Raja Ampat Amidst Climate Change

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Abstract

The Raja Ampat Archipelago contains some of the most biodiverse and well maintained reefs in the world. As an overview, this research will explore the human impacts, biological impacts, and physical impacts that coral reefs in the Raja Ampat Archipelago have dealt with, as well as the history of the islands. Raja Ampat has an extremely rich history, and key events of the Archipelago will be highlighted. Concerning physical impacts, this paper will look into the reefs of Raja Ampat and their reactions to climate change. For example, the impact climate change has on climatic phenomena such as El Niño Southern Oscillation (ENSO), which affects the populations of native Raja Ampat species such as the Manta Ray and others. For human impacts, this paper will detail human activities such as commercial and illegal fishing, as well as nickel mining carried out in Raja Ampat. Other activities, such as tourism and boats, also harm Raja Ampat reefs. Next, concerning biological impacts, coral predators, such as the crown of thorns starfish in the Raja Ampat region also negatively affect coral reefs. Finally, both the negative and positive actions humans have committed towards the health of the Archipelago's coral reefs will be outlined. It is up to humans to decide if we want to continue down the path of environmental destruction, or place an emphasis on positive actions to save the health of Raja Ampat's beautiful, biodiverse reefs.

Introduction

The Raja Ampat Archipelago is one of the most marine biodiverse regions in the entire world. The Archipelago is situated in the coral triangle, in which 76% of all known coral species and 33% of the world's known coral reef fish species are located. Raja Ampat specifically contains around 600 species of hard corals and 1700 species of reef fish.The coral triangle spans 6 million square kilometers across Indonesia, Malaysia, the Philippines, Papua New Guinea, Timor Leste, and the Solomon Islands. One of the most biodiverse areas of the Coral Triangle is the Bird's Head Seascape, a region on the North West of Papua, in which the Raja Ampat Archipelago is located.

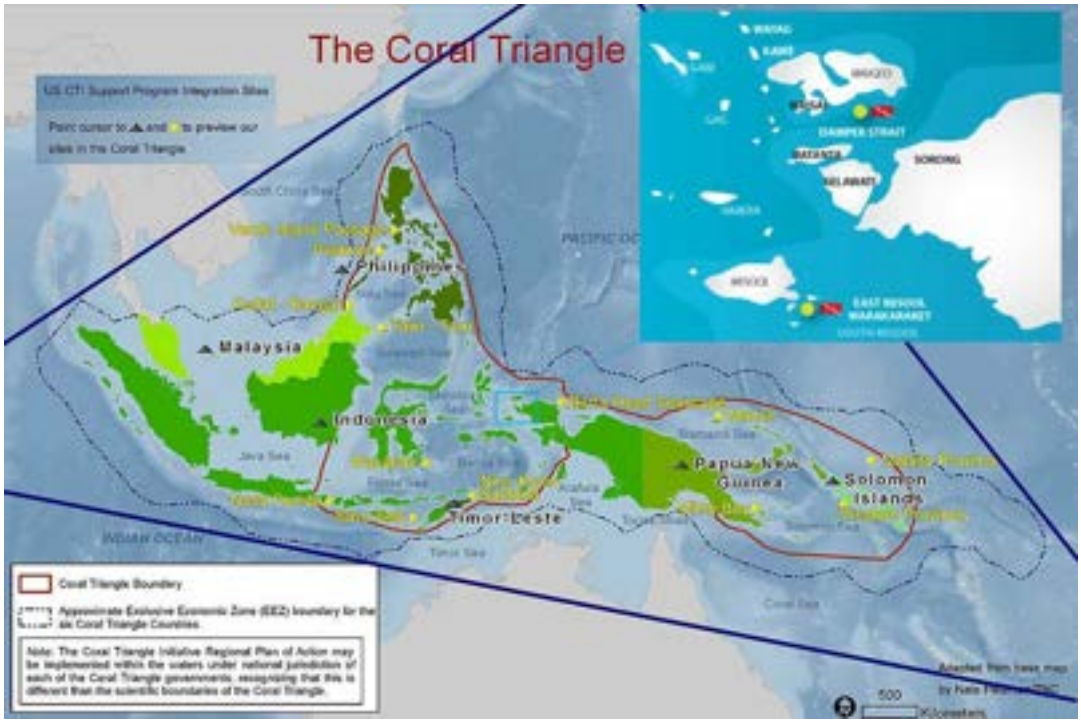

Figure 1: Map of the Coral Triangle and Bird's Head Seascape
Credit: https://www.diveplanit.com/dive-destination/raja-ampat/

As mentioned before, Raja Ampat's coral reefs are extremely biodiverse, containing multitudes of fish, coral, crustacean, cetacean, and other marine species. The extreme abundance of biodiversity of Raja Ampat's reefs marks the importance of protecting and conserving these reefs. For example, endemic species such as the Papuan Garden Eel, Raja Ampat Epaulette Shark, Mantis Shrimp, and more. Raja Ampat's coral reef ecosystems depend on a delicate balance of biotic and abiotic factors, which if altered, can lead to significant degradation of these ecosystems such as loss of certain species' density and abundance.

Each island on Raja Ampat has its own micro-climate. Due to Raja Ampat being located along the equator, there are not really seasons as with the northern and southern hemispheres. However, the micro-climates do make for varying weather conditions depending on the island. For example, thunderstorms can occur on one island, while another nearby island exhibits a calm breeze with sunshine. Raja Ampat altogether has consistent tropical weather throughout the year. Raja Ampat's tropical climate means that on average, the temperature peaks at 32 degrees Celsius during the day, and drops down to 25 degrees Celsius at night. Water temperatures generally range between 20 degrees Celsius and 29 degrees Celsius throughout the year.

Raja Ampat has a rich cultural history; its name roughly translates to "the four kings," which refers to the four main islands. These islands are: Misool, Salawati, Batanta, and Waigeo. The islands are named after a local myth about a woman who discovered seven eggs and took them home. Six of the seven eggs hatched, with four being boys, one being a girl, and the last a ghost. The remaining egg did not hatch and turned into a stone. Eventually, the four boys grew up to become kings of the four islands Misool, Salawati, Batanta, and Waigeo. The girl became

pregnant and was banished by her family to nearby Biak Island, where she was taken in by their king. Finally, the stone egg became an item of worship for the locals.

The Archipelago has always maintained a diverse blend of cultures, whether it be different tribes or various races. This began around 60,000 years ago, when Melanesians arrived and settled in the region. As time went on, Austronesians made their way to Raja Ampat, and settled as well. In the following centuries, Raja Ampat became a place where multiple cultures and tribes coexisted. During the early 1500s, Europeans discovered the Archipelago. They immediately began attempts of colonization on the islands and its surrounding areas. In the 1600s, the Dutch East India Company established a lucrative spice trade in the region. Following this, the Dutch continued to gain increased control through their spice trade, eventually exiling the original sultan and establishing a dutch vassal as the new sultan of Tidore, which was the main eastern kingdom of Indonesia at the time, and encompasses Raja Ampat.

Figure 2: Map of Sultanate of Tidore
Credit: https://en.wikipedia.org/wiki/Sultanate_of_Tidore

Not being able to endure this any longer, the locals, led by Nuku, son of the exiled sultan, waged a rebellion that began in 1783 against the Dutch. By 1797, the natives had regained control of most of the region, and Nuku became the unofficial Sultan of Tidore. The Dutch, however, continued to have influence over the region, and it was only in 1945 that Indonesia was officially declared independent.

Geologically, Raja Ampat contains a variety of rock types and formations, along with rocks of staggering age. Metamorphic rocks on Misool Island are some of the world's oldest exposed rock, and were formed during the Silurian and Devonian periods, ranging from 439 to 360 million years ago. Raja Ampat's high concentration of ultramafic rock, a type of igneous and meta-igneous rock with low silica content — especially those riddled with nickel in Waigeo —

are one of the reasons behind Raja Ampat's nickel mining economy. In addition to ultramafic rocks, Raja Ampat has many limestone outcroppings, which lead to Karst formations.

Figure 3: Raja Ampat's Karst Formations
Credit: https://rajaampatgeopark.com/our-heritage/geoheritage/

Karst are a phenomenon in which caves form underwater and on land. One important aspect of the creation of Raja Ampat's intriguing geological formations are the fault lines that run through the region. These fault lines specifically create the wide variety of hills in Raja Ampat, such as those in Wayag. Overall, the Raja Ampat Archipelago not only holds extremely diverse life, but also possesses a wide variety of rock formations and types.

Raja Ampat is abundant with natural resources, biodiversity, history, and culture. However, all of these things are at risk due to damages brought on by humans and climate change. Increasing amounts of carbon dioxide are being emitted into the atmosphere, leading to rising global temperatures, water temperatures, and ocean acidification. Ocean acidification especially is extremely dangerous to the rich coral ecosystems of Raja Ampat. The bleaching of corals, as well as alteration of breeding and migration patterns of marine life are all affected by climate change. The physical, biological, and human impacts on Raja Ampat will be explored. If changes are not made, the Archipelago will continue to endure negative impacts of these factors.

Physical Impacts

Raja Ampat is impacted physically by many factors. First, there are water characteristics, such as pH, salinity, temperature, turbidity, dissolved oxygen concentration, as well as total dissolved solids. Next, there are climate related factors such as El Niño Southern Oscillation and La Niña Southern Oscillation, which can cause typhoons and storms. Other physical impacts include insolation and currents.

Climate change has caused a steady shift in many of the ocean's characteristics. For example, due to increased carbon dioxide emitted into the atmosphere, the ocean as a whole has begun to acidify and heat up. Specifically concerning Raja Ampat, the lowering of water pH

through ocean acidification and increase in temperature from higher amounts of greenhouse gasses in the atmosphere can have adverse effects on its marine ecosystems as a whole. The main impact of ocean acidification and increased temperatures on Raja Ampat is coral bleaching. As the pH of Raja Ampat's waters slowly decreases, and the temperature increases, the zooxanthellae — the algae that shares a symbiotic relationship with coral, in which coral provides shelter and zooxanthellae provides food and energy — become stressed. This causes the zooxanthellae in the coral to vacate, and thus the coral is unable to get its food and energy. Without food and energy, the coral bleaches and slowly begins to die.

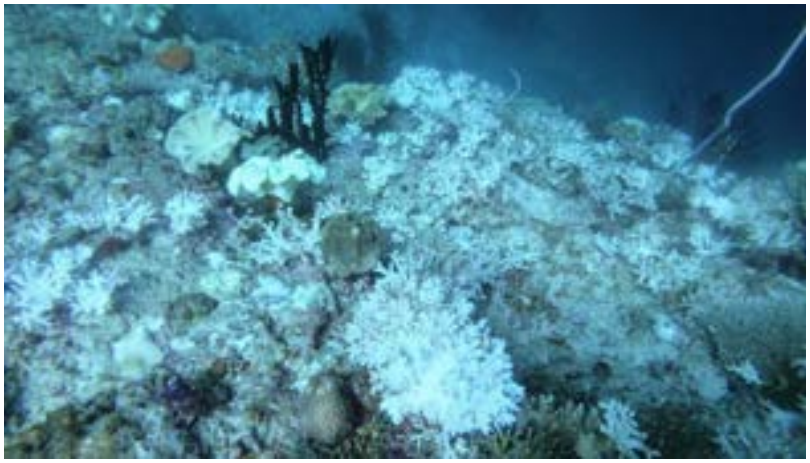

Figure 4: Bleached coral near Waigeo Island
Credit: https://voi.id/en/news/23910

According to the head of the Regional Public Service Agency for the Technical Implementation Unit of the Raja Ampat Regional Water Conservation Area Service, preliminary data from a survey that was conducted at more than 10 popular diving sites found that bleaching of soft, table, and branch corals was present at all sites.

Two climatic events that have a regular effect on the marine ecosystems of the Raja Ampat Archipelago are the El Niño and La Niña Southern Oscillations (ENSO and LNSO). During ENSO events, the warmer surface waters are blown east towards the Americas, and thus drier conditions in Raja Ampat will occur. Conversely, during LNSO events, the normal East to West trade winds are amplified, and more warm surface waters are blown west towards Southeast Asia. This causes Raja Ampat specifically to experience heavy rainfall, monsoons, and typhoons. These typhoons and high winds lead to more wave movement and higher wave amplitudes. Intense wave action by way of large and powerful waves can break and shatter corals. Although this is detrimental for coral reefs, they generally are able to recover properly during normal LNSO events. However, due to climate change, LNSO and ENSO events have started to become more and more intense. As the intensity and strength of these events continue to increase year after year, the stronger and more frequent waves could make it harder for coral reefs to recover from future LNSO events. Although I could not find any studies on coral recovery following storms during LNSO events, it can be speculated that Raja Ampat's coral would experience breakage following typhoons and storms, but eventually recover at least somewhat.

The ENSO and LNSO climatic phenomena also affect certain species of marine life in the Raja Ampat Archipelago. A study published by Beale, Calvin S. et al. 2019 looked into the

impacts ENSO had on Manta Ray populations in Raja Ampat. Data collected from this study displaying the sea surface temperature drop during late August of the 2015 to 2016 ENSO event is shown below.

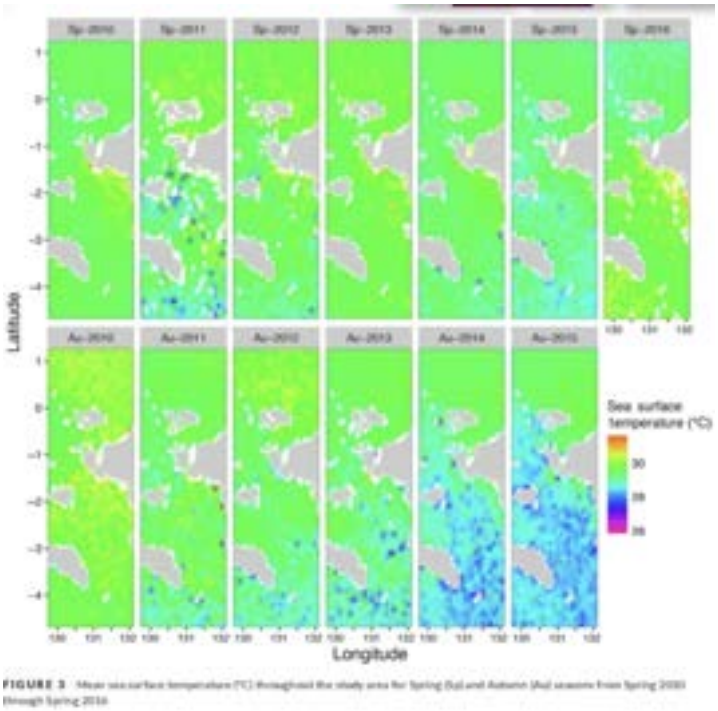

Figure 5: Graph of sea surface temperature drop during late August of the 2015 to 2016 ENSO event
Credit: Beale, Calvin S. et al. 2019

The study cataloged photos of the rays for their sightings database. 75.4% of these photos came from tourists who submitted their photo identifications to the study's sightings database. These photos were collected mostly from September to June, as this is generally the tourism season in Raja Ampat. Due to monsoons and unsafe ocean conditions from the months of July to August, the study was not able to get data during this period each year. Using a POPAN mark and recapture model — a Jolly-Seber model used for estimation of population size and survival and capture probabilities — the team was able to estimate the abundance, recruitment, survival, and sightings probability of the Manta Ray population in Raja Ampat. Over the period of six years, they identified 588 individuals, 28.2% were seen again, 71.8% were not, and of those 588 individuals, 72.4% were female and 27.6% male. Most of the Rays were sighted in the Misool region of Raja Ampat (84.8%), 14.8% were sighted in the Dampier region, and only three total sightings came from the Fakfak region. During the 2015 to 2016 ENSO event, there was an exponential increase in Manta Ray sightings. This event was the third strongest recorded in history, and it caused a drop in surface sea temperature, increase in zooplankton populations, and a prolonged monsoon season. Looking at their models, even the most ungenerous estimation predicted a population of 1,875 individuals. Below are a few graphs of Manta Ray sightings in relation to ENSO MEI, an ENSO severity index, sea surface temperature, and chlorophyll-a concentration.

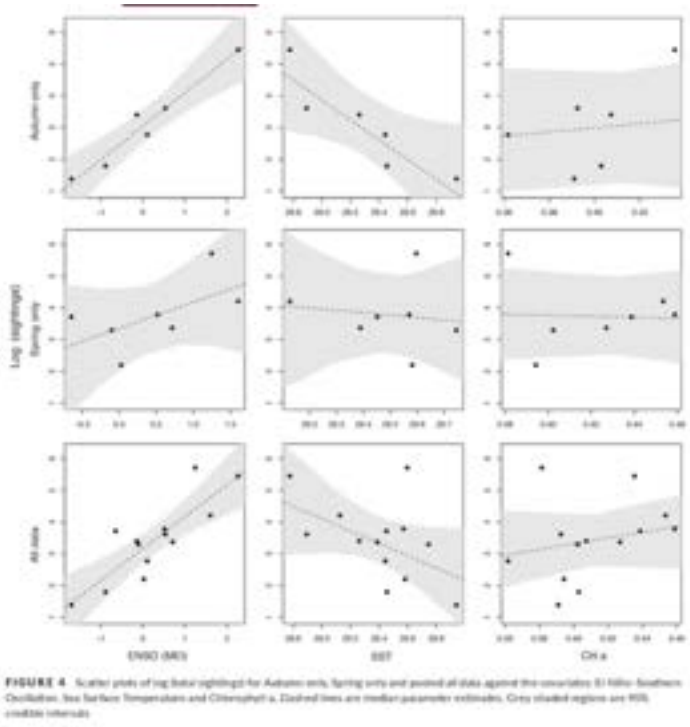

Figure 6: Graphs of Manta Ray sightings in relation to ENSO MEI, an ENSO severity index, sea surface temperature, and chlorophyll-a concentration
Credit: Beale, Calvin S. et al. 2019

Looking at the graphs, it can be observed that there is a clear correlation between ENSO severity increase and manta ray sighting increase. Additionally, the graphs indicate that sea surface temperature decrease is also associated with increased sightings of manta rays.

From this, the team concluded that Manta Ray populations do appear to be impacted by the ENSO events and the associated drop in sea surface temperature. They state that with climate change, sea surface temperatures are predicted to rise between 1 and 3 degrees Celsius within the 21st century, shifting zooplankton concentrations away from the tropical regions. This can cause a trophic cascade effect, as zooplankton and phytoplankton are the backbone of many marine ecosystems, and specifically affect manta rays as zooplankton is their primary food source. Furthermore, they claim that Manta Ray populations are most likely sensitive to large scale climatic changes. Additionally, they also believe that similar changes could occur in tuna, leatherback turtles, whale sharks, and black turtles due to ENSO and sea surface temperature decrease. Finally, due to Manta Ray populations and possibly other species' sensitivity to ENSO and LNSO climate variations, actions should be taken to slow down climate change and protect Manta Rays and other species.

Overall, it can be concluded that climate change has led to Raja Ampat experiencing many physical impacts. Coral bleaching due to ocean temperature and acidification increase, shifting of zooplankton and phytoplankton populations away from tropical regions, and most importantly, altered migration patterns of marine species such as Manta Rays and possibly other species due to increased intensity of ENSO events.

Human Impacts

Raja Ampat is also impacted heavily by human actions and activities. Mainly, negative impacts consist of tourism, boats, illegal and commercial fishing, agriculture, nickel mining, human waste pollution. Conversely, conservation efforts and regulations from humans are positive impacts.

One of the most well known human impacts on Raja Ampat is tourism. Tourism is an overarching impact that can actually cause many separate issues such as boating, illegal fishing, waste pollution, and sunscreen pollution.

First, boats by way of tourism or commercial transport have caused damage to Raja Ampat's coral reefs multiple times. The most recent example occurred on December 18, 2019, when the AQUA BLU yacht crashed into a reef off the coast of Wayag Island. The ship was carrying dozens of tourists, and was headed towards Batanta Island. Although no serious damage was done to the ship itself, sections of the reefs were damaged. The specific damage severity to the reef is not stated, and there are no sources that examine or display the damage caused to the section of reef off of Wayag Island. However, an earlier, more well known incident does give insight into how much damage is caused by ships crashing into Raja Ampat's coral reefs. On March 4th 2017, the 90.6 meter long MS Caledonian Sky of Noble Caledonia Cruises crashed into a pristine reef in the Raja Ampat Archipelago. According to *MongaBay*, the ship destroyed close to 19,000 square meters of untouched coral reef. This damage is substantial, and caused outrage among the locals and authorities. Below are images depicting the damage done.

Figure 7: Destroyed section of reef off of Wayag Island,
Credit: https://www.cnn.com/2017/03/15/asia/raja-ampat-ship-coral-reef/index.html

Figure 8: MS Caledonian Sky on Reef
Credit:
https://www.deeperblue.com/cruise-ship-mv-caledonian-sky-runs-aground-onto-raja-ampat-reef/

Figure 9: The MS Caledonian Sky aground on the reef
Credit:
https://news.mongabay.com/2017/06/restoration-of-shattered-coral-reef-at-raja-ampat-on-hold/

Many parts of the reef were reduced to rubble. Sand and sediment were kicked up by the movement of the ship as well, causing an unwanted increase in turbidity. In addition to the physical damage done to the reef, many organisms that rely on the reef for survival are harmed. Furthermore, *MongaBay* states that the reduction or even loss of diversity in at least eight coral genera, which include *Porites*, *Acropora*, *Stylophora*, and *Montipora*. Although the reef has recovered, it will never be able to return to its former state.

Knowing the damage that tourist ships have caused to Raja Ampat, the authorities have attempted to create regulations to limit the harm that can be inflicted on coral reefs. Following the recent incidents, the Raja Ampat Administration in West Papua began to brainstorm regulations to protect the reefs. They proposed creating a circular that would require agents and operators of cruise ships that wish to sail in Raja Ampat to pay a deposit, as well as employ locals on board. The deposit will be returned at the end of the trip, as long as no coral is destroyed. Therefore, the deposit encourages vessels to be more careful and mindful as to avoid crashing into reefs.

Not only do boats destroy coral reefs in Raja Ampat, but they also directly harm and kill marine life, especially whales. Heike Iris Vester, the Founder and Director of Ocean Sounds, an

organization focused on cetacean communication, and Ricardo F. Tapilatu, Director of the Research Center for Pacific Marine Resources at the University of Papua, wrote an article published to *MongaBay* highlighting general information about whales and dolphins in Raja Ampat. In the article, they mention the harm boats inflict on cetaceans in the Archipelago. Specifically, whales are often scarred from boat collisions, and can even have their fins ripped off. This problem is extremely evident in the Dampier Strait, where shipping traffic is heavy, and whale-watching tourism runs rampant. Below is an image of a pilot whale with a severed dorsal fin, photographed in the Dampier Strait in 2015, by Heike Iris Vester.

Figure 10: Pilot whale with severed dorsal fin
Credit: https://news.mongabay.com/2017/06/surprisingly-indonesias-most-famous-dive-site-is-also-a-playground-for-whales-and-dolphins-commentary/

Looking at the damage done to cetaceans in Raja Ampat by boats, it can be concluded that boats for use in tourism, shipping, and fishing are a human activity that significantly harms marine life.

Illegal and commercial fishing both have detrimental effects on Raja Ampat's marine life as a whole. However, the stand out examples come from illegal fishing, where many fishers utilize strategies such as blast fishing and cyanide fishing—where explosives or cyanide is used to stun or kill fish for easier collection—to catch greater quantities. Since the 1980s, when commercial demand for fish began to skyrocket, these illegal and extremely harmful fishing methods have been employed.

Figure 11: Blast-fished reef
Credit: https://www.unep.org/news-and-stories/story/stopping-fish-bombing

Figure 12: Fisherman utilizing cyanide fishing in Palawan
Credit: https://www.nationalgeographic.com/animals/article/160310-aquarium-saltwater-tropical-fish-cyanide-coral-reefs

According to a study conducted by Varkey et al. 2009, 20% of the total reef fish catch came from Illegal, Unreported, and Unregulated (IUU) fishing in 2006. Furthermore, this 20% accounted for upwards of 40,000 tonnes in the year 2006 alone. Indonesia ranks as the sixth most important fishing nation, and due to widespread IUU fishing, the country as a whole would most likely rank higher on the list. This substantial amount of fishing, some by way of harmful illegal methods can have extremely detrimental effects on the marine life in Raja Ampat.

A study carried out by Larsen et al. 2018 examined the trends of fishery decline in Raja Ampat and West Papua. The team surveyed multiple local fishermen from 88 of the 89 known villages with varying years of experience, methods of fishing, and types of boats, asking them if they believed that the fish catch had decreased compared to “before”. 74% of respondents claimed that they believed fish catch had dropped, 23.6% claimed it was the same, and only 2% believed it had increased. The team then further surveyed those who believed fish catch had dropped, asking them what they believed were the causes behind the lower fish catch. Of all the causes, the three most prevalent were Blast Fishing (62%), Cyanide Fishing (41%), and Outsiders (17%). Below is a graph created by the team depicting the responses for “causes of decreased catch”.

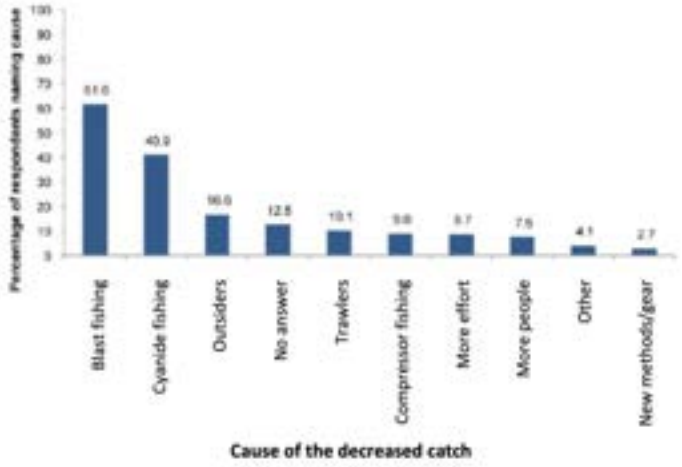

Figure 13: Graph depicting the responses for “causes of decreased catch”
Credit: Larsen, Neil S. et al. 2018

Based on the surveys conducted by the research team, it can be concluded that Blast fishing and Cyanide fishing most likely have a significant impact on the abundance of marine, specifically fish life, in Raja Ampat’s waters. This is important because it is a clear cut example of human activity (IUU fishing) that has caused decline in the health of Raja Ampat’s marine ecosystems.

Moving on, nickel mining in Raja Ampat and much of Eastern Indonesia can have serious implications for marine life in the Archipelago. Catching on in 2006, nickel mining has become a substantial part of the economy in Raja Ampat, especially on islands such as Gag. During the COVID-19 outbreak, the tourism industry was greatly hurt, which was detrimental to the overall economy of Raja Ampat, as tourism is a pillar of the economy. An article titled *The Nickel Mining that Helps the Economy Grow in Gag Islands, Raja Ampat, West Papua* from the West Papua Diary, outlines the positive impacts the establishment of nickel mining has had on Gag Island’s economy. Nickel mining was established by PT Antam through PT Gag Nickel Company, and has provided jobs as well as paid for schools to be built in the area. As of May 2022, the company has used 169 Hectares of the 600 Hectares of forest mining area granted by the government. Yulianas Therbu, a leader of a local indigenous community in the area, claims that the company has carried out reforestation of cleared land, transplanted coral reefs on the shoreline of the island, and helped conserve turtle hatchlings. Syarul Budiman Sarif, a Yogyakarta National Institute of Technology student and Faculty of Mineral Technology who researched mining on the Island, supports the steps taken by PT Gag Nickel to support the environment. He states that waste management from the cleared areas through filtration is sufficient for protecting organisms and microorganisms of nearby environments.

Figure 14: Nickel Mine on Gag Island
Credit: https://westpapuadiary.com/nickel-mining-helps-economy-grow-gag-islands-west-papua/

While this may seem ideal, nickel mining in Raja Ampat has a dark history. A 2011 Sydney Morning Herald article by Tom Allard and Jakarta outlines the harms of nickel mining in Raja Ampat. Allard claims that according to marine conservationists and scientists, nickel mining in Raja Ampat poses a significant threat to its marine ecosystems. Dr. Charlie Veron, an expert on the region as well as a former chief scientist of the Australian Institute of Marine Science compares nickel mining in Raja Ampat to mining without doing any proper environmental impact studies in a rainforest with the most diverse range of species in the world. Furthermore, Dr. Veron mentions how there would be outrage with the rainforest example, and thus there should be similar outrage regarding the nickel mining in Raja Ampat. The article also explains how mining companies use financial incentives to gain support of the local residents. This connects back to the previous *West Papua Diary* article as incentives by the mining companies were possibly offered to locals as well as the *West Papua Diary* itself to promote nickel mining as a positive. Although nickel mining may be positive economically, it is most certainly not beneficial environmentally. The Sydney Morning Herald article further explains how although mining companies claim environmental safeguards, they are ineffective. One local from Rauki Village, which neighbors a mining site owned by PT ASP (PT Anugerah Surya Pratama), claims that rain causes the ocean to turn red, sometimes yellow, and that even though the runoff is supposed to go into a hole, it flows into the sea.

Figure 15: Waters off the coast of Obi Island, an Island in a separate area of Indonesia whose economy is also dominated by Nickel Mining
Credit: https://news.mongabay.com/2022/02/red-seas-and-no-fish-nickel-mining-takes-its-toll-on-indonesias-spice-islands/

This is significant because runoff from mining is a well known point-source pollutant that can devastate marine and terrestrial environments. Additionally, strip mining of nickel destroys the landscape and tree cover, exposing soil and leading to erosion. The frequent rains due to Raja Ampat's tropical climate and steep cliff formations exacerbate the problem, as soil is sent into the ocean. This causes increased turbidity from sedimentation, which is extremely detrimental to coral reefs. Sediment runoff blocks sunlight, decreasing photosynthetic rates of the zooxanthellae that inhabit corals, which is particularly harmful to coral reef ecosystems.

It can be concluded that human activities have contributed to significant and noticeable harm to coral reefs in Raja Ampat. The most well known impact is through physical damage by boats through tourism to the coral reefs. Next, boats and their propellers physically harm marine life such as dugongs, whales, and other cetaceans inhabiting Raja Ampat's waters. Also, illegal fishing through overfishing and harmful methods such as blast and cyanide fishing have harmed Raja Ampat's marine ecosystems as well. Finally, pollution from sediment and heavy metal runoff caused by nickel mining is greatly detrimental to the coral reefs of Raja Ampat.

Biological Impacts

Biological factors also affect the health of Raja Ampat's marine and coral reef ecosystems. The primary biological factors that are detrimental to the reefs include coral predators and invasive species.

Figure 16: Crown of Thorns Starfish
Credit:
https://theconversation.com/love-connection-breakthrough-fights-crown-of-thorns-starfish-with-pheromones-75779

A major coral predator in the Indo-Pacific waters in which Raja Ampat is located is the Crown of Thorns Starfish (COTS). COTS are native to the Indo-Pacific region of the ocean, and are well known for their outbreaks in the Great Barrier Reef. When regulated properly, COTS are essential to the balance of a coral reef ecosystem. COTS feed on hard and faster growing coral, allowing more space for slower growing corals to grow. This is critical as COTS help control the balance between faster and slower growing corals, making a healthy COTS population extremely important. However, when COTS populations get out of control, their effects on coral reef ecosystems can be extremely harmful. COTS are fast-reproducing species, and they are able to quickly decimate reefs due to their widespread feeding. COTS do have natural predators though, including giant triton snails that prey on fully grown COTS, and reef fish such as triggerfish and napoleonfish which feed on COTS larvae.

Many factors affect the population fluctuation of COTS, and this in turn will have an effect on the coral reef ecosystem as a whole. When COTS predators are low in population, COTS are able to reproduce without regulation, and cause more damage to coral reefs. This is because although COTS are r-selected mass-reproducing species, their populations are often regulated through the preying of their larvae by reef fish and low availability of food. Therefore, decline in populations of reef fish, caused by human fishing and habitat range changes due to rising sea temperatures, can cause an increase in COTS populations. Additionally, increased nutrient runoff in coastal areas leads to larger zooplankton populations, which allows more food for COTS larvae to consume and grow, increasing predatory populations.

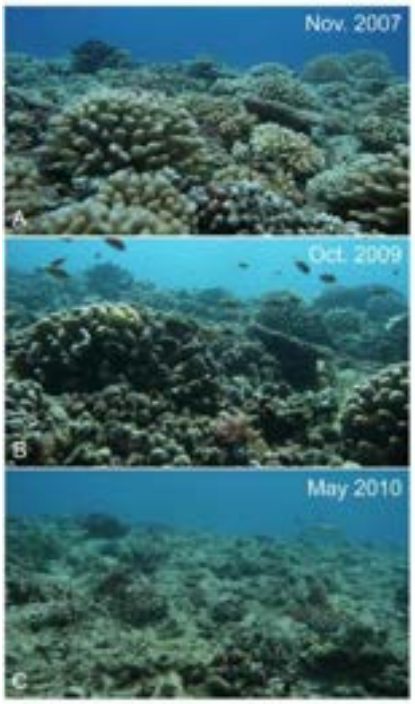

Figure 17: Picture of Vaipahu reef
Credit: https://sharkresearch.earth.miami.edu/crown-of-thorns-starfish-a-threat-to-coral-reefs/

The effects of out-of-control COTS populations are well documented in the Great Barrier Reef, and less discussed in the Raja Ampat Archipelago. However, there have been many COTS outbreaks in Raja Ampat. An article from *Raja Ampat Marine Park* describes the amount and reasons for COTS outbreaks. The article states that there are known areas of outbreaks, and are very important. Scientists usually attribute the outbreaks to ocean nutrient spikes caused by wastewater and agricultural runoff. Nevertheless, causes for certain remote reefs far from shore with outbreak level populations of COTS are unknown.

Despite outbreaks in the region, there is also a lot being done by humans to mitigate and reduce the severity of these outbreaks. Sightings systems and routine removals of COTS make up the mitigation movement in Raja Ampat. The aforementioned *Raja Ampat Marine Park* article of the previous paragraph encourages reporting of sightings through their official report. Another example of COTS outbreak mitigation in the area is explained by *Meridian Adventure*'s dive blog. The article outlines how the company participates in outbreak mitigation through common methods. These methods begin with location and documentation of COTS followed by injection of vinegar into the sea stars, which kills them. Then, the COTS are taken onto the beach, dried, and buried.

Figure 18: Dr. Lisa Bostrom-Einarsson injecting a COTS with vinegar
Credit:
https://www.australiangeographic.com.au/news/2017/04/vinegar-new-weapon-against-crown-of-thorns-starfish/

This method is widespread throughout most regions affected by COTS because of its effectiveness. Vinegar injection has proven to be extremely effective in inducing mortality of COTS, and is also cheaper than compounds of similar effect such as bile salts. Therefore, vinegar injection is the most common method of COTS population reduction.

All in all, it can be concluded that biological factors such as coral predators by way of COTS have significant effects on coral reef ecosystem health in Raja Ampat. Through COTS outbreaks, coral health and population are reduced, raising significant attention to the subject. Luckily, humans have been and are currently taking action against outbreaks, which is something that should also be done regarding the other factors that harm Raja Ampat's marine ecosystems. Through monitoring and killing of COTS, organizations in Raja Ampat are able to regulate COTS populations to healthy levels a majority of the time.

Conclusion

Due to Raja Ampat's abundant marine biodiversity, its marine ecosystems, specifically coral reefs, should be vigorously protected. Three main impacts: physical, human, and biological, affect the health of Raja Ampat's marine ecosystems, each related to climate change. Therefore, specific actions must be taken to limit the harm of the three main impacts, in addition to larger-scale action carried out to slow down and reduce the harm of climate change.

Climate change has significantly altered specific physical characteristics of the ocean. These include sea surface temperature, ocean acidity, dissolved oxygen content, turbidity, as well as sea level. The effects of these changes can be seen in coral bleaching, caused by increased temperature and acidity of the ocean, along with other stressors. Bleaching of coral can be observed all throughout the world, including in Raja Ampat's coral reefs. In addition to harmful bleaching, which affects coral reefs and the organisms that inhabit them, climate change is also linked to greater intensity and severity of climatic events such as ENSO and LNSO. Specifically, scientists have observed that ENSO affects the migration patterns of Manta Rays in Raja Ampat. Additionally, due to the sea surface temperature drop and phytoplankton

shift away from the tropics associated with more intense ENSO events, scientists predict that ENSO and other climatic events will affect other marine species such as tuna, leatherback turtles, and even cetaceans. Overall, climate related physical impacts on Raja Ampat's marine ecosystems are clearly observed, and can be detrimental to the ecosystem's future health.

Previous to modernization, humans mostly co-existed harmlessly with Raja Ampat's marine ecosystems. However, modernization brought many negative human impacts to Raja Ampat. Tourism and fishing are the two main human stressors affecting the Archipelago today. Tourism brings boats, and incidents such as the M.S. Caledonian Sky physically destroying large sections of pristine reefs have and will continue to occur. Additionally, tourism causes pollution to Raja Ampat's marine ecosystems through non-reef-safe sunscreens and physical waste. Fishing, both commercial and illegal, causes great harm to not only Raja Ampat's coral reefs, but also the marine ecosystems of the world. Large-scale commercial fishing methods such as bottom trawling cause physical damage to coral reefs and deplete Raja Ampat's reefs of essential fish species, throwing off the ecosystem's balance. Through methods such as cyanide and blast fishing, as well as fishing in marine protected areas, Raja Ampat's reef ecosystems are constantly damaged. Additionally, both commercial and illegal fishing in Raja Ampat's marine ecosystems often overfish, making it extremely hard for the ecosystems to recover and exist healthily. Other slightly smaller-scale human impacts on Raja Ampat's reefs include physical harm to marine species, such as whales and dolphins done by boats, and sediment, nutrient, and heavy metal pollution caused by nickel mining. All in all, human impacts on Raja Ampat are very widespread, and are especially harmful to the Archipelago's marine ecosystems.

The main biological impact on Raja Ampat's reefs are caused by breakouts of COTS, a coral predator whose harmful effects are well-documented on Australia's Great Barrier Reef. COTS are r-selected, fast growing species, and if left untamed, can significantly decrease the size and health of coral reefs. In Raja Ampat, outbreaks are caused by nutrient pollution and decrease of natural predators from overfishing, both of which increase the survival rates of COTS larvae — either through increasing food source abundance via phytoplankton blooms from nutrient pollution, or decreasing the amount of larvae being preyed on by natural predators from overfishing. Human impacts are tied into this specific negative biological impact, however there are actually positive human actions towards regulating COTS populations. Large-scale organization of COTS sighting and removal logs are used constantly to monitor and reduce the harm caused by outbreaks on Raja Ampat's coral reefs.

It is extremely evident that climate change is slowly destroying the healthy, biodiverse, and beautiful marine ecosystems of the Raja Ampat Archipelago. This story is similar to countless other ecosystems and locations on our planet, with most humans being ignorant to the decline of these ecosystems worldwide. However, there is an ultimatum. Despite humans causing significant harm to Raja Ampat's marine ecosystems, human actions in COTS outbreak mitigation and regulations demonstrate that humans can positively contribute to the health of these ecosystems. Actions like these must continue in order to save Raja Ampat's one-of-a-kind marine ecosystems. Finally, small, basic steps such as recycling, reducing waste, and reducing greenhouse gas emissions can add up and contribute to a positive change for Raja Ampat's reefs and other ecosystems across the globe.

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