US may focus on the personal financial benefit of creating a reef, the Rigs-to-Reef program takes both economics and the environment into consideration. These reefs have provided habitat and hard substrate in areas with clay and sand-based bottom. The substrate allows for organisms like coral to have a better chance of successfully recruiting and staying healthy (Bureau, 2018). Creating these reefs also decreases the cost of recycling and the carbon emissions that would result in said recycling (Bureau, 2018; Hynes et al., 2004).

2.3) Intentions Behind the Creation of Artificial Reefs

In addition to increasing fish stocks, providing cheaper recycling methods, and allowing marine communities to form, artificial reefs have a multitude of benefits that extend beyond the scope of natural coral reefs. According to Carr and Hixon's article comparing natural reefs to artificial reefs, in the 1990s the main purposes of artificial reefs in the US were to "enhance the production of reef-associated species…[and] to increase the convenience or efficiency of harvesting reef-associated species" (1997, Page 28). Unlike the US in the 90s, in Europe, the goals of artificial reefs have expanded beyond human benefit alone, and instead include conservation and research. Even the human uses expanded: artificial reefs were useful for recreational swimming and diving, aquaculture, fishery management, as well as increased fish stock (Fabi, 2011). Waste disposal, water quality, and coastal protection are also valuable human benefits from artificial reefs (Baine, 2001). Bortone et al. also analyzes artificial reefs with a focus on food sources, specifically in regards to marine ranching, a process similar to aquaculture, and extending kelp forests (1997). This use of artificial reefs, while not particularly common, is described as a way to "provide in-kind kelp habitat resources for the loss of kelp

forest habitat." Bortone et al. specifically refers to a project to restore 61 hectares of kelp forest at San Onofre (1997).

Dr. William Seaman Jr. adds to this ever growing list of artificial reef utility by including artisanal production, recreational fishing, resource allocation and protection, species manipulation, and research (2000). As his focus is more on the evaluation of reefs as successes or failures, Seaman's book *Artificial Reef Evaluation: With Application to Natural Marine Habitats,* poses several questions to evaluate the success of an artificial reef. These questions include:

> "What organisms (will) occur at a reef? What species can be harvested? Is overharvesting a possibility? Will the reef interfere with existing uses or resources of the sea? What economic benefits and costs are expected? Are reefs useful in ecological restoration? (When) will the reef sink into the seafloor? Can research questions be answered at the reef(s)?" (2000, Page 8).

As described in Dr. Seaman's work, it is not simply enough to create these reefs; they must have a purpose. This makes the modern creation of artificial reefs drastically different from their use centuries ago. To create these structures, there needs to be a strong understanding of the intent behind their creation, as well as the foreseeable consequences of their introduction to their environment. This easily leads us into the use of artificial reefs in marine science, and even as an individual branch of said science.

Chapter 3: Artificial Reefs Research as a Scientific Field

Science, while an incredibly broad term, is used to describe both an extensive collection of information and a process (Thanukos et al.). To truly be a unique sect of science, a field of study must fall into a previously established branch of science while also adding a unique perspective within that branch of science. Artificial reefs are studied and utilized under the branch of both ecology and marine biology. As such, the connection these reefs create between the natural environment and a man-made one provides an interesting and unique lens for new scientific perspectives. The presence of research emerging from this collaborative perspective has been increasing over the past 5 decades, resulting in more scientific papers, conferences, and journals dedicated to studying artificial reefs.

To better understand natural coral reefs, or reefs that form without any human assistance, scientists have been comparing naturally formed reefs to artificial reefs (Carr and Hixon 1997). Over the past 60 years, these artificial reefs have advanced in design, materials, and usage as marine science has progressed. Likewise, the research conducted on these reefs and the advancements that stem from that research have resulted in numerous conferences, papers, symposiums, and books, increasing at an exponential rate as seen in Figure 4.

3.1) Use in scientific research

Artificial reefs, while originally focused on removing scrap metal and benefiting private organizations, local governments, or private individuals, are now commonly used as scientific tools today (Bohnsack and Sutherland 1985). When studying artificial coral reefs, scientists tend

to focus on three essential topics: engineers-based researchers focus on how artificial reefs mitigate the anthropogenic harm marine ecosystems have suffered, marine ecology-based researchers focus on how these reefs ecologically impact the surrounding area, and environmental policy-based researchers focus more on how artificial reefs impact fishing stocks with regards to seafood. These three topics, as well as some management-based studies explained in a later section, help to explain the overall usefulness of artificial reefs in different marine environments as well as the common areas of focus in this scientific field.

Themes/Topic Interest	**Grove and Sonu (1991)**	**Baine (2001)**	**Present Study (2017)**	**Total**
General Review	73	41	6	120
Fisheries Enhancement/ Mariculture	0	9	16	25
Community Structure/ Composition/ Biodiversity	0	0	19	19
System Design/ Deployment/ Performance	33	45	15	93
Coastal Protection/ Development/ Seabed Changes	0	2	2	4
Physical/ Ecological Functions	132	121	17	270
Fish Behavior Patterns	0	0	4	4
Habitat Protection/ Mitigation	0	25	0	25
Other	63	6	51	120
Total	301	249	130	**680**

Figure 3. *This table shows the topics discussed in papers, as described by two literature reviews (Grove and Sonu 1991 and Baine 2001), as well as more recent research papers (up until 2017) and is a summarized version of table 3 in Lee, Otake, and Kim's literature review of artificial reefs (2018). As seen above, there has been an increase in papers focused on fisheries enhancement and community structure with regards to artificial reefs. There are also the greatest number of papers focused on the physical and ecological functions of artificial reefs.*

3.1.1) Anthropogenic Harm

Climate change has drastically affected the world as we know it, and has a particularly detrimental effect on coral reef ecosystems. Due to the increasing storms, water levels, temperatures, and hydrogen ion concentration, natural coral reefs have suffered great losses (Hoegh-Guldberg et al. 2017). Likewise pollution, destructive sampling of marine habitats, and fishing are additional harmful anthropogenic processes (Hoegh-Guldberg et al. 2017). Artificial reefs provide services that the human population has relied on natural coral reefs to provide for centuries. These services include protection against waves, habitat for fish species, and locations for recreational marine activities (Hoegh-Guldberg et al. 2017; Baine 2001). Recent work on artificial reefs has been focused on undoing the harm that has been anthropogenically occurring for centuries, and trying to keep coral reef ecosystems alive.

To combat the loss of many coral reefs that protect coastal areas from intense waves, some artificial reefs have been created with the intent of protecting shorelines (Lee, Otake, and Kim 2018). Coastal erosion, while a global problem, heavily affects islands, as waves can reduce the coastal area from all sides (Lee, Otake, and Kim 2018). In a literature review focused on artificial reef research and prospects, several papers recounted the impact that artificial reefs had on both protecting the shoreline and preserving the local marine environment (Lee, Otake, and Kim 2018). While each paper reviewed had different reef designs, they all used some form of artificial habitat to combat the increasing wave action (Lee, Otake, and Kim 2018). Some papers, while not focused on preventing coastal erosion, stated that the creation of artificial reefs did in fact protect the shoreline (Lee, Otake, and Kim 2018).

Additionally, to reduce the rate at which the atmosphere is changing, some areas have invested in offshore renewable energy projects that provide both an alternative energy source and a hard substrate that can act as an artificial coral reef (Langhamer 2012). As offshore wind turbines are often placed in areas with soft sediment and poor biodiversity, the addition of a solid structure, like that of a wind turbine, could provide the necessary solid substrate needed for marine organisms to recruit onto, thus increasing biodiversity (Langhamer 2012). These marine areas will also benefit from the wind turbines, as it means that the nearby area cannot be trawled due to the large nature of the turbines. A lack of trawling means that organisms can stay in the environment without risking a potential capture and death from net trawls (Langhamer 2012). Likewise, areas selected for offshore renewable energy projects are usually turbulent, meaning that nutrients and oxygen flow freely and rapidly in the environment. This suggests that any organism looking to colonize the solid structure would have access to the nutrients necessary for growth at varying depths (Langhamer 2012). While there are some risks and problems associated with the creation of wind turbines, further research could help to increase the utility of and decrease the issues associated with offshore wind farms.

3.1.2) Ecology

Because of the anthropogenic harm done to marine environments, ecosystems like coral reefs, have suffered great losses of biodiversity, biomass, and overall health. Artificial reefs have been one of many technologies put in place to combat the declining health of these ecosystems. While not always useful in a system, artificial reefs can provide habitat for organisms that need hard substrate to colonize or shadowy waters to hide from predators (Pickering and Whitmarsh 1997). They also result in aggregation of species which can allow organisms to more easily find mates and reproduce (Pickering and Whitmarsh 1997).

One paper summarized within a literature review questioned the impact of artificial reefs on fish biomass, weight, and abundance. While fish biomass as a whole increased with more artificial reefs, the size and growth rate of the fish decreased when more artificial reefs were added to the system (Lee, Otake, and Kim 2018). Within the same literature review, there are many additional studies focusing on the physical and ecological impacts of artificial reefs, suggesting that it still requires more research and is a topic of interest.

3.1.3) Aquaculture studies

While the impact of artificial reefs on marine life is important for a multitude of reasons, current research commonly focuses on the impact of artificial reefs on fisheries enhancement and seafood production (Lee, Otake, and Kim 2018). As an important source of income for many coastal countries, the connection between artificial reefs and seafood production has been a topic of interest for many researchers both in regards to aquaculture and offshore fishing. One of the many artificial reef designs is the reef ball, which is able to be customized for aquaculture usage and coral propagation (Harris 2006). Artificial reefs, like the ball reef, have been used as tools for aquaculture for over 20 years in Italy (Jenson and Collins 2000). Eco-Rigs, a non-profit organization based in Louisiana, has even pushed to transform oil and gas rigs into artificial reefs for aquaculture, thus decreasing the harvesting of fossil fuels while still keeping employment levels high (Kolian Sammarco 2006).

Artificial reefs have been known to result in the aggregation of multiple fish species, as well as other common seafood species. Algal species, sea cucumbers, abalone, and various other seafood species are just some of the many profitable organisms that utilize artificial reefs for growth (Chai et al. 2014; Xu et al. 2017; James, Day, and Shepherd 2007).

3.2) Becoming a Science

While there is no official guide as to how something may become its own separate branch of science, sects of scientific research and study often have several shared traits. In order for an aspect of marine science to become a unique and distinguished branch, it must have several lines of communication among those who study it. This allows for the flow of new ideas and discoveries in such a way that further encourages the study of a topic. Often in the sciences, communication is done in one of two ways: either a new discovery is shared orally, like at a talk during a conference for that branch of science or the discovery is shared in a written format, like through an article in a scientific journal for that sect of study. As a field with both conferences and journals dedicated to it, artificial reefs have become an independent science; they are more than a tool for marine research, they have become a subdivision of it.

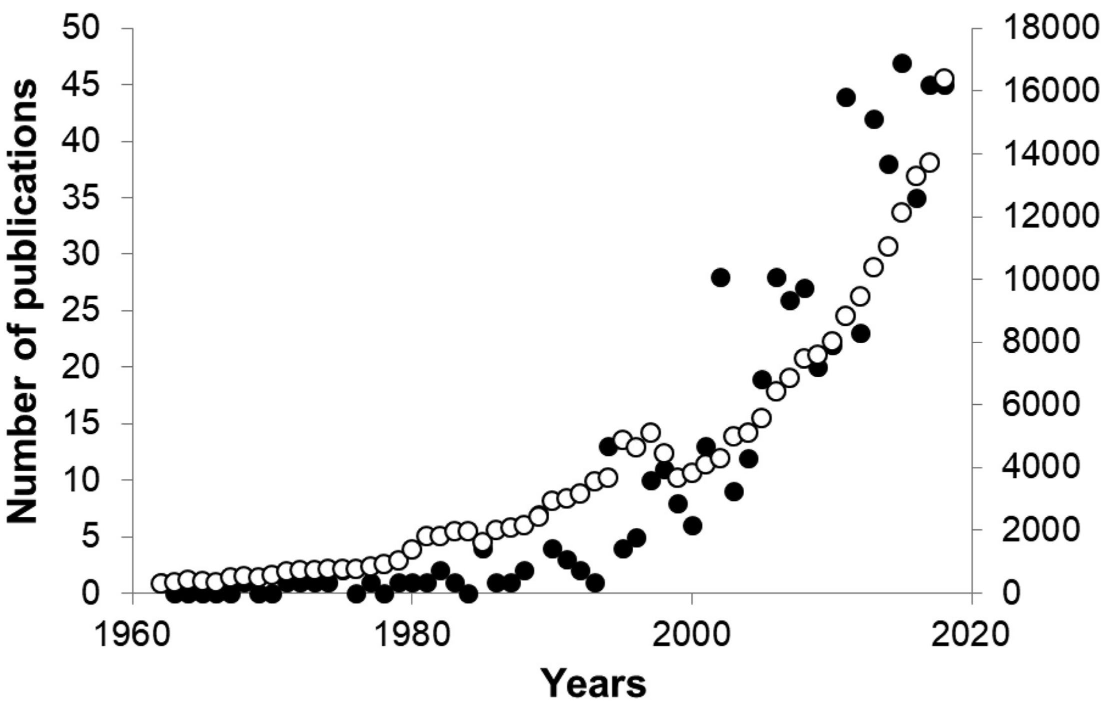

Figure 4. *Graph taken from Lima et al. 2019 showing the general increase in publications about ecology (black dots and right axis), specifically focusing on artificial reefs (white dots and left axis). As shown in this figure, there has been an exponential growth in publications regarding artificial reefs, suggesting an exponential increase in scientific interest.*

3.2.1) Conferences

Despite the relative newness of artificial reefs as a branch of marine science, there have been several conferences held to discuss and share research in the field of artificial reef science. One of these conferences, called the European Artificial Reef Research Network Conference (EARRN), focused on modern developments of artificial reef science and ran from 1995 to 1998 (University of Southampton 1995). This conference was created with the intent of unifying all of the EU in artificial reef research and regulation, as well as communicating artificial reef data with other countries that were also studying these man-made structures like Japan, the United States, and Taiwan (University of Southampton 1995). Likewise, multiple literature reviews about artificial reefs cite dozens of conferences, workshops, and symposiums that all focus on artificial reefs. One of the most commonly cited conferences was the International Conference on Ecological System Enhancement Technology for Aquatic Environments (Pickering and Whitmarsh 1997; Lee, Otake, and Kim 2018; Baine 2001).

While dozens of conferences and other scientific meetings exist to share information about artificial reefs, not all of these conferences recur on a yearly basis. In fact, many artificial reef conferences were brief and only met for a year or so before disbanding (Pickering and Whitmarsh 1997; Lee, Otake, and Kim 2018; Baine 2001). Some artificial reef conferences have more generic themes than the study of these artificial habitats themselves, but have had certain talks or presentations dedicated exclusively to artificial reef knowledge, like Whitmarsh' paper presentation on artificial reef investment at the VIIIth Biennial Conference of the International Institute of Fisheries Economics and Trade (Pickering and Whitmarsh 1997). The International Center for Living Aquatic Resources Management, or ICLARM, is another conference dedicated

to aquatic research generally, but occasionally contains papers and presentations that focus on artificial reefs (Roedel 1981).

3.2.2) Papers/ Journals

Much like the conferences, there are a multitude of papers dedicated to the study of artificial reefs, some even coming from full issues of famous marine journals that focus on these man-made habitats. Unfortunately, no journal has been created to exclusively focus on artificial coral reefs as of yet. In 2009, however, the second edition of the Encyclopedia of Ocean Sciences contained an article that focuses exclusively on the use of artificial reefs and their impact on the environment (Seaman and Lindberg 2009). Additionally, the *Journal of Marine Science and Engineering (JMSE)* had an entire special issue of its publication within the section of ocean engineering that focused on artificial reefs titled “Reefs” (Do Carmo 2021).

Likewise, in connection to the many conferences, workshops and symposiums about artificial reefs, many papers have been published relaying that summarized information. One literature review from 1996 to 2017, analyzed over 130 papers that referenced artificial reefs (Lee, Otake, and Kim 2018). The *Bulletin of Marine Science*, another well-known journal for marine science, has also contained articles about artificial reefs for decades. The National Research Institute of Fisheries Engineering in Japan also frequently releases new information about artificial reefs (Lee, Otake, and Kim 2018). The presence of artificial reefs in relatively high concentrations within papers and journals suggests that artificial reefs have been an important, yet distinct part of marine science research for many years, thus supporting its independence as its own sect of science.

3.2.3) Books

There are a large number of books about artificial reefs, as well as conferences and papers. This again suggests that the study of artificial reefs has in fact separated itself from marine science and the science of natural coral reefs so that it is now its own distinct aspect of science. William Seaman, one of the many contributors to the book scene for artificial reefs, has published books titled *Artificial Reef Evaluation* and *Artificial Habitat for Marine and Freshwater Fisheries* (2000; 1991).

Some books about artificial reefs focus on one particular area, like *Artificial Reefs in European Seas* and *Islands in the Sand: An Introduction to Artificial Reefs in the USA (Jensen et al. 2000; Hudson 2009)*. Other books that discuss artificial reefs are not solely about artificial reefs, instead focusing on marine engineering or marine ecosystem management. For instance, *Modern Fisheries Engineering: Realizing a Healthy and Sustainable Marine Ecosystem* is a book that looks at artificial reefs in the context of marine engineering (Bortone and Otake 2020).

Chapter 4: Monitoring Artificial Reefs

Because the science of artificial reefs is still in its infancy, monitoring has been an important step to ensure reefs are being used in safe and beneficial ways. As the creation of artificial reefs have become more commonplace, the need to monitor these new habitats has increased. Artificial reefs have been used to better tourism and increase safe fishing practices, thus supporting the environment and human populations. In an attempt to connect the science

and monitoring of these reefs to each other, there have been several studies focused on how to best regulate artificial reefs with regards to both human and ecosystem benefit.

4.1) Tourism

Tourism is a monumental source of income for many countries that can support natural and artificial reefs; it is estimated that the total value of coral reef tourism is around $36 billion per year (Spalding et al. 2017). Often these vacation spots are visited specifically for their proximity to coral reefs which will allow tourists to enjoy a multitude of activities, most commonly SCUBA diving, snorkeling, and fishing. In some studies, tourists had returned to the same areas dozens of times to enjoy the same reef-based experiences, suggesting reefs and their quality may have a great impact on where people choose to vacation (Kirkbride-Smith et al. 2013).

4.1.1) Diving

SCUBA diving both helps and harms reefs. More than 21 million people have obtained PADI certification before the year 2012, and the number of divers being certified has increased ninefold in the past 40 years (Polak and Shashar 2012; Edney and Spenneman 2015). This suggests that SCUBA diving is becoming a rapidly more common tourist activity. While having more people explore coral reefs and grow attached to these environments is a valuable way to encourage individuals to combat climate change and other sources of harm to reefs, not all divers are experienced (Polak and Shashar 2012). A lack of experience on a dive site can lead to displacement of sediment on top of corals, toppling of corals, touching of corals or other organisms, and many other sources of harm (Polak and Shashar 2012; Tynyakov et al. 2017). As

such, there has been a movement towards teaching less experienced divers how to safely dive on artificial reefs rather than natural ones in order to protect natural reefs (Kirkbride-Smith et al. 2013). Likewise, there has also been a movement for inexperienced divers to avoid unintentional shipwrecks and instead focus on wrecks intentionally sunk to form artificial reefs although this movement focuses more on the diver's health than the reef's (Edney and Spenneman 2015).

To better understand the receptiveness of divers to restrictions impacting available dive locations, several studies have been conducted to determine the willingness of divers with different skill levels to dive on artificial reefs compared to natural ones, paying special attention to the diver's experience level. While most divers saw artificial reefs as positive tools for the environment, the more experienced divers tended to reject the idea of diving on man-made reefs instead of natural ones (Polak and Shashar 2012). Overall, divers preferred their experiences on natural reefs compared to artificial ones, but in separating experienced from inexperienced, the study found that inexperienced divers had less of a preference between the two (Kirkbride-Smith et al. 2013; Polak and Shashar 2012). This would suggest that if regulations were put in place requiring inexperienced divers to begin their training on artificial reefs rather than natural ones, there would be little backlash (Edney and Spenneman 2015). As such, there has been a push to implement rules that prevent divers with little training from accessing natural reefs, but rather encourages inexperienced divers to train on artificial reefs (Polak and Shashar 2012).

4.2) Fishing

Coral reefs are home to hundreds of marine organisms and provide habitat for various reef fish. As such, the ability to fish on or near a coral reef is often a common draw to tourists

interested in aquatic relaxation (Prayaga 2010). Fishing, whether as a tourist, an employee of a larger company, or a local, can have harmful effects on the marine ecosystem. To limit these adverse effects, some reefs have their own unique set of rules and regulations under local government enforcement. While there are limitations already in place for both recreational and commercial fishing with regards to many natural coral reefs, artificial reefs add another complex layer.

In some cases, artificial reefs are seen as a superior alternative to natural reefs due to their less fragile nature. Additionally, artificial reefs have been said to act as fish aggregating devices that attract fish to a relatively confined area, making them easier to catch (Pickering and Whitmarsh 1997; Islam et al. 2014). While this is beneficial for fishing initially, if the artificial reefs solely act as fish aggregators, there may be a significant decrease in fish populations. This is because there may not be enough surviving fish to breed fast enough to replenish the fish that were harvested previously (Teh et al. 2009).

4.2.1) Artisanal Fishing

Artificial reefs are often deployed near natural coral reefs with the intent to increase the number of fish in the ecosystem by providing more habitat. Likewise, artificial reefs are established to prevent trawling from occurring, thus giving artisanal fisheries a better chance at catching fish (Islam et al. 2014). Despite this, a study in Malaysia showed that the income of artisanal fishers who fished around artificial reefs was lower than those with comparable gear fishing in areas without artificial reefs (Islam et al. 2014). This suggests that artificial reefs do not actually benefit artisanal fishers, but instead may actually harm them. This study also suggests, however, that the type of gear used may also play a role in the small catch size that

fishers on artificial reefs collect (Islam et al. 2014). While this particular study does not support the idea that artificial reefs benefit artisanal fisheries, there are several other studies it mentions that do support that idea (Islam et al. 2014; Whitmarsh et al. 2008). As such, more data is needed to distinguish the impact of fishing gear from the presence of artificial reefs on the income of fishers.

Due to the possibility of fish aggregation near artificial reefs, there needs to be policies put in place to prevent overfishing and depletion of fish created from the artificial reef ecosystem (Islam et al. 2014; Whitmarsh et al. 2008). This management and regulation will help to maintain fish populations and prevent exploitation and overfishing of a somewhat limited resource (Whitmarsh et al. 2008). Without strong regulation, any benefits seen in the fishing industry as a result of artificial reefs could easily disappear (Whitmarsh et al. 2008).

4.2.2) Industrial Fishing

While artificial reefs have unknown impacts on artisanal fisheries, they can help stop dangerous and harmful fishing practices like net trawling. Net trawling is the use of a large net to capture organisms in a somewhat indiscriminate way and it often results in the harming of coral reefs or frequent by-catch that harms the ecosystem (Kurien 1995). Artificial reefs can be put in place as a way to combat the adverse effects of industrial fishing in particularly popular trawling locations. Some artificial reefs are put in place with the intention of limiting the area that trawlers can easily access with their nets while other reefs may be created to help rebuild a marine community devastated by trawlers (Kurien 1995).

In many locations, bottom trawling is prohibited due to its destructive nature. Despite this, trawling is still a relatively common practice, both in areas where trawling is banned and in

areas without regulations against it (Iannibelli and Musmarra 2008). Adding artificial reefs to the areas where bottom trawling is prohibited serves as a way of preventing trawling and preserving biodiversity (Iannibelli and Musmarra 2008). These artificial reefs protect areas, allowing the surrounding communities to grow and thrive. Having trawling in mind, artificial reefs, like the one depicted in Figure 5, can be made to tear nets (Muñoz-Pérez et al. 2000). Adding certain aspects like steel-hooked concrete, called torpedos, on and around the reef structure can also rip trawling nets (Iannibelli and Musmarra 2008).

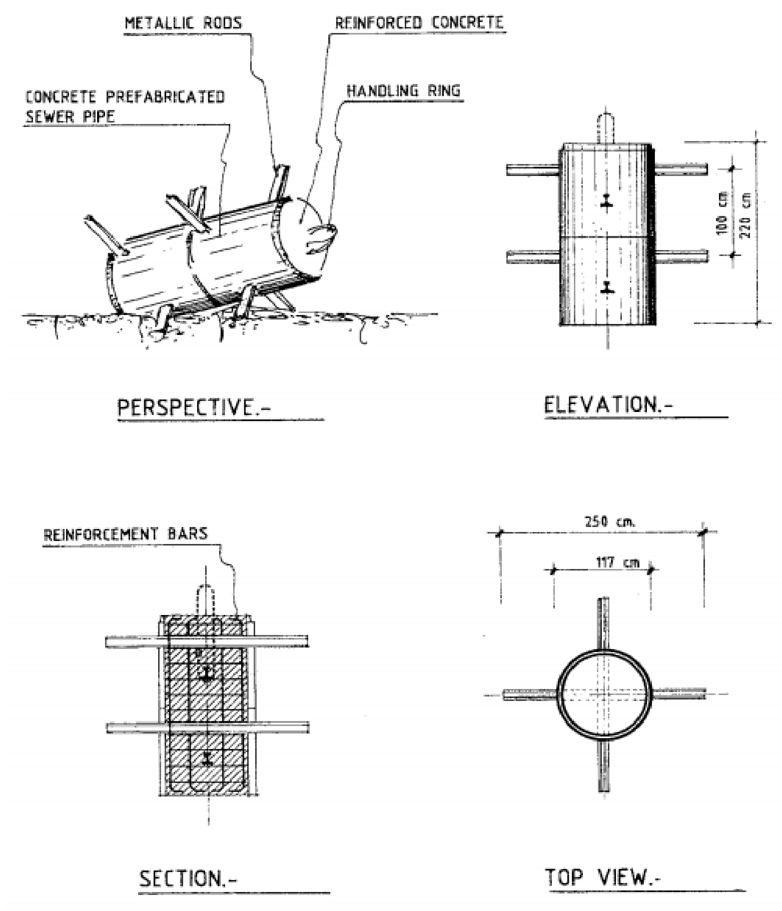

***Figure* 5.** *Image of an anti-trawling artificial reef design taken from Muñoz-Pérez et al. 2000. Within this study, 610 of these structures were deployed in 11 groups. These units are composed of non-toxic cement and steel and weigh about six tons each (Muñoz-Pérez et al. 2000). These structures are considered a relatively cheap alternative to the structures with torpedoes mentioned in Iannibelli and Musmarra 2008. The cost of each individual structure (materials, placement, monitoring, etc.) was approximately $1060.*

4.3) Marine Protected Areas

Marine Protected Areas (abbreviated MPAs) are designated spaces that are protected under governmental law in one way or another. Some MPAs are protected so that fishing is not allowed in that zone; others prevent people from entering that area without official permission. Often artificial reefs are put in close proximity to MPAs to increase the benefits from both as conservation tactics.

4.3.1) Diving

Although the impact of divers on reefs was originally considered low when compared to the effects of storms and harsh waves, with the rapid growth in diving popularity, the supposedly low impacts have been adding up (Polak and Shashar 2012). To mitigate these impacts on natural coral reefs, however, artificial reefs are starting to be used as training areas for inexperienced divers. This diverts inexperienced divers' attention from the natural reef dive sites, many of which are considered marine protected areas, or MPAs. Using artificial reefs to mitigate destruction from inexperienced divers means that when those newer divers progress to natural reefs, they will have the skills and experience necessary to keep the reef safe.

One study looked at the time divers spent in an MPA when there was an artificial reef nearby (Polak and Shashar 2012). After analyzing the data, it appeared that creating artificial reefs in close proximity to MPAs actually helps to lessen the stress put on reefs within the protected area, with regards to diving (Polak and Shashar 2012). The study found that inexperienced divers tended to have behavioral shifts in regards to inexperienced divers more so than more experienced divers (Polak and Shashar 2012). Additionally, intentionally creating artificial reefs with tourists in mind may help to increase an artificial reef's appeal to divers of

varying experience (Polak and Shashar 2012). If aesthetics are considered when an artificial reef is being created, then the reef will likely have more of an appeal to tourists interested in exploring reefs.

4.3.2) Fishing

As two tools used to increase biomass and biodiversity, several studies have analyzed the benefits of combining artificial reefs with MPAs. While great conceptually, this in practice has a few issues. If an artificial reef is added inside of a marine protected area, then the fish populations may aggregate to areas within the MPA, thus making fishing trickier in the areas surrounding the MPA where fishing is legal. If an artificial reef is added outside of a marine protected area, then the fish populations may aggregate to areas outside of the MPA, making the collection of these fish very easy. While the first option preserves the fish, it may harm those who need to fish for a living (Brochier et al. 2015). Contrastingly, the second option is great for fishing, but could negate the work of the MPA and result in overfishing and exploitation (Brochier et al. 2015).

Using mathematical models, Brochier et al. discovered that artificial reefs built within marine protected areas are likely to benefit both the fishing communities and the ecosystem (Brochier et al. 2015). Their models also indicated that there is a point where adding more artificial reefs may benefit the growth of fish populations and biomass, but will harm the fisheries, although that point itself is not specified (Brochier et al. 2015). Lastly, Brochier et al.'s models suggest that artificial reefs require strict management and frequent monitoring in order to have positive impacts (2015).

Chapter 5: Artificial Reefs Vs Natural Reefs

While both natural and artificial coral reefs create habitat, break waves, and attract tourists, artificial reefs have additional uses in an aquatic ecosystem. Artificial reefs can prevent trawling, monitor ecosystems, and preserve coral species in addition to most benefits natural reefs provide human populations. Unfortunately, artificial reefs also pose problems that are distinct from those found within natural coral reef habitat as they have been found to support the transferral of invasive species from one area to another and may not result in increased fish production. Additionally, some metallic structures sunk to create artificial reefs have been known to have mild consequences on the natural environment.

5.1) Additional Uses

Artificial reefs have been used as recycling methods, tourist draws, wave breakers, trawling inhibitors, and climate change combatters. Multifunctional artificial reefs are reefs that are created and implemented in a system where their presence will benefit the ecosystem and/or the surrounding human populations in more than one way (Maslov et al. 2018). While many artificial reef uses mimic those of natural coral reefs, some extend beyond natural reefs' functions. This separation provides further evidence that artificial coral reefs are their own distinct sect of marine science.

5.1.1) Resilience

Climate change has severe impacts on both marine and land ecosystems, thus harming far more than just human populations. With rising water levels, people that live on islands or along

the coast are worried about losing their homes due to sea level rise. Additionally, the increases in temperature can cause coral bleaching and ocean acidification, both of which drastically impact all organisms that rely on coral reefs for food, shelter, and breeding areas. To help preserve both coastal areas and reef ecosystems from the changes occurring due to a shift in climate, artificial reefs have been created and adjusted with specific needs in mind.

5.1.1A) Multifunctional Artificial Reefs

For humans, multifunctional artificial reefs (MFARs) are a recent "soft-engineering solution" used to protect shorelines from waves and help limit the erosion of coastal areas while simultaneously providing better surfing conditions locally (Lopez et al. 2016). Since the first MFAR was established in 1999, this technology is still a relatively new approach to combating climate change and thus, has yet to be fully developed as a tool (Lopez et al. 2016). Despite their recent creation, MFARs have been shown to have promising results, as several MFARs have resulted in sand accretion, bigger surfing waves, and coastal growth (Lopez et al. 2016). Additionally, on several occasions, the implementation of MFARs has resulted in increases in organisms surrounding the man-made reefs (Lopez et al. 2016).

While these multifunctional artificial reefs can have several benefits, much research is needed prior to their implementation in a region; this includes the study of waves and currents, sediment type and transport, liquefaction, and settlements (Lopez et al. 2016). Additionally, some scientists analyze the biodiversity of a location compared to surrounding areas to determine if a MFAR would likely increase the species richness and general diversity of the area in which it was being implemented (Lopez et al. 2016). Some MFARs are designed to combine previously mentioned uses with a monitoring system. This allows scientists to better understand the health

of the surrounding environment as well as the success of the MFAR with regards to ecological benefits (Maslov et al. 2018).

5.1.1.B) Genetically Manipulated Artificial Reefs

As the oceans all warm and become more acidic, coral reef ecosystems suffer from bleaching, increases in diseases, and more competition among other organisms for resources (Correa et al. 2009; van Oppen et al. 2015). Some corals are better suited to fight against these disasters than others, however. Coral bleaching occurs when *Symbiodinium*, the algae that live inside coral tissue, are ejected from the tissue, leaving the coral colorless, and can result in coral death. *Symbiodinium* are ejected when the temperature or acidity of coral's surrounding water reaches a certain point. This point is different for different species of coral as well as different clades of *Symbiodinium* (van Oppen et al. 2015). As such, researchers have been studying more resistant species of coral and clades of *Symbiodinium* to determine the most resilient types of coral with regards to these stressors (Correa et al. 2009; van Oppen et al. 2015).

To combat the stressors of climate change, scientists have begun breeding and genetically engineering corals to better withstand these stressors (van Oppen et al. 2015). In doing so, however, scientists may reduce biodiversity and may even create "exotics," or organisms that are enhanced as a result of human manipulation and can sometimes become invasive in systems (van Oppen et al. 2015). Creating "exotics" or "invasive hybrids" can lead to a decrease in biodiversity as weaker native species can no longer survive the changes occurring within their ecosystem or a decrease in biodiversity can be the result of the new "exotic" species outcompeting its natural counterparts (van Oppen et al. 2015).

5.1.2) Restoration

In addition to helping increase resilience of reefs and coastlines, artificial reefs are often created with the intention of restoring a community to an earlier, healthier state. Reefs can help to prevent net trawling, a way of catching and collecting fish that can harm the diverse fish populations as well as coral reefs in the way. As mentioned before, a decrease in trawling can lead to an overall decrease in coral breakage, as trawl nets are no longer able to scrape along the bottom of the ocean and knock over corals (Kurien 1995). This helps to protect and restore habitats once destroyed by these nets, as the coral can now grow undisturbed by trawls (Kurien 1995).

Trawls also collect fish somewhat indiscriminately, meaning a fisherman using a large net trawl has little control over what fish are and are not captured by the net. As such, trawlers can result in bycatch, or non-targeted organisms (Davies et al. 2009). This bycatch can result in the capturing and killing of fish that are protected by law, as these species, as well as other unwanted species, are removed from nets and released into the ocean, more often dead than alive (Davies et al. 2009; Hill and Wassenberg 2000). Dead fish in the water column provide increases in nutrients that can lead to algal blooms and a general decrease of grazing on reefs, both of which have adverse effects on the reef (Furman and Heck 2008).

Additionally, artificial reefs are created to increase biomass and diversity in a region, providing hard substrate for baby corals to recruit onto, habitat for fish to hide within, or other helpful uses for marine communities (Ng, Toh, and Chou 2017). In helping corals to grow and protecting fish from trawls, artificial reefs are one piece of the restorative puzzle needed to help protect coral reef ecosystems.

5.2) Potential Risk

Artificial reefs have unique challenges that distinguish them from natural coral reefs. Due to these unique characteristics and unknown difficulties, more studies are needed to better determine and limit the unintended harmful effects of creating artificial habitat in a marine system. The potential harm of these stressors stems from a limited understanding of artificial reefs and artificial reef science. Scientists are still determining what functions artificial reefs truly serve, how they impact surrounding organisms and environments, and whether they benefit non-indigenous species more than native species.

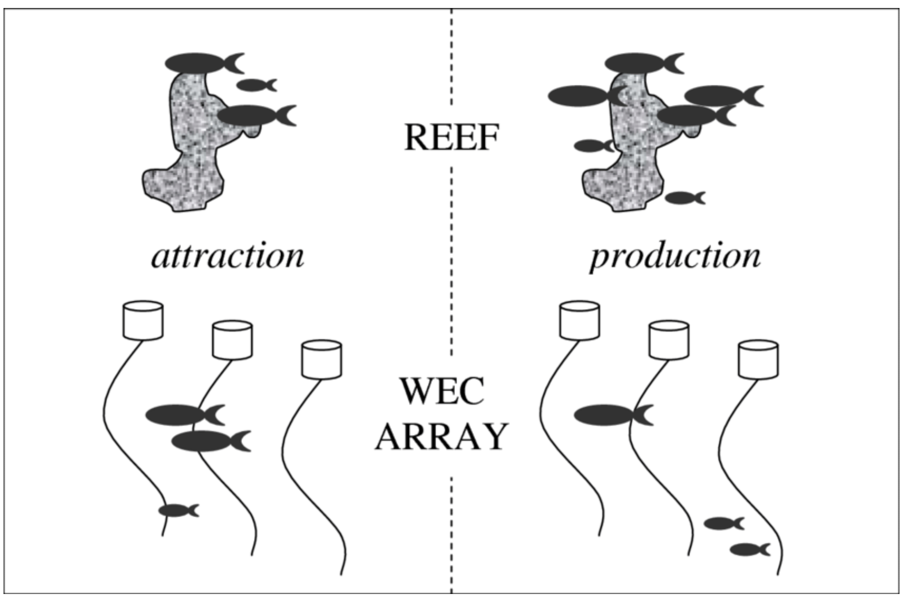

Figure 6. *This graphic taken from Nelson and Harvey 2008 shows the difference between attraction and production. If an artificial reef, as shown on the bottom half of the figure, simply attracts fish, then the overall population of fish does not change. If the reef increases production, however, then there will be more fish in the surrounding area than there were prior to the installation of an artificial reef. On the right side, labelled production, there are more fish than on the left side, and these fish are not all adults. This is because heightened production will result in more reproduction, and thus more juvenile fish that will eventually mature and reproduce on their own. Not knowing whether a reef attracts or produces fish can result in overfishing and overestimating fish populations, as scientists may assume that the total population has been growing, but really fish are simply leaving the natural reef to aggregate to an artificial reef.*

5.2.1) Attraction vs Production

Since the early usage of artificial reefs in a scientific capacity, researchers have questioned whether artificial reefs result in overall population growth and increases in fish production or simply act as aggregating devices that attract fish. This argument is very important, as it can help to determine the best way to safely and sustainably fish on artificial reefs (Pickering and Whitmarsh 1997).

Artificial reefs will attract fish and aggregate them to one location, as the organisms that grow on the artificial reef provide food for the fish; aggregation can be seen on the left side of Figure 6. Artificial reefs, theoretically, can also lead to an increase in breeding, a higher carrying capacity, more available food, an increase in protection against waves and predators, more habitat, and more material for corals to recruit onto (Pickering and Whitmarsh 1997; Bohnsack and Sutherland 1985). This may result in an overall increase in fish population and production on the reef, as seen on the right side of Figure 6. In the early use of artificial reefs, different studies declared different conclusions about fish aggregation. Some declared that artificial reefs did not attract fish from other nearby reefs while others declared that fish would only ever travel from natural reefs to artificial ones (Bohnsack and Sutherland 1985). More recently, however, artificial reefs have been considered as one of the most productive habitats for fish, but do not greatly increase the population of fish in a system (Smith et al. 2016).

Based on the benefits artificial reefs provide, studies suggest that territorial fish limited by habitat benefit the most from these structures (Pickering and Whitmarsh 1997). For areas that already have abundant habitat, experience large losses due to fishing, have fish that are mobile,

have opportunist fish, or are pelagic, an artificial reef likely would not increase productivity or biomass, but rather would result in aggregation of local fish (Pickering and Whitmarsh 1997).

5.2.2) Invasive Species Argument

Additionally, artificial structures have been found to have higher ratios of nonindigenous species to indigenous species than natural areas like rocky reefs (Glasby et al. 2006). In particular, nonindigenous species recruited well to concrete as a material (Glasby et al. 2006). As mentioned in chapter 2, concrete is a very common building material for artificial reefs (Baine 2001). Several studies have also concluded that the presence of artificial reefs that mimic hard-bottom habitat can result in the dispersal of nonindigenous species as it provides hard substrate where there would otherwise be none (Feary, Bart, and Bartholomew 2011). While not all nonindigenous species are classified as invasive species, invasive species are nonindigenous. This may indicate that building artificial habitat, especially out of concrete, may result in an increase in invasive species.

Likewise, the sinking of ships or other materials that traveled prior to becoming artificial reefs may also result in the transporting of nonindigenous, and perhaps invasive, species. Non-indigenous species are often transported via boat, typically via ballast water discharge (Feary, Bart, and Bartholomew 2011). This means that if a species existed either in or on a boat that was sunk away from where the species lived, that non-indigenous species could easily become a part of the local ecosystem where it is not native.

5.2.3) Trace Metals

As seen in the previous section, adding outside materials into a particular environment often results in unintended consequences. In particular, shipwrecks, sunken metal structures, and

other artificial reefs containing metals may result in a general increase in trace metal concentrations in the surrounding waters. Shipwrecks can impact the environment years after the ships run aground (Dempsey et al. 2016; Hartland et al. 2019). For instance, even years after the *MV Rena* sank, there were still increased concentrations of trace metals, particularly copper, in the surrounding water (Hartland et al. 2019). Metals and other potential contaminants can be found in nearly every part of a ship, including the electrical equipment, the protective paints, and the fuel (Hartland et al. 2019). When these components remain underwater for long periods of time, the contaminants can easily begin permeating through the water, causing harm to the surrounding ecosystems (Hartland et al. 2019).

Trace metals, like those that are expelled over time as a shipwreck becomes a reef, can have harmful effects on coral fertilization, among other important processes that occur during the development of a coral reef ecosystem (Reichelt-Brushett and Harrison 2005). Copper, one of the metals found in high concentrations around the *MV Rena* wreck, can decrease coral fertilization in some species by 50 percent when found in concentrations as little as 15 micrograms per liter (Reichelt-Brushett and Harrison 2005). Similar levels of copper in a system negatively affect other marine invertebrates as well (Reichelt-Brushett and Harrison 2005). Likewise, heightened levels of zinc, lead, and nickel also had negative effects on coral fertilization success (Reichelt-Brushett and Harrison 2005).

Unfortunately, increased levels of trace metals are not only a concern for shipwrecks. After the construction of an artificial reef made of concrete in China's Pearl River Estuary, elevated levels of zinc were found while other elements decreased in concentration after the reef's construction (Chen and Chen 2019). Elevated levels of zinc were found both in the sediment and in the water near the artificial reef; these locations had decreased levels of mercury,

copper, lead, and cadmium, however (Chen and Chen 2019). While this suggests that not all artificial reefs emit metals, more research needs to be conducted to determine the precise impact of different reef-building materials on the surrounding environment.

Chapter 6: Conclusion

Artificial reefs, while appropriately categorized within marine science, historically entailed rich technologies, frequently studied ecosystems, and are distinct from natural coral reefs. Their increasing presence in scientific journals, conferences, and books suggests that the study of these man-made reefs extends beyond a simple component of marine science and is in fact, its own unique sect of marine science. This relative newness as a technology means that artificial reefs require strict monitoring and regulation, as well as more research conducted to learn about their potential, whether positive or negative, in environments.

While a recent addition to marine science research, artificial reefs have been around for centuries, and continue to grow and shift as humans continue to better their understanding of the environment. Only within this past century have individuals questioned their importance, tested their usefulness, and studied their environmental impact. In learning more about the utility of these reefs, researchers, fishermen, and governments have all become more invested in managing this technology, enhancing it, and using it to protect and preserve pre-existing reefs.

Artificial reefs greatly benefit humans by providing coastal protection, habitat for various species of seafood, recreational diving, swimming, and fishing areas, as well as many other benefits. These reefs also can increase the diversity of communities where organisms require a

hard substrate to grow and be successful. As shown in Figure 7, artificial coral reefs are found on large scales all around the world, and the research conducted on these habitats is rather extensive. Despite this incredible growth, there are still hundreds of unanswered questions about artificial reefs and their environmental impact. As the climate continues to warm and anthropogenic factors continue to detrimentally impact marine ecosystems, the scientific community will continue to fill in research gaps about artificial reefs.

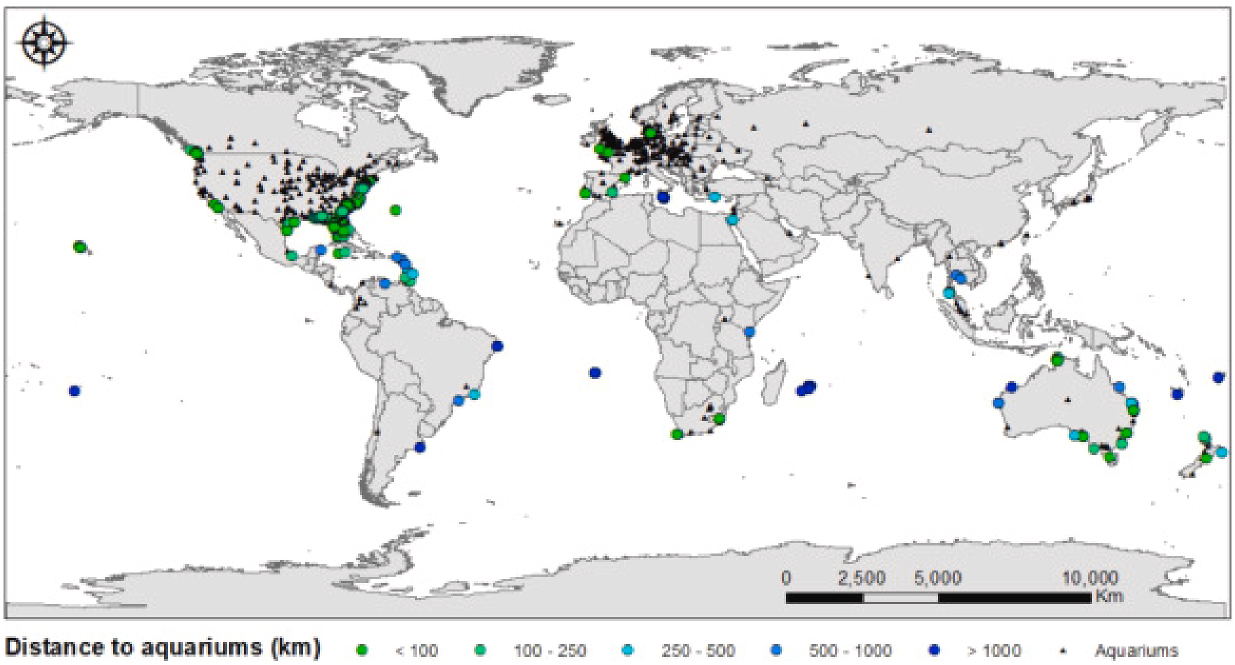

Figure 7. *This figure, taken from Ilieva et al. 2019, shows the distribution of intentionally sunk shipwrecks worldwide. The dots, both colorful and black, each represent a ship that was intentionally sunk for one reason or another. While this image does not show all of the artificial reefs in the world, it does provide a good base understanding as to just how many artificial reefs have been created in both marine and freshwater ecosystems.*

The study of artificial reefs, like the practice of using said habitats, has also grown drastically. As such, this area of research has arguably become its own, separate sect of marine science, totally distinct from the study of natural reef science. While the two share a great deal of

similarities, artificial reefs are far more complex, as they can result in both incredible ecosystem health as well as damage the very ecosystems they are designed to support.

With all the benefits of artificial reefs, however, come some risks; most risks relate to the inputting of foreign materials into a natural environment. The addition of a metal structure can cause trace metal concentrations to increase, while the movement of an artificial reef from one location to another can spread non-indigenous species to new areas, thus risking a new invasive species present in the nearby area. Adding larger artificial reefs, like wind farms, to a marine environment can cause disruption of the ecosystem, as well. Extra precaution and additional research on these subjects, however, should allow future reefs to minimize the potentially harmful effects and maximize the benefits of this technology.

As a technology that has been around for centuries, artificial reefs have expanded in regards to their utility, the materials used to create them, and their overall popularity. This transition from a useful tool to a complex science has involved growth, research, monitoring, and understanding. Stemming from marine science, the new and distinct science of artificial reef research has grown exponentially in popularity and has provided incredible findings in the scientific community as a whole.

While only one example of the development of a new scientific field, the process of artificial reef science becoming a unique sect of marine science may provide key insights into the process with regards to other scientific fields. As the field of artificial reef research continues to grow, it will be interesting to see what new fields of science and technology emerge from the understanding of artificial reefs, as this field itself emerged from marine science, which in turn stemmed from ecology, which can also be seen as a branch of a specified scientific field.

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