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An assessment of the population of crown-of-thorns starfish (*Acanthaster planci* L.) around the island of Malapascua, Republic of the Philippines.

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people and the sea

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NATASHA KENSINGTON

6th September 2019

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ABSTRACT

Crown-of-thorns starfish (*Acanthaster planci* L.), or COTS, is a predatory starfish that feeds on corals across the Indo-Pacific. If the COTS population density increases sufficiently for their feeding rate to exceed the average growth rate of the coral, this is referred to as an 'outbreak'. These outbreaks are a major cause of coral mortality in the Indo-Pacific and, without management, have the potential to diminish live coral cover in a matter of years.

This study was a joint effort between the author and People and the Sea, which is a marine-based conservation initiative based on the island of Malapascua, Republic of the Philippines, that works to improve the biodiversity and overall health of the reefs. In January 2018, there was a COTS outbreak on the east coast of the island. From this point until March 2019, a manual control programme was in place, removing COTS from the affected site. The aim of this study was to determine if the coral reefs around the island would benefit from a new control programme to manage the population of COTS, while looking at the success of the previous removal effort, other sites which could be experiencing outbreak densities of COTS, and COTS feeding preferences.

A SCUBA search survey of seventeen reefs around the island of Malapascua was used to create a baseline of the population dynamics of the resident COTS. These surveys showed that twelve of the reefs have COTS numbers which exceed the outbreak threshold, with over two-thirds of the individuals identified being sexually active and therefore actively contributing to the growing population. This was also the case at the site which had previously been the focus of the COTS removal effort, showing that the manual methods alone were insufficient in restoring the COTS numbers to a sustainable level on the reef. An assessment of the proportion of coral genera and form that was predated, against the proportion that was abundant per site, showed that COTS demonstrate highly selective feeding, choosing table *Acropora* significantly more than expected, and more so than any other genus.

A future control programme should be implemented while ongoing coral loss can still be reversed. A combination approach, using both the poison injection method and the manual removal method, may be the most efficient at restoring the reefs of Malapascua to pre-outbreak densities of COTS. After which, frequent monitoring must be set up to ensure that COTS densities do not become unsustainable again. Furthermore, sites that have a high abundance of table and branching *Acropora* corals should be frequently monitored, as they can be used as indicators to suggest that densities of COTS are climbing too rapidly, showing that repeated action needs to be taken.

KEYWORDS

Crown-of-thorns starfish, *Acanthaster planci*, control programmes, Malapascua, coral reefs, *Acropora*.

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1.1 *Acanthaster planci*

The crown-of-thorns starfish (*Acanthaster planci* L.), here referred to as COTS, was first described by Georg Ebhard Rhumphius in 1705 as *Stella marina quindecium radiotorum*, which roughly translates to a sea star with fifteen radial arms. However, once Carl Linnaeus introduced the binomial nomenclature method of taxonomy, the COTS was re-described as *Asterias planci* in *Systema Naturae* (Linnaeus, 1758). This was based on an illustration by Plancus and Gaultieri in 1743 (Vine, 1973). The genus was later changed to *Acanthaster* by Gervais in 1841, with the species name staying as *planci*, and *Acanthaster planci* remains as the currently accepted classification of COTS. *Acanthaster* is the only genus within the Acanthasteridae family. COTS is one of two species of *Acanthaster*, the other being *A. brevispinus* (Fisher), which is known as the short-spined crown-of-thorns starfish and is rarely found in coral reef habitats (Birkeland and Lucas, 1990). COTS is an iconic keystone species (Paine, 1969) which predates on corals and whose population outbreaks have the potential to decimate Indo-Pacific coral reefs (Allen *et al*., 2019).

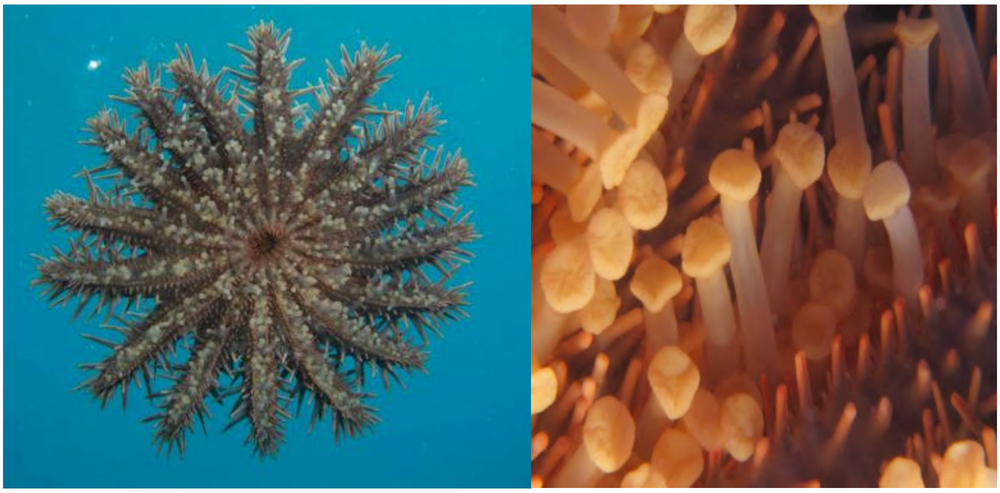

Figure 1. *Left: Oral side of COTS with madreporites in the middle of the central disc © Daniel Schultz. Right: Close up of podia (tube feet) © Jennifer Wilmes (GBRMPA, 2017).*

1.2 Description

The following description is largely based on Moran's 1986 book 'The *Acanthaster* Phenomenon'. COTS are typical starfish, with a central disk and radiating arms (Figure 1). They have prehensile ability due to the numerous podia (tube feet) along each arm. Adult COTS normally range from 25 to 35 cm in size, with some individuals reaching 70 cm in diameter. They have light-sensitive eye spots at the tip of each arm, of which they can have up to 21, losing the typical five-fold symmetry of other starfish. They have 3 to 16 madreporites (Moran, 1990), which are located on the oral (lower) surface of the central disk. COTS have long, sharp spines on the side of each arm, which can grow up to 5 cm in length, along the aboral (upper) surface, resembling the biblical crown of thorns (hence the name). These spines are extremely sharp on the aboral surface, yet blunt on the oral surface. COTS colour varies significantly, from red and orange to purple, largely due to diet (Ault *et al*., 2011). The skeletal structure is composed of ossicles, which are tiny structures made of magnesium calcite.

COTS contain concentrated chemicals in their dermal tissues and organs, including saponins (Barnett *et al*., 1988) and plancitoxins (Shiomi *et al*., 1988), both of which are highly toxic to most other organisms. Although COTS have no mechanism to inject the toxin, when their spines perforate the tissue of a predator, saponin-containing tissue is inserted into the wound. The spine may also become embedded in the tissue.

1.3 Habitat and Distribution

COTS are found throughout the Indian and Pacific Oceans and are found on tropical reefs across the globe (Kayal *et al*., 2012), making them one of the most widely distributed of all reef species (De Vantier and Deacon, 1990). Nevertheless, they have yet to be recorded in the Caribbean or Atlantic Ocean (Pratchett *et al*., 2014).

COTS are found in a wide range of latitudes (De Vantier and Deacon, 1990) and there are marked geographic differences in appearance across this broad geographic range. It is suggested that the wide distribution of COTS populations is due to passive planktonic dispersal of larvae in oceanic surface currents (Yamaguchi, 1987), as well as adult migration.

Juveniles are often found underneath boulders, in coral rubble or at the base of corals (Moran, 1990), while adults are commonly found on coral reef perimeters, in shallow, protected areas. COTS prefer to live in sheltered areas such as lagoons, and in deeper water along reef fronts, avoiding shallow water on the tops of reefs (GBRMPA, 2017), with individuals being recorded as deep as 65 m (Moran, 1990).

1.4 Life Cycle and Reproduction

The life cycle of COTS is typical of most asteroids. Once the egg is fertilised, the embryo develops into the blastula stage after around 8 hours, and hatches after a day as a free-swimming gastrula larva. The larval development is divided into two bipinnaria stages and three brachiolaria stages (Figure 2). Phytoplankton is the main food source during larval development; however, it has been suggested that larval COTS can exploit a diverse range of nutrition sources (Olson and Olson, 1989). During this stage, larvae are at risk of the highest rate of mortality by predation. After one month, the larvae settle onto the benthos, beginning the final metamorphosis into their juvenile phase.

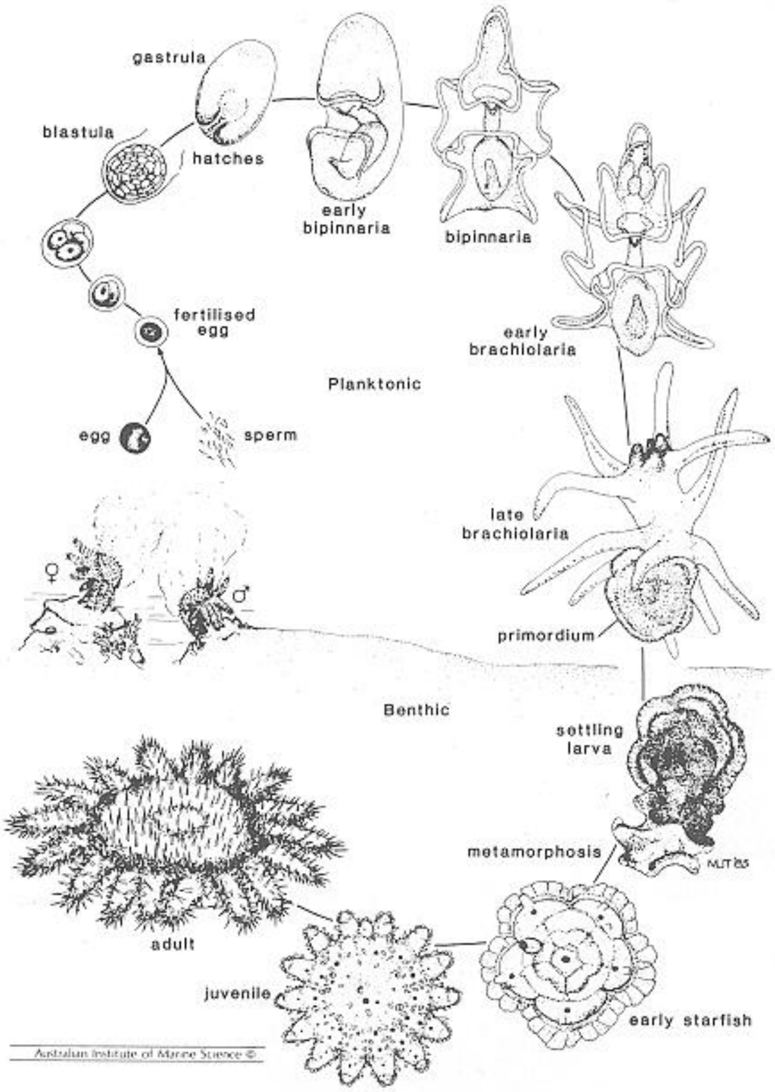

Figure 2. *Schematic diagram of the lifecycle of COTS (Moran, 1997).*

COTS are gonochoristic, which means that males and females are separate, and reproduce sexually as adults, reaching sexual maturity at the end of their second year. For sexual reproduction to be at its most effective, males and females must be close to each other and spawn simultaneously (Levitan *et al*., 1992). COTS have a clearly defined annual reproduction cycle (Bos *et al*., 2013), which coincides with increased water temperatures, normally reproducing in June in the northern hemisphere and November in the southern hemisphere.

Females release millions of eggs into the water column and males release sperm, fertilising these eggs. It is thought that females release a pheromone during spawning which induces males in close proximity to release sperm (Beach *et al*., 1975). High levels of aggregation are not essential for successful fertilisation as there is a high potential for long-distance fertilisation (Babcock and Mundy, 1992; Babcock, *et al*., 1994). Babcock and Mundy (1994) reported that eggs released 64 m downstream from a single spawning male had fertilisation rates of over 20 %. However, fertilisation rate increased to 90 % when one male was next to one female (Wilmes *et al*., 2018).

Despite only reproducing once a year, COTS have an enormous reproductive potential, with fecundity being one of their most important biological traits (Bos *et al*., 2013; Pratchett *et al*., 2014; Wilmes *et al*., 2018). Large females can give up to 45 % of their total energy to reproduction (Moran, 1990). The amount of eggs released by a female in a season is size-dependent, with a large female (>40 cm in diameter) producing up to 65 million eggs while a smaller female (<30 cm) may only produce up to 2.5 million eggs (Kettle and Lucas, 1987). However, not all of these eggs will be fertilised and, of the fertilised eggs, few will survive to adulthood. There is an extremely high mortality of juvenile COTS, with individuals aged 8-23 months having approximately a 99.3 % mortality rate (Zann *et al.,* 1987), while those aged 22-34 months have a 75 % mortality rate (Doherty and Davidson 1988).

A recent study by Allen *et al*. (2018) also found that COTS larvae have an ability to clone in oligotrophic conditions. Therefore, in addition to the incredible fecundity of the species, the larval ability to reproduce asexually may also contribute to their longevity and widespread dispersal (Allen *et al*., 2018). Furthermore, Kamya *et al*. (2016) found that juveniles grow faster with increased ocean acidification, and Uthicke *et al*. (2015) found that a 2^{o}C increase in temperature led to a 4.2 – 4.9 times increase in larval development of COTS, showing that warmer sea temperatures and acidification are important co-factors in promoting COTS larval survival. Therefore, climate change may lead to an increased likelihood of outbreaks in the future, exacerbating the decline of live coral cover due to COTS.

The maximum adult growth and longevity of COTS has been highly controversial. Endean (1982) suggested that COTS should have low mortality and live for decades due to their regenerative ability and physical and chemical defences. However, this is unlikely in high densities during outbreak events due to strong intraspecific competition and rapid depletion of prey resources (Mills, 2012). Lucas (1984) reported COTS had a size maximum of 34 cm after 3 years of age, while Stump (1996) reported a size maximum of 75cm after 8 years of age (Stump, 1996). However, Pan *et al*. (2010) showed that, even in an outbreak population, COTS have the ability to grow beyond 35 cm and live longer than 8 years. One reason that longevity has been difficult to quantify is because there have been very few recorded observations of dead or dying individuals (Moran, 1990), which is likely due to the rapid rate of decomposition of COTS (Moran, 1992; Pratchett *et al*., 2019). Regardless, adults that are more than five years of age have low feeding rates, low growth rate (or potentially undergo shrinkage) and a decline and subsequent cessation of gametogenesis (Pratchett *et al.*, 2014).

1.5 Feeding Behaviour

Juvenile COTS are herbivorous and display cryptic behaviour, emerging at night to feed. During this stage, they feed on crustose and coralline algae, as well as the associated biofilm (Zann *et al*., 1987). COTS move on to the next feeding stage when their size exceeds 10 mm in diameter (Kamya *et al*., 2016). Adult COTS are specialist corallivores (De'ath and Moran, 1998b), which means they prey on coral polyps, largely scleractinian (hard corals) or reef-building corals. They first prey upon faster-growing species, as in the Acroporidae family (Branham *et al*., 1971), and less commonly upon slower-growing species, such as *Porites* spp. However, when food sources are scarce or there are high levels of intraspecific competition, COTS have been observed feeding on a wide variety of organisms (Moran, 1986) even, in rare circumstances, their own species. Alternatively, when corals are abundant, COTS exhibit a strong feeding preference across the most common corals, with *Acropora* corals being preferred over *Porites* corals by a ratio of 14:1 (De'ath and Moran, 1998b; Keesing *et al*., 2019), while also showing a preference among closely related coral species (Pratchett, 2001). Moreover, COTS show a preference for certain coral forms, with table and branching forms being the most popular (Keesing, 1990) likely due to their greater surface area, which provides the COTS with more tissue per feed as well as offering shelter and protection from other predators.

Evidence of COTS coral-feeding can be observed as a white scar of coral skeleton (Figure 3) which can be infested with filamentous algae, sometimes within less than 24 hours (Schug Belk and Belk, 1975). COTS do this by using their podia to climb on to a section of coral. They are then able to extrude their stomachs, secreting digestive enzymes which break down the coral, allowing the starfish to absorb the nutrients (Jangoux, 1982; Pratchett *et al*., 2014). A single individual can consume up to 6 m^2 of living coral reef per year.

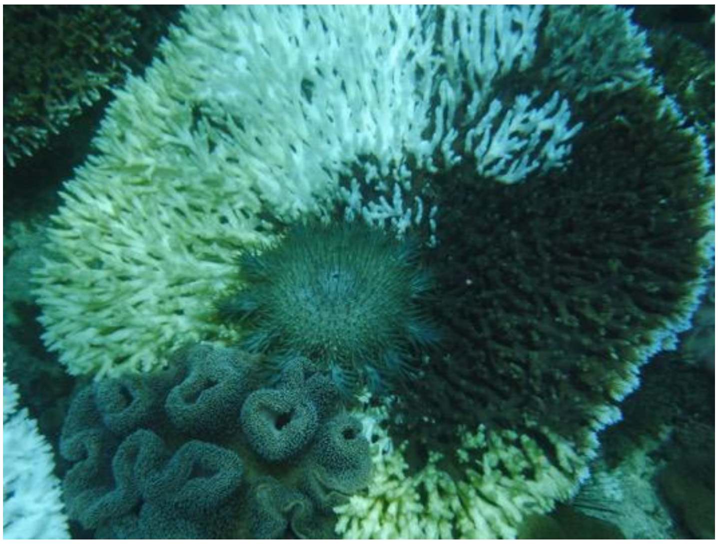

Figure 3. *Photo of a table* Acropora *coral, displaying the white feeding scars left by the COTS (Photo: Author).*

1.6 Predators

Due to the unpalatable and highly toxic nature of the COTS spines, one would expect these starfish to be protected against predation. However, this is not the case, especially during the juvenile stage at which predation is highest, despite their cryptic behaviour (Rivera-Posada *et al*., 2014a).

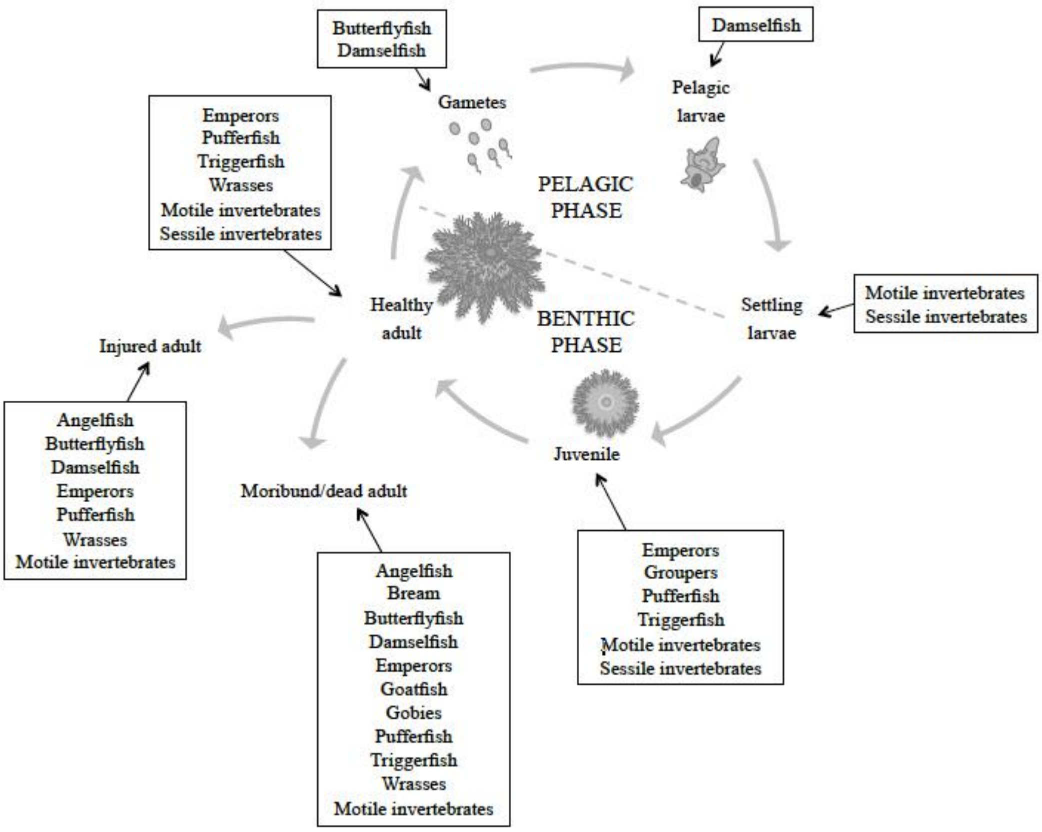

Figure 4. *Main predatory groups acting at each life stage of COTS (Cowan* et al.*, 2017).*

There is a total of 80 species of reef organisms that have reportedly predated on COTS, throughout each life stage (Figure 4); however, the majority of these have been observed consuming dead individuals (Cowan *et al*., 2017), and hence may be scavenging. The predators which are most commonly observed feeding on live COTS are: triton's trumpet (*Charonia tritonis* L.), white-spotted pufferfish (*Arothron hispidus* Matsuura), starry toado (*Arothron firmamentum* Temminck & Schlegel), titan triggerfish (*Balistoides viridescens* Bloch & Schneider), yellowmargin triggerfish (*Pseudobalistes flavimarginatus* Rüppell), harlequin shrimp (*Hymenocera picta* Dana) and lined fireworm (*Pherecardia striata* Kingberg) (GBRMPA, 2017). In the Philippines specifically, there have been observations of the frog shell (*Tutufa rubeta* L.), the sponge crab (*Dromidiopsis dormia* L.) (Alcala, 1976) and even a polyp of *Pseudocorynactis* spp. (Den Hartog), belonging to the order of Corallimorpharia (Bos *et al*., 2008), feeding on COTS.

Predation is often observed on COTS as injuries resulting in the loss of an arm (Rivera-Posada *et al*., 2014a; Messmer, *et al*., 2017), suggesting that it is common for predators only to be able to remove one arm before the starfish manage to escape. Cowan *et al*. (2017) suggested that predators may be able to regulate COTS populations and mitigate or even prevent outbreaks, known as the predator removal hypothesis (Endean, 1969). However, there is no evidence of predatory fish significantly impacting numbers of COTS and therefore they would be insufficient in controlling large increases in populations of COTS (Sweatman, 1995). Furthermore, triton's trumpet, which is considered one of the principal predators of adult COTS (Pearson and Endean, 1969), have rapidly declined in numbers due to harvesting of their shell for sale as curios (Pratchett *et al*., 2014). It is suggested that they would not be effective at controlling COTS numbers, as their average consumption of COTS is low, even at high abundance of COTS (Pearson and Endean, 1969).

1.7 Outbreaks

In low numbers, COTS can increase the biodiversity of a reef, as they prey on faster-growing corals (e.g. *Acropora* spp.), giving way for slower-growing corals (e.g. *Porites* spp.) to succeed, filling an ecological niche and providing a service that benefits the whole community. Walbran *et al.*'s (1989) study of the sediment record indicates that COTS have been an integral part of the reef ecosystem for thousands of years. However, when density increases too quickly, large-scale predation of corals can lead to habitat destruction, as their feeding rate exceeds the average growth rate of the coral (Fabricius, 2013). This is known as an 'outbreak' (Bos *et al.*, 2013). There are three stages of an outbreak: the build-up, which is when the numbers begin to increase; the outbreak, which is when the COTS density exceeds local resource availability (Figure 5); and the epidemic, which is when the COTS outbreak has spread to other reefs due to reef connectivity (Hock *et al*., 2014). Outbreaks can arise from two mechanisms: a single mass recruitment event, or the gradual accumulation of starfish over time from multiple areas (Johnson, 1992). A large outbreak can reduce live coral cover by more than 90 % in a period of just two to three years (Chesher, 1969; Buck *et al.*, 2016).

The mechanism of an outbreak is not well understood; however, there are several hypotheses about the causes, the most likely being a combination of overfishing of predators of COTS (Bradbury, 1991) and warmer sea temperatures, which have been shown to enhance the larval development of COTS (Uthicke *et al*., 2015). During outbreak events, with males and females in close proximity, fertilisation rates can reach 95 % (Lucas, 1973), increasing the population by several orders of magnitude in a short space of time.

Outbreaks of COTS are a major cause of coral mortality in the Indo-Pacific (Kayal *et al.*, 2012; Pratchett *et al*., 2014; Nakamura *et al*., 2016) and are responsible for over 40 % of the coral loss on the

Great Barrier Reef over the last 30 years (De'ath *et al*., 2012). The effects of outbreaks are often widespread and can reduce live coral cover by over 90 % (Kayal *et al*., 2012). This, in turn, causes a reduction in the abundance of reef fishes, loss of shelter space (Holbrook and Schmitt, 2002) and behavioural changes (Boström-Einarsson *et al*., 2014). Although outbreaks were originally a natural phenomenon, human disturbance, such as fishing and excessive eutrophication, have led to much larger, more recurrent outbreaks (KBRF, 2012), which are occurring too frequently for the coral communities to recover (Fabricus *et al*., 2010; Trapon *et al*., 2011).

Figure 5. *Photo displaying an outbreak on a reef north of Malapscua Island, Republic of the Philippines. Multiple COTS (> 8) are feeding on a single table coral (Photo: author).*

COTS larvae have a higher survival rate under enhanced chlorophyll concentrations (Wolfe *et al*., 2017) and, therefore, it is likely that the increased level of nutrients due to human activities has yielded a higher success of recruitment events (Brodie *et al*., 2005). Moreover, it has been suggested that phytoplankton food availability may be an inducer of larval cloning in echinoderms (Allen *et al.,* 2019). Without intervention, COTS outbreaks may cause the disappearance of the corals in a region within only a few years. Although coral reefs can recover from outbreaks, this may take decades, with a range of anywhere between 5 and 100 years (Pratchett *et al*., 2017) before the corals will be restored to a pre-outbreak level, with most reefs estimated to take 10-25 years for full recovery (Fabricius *et al*., 2010). Highly impacted corals may never be fully restored (Berumen and Pratchett, 2006), with 25 % of reefs impacted by COTS around the Great Barrier Reef showing no sign of recovery (Lourey *et al*., 2000).

1.8 Control Programmes

There are a multitude of different methods for controlling numbers of COTS. A method involving cutting COTS into small pieces was used in the past; however, this is now strongly discouraged as COTS has the capacity to regenerate from fragments (Baker and Scheibling, 2008). A common method is manual removal (see section 2.2); however, a disadvantage is that there is risk of injury to the collectors by the venomous spines (Sato *et al*., 2008), especially as they have to handle the COTS twice: first for the initial removal from the reef, and then to be discarded, typically by burial in the sand.

The most successful, yet most expensive, method of control is by injecting COTS with a poison such as ammonia or citric acid (Branham *et al*., 1971; Buck *et al*., 2016). A recent study by Boström-Einarsson and Rivera-Posada (2016) reported that injecting COTS with vinegar caused 100 % mortality in less than 48 hours, showing that regular household vinegar could be used as an effective and cheaper method of lethal injection. Furthermore, vinegar is widely available and requires no dilution or prior mixing of the product. However, this method is still new and there have been several failed attempts (KBFR, 2012; Yamamoto and Otsuka, 2013; Rivera-Posada *et al*., 2014b), showing that further research is required. Moreover, the administration of chemicals often requires permits, as well as access to specialised equipment and training (Boström-Einarsson and Rivera-Posada, 2016).

For any control programme to be successful, seasonal timing and location must be taken into consideration (Bos *et al*., 2013). Fringing reefs, for example, would easily be recolonised across shallow corridors as adult COTS readily migrate from one reef to another (Mueller *et al*., 2011). The chances of an eradication being successful are significantly higher on smaller, more isolated reefs (Bos *et al*., 2013; Nakamura *et al*., 2016). However, the aim of any removal is to prevent further outbreaks, not to fully eradicate the population (Yamaguchi, 1986).

1.9 Aims and Objectives

People and the Sea (PepSea) are a marine-based conservation initiative located on the island of Malapascua, Republic of the Philippines. They are working to promote community-based marine resource management as a way to alleviate poverty and increase the resilience of coastal communities, whilst also raising local awareness about marine conservation. They work closely with the local community of Malapascua, as well as the wider Municipality of Daanbantayan, to identify innovative ways to protect their marine environment, whilst also having a positive economic impact. There are clear links between social welfare and mobility, food security, health, education and the welfare of the marine environment.

The economy of Malapascua largely relies on the tourism industry which thrives due to the high demand for people to come and SCUBA dive in the healthy, biodiverse coral reefs, as coral reefs are regarded as one of the world's most threatened ecosystems (Pratchett *et al*., 2014). The majority of the people who work on the island are directly involved in the SCUBA diving or snorkelling industry, which includes accommodation, restaurants, dive operators and more. Furthermore, 200 families are dependent on commercial fisheries for their livelihood (People and the Sea, unpublished data), and are therefore also reliant on healthy reefs.

One of the biggest attractions that brings tourists to the island is the opportunity to dive at the Monad Shoal, a shallow coastal seamount, which is the only place where the threatened pelagic thresher shark (*Alopias pelagicus* Nakamura) is regularly seen. The pelagic thresher shark is listed as Vulnerable on the IUCN Red List (Reardon *et al*., 2009) and is one of three extant species of thresher sharks, alongside the bigeye thresher (*Alopias superciliosus* Lowe) and the common thresher (*Alopias vulpinus* Bonnaterre). The Monad Shoal is a natural cleaning station for fish, with the pelagic thresher shark frequenting the area for cleaner wrasses, such as the bluestreak cleaner wrasse (*Labroides dimidiatus* Valenciennes), which remove ectoparasites from their skin and also clean their gills and teeth (Oliver *et al*., 2011).

Coral reefs provide important habitats and food for a wide variety of species. COTS pose a biological threat to coral reefs around the island of Malapascua. If COTS density reaches outbreak levels and reduces the live coral cover, then this has the potential to cause a decrease in the diversity and abundance of numerous species of fish and invertebrates, which would have cascading effects on both the tourism and fisheries industries. The island environment and the community both rely on the survival of the coral reefs (Turner *et al*., 2007). Controlling COTS numbers seems to be one of the only manageable ways of ensuring the survival of these coral reef habitats (De'ath *et al*., 2012; Bos *et al*., 2013).

This study provides an assessment of the COTS population and overall abundance around the island, while looking closely at a reef that recently underwent a year-long manual control programme following an outbreak. Programmes like this allow us to gain insight into the reproductive biology and ecological impact of the species. It is important to be able to understand the COTS demographics and population dynamics in order to create a successful, long-term management plan for controlling COTS population outbreaks, while also creating a baseline for future research. The causes of outbreaks are still not well understood; this is likely due to lack of observations of the development of the outbreaks (Kayal *et al*., 2012), with many studies only beginning once an outbreak has already been established, making it difficult to understand the origins of the problem. The creation of databases in areas of high risk such as this is therefore important in order to provide baseline data. Long-term assessments of conservation management programmes can be implemented across the Indo-Pacific in similar locations, to help mitigate the damage that can be caused by unmanaged COTS numbers.

1.10 Research Questions

The overarching aim of this research is to determine whether the COTS population of Malapascua is at or above the outbreak threshold, and whether a new control programme needs to be implemented. The research questions addressed in this study are as follows:

- What are the biometrics (sex ratio, mean weight and diameter etc.) of COTS around the island?
- How successful was the manual control programme?
- What is the size range of COTS around the island of Malapascua?
- Which sites are currently experiencing an outbreak?
- What is the observed effect of COTS on the coral reef ecosystems?
- Which coral genus (and form) is most predated?
- What is the most appropriate future strategy to control the COTS population around the island?

Answering these questions will provide a broader understanding of the biology and ecology of COTS. The data collected on size and age can be used to assist management efforts in securing coral reef ecosystem services and to increase the effectiveness of future management programmes, while also identifying which sites are at risk of future outbreaks. The sites that have a high proportion of the coral genera that COTS selectively feed upon are more likely to experience future outbreaks, as COTS that migrate to the area would likely settle due to the abundance of their preferred food source.

2. MATERIALS AND METHODS

2.1 Survey Area and Sites

Surveys were undertaken at seventeen sites on the reefs surrounding the island of Malapascua, Republic of the Philippines (Figure 6). Malapascua is a small island (1 by 2.5 km) which is located in the Visayan Sea, approximately four miles north of Cebu, and is part of the barangay of Logon, Daanbantayan, Cebu.

Figure 6. A map of the Republic of the Philippines, showing the location of the island of Malapascua. The map was made using ©Google Maps.

PepSea, which is based on the south-west coast of the island, regularly monitor ten sites around the coast of the island: Bantigue, Barrio, Coral Garden East, Coral Garden North, Dakit Dakit Survey Site, Lapus Lapus, Lighthouse Survey Site, Mermaid Survey Site, Sunken Dakit and Two Rocks. The Coral Garden (encompassing both Coral Garden East and North), on the east coast of the island, has been the most impacted by COTS. There is no evidence of COTS at Barrio, Lapus Lapus or Sunken Dakit due to the lack of hard corals in these areas, and therefore these sites were not surveyed for this study. Seventeen sites were surveyed in total (Figure 7): seven of the PepSea sites (excluding Barrio, Lapus Lapus and Sunken Dakit), a further nine sites around Malapascua (Dakit Dakit Buoy, Dakit Dakit, Ka Osting, Langub, Lapus Buoy, Lighthouse Buoy, Lighthouse Wreck, Mermaid Confined Water and Quiliano), and one site around the Monad Shoal (Manta Point) which is about eight kilometres due east from Malapascua Island.

Each site was surveyed for COTS abundance using the SCUBA Search method (see section 2.4), the north and north-west of the island were surveyed for COTS location using the manta tow method (see section 2.3), and the Coral Garden was the only area to undergo a manual control programme (see section 2.2). However, local dive centres have also recently been performing removals from both Ka Osting and Manta Point, but not using a standardised method or recording any data, and therefore have not been included in this study. For each site where the SCUBA Search found more than one COTS per 20 minutes of search time, a benthic survey was also done (see section 2.5), with three areas that had no COTS or numbers of COTS below outbreak level also being surveyed as controls.

All data from the manual control programme were provided by PepSea and not collected by the author. The data from the manta tow, the SCUBA search and the benthic survey were collected by the author during a two-month expedition to Malapascua, working alongside PepSea staff and volunteers.

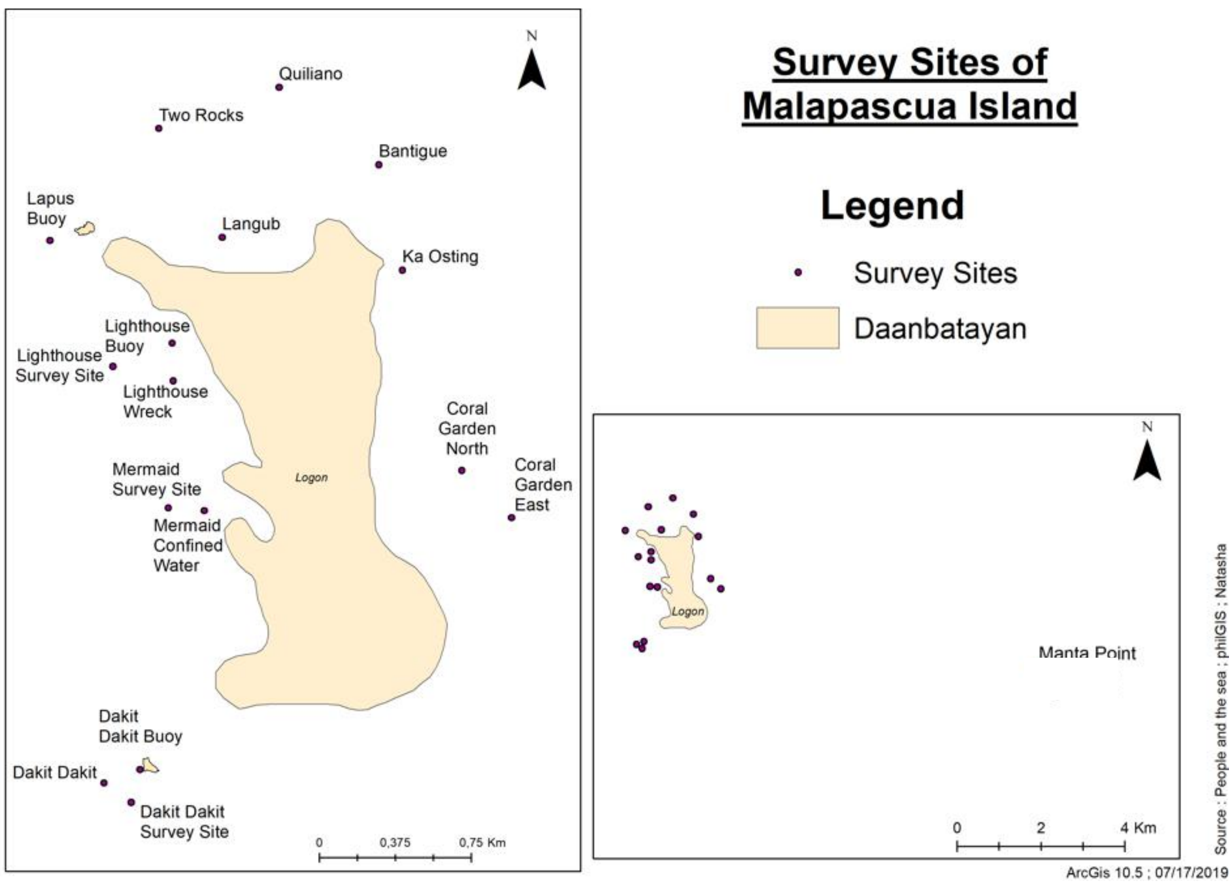

Figure 7. *Map of the sixteen sites (left) that were surveyed around the island of Malapascua and the site (right) that was surveyed around the Monad Shoal, Republic of the Philippines. The map was made using ©ArcGIS.*

2.2 Manual Control Programme

There are several methods of controlling COTS numbers, including injections, but the cheapest and easiest method is manual removal. In January 2018, there was a COTS outbreak on the east coast of Malapascua in an area known as Coral Garden (Figure 8). This site was chosen for manual removal to mitigate the effects of this enlarged population on the coral reefs.

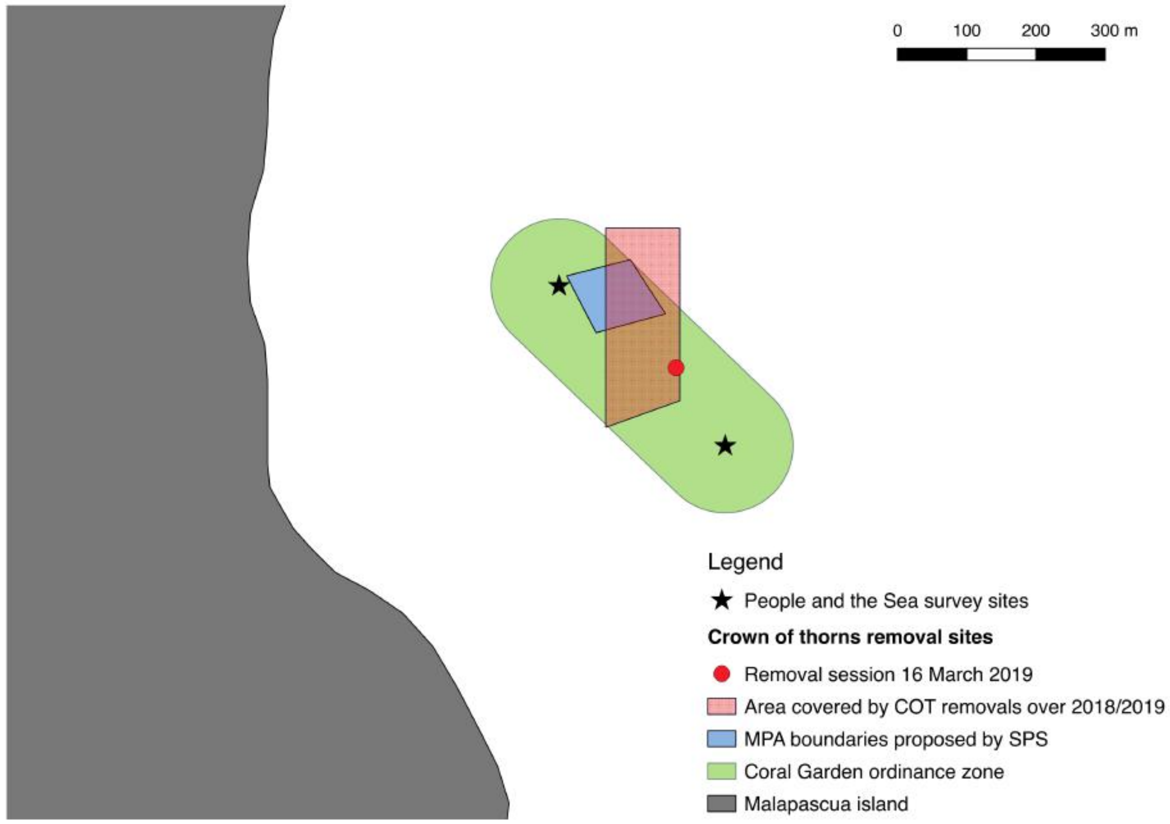

Figure 8. *A map of the area (Coral Garden) on the east coast of Malapascua that was the location of the COTS manual removal programme (final removal session on 16 March 2019), highlighting the two survey sites: Coral Garden North and Coral Garden East. The ordinance zone (green) is the 'Snorkelling and No-Fishing Zone' which is protected by Municipal ordinance. The proposed Marine Protected Area (blue) has been put forward by the association Save Philippines Sea, however it is not yet protected. ©People and the Sea.*

A manta tow (see section 2.3) was performed around the Coral Garden to locate areas with high COTS densities. Free-divers then collected as many COTS as possible, spotted within 100 m of the boat, in one hour. COTS were collected using BBQ tongs and brought directly to the surface, where they were placed in floating buckets to prevent stress-induced spawning from occurring whilst still in the sea. It was essential to ensure that none of the water from the floating buckets entered the ocean in case any gonads had been released. Once the buckets were half-full, they were brought back to the boat and their contents were emptied into larger buckets to be transported to shore. It was important that the COTS remained submerged in a bucket of sea water and kept in the shade during the boat transportation back to land, to keep the individual alive for precise measurements.

On land, one individual at a time was removed from the bucket and drained of excess water. The COTS was placed on the aboral side (spines facing down) and the arms were allowed to settle flat. The longest ventral diameter was then measured and used to estimate the age of the individual. The weight of the individual was also recorded by placing them on a tared kitchen scale. Areas of asymmetry were identified (Figure 9) and the number of whole, undamaged arms and short, regenerating arms were counted. Areas that were clearly 'missing arms' were used to assume the total number of arms that the starfish would otherwise have had.

***Figure 9**. Photos of symmetrical COTS (left) and asymmetrical COTS (right) taken from the Coral Garden, Malapascua. ©People and the Sea.*

Next, an incision was made along the arm and, if present, a quarter teaspoon of gonads was removed. The gonads were then placed into a small, clear vial with clear seawater and shaken. The vial was then held up to the light and observed: female gonads are orange to yellow in colour (Figure 10), while male gonads are light yellow to beige. Furthermore, agitated male gonads will make the water in the vial cloudy due to the presence of sperm. If the starfish is immature or spent, histological analysis would be needed to confirm the sex.

Once analysis was finished, the COTS carcasses were disposed of appropriately: either placed in a compost bin or buried in the sand. It was ensured that the seawater from the bucket was discarded onto dry sand, and not into the sea, again as the water may have contained COTS gonads.

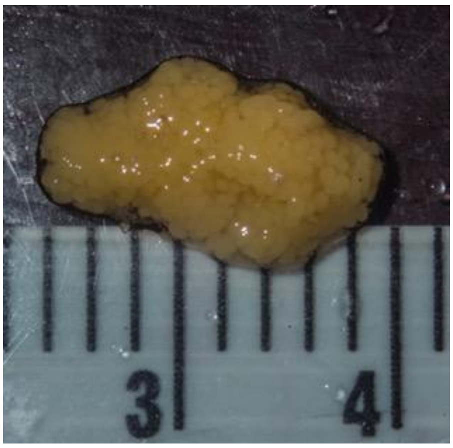

***Figure 10.** Photo of female COTS gonads taken during an examination after a manual eradication. © People and the Sea.*

Manual removals around the Coral Garden took place bi-monthly between January 2018 and March 2018 and then monthly until the final removal in March 2019. This method gains insight into the demographics and population dynamics of COTS on a spatial and temporal scale. One problem with this method is that it is only effective on adult individuals which are easily captured using tongs, and easily spotted from the surface by the free-divers. Many COTS hide or display cryptic behaviour which would stop them from being identified and removed. However, manual removals are the cheapest option as they require little equipment.

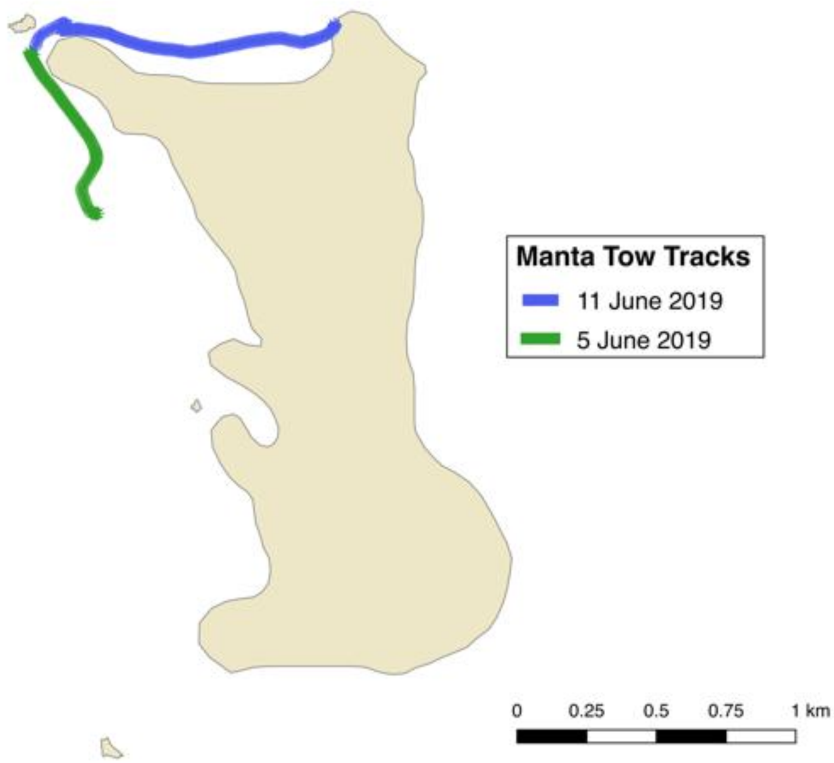

Figure 11. *A map to show the manta tow tracks along the north and north-west coast of Malapascua ©People and the Sea.*

2.3 Manta Tow Method

Along the north and north-west coast of the island, a manta tow was done determine the exact area where a SCUBA search may need to be undertaken (Figure 11). The manta tow technique consisted of a snorkel diver being towed at a constant speed behind a boat (Figure 12). The snorkeler, known as the observer, held on to a manta board which was attached to the boat by a rope. While being towed, the observer actively searched for COTS; when any were spotted, they raised their hand to indicate COTS presence. A second person, on the boat, once seeing this signal, input the coordinates of this location into a GPS tracker, providing a more precise idea of the density and location of the COTS populations.

Figure 12. *An observer displaying the manta tow technique. The individual is being towed behind a boat, holding on to a manta board while surveying for COTS (Miller* et al.*, 2009).*

2.4 SCUBA Search Technique

For each dive, a team of 2-3 SCUBA divers would descend at the site and record the time that they began actively searching for COTS, ensuring that they stayed close to one another. When an individual was identified, one diver would measure the COTS (Figure 13), while the other would record the number of COTS, the size class, and the form and genus of the predated coral. The COTS was lifted using the end of a pencil to observe if the individual was currently feeding on a coral, and a perimeter of 2 m was also examined for the tell-tale white feeding scars on corals which indicated recent COTS predation (as in Kayal *et al*., 2012). The time was also recorded at the end of the search to allow a comparison between the number of COTS found per minute of search effort across the different sites.

Figure 13. *Photo taken during a SCUBA Search, showing a COTS individual being measured ©People and the Sea.*

SCUBA searches allow the observer to examine the coral reef and gain a deeper insight into the ecology of the reef than a manta tow survey, as corals can be examined in more detail. Furthermore, SCUBA searches are more accurate at detecting small populations of COTS, as at low densities they are cryptic. Additionally, not all coral mortality is due to COTS, and SCUBA searches can assist in detecting other coral predators, bleaching or diseases.

2.5 Benthic Survey

Two divers began by searching for COTS. When the first individual was identified, or when enough tell-tale white feeding scars were seen to indicate COTS presence, a 30 m transect was laid out. The benthic survey was conducted using the Point Intersect Transects method (Hill and Wilkinson, 2004): beginning at 1 m, a plumb line was dropped at 25 cm intervals, and whatever it touched first was recorded. The results were then separated into five categories: Hard Coral; Soft Coral; Impacted Coral; Algae; and Other, which comprised all substrate and other biotic organisms such as corallimorphs, sponges and anemones. If the plumb line touched a hard coral, then the form and genus of the coral were also recorded. The percentage cover for each category was then calculated, as well as the percentage for each coral genus. Two transects were performed at each site and the average was taken. SCUBA search sites that were close to each other and shared similar benthic composition had only one set of benthic surveys: Coral Garden encompassed both Coral Garden North and Coral Garden East; Mermaid encompassed both Mermaid Survey Site and Mermaid Confined Water; and Lighthouse encompassed both Lighthouse Wreck and Lighthouse Buoy. One 30 m transect was also performed at three sites that had no or few COTS (Dakit Dakit, Langub and Lighthouse Survey Site) to provide a control. In these cases, the transect was laid randomly and the benthic survey was conducted in the same manner as above.

2.6 Statistical Analysis

The data that was provided by PepSea (see section 2.2) and the data that was collected by the author (see sections 2.3, 2.4 and 2.5) were checked for consistency and standardised using point tables on Microsoft® Excel (version 16.28) to ensure any anomalies were highlighted and removed. The Great Barrier Reef Marine Park Authority 'Crown-of-Thorns Starfish Control Guidelines' (GBRMPA, 2017) describes an outbreak as when more than one COTS is identified during 20 minutes of active SCUBA searching. This measure of time will be referred to as 'COTS per SCUBA search unit (SSU)' in this study.

RStudio (version 1.1.463) was used to analyse these data and check for statistical significance. Correlation tests were used to test for a significant relationship between the weight and the diameter of the COTS using the Pearson product-moment correlation coefficient. A multivariate analysis of variants (MANOVA) was used to explore if there was any variation in weight and diameter based on sex, with the weight and diameter as the dependent variables and sex as the independent variable. Pearson's correlation tests were also performed on the percentage of impacted coral against the number of COTS at each site. Simpson's Diversity Index (Simpson, 1949) was used to determine the genus richness of each site of the benthic survey. The Simpson index is expressed as

$$D = \frac{\sum n_i(n_i - 1)}{N(N-1)}$$

where n_i is the total number of organisms of each genus and N is the total number of organisms of all genera. Simpson's Diversity Index is expressed as $1 - D$, with 0 representing no diversity, and 1 representing infinite diversity (Biranvand *et al*., 2014). Finally, a chi-squared test for given probabilities was used to compare the abundance of coral at each site compared to the coral that was predated upon for *Acropora* and *Porites* in their various forms, and each form for all genera combined. The chi-squared statistic is defined by

$$X^2 = \sum_{all\ cells} \frac{(observed - expected)^2}{expected}$$

Excel was used to calculate the relative frequencies and RStudio was used for the analysis. For all analyses, the threshold for significance was taken as $p < 0.05$.

3. RESULTS

3.1 Removal Data

Between February 2018 and March 2019, a total of 3782 COTS were removed from the Coral Garden, 1497 of which were measured. There was a significant correlation between weight and diameter (correlation coefficient = 0.74, $p < 0.0001$, n = 1497). The mean weight was 193.86 grams (95% CI: 188.20 – 199.53) and the mean diameter on land was 18.46 cm (95% CI: 18.27 – 18.65). There were 6 % more females than males in the population that was measured (Figure 14). A MANOVA was done to determine if weight and diameter was affected by sex (n=339), however the test found no significant difference between the size of the COTS and its sex (Pillai = 0.00028, $f = 0.047$, $p = 0.954$). There was no significant effect of the sex of the COTS (n = 339) on either the weight ($f = 0.0015$, $p = 0.969$) or the diameter ($f = 0.026$, $p = 0.872$).

There were seventeen manual removal sessions in total, with an average of 11.4 participants per session. Throughout the entire removal effort, the average number of COTS collected per person per hour-session was 20.9 individuals. The mean number of COTS removed per hour decreased over time, however it peaked at 44.9 per hour of effort in August 2018 (Figure 15), six months into the removal effort. The lowest number of COTS removed was 3.1 per hour of effort in October 2018, which is 0.1 units above the outbreak threshold. There was a slight decrease in the mean weight and diameter of the COTS throughout the removals at Coral Garden (see Appendix Figure S1).

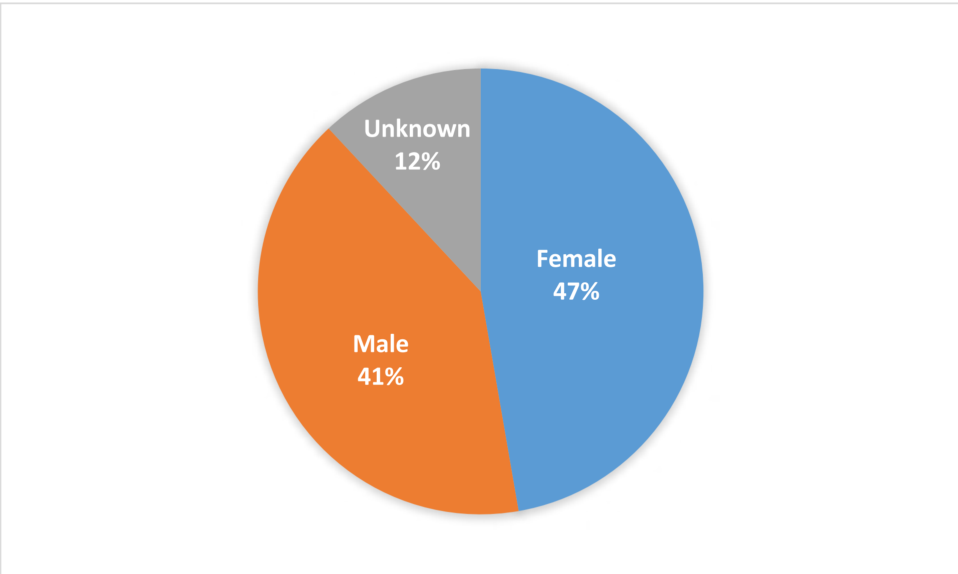

Figure 14. The percentage of males, females and unknown (either immature or spent gonads) in the sample of COTS removed from the Coral Garden, Malapascua.

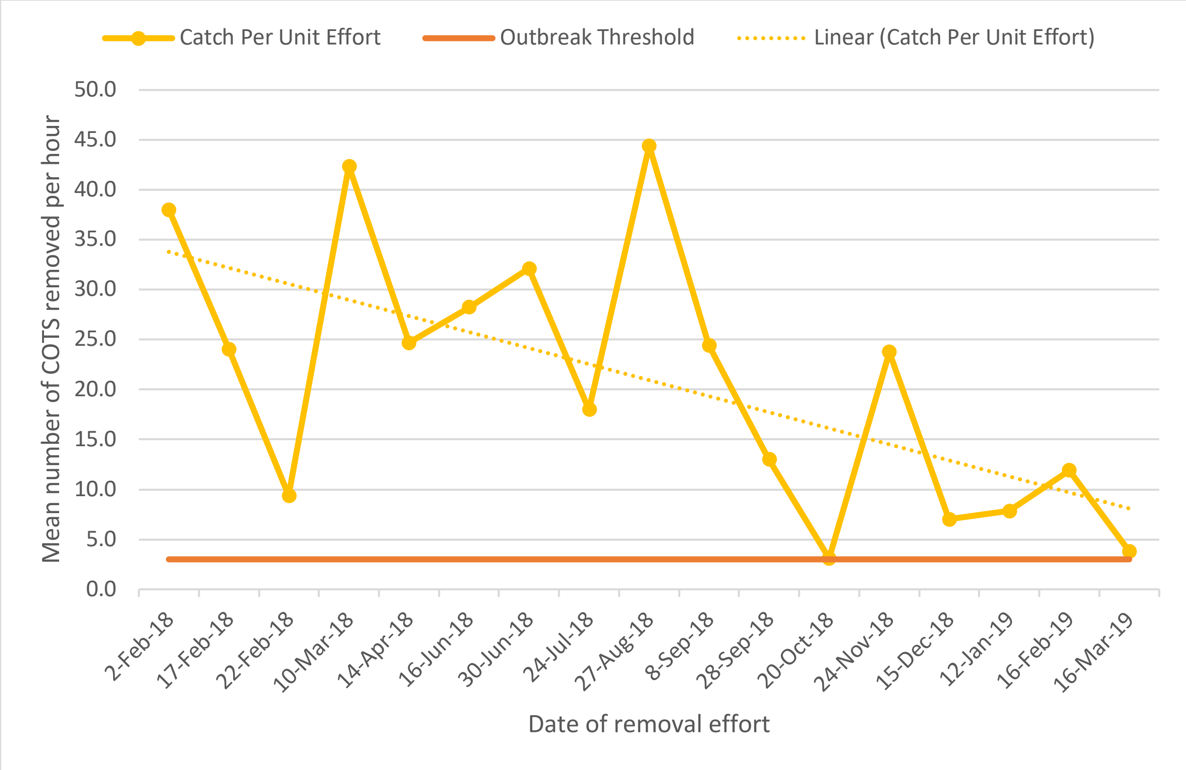

Figure 15. *The mean number of COTS removed per hour for each removal session between February 2018 and March 2019, compared to the outbreak threshold (in red). The dotted line shows the linear trend of Catch Per Unit Effort over time.*

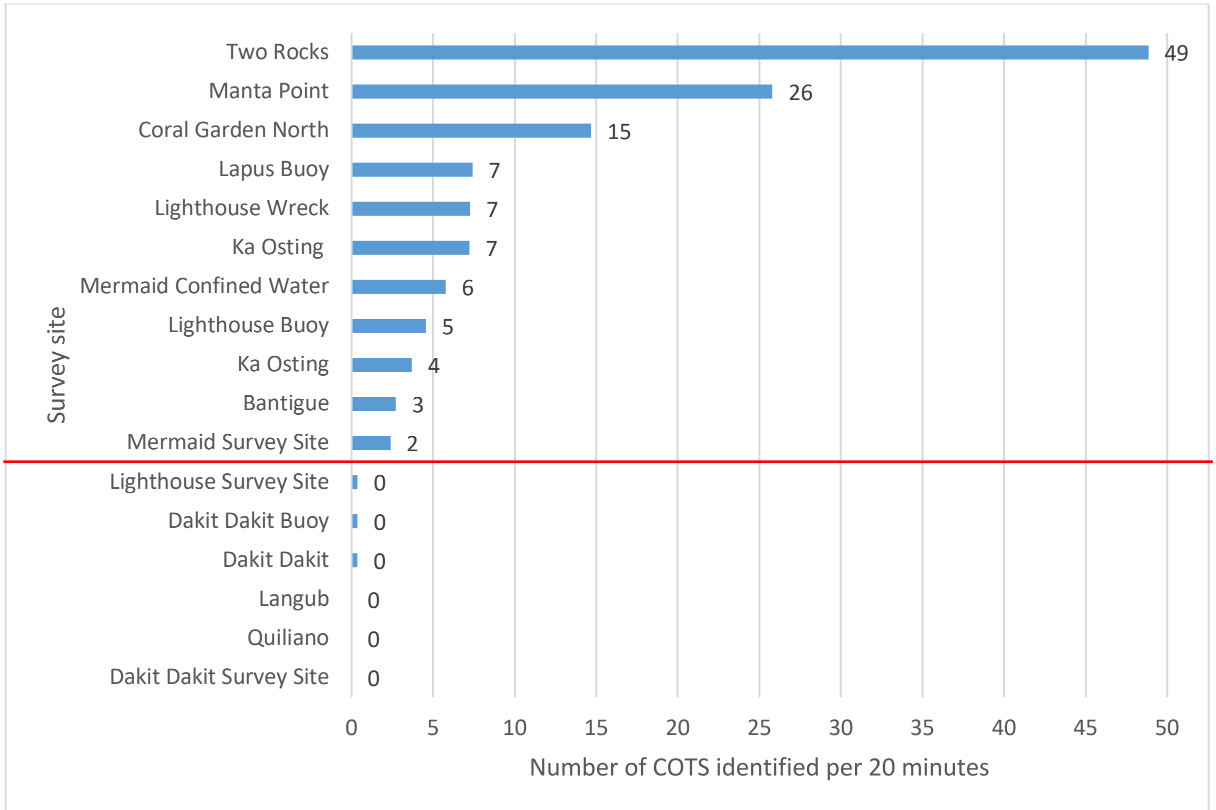

Figure 16*. The number of COTS identified at each site per SSU. All sites where more than one COTS was identified within 20 minutes are considered to be above the outbreak threshold (in red).*

Table 1. The total number of COTS within each size class across all survey sites.

Size Class	Total Number of COTS
J (< 5 cm)	0
A (5 – 15 cm)	34
B (15 – 25 cm)	68
C (> 25 cm)	228
TOTAL	**327**

3.2 SCUBA Search Data

Seventeen sites were surveyed for number of COTS, twelve of which had numbers that are considered above the outbreak threshold (Figure 16). Two Rocks was the most affected site with 49 COTS per SSU, followed by Manta Point with 26 individuals per SSU.

A total of 327 COTS were identified and measured across fourteen of the seventeen sites, with none being found in Langub, Quiliano or Dakit Dakit Survey Site. Individuals that measured > 25 cm in diameter (Table 1), were by far the most abundant, representing 69.72 % (228 individuals) of the total COTS found around the island.

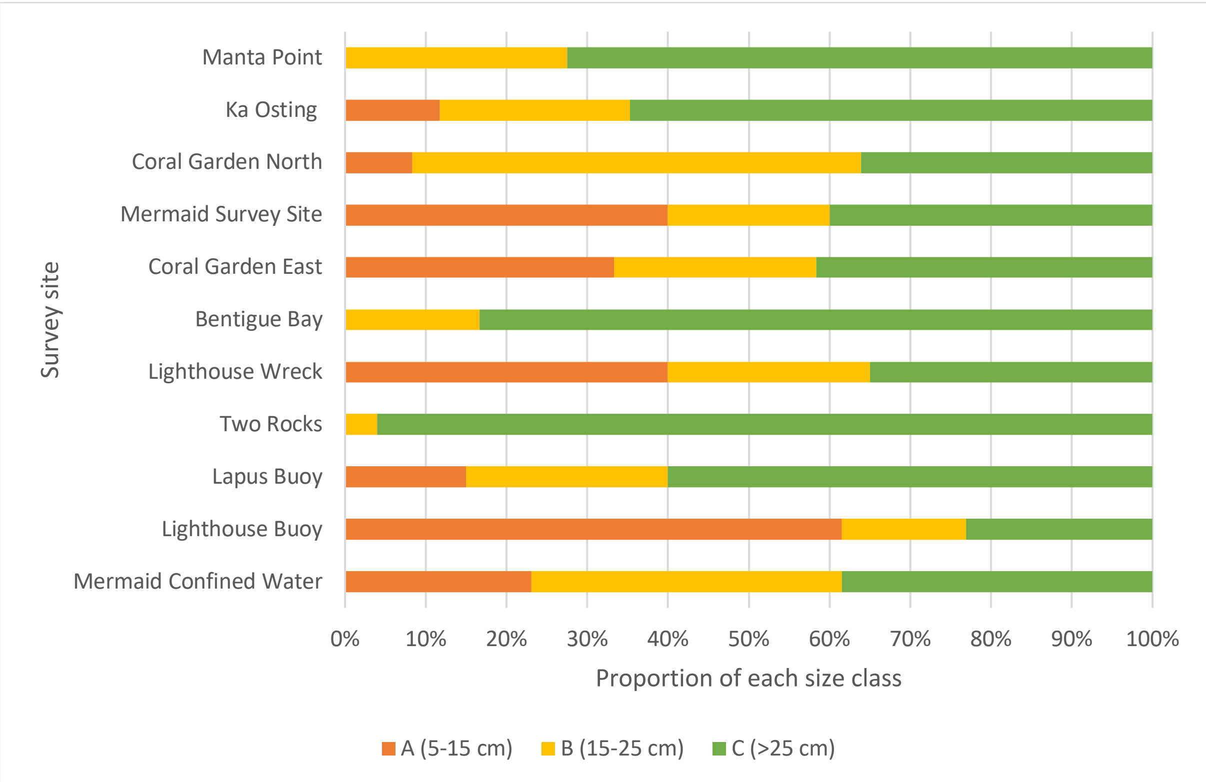

***Figure 17.** The proportion of each size class of COTS (J = < 5 cm; A = 5 – 15 cm; B = 15 – 25 cm; and C = > 25 cm) at all survey sites.*

Size class "J" (< 5 cm) was not found at any site, while size class "C" (> 25 cm) was the most abundant size class in half of the sites surveyed (Figure 17). Size class "A" (5 – 15 cm) was the most abundant in Lighthouse Buoy and size class "B" (15 – 25 cm) was the most abundant in Coral Garden North.

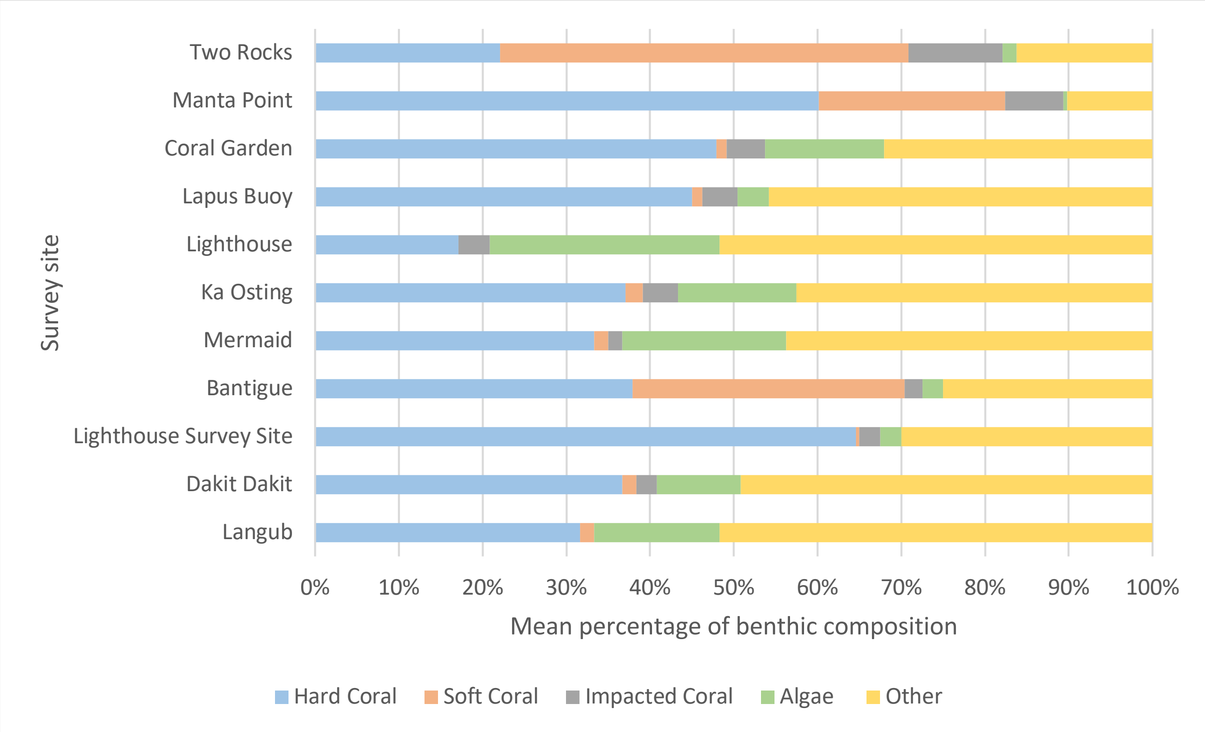

Figure 18. *The mean percentage of hard coral, soft coral, impacted coral, algae and other, of two 30 m transects at each survey site.*

3.3 Benthic Survey Data

Benthic surveys were undertaken at eleven sites. Both Lighthouse Survey Site and Manta Point had more than half of their benthos identified as hard corals (64.58 and 60.19 % respectively), while Two Rocks is the only site to be dominated by soft corals (48.75 %; Figure 18). Two Rocks also had the highest percentage of impacted coral (11.25 %).

The number of COTS identified at each site was not significantly correlated to the percentage of hard coral (p = 0.617); however, there was a significant correlation between the number of COTS identified and the percentage of impacted coral (correlation coefficient = 0.95, p < 0.0001; Figure 19). Two Rocks had the highest percentage of impacted corals, followed by Manta Point.

Recently-killed corals were categorised as hard corals that had been killed less than three to four months prior, and hence appeared white with little filamentous algae covering them. This may be down to disease or other coral predators; however, as these white scars are typically larger than *Drupella* spp. (Thiele) or *Coralliphila violacea* (Kiener), the other common coral predators in the area, then the scarring was assumed to have been as a result of COTS predation. Across all the sites, *Acropora*, was the most common genus of the recently-killed corals (Table 2). 80 % of the recently-killed *Acropora* corals were observed at Two Rocks.

Table 2. *The percentage of the ten most commonly predated genera of hard corals that were identified as 'recently-killed' during the benthic surveys.*

Coral Genus	Recently-Killed Coral (%)
Acropora	68.97
Porites	10.34
Seriatopora	3.45
Fungia	3.45
Pocillopora	0
Favia	0
Favites	0
Montipora	3.45
Echinopora	0
Galaxea	0
Other	10.34

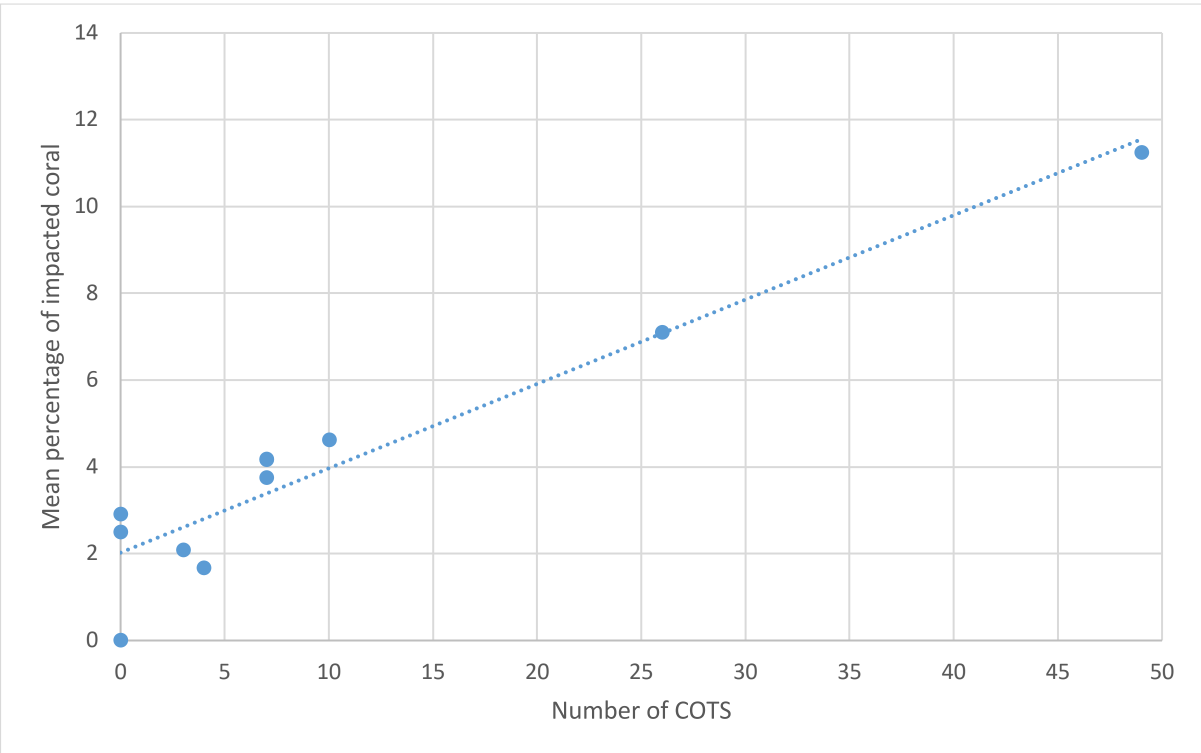

Figure 19. *The mean percentage of impacted coral on a 30 m transect depending on the number of COTS identified per SSU at each survey site.*

Table 3. *The most abundant coral genus, total taxon richness and Simpson's Diversity Index (1 – D) at each benthic survey site.*

Site	Most Abundant Coral Genus	Total Taxon Richness	Simpson's Diversity Index $(1 - D)$
Two Rocks	*Acropora*	12	0.68
Manta Point	*Acropora*	7	0.09
Coral Garden	*Porites*	10	0.59
Lapus Buoy	*Porites*	19	0.81
Lighthouse	*Porites*	11	0.49
Ka Osting	*Acropora*	20	0.81
Mermaid	*Porites*	25	0.91
Bantigue	*Acropora*	13	0.46
Lighthouse Survey Site	*Porites*	24	0.91
Dakit Dakit	*Porites*	15	0.89
Langub	*Porites*	11	0.87

Across all the sites, 38 different genera of hard corals were identified (Appendix Table S1), however each site was either dominated by *Acropora* or *Porites* (Table 3). Mermaid was the most diverse site ($1 - D$ = 0.909615), followed by Lighthouse Survey Site ($1 - D$ = 0.909297913), and Manta Point was the least diverse ($1 - D$ = 0.091226). *Cycloseris*, *Hydnophora*, *Mycedium* and *Oxypora* were each only present at one site (Lapus Buoy, Ka Osting, Lighthouse Survey Site and Bantigue respectively) and *Porites* was present at every site except for Manta Point.

3.4 Feeding Preferences

Acropora corals were the most abundant at Two Rocks, Manta Point, Ka Osting and Bantigue (Figure 20) and were also the most predated coral at each of these sites (Figure 21). Similarly, *Porites* was most abundant at Coral Garden, Lapus Buoy, Lighthouse and Mermaid, while again being the most predated coral at each of these sites, except the latter which had an equal proportion of predated *Acropora* and *Porites* corals.

Across the island as a whole, *Acropora* was the most abundant genus of hard coral, while also being the most predated upon coral (Figure 22). There was a significant correlation between the average percentage of each genera that was predated by the COTS and the average abundance at each site (correlation coefficient = 0.90, $p < 0.0001$, n = 38, 95% CI = 0.82 – 0.95).

There were 338 instances where COTS were observed feeding on hard corals, 297 of which were on just ten genera (Table 4). The most frequently observed prey was table *Acropora* (35.80 %), followed by branching *Acropora* (11.24 %) and then submassive *Porites* (7.69 %).

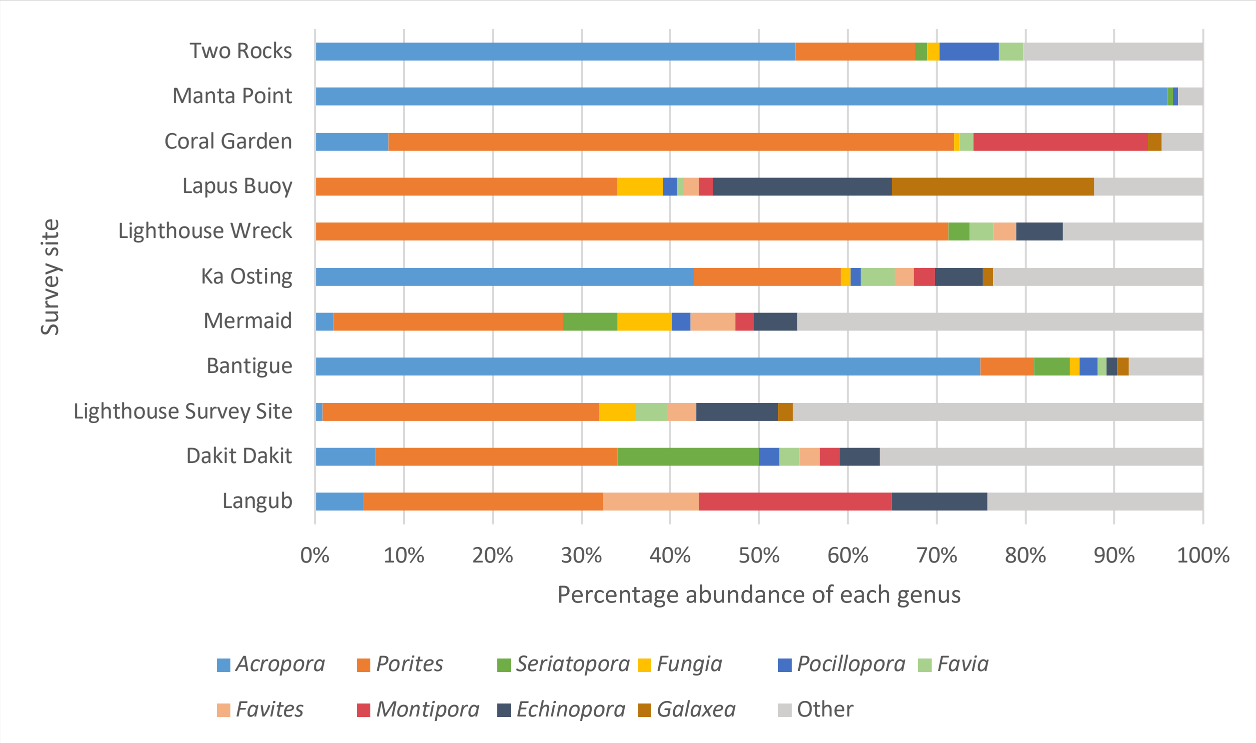

Figure 20. *The relative abundance of the ten most commonly predated hard coral genera at each site.*

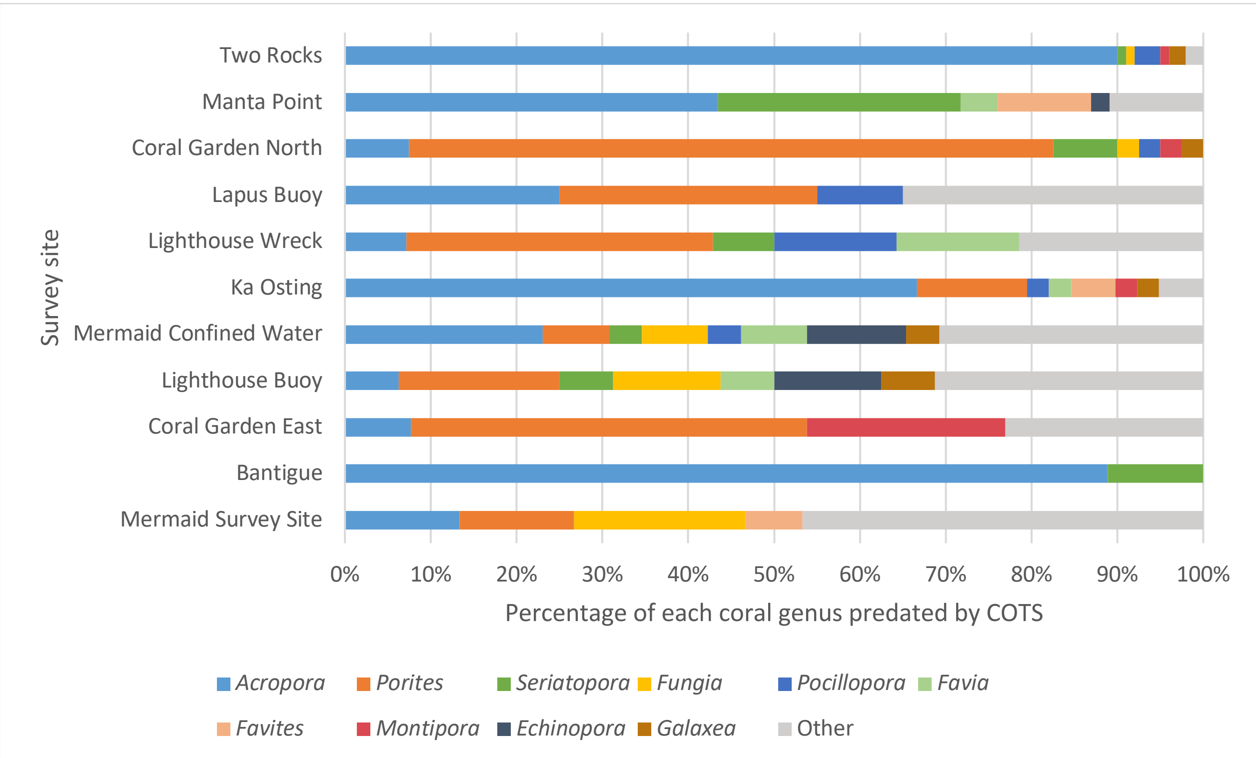

Figure 21. *Relative frequency of the ten most commonly predated hard coral genera that were observed being fed on by COTS during the SCUBA search surveys at survey site.*

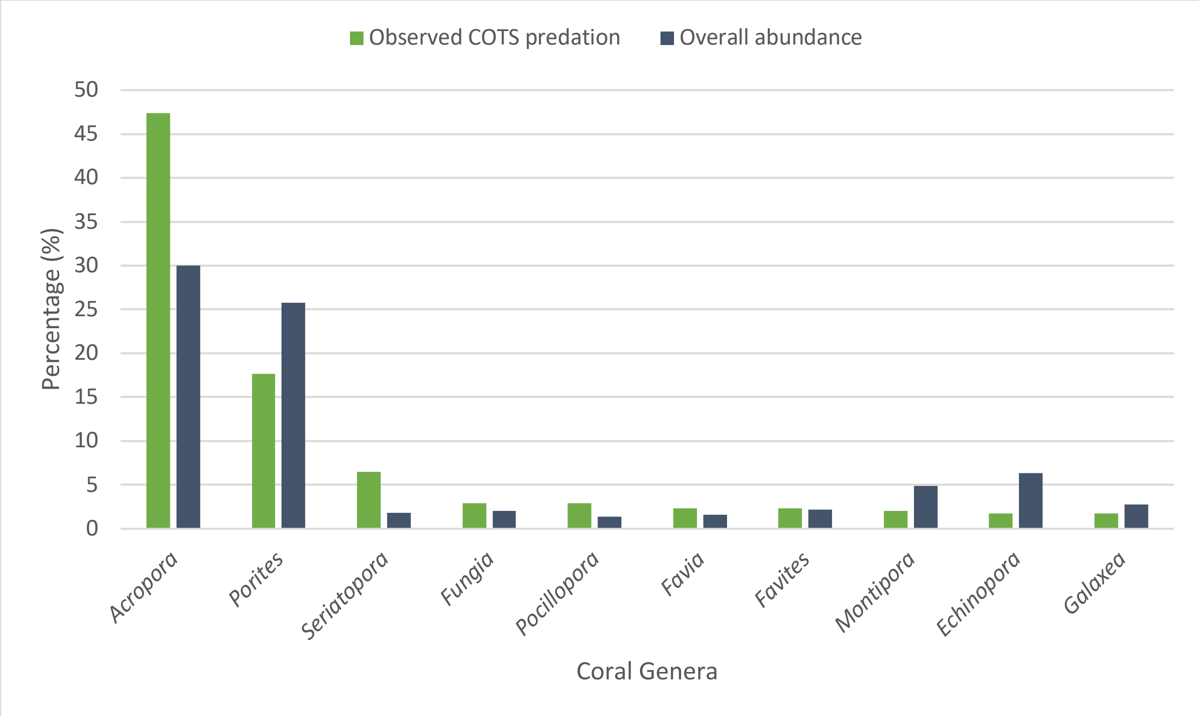

Figure 22. *The mean percentage of the ten most predated genera by COTS observed around the island compared to the mean percentage of each genera of hard coral identified across the 11 benthic surveys.*

Across all benthic surveys, there were 944 instances where the plumb line landed on a live hard coral. Over half of the hard coral recorded (Table 5) across all sites was either submassive or branching in form (29.66 and 26.06 % respectively). The most abundant coral from across these surveys was branching *Acropora* (16.70 %), followed by submassive *Porites* (17.27 %) and then table *Acropora* (11.23 %). There were only two occasions where a columnar coral was identified (*Isopora* spp.).

The frequencies of *Acropora* and *Porites* that were observed being predated upon were compared against the frequencies that were recorded during the benthic surveys. The frequency that *Acropora*, in all forms, was observed being predated by COTS was higher ($p = 0.031$) than the frequency of *Acropora* that was observed on the reef (Table 6), which means that COTS were positively selecting to feed on table *Acropora* instead of other, more abundant corals. Specifically, the frequency of table *Acropora* that were predated by COTS was significantly higher ($p < 0.0005$) than the observed frequency of table *Acropora* across all sites. The values for branching *Acropora* and submassive *Porites* were insignificantly different (p = 0.254 and 0.145 respectively) from the expected value. The frequency of all genera in each coral form were also compared to the frequency observed on the reef, and table corals were, again, significantly selected ($p < 0.0001$) over other forms, as were branching and encrusting corals (p = 0.013 and 0.028 respectively).

Table 4. *The total number of the ten most commonly predated on genera of hard corals that were observed being fed on by COTS across each survey sites, categorised by form.*

Coral Genus	Branching	Corymbose	Encrusting	Foliose	Massive	Solitary	Submassive	Table	Total
Acropora	38	0	1	0	0	0	0	121	**160**
Porites	21	6	2	0	5	0	26	0	**60**
Seriatopora	22	0	0	0	0	0	0	0	**22**
Fungia	0	0	0	0	0	10	0	0	**10**
Pocillopora	10	0	0	0	0	0	0	0	**10**
Favia	0	0	2	0	2	0	4	0	**8**
Favites	0	0	5	0	0	0	3	0	**8**
Montipora	2	0	3	2	0	0	0	0	**7**
Echinopora	1	0	2	1	1	0	1	0	**6**
Galaxea	0	0	0	0	5	0	1	0	**6**
Other	1	1	12	9	6	0	12	0	**41**
Total	**94**	**7**	**27**	**12**	**19**	**10**	**47**	**121**	**338**

Table 5. *The total number of the ten most commonly predated on genera of hard corals that were identified across the 11 benthic survey sites categorised by form.*

Coral Genus	Branching	Corymbose	Columnar	Encrusting	Foliose	Massive	Solitary	Submassive	Table	Total
Acropora	163	0	0	0	0	0	0	0	106	**269**
Porites	39	32	0	32	2	1	0	137	0	**243**
Seriatopora	17	0	0	0	0	0	0	0	0	**17**
Fungia	0	0	0	0	0	0	18	0	0	**18**
Pocillopora	13	0	0	0	0	0	0	0	0	**13**
Favia	0	0	0	0	1	4	0	10	0	**15**
Favites	0	0	0	3	0	4	0	14	0	**21**
Montipora	6	1	0	1	36	0	0	2	0	**46**
Echinopora	1	0	0	35	12	1	0	11	0	**60**
Galaxea	0	0	0	5	0	6	0	16	0	**27**
Other	7	7	2	44	20	43	2	90	0	**215**
Total	**246**	**40**	**2**	**120**	**71**	**59**	**20**	**280**	**106**	**944**

Table 6. *Chi-squared test for given probabilities for Acropora and Porites, and the forms each coral was observed in, comparing observed feeding against frequency. (* = p < 0.05, ** = p < 0.005)*

Coral Genus Form	Chi-squared test for given probabilities	
	χ^2	*p*-value
Acropora		
All forms	4.61	0.031 *
Branching	1.30	0.254
Encrusting	0.30	0.587
Table	12.77	< 0.0005 **
Porites		
All forms	1.50	0.220
Branching	0.41	0.521
Corymbose	0.51	0.474
Encrusting	1.98	0.159
Foliose	0.21	0.645
Massive	1.89	0.276
Submassive	2.13	0.145
All genera		
Branching	6.21	0.013 *
Columnar	0.08	0.782
Corymbose	0.06	0.799
Encrusting	4.85	0.028 *
Foliose	0.31	0.579
Massive	1.00	0.317
Solitary	2.06	0.151
Submassive	0.10	0.754
Table	20.42	< 0.0001 **

4. DISCUSSION

4.1 Key Findings

The overarching aim of this study was to determine if the coral reefs around the island of Malapascua would benefit from a new control programme to manage the population of COTS. In order to do this, I looked at the biometric data from a previous removal attempt (provided by PepSea) to understand the population dynamics of the COTS on the reefs around Malapascua, as well as to determine the success of this previous programme that targeted the Coral Garden. At the time of this study, even though the number of COTS collected per session has been decreasing, the Coral Garden was still above the outbreak threshold, meaning that after just over one year of frequent collections, the removal goal was not reached and, therefore, a more efficient method is required in order to be successful. Furthermore, two-thirds of the reefs that were surveyed are currently above the outbreak threshold, with Two Rocks and Manta Point both far more heavily affected than Coral Garden North. Moreover, the majority of the COTS observed around the island were identified as being sexually active. This suggests that the COTS numbers are still increasing which has the potential to have devastating effects on the coral reefs, as the more COTS that were present on a reef, the higher the abundance of recently-killed or dead coral. Finally, I looked at the feeding habits of the COTS to understand which sites are more likely to be affected by future outbreaks. The most frequently predated corals were *Acropora* spp. followed by *Porites* spp.

4.2 Manual Removal

Over the course of thirteen months, there were seventeen manual removal sessions, removing a total of 3782 COTS from the Coral Garden off the east coast of Malapascua. Considering that such a high number of individuals were removed from the reef, it is likely that this reduced the potential damage to the reef (Chak *et al.*, 2016), with < 10 % of impacted hard coral being observed in the Coral Garden. Furthermore, both the mean diameter and the mean weight of the collected COTS slightly decreased over time, which suggests that the larger adults were being removed first. This also explains why the SCUBA search found both Coral Garden North and Coral Garden East to have more COTS in size class “A” and “B”. However, there were still a high number of size class “C” individuals present, suggesting that the removal effort had not managed to remove all the reproductive adults. There was, however, a clear decrease over time in the number of COTS removed within an hour, yet this number has still not fallen below the outbreak threshold. The SCUBA search showed that the Coral Garden is still experiencing an outbreak, with 15 and 5 COTS being identified per SSU at Coral Garden North and Coral Garden East respectively. Once an outbreak has begun, COTS can cause extensive damage to coral reefs (Pratchett, 2005), with evidence of COTS killing up to 90 % of scleractinian corals in Guam

(Chesher, 1969) and Japan (Yamaguchi, 1986). This shows that a manual effort such as this is not efficient enough as, after 13 months, the number of COTS is still out of control. Furthermore, towards the end of a removal effort, it becomes harder to ensure find all the remaining COTS as the ones that remain are likely smaller (Bos *et al*., 2013), so therefore several more months, or even years, of removal effort would be required to restore this reef to a sustainable level. Moreover, juvenile COTS are rarely seen due to their small size, preference for nocturnal feeding and cryptic behaviour during the day (Keesing, 1995; De'ath and Moran, 1998a); therefore, even if it appeared that all the COTS in an area were removed, after one or two years, the juvenile COTS would have grown in size and then continue the cycle of feeding on the corals and reproducing, maintaining the outbreak level. This could be the issue at Lighthouse Buoy, as over 60 % of the observed COTS were in size class "A".

This extensive removal effort has been focussing on one area on the east coast of the island, yet there are multiple other sites experiencing an outbreak in Malapascua which also need attention, but which are too deep for free-diving removal to be efficient – predominantly Two Rocks in the north. For a control programme like this to be successful, it requires continuous monitoring, to ensure that any COTS that were initially too small to see, were not found, or subsequently migrated onto the reef, are removed as soon as they emerge. However, PepSea is a relatively small NGO which relies on funding from international volunteers, and a lot of time and resources go into training the volunteers in species identification and scientific diving techniques for the monthly reef-monitoring surveys. Therefore, it is difficult to ensure that there will always be time set aside for frequent COTS monitoring. Furthermore, waves and strong seasonal currents can cause certain sites to be inaccessible to divers and snorkelers.

The most popular alternative method of control is using poison injections. However, this not only requires government permits but, in addition, requires specialist equipment which needs training on its use and also has a high start-up cost (Boström-Einarsson and Rivera-Posada, 2016). PepSea's goal, once the governmental permit has been granted and the equipment purchased, is to train divemasters and instructors from local dive centres on COTS injection protocol, and then establish a collaborative plan for injection dives. This could then allow weekly injection dives, each week led by a different dive centre, to ensure that monitoring is continuous. At the beginning of the programme, several dives should occur within a few days to attempt to inject all COTS on the affected site, followed by weekly check dives to inject any remaining COTS lasting one to two months. After this, regular monitoring of the site is recommended to ensure that any future COTS are identified quickly, and numbers are managed before outbreak levels are reached. This should lead to the overall COTS population across the whole island decreasing to a sustainable level within just a few years. Furthermore, attention should be brought to external factors that contribute to COTS outbreaks, such as high levels of water pollution and over-harvesting of COTS predators, with an aim to mitigate and spread awareness of these issues.

4.3 Outbreaks and Size

Two thirds of the sites surveyed around Malapascua have COTS numbers which are above the carrying capacity of the reef. Without intervention, an outbreak of COTS has the potential to destroy a reef in just two to three years (Buck *et al.*, 2016). According to the Kuroshio Biological Research Foundation guidelines (KBRF, 2012), the density of COTS at Two Rocks, Manta Point and Coral Garden North is considered to be a "massive outbreak". This current outbreak at Two Rocks (49 COTS per SSU) is devastating the reef, with almost all table *Acropora* corals at the site branded with the white feeding scars that are evident of recent COTS predation (Figure 23). Two Rocks has the second lowest abundance of hard coral (22.08 %) across the survey sites and therefore the presence of COTS on the hard corals can quickly change the seascape of this reef. Not only does this have the ability to diminish the biodiversity and abundance of other reef associated organisms, including commercial fish and invertebrate species in the area, but it could also lead to declines in tourism around the island, as the majority of the SCUBA diving tourists that frequent Malapascua are searching for pristine, biodiverse reefs rather than large areas of dead coral skeletons (Fraser *et al.*, 2000). These underwater eyesores can impact the tourism industry and local fisheries, which will have a knock-on effect on the local community of Malapascua, as so many local people rely on these industries for their income (Turner *et al.*, 2007; Dugan, 2013).

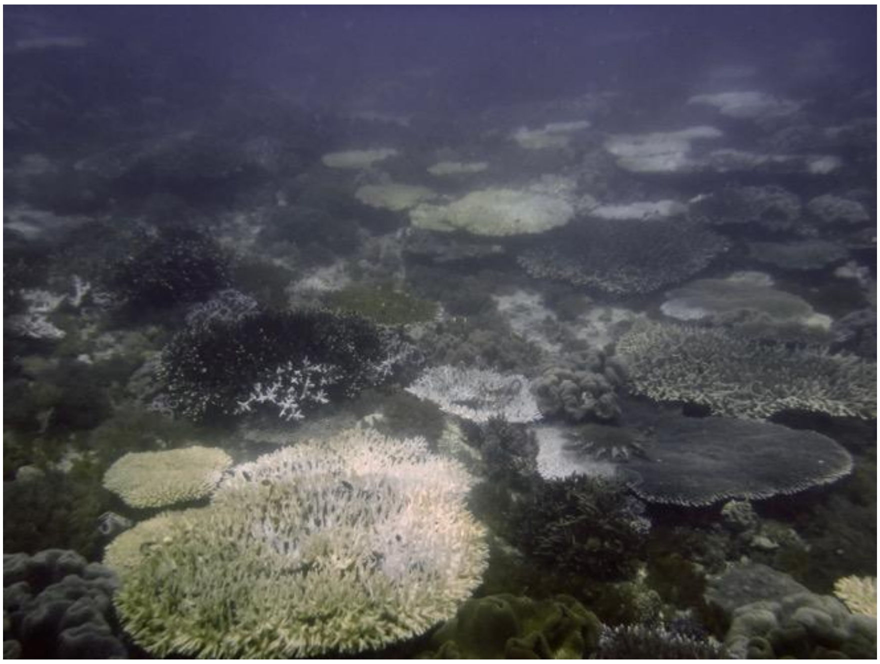

Figure 23. *Photo taken at Two Rocks, Malapascua, displaying the effect of a COTS outbreak, with white feeding scars evident across the reef (Photo: author).*

The majority of the COTS around the island are over 25 cm in diameter, which means that they are estimated to be ~ 3 years of age and are therefore sexually active (Pratchett, 2005). However, there is a wide variety of size, and therefore age, suggesting that the populations are the result of ongoing COTS recruitment. Over two-thirds of the COTS population in Malapascua are sexually active, suggesting that a future increase in population is highly likely as there is an abundance of COTS which are likely to spawn simultaneously (Beach *et al*., 1975). Furthermore, egg and sperm production increase exponentially as the COTS diameter increases (Babcock *et al*., 2016). Any future control programme should begin by targeting these larger individuals, as the fecundity is related to size (Kettle and Lucas, 1987). The larger the individual, the more sperm/eggs are released. Similarly, COTS in larger aggregations should also be targeted, as an individual's reproductive potential is higher when in close proximity to other spawning individuals (Beach *et al*., 1975). COTS tend to only have one spawning event in a year, which is around April in Malapascua (Bos *et al*., 2013), as this coincides with warmer sea temperatures. Control efforts should be amplified in the run-up to this event, to try and lessen the number of potential offspring.

As stated above, it is very difficult to find and remove COTS when they are too small as they display cryptic behaviour and are hard to find. This is shown in these data, as only 34 individuals in size class "A" (5 – 15 cm diameter) were found and no size class "J" (< 5 cm diameter). It is extremely unlikely that there were no size class "J" COTS present at any site, but this result just highlights how difficult they are to find, and how implausible it would be to ensure that all were removed from an area during a manual removal effort. For this reason, frequent monitoring is essential to ensure that juvenile starfish, that were previously too hard to find, can be removed or injected before they reach sexual maturity. This will assist in preventing future outbreaks, as COTS are extremely fecund and, therefore, even one successful mass spawning event could lead to millions of fertilised eggs. It is important to eradicate a primary outbreak before a secondary outbreak can be initiated (Fabricius, 2013).

4.4 Effect of COTS on Coral Reefs

Coral reefs are one of the most threatened ecosystems in the world (Pratchett *et al*., 2014), with 19 % of the world's reef already destroyed (Wilkinson, 2008). Extensive damage to live corals leads to a decline in the abundance and diversity of coral reef fishes (Pratchett *et al*., 2011). COTS outbreaks are one of the largest contributors to the decline of coral reefs in the Indo-Pacific (Birkeland and Lucas, 1990; Bruno and Selig, 2007; De'ath *et al*., 2012; Pratchett *et al*., 2014). As COTS numbers increase, the percentage of impacted corals also increases. This suggests that COTS predation is currently the main cause of coral mortality in the reefs around Malapascua. Most coral predators have to selectively pick live tissue from the surface of corals (Motta, 1998), whereas COTS are extremely well-adapted to feeding on scleractinian corals and are able to digest tissue from a large surface area at one time by everting their stomach (Pratchett *et al*., 2014). Moreover, COTS do not only prey on hard corals but, when their primary food source becomes scarce, they can become opportunistic feeders and feed on soft corals, algae and other COTS (Moran, 1986).

The community composition, structure and function of an ecosystem are heavily influenced by the indirect effects of species interactions (Kayal *et al*., 2011). These interactions become more complex in areas with high biodiversity and high organism density, such as a coral reef (Lenihan *et al*., 2008). Kayal *et al*. (2011) stated that high densities of corals could enhance survival due to the associated refuges, such as physical structures that impeded COTS predation, as well as density-dependant prey dilution which reduces predation rates. This could be the reason that Two Rocks was so heavily affected, as it has one of the lowest proportions of hard corals. An issue that was further exacerbated by the fact that the majority of the hard corals at the site were table *Acropora* which has widely been accepted as the preferred food source of COTS, with Acroporid populations already being highly susceptible to bleaching and therefore known as climate change losers (Keesing *et al*., 2019).

4.5 Feeding Preferences

COTS fed selectively on corals in the Acroporidae family in more than half (51 %) of instances recorded in this study, with table *Acropora* being the most commonly observed (41 %). This is in line with the literature from elsewhere (see Branham *et al*., 1971; Ormond *et al*., 1976; De'ath and Moran, 1998b; Pratchett, 2001; Bos *et al*., 2013; Keesing *et al*., 2019). The second most commonly predated coral was branching *Acropora*, followed by submassive *Porites*. The latter is surprising as De'ath and Moran's (1998b) study showed *Porites* to be the least preferred genus of coral, which Pratchett (2001) suggests could be due to coral symbionts, with *Acropora* being chosen above *Porites* at a ratio of 14:1. However, the chi-squared test showed that these values were insignificant and therefore the high frequency of feeding on submassive *Porites* is due to the high abundance of *Porites* in Malapascua. Furthermore, in De'ath and Moran's (1998b) study, *Porites* was also one of the ten most predated upon genera. Across the eleven sites that underwent benthic surveys, *Porites* was the dominant genus in seven of the eleven sites surveyed, accounting for over half the hard corals at Lighthouse and Coral Garden (71.31 and 63.39 % respectively). When COTS numbers are at such a high density, there is a rapid depletion of food which leads to opportunistic feeding. Therefore, even though genera such as *Porites* are not typically their preferred food source, COTS must feed on it due to the high densities of COTS and the sheer abundance of *Porites* corals (Keesing *et al*., 2019). *Acropora* was the dominant genus at the other four sites, and accounts for 95.96 % of the hard coral cover at Manta Point.

Of the ten most heavily predated coral genera, eight were also within the top ten abundance. This, again, shows that abundance is connected to predation (Pratchett 2001). The two genera that were within the ten most predated corals, but that did not follow the trend for abundance were *Favia* (which ranked 12th for abundance at 1.58 %) and *Pocillopora* (which ranked 16th for abundance at 1.37 %). Eight of these genera were also in the ten most predated coral observed by De'ath and Moran (1998b), with the exception of *Goniastrea* and *Platygyra* which were replaced by *Favites* and *Galaxea* in this study.

It is heavily suggested in the literature that COTS are extremely selective when it comes to their prey (Okaji *et al.*, 1997; Pratchett, 2007). However, in this study, COTS were observed feeding on a wide variety of corals (a total of 26 different genera). Nevertheless, nearly 50 % of these observations were of COTS feeding on just one genus, *Acropora* (47.35 %), with COTS significantly choosing to feed on *Acropora* more than expected ($p < 0.05$). Furthermore, there were twelve genera of corals which were present in the abundance survey, but which displayed no evidence of predation by COTS. The most abundant of which was *Diploastrea*, which was the tenth most abundant coral, making up 1.58 % of the hard corals identified around the island.

The chi-squared statistic showed that the coral genus *Acropora* is positively chosen over other genera when it is present. Furthermore, *Acropora* in table form is predated upon significantly more than expected ($p < 0.0005$), which shows that COTS are selectively choosing to feed upon table *Acropora* over other available genera/forms. This further explains the outbreak at Two Rocks as, even though it has a low abundance of hard corals (22.08 %), it contains the highest abundance of table *Acropora* across all the sites. COTS also selectively choose table and branching corals more than expected ($p < 0.01$ and $p < 0.05$ respectively) which is unsurprising (Kayal *et al.*, 2012), as these coral forms have larger surface areas on which the COTS can feed, providing them with a higher proportion of food at one time compared to other coral forms. Table corals are particularly popular with COTS, as they also offer shelter from predators (Keesing, 1990; Kayal *et al.*, 2011).

4.6 Strengths and Limitations of the Data

COTS monitoring has been inconsistent in the past across Malapascua, as multiple dive centres have used various and unreliable techniques to control COTS populations. As with most other coral reef ecosystems, until COTS densities reached outbreak levels, they had not been closely monitored (Kayal *et al.*, 2012). By performing a SCUBA search across multiple reefs around the island, this study creates a baseline of data for future monitoring and assessment in Malapascua. The overall health of a reef can be measured by looking at the change in the percentage of hard coral cover and the percentage of impacted corals. Furthermore, any change in population dynamics of COTS at each site can be monitored more successfully now that this initial survey has been completed.

There are, however, limitations to these data as all of these surveys were taken across a two-month period, between June and July 2019. In the future it would be good to repeat these surveys at other times of the year to check for seasonal variation, while also incorporating other environmental factors and adding to the reliability of the baseline data. Future SCUBA searches should also try to estimate the area searched, by recording average depth and distance swum, as this could be used to create a density estimate of COTS which would provide more understanding of the outbreak levels at each site. Furthermore, there are more reefs around the island which should be monitored for COTS.

4.7 Management Suggestions

As stated above, without intervention, high densities of COTS can have devastating effects on coral reefs. Effective management action is required to reduce or reverse ongoing coral loss (Wilkinson, 2008), and COTS outbreaks are one of the few factors connected to coral decline that can be controlled (Pratchett *et al*., 2014). Endean and Cameron (1990) stated that controlling COTS outbreaks could be the best opportunity to reverse coral loss and reef degradation in the Indo-Pacific. There is currently an unsustainable number of COTS around the island of Malapascua which therefore needs to be controlled. The previous attempt at manually controlling the population helped to mitigate coral damage; however, it was overall ineffective at reducing COTS numbers to below the outbreak threshold. This method is not scalable enough to tackle the problem at multiple sites, and the exhaustive nature is too labour-intensive and time-consuming with little reward. Additionally, manual removals require COTS to be collected while free-diving, as the longer the COTS remain in the water column after being disturbed, the more likely they are to stress-spawn (Fraser *et al*., 2000) and further exacerbate the problem. Due to visibility restrictions, it would be too difficult to see COTS from the surface at any site that is deeper than 5 – 6 m. Thus, the majority of the sites around Malapascua are too deep for effective free-diving, especially as PepSea largely relies on untrained volunteers. Additionally, SCUBA-based methods using poisonous injections, have been shown to be more effective than manual removals (Boström-Einarsson and Rivera-Posada, 2016). Injections are far safer for the diver, as administration of the chemical is through a syringe or, more often a DuPoint Velpar Spot Gun (Fraser *et al*., 2000), which has a long needle, minimising the risk of injury from COTS spines (KBRF, 2012). These guns also have large reservoirs for the chemical, meaning that multiple COTS can be injected before the container requires refilling. Furthermore, avoiding dangerous chemicals, methods using just household vinegar have been shown to cause COTS mortality in just 48 hours (Boström-Einarsson and Rivera-Posada, 2016), and have shown no adverse effect on any scavengers of COTS.

As many COTS as possible should be removed or culled before April, as this is when reproduction occurs in tropical reefs (Bos *et al*., 2013). A combination of both poison injections and manual removals may be the most efficient way to quickly reduce COTS numbers, as this would allow untrained, non-diving volunteers to assist with removal efforts. Divers trained on injections could focus on the deeper sites, while free-divers could focus on shallow sites, removing as many large COTS as possible. Once a reef is 'clean', it still requires regular monitoring (Bos *et al*., 2013), with particular focus on sites which are known to have a high abundance of table *Acropora* corals. External factors that are known to cause or amplify COTS outbreaks, such as nutrient overload, ocean warming and overharvesting of COTS predators, should also be mitigated to limit the risks of future outbreaks.

4.8 Future Research

Studies about COTS are widespread throughout the literature (> 12,000 published studies, Pratchett *et al*., 2014 and see references therein); however, there are still many unanswered questions, especially with regard to the causes of population outbreaks (Pratchett, 2005). Now that a baseline of data has been established for a selection of reefs around Malapascua, and, considering the small size and contained nature of said reefs, this location could be used to create a long-term study. Different areas could be subjected to different control methods, for example one site with just manual control, one site with just poison injections, another site using a mixture of both and a final site left unmanaged, to be used as a control. This would help to show which control method, or combination of methods, is the most practical and effective approach to reducing COTS numbers to a sustainable level. Long-term studies such as this could help to understand fully the intricate role that COTS play within a coral reef, as well as providing more detail about what triggers the occurrence of an outbreak. Alongside this, water quality surveys should be used to ascertain whether outbreaks are being caused by nutrient overload (Brodie *et al*., 2005; Babcock *et al*., 2016).

The connectivity of the reefs could also be assessed, potentially using ocean general circulation models (Munday *et al*., 2009), to help understand how COTS spread between reefs, especially as newly 'cleaned' reefs are easily recolonised by affected reefs (Mueller *et al*., 2011). Additionally, PepSea already perform monthly surveys, for which several environmental factors are recorded (such as salinity, sea temperature, sea state). If these were combined with monthly COTS surveys, and COT predator surveys, then a model could be created to help predict COTS movement and maybe even forecast future outbreak events, while also following trends in predator-prey relationships (Morello *et al*., 2014). Research such as this is increasingly important, as coral reefs are especially vulnerable due to rising sea temperatures, increased ocean acidification, and other emerging threats associated with climate change (Hughes *et al.*, 2003; Pratchett *et al*., 2014).

5. CONCLUSION

Coral reefs are one of the most biologically diverse yet one of the most threatened ecosystems in the world (Pratchett *et al*., 2014). COTS outbreaks are one of the largest drivers of coral mortality in the Indo-Pacific (Kayal *et al*., 2012; Nakamura *et al*., 2016) and have the ability to reduce live coral cover by over 90 % within only two to three years (Buck *et al*., 2016). Although the causes of COTS outbreaks are still not well-understood, implementing control programmes to reduce COTS densities is one of the only manageable and controllable ways to mitigate coral decrease (Bos *et al*., 2013).

This study focused on the coral reefs around the island of Malapascua, Republic of the Philippines, working with a local NGO, PepSea. The island environment, community and economy all rely heavily on coral reef habitats, with the majority of the island's inhabitants being dependent on the marine environment for either the SCUBA diving and tourism industry or for artisanal fisheries. COTS outbreaks are threatening coral survival and thus pose a threat to these industries. This study surveyed the reefs around the island to create a baseline database of COTS numbers, sizes, location and feeding preferences, whilst also determining the most effective management programme to be implemented in the future.

After a COTS outbreak on the east coast of Malapascua, a manual control effort had been initiated. Unfortunately, after seventeen removal sessions, it was found that there had been little change in the size or number of COTS collected, highlighting that monthly manual removals are insufficient at controlling an outbreak. Subsequent SCUBA search surveys of a further fifteen reefs identified that two-thirds of the reefs around Malapascua have COTS densities that exceed the outbreak threshold, and therefore are depleting the coral reefs at rates faster than the coral is able to recover. Benthic surveys detailed the abundance and diversity of different hard coral genera at each affected site. During the SCUBA search surveys, the genus of any hard coral that was observed being predated by COTS was recorded. Comparing these results with the relative abundance of coral genera at each site, it was shown that COTS demonstrate a strong feeding preference towards *Acropora* corals, especially in table form. This was further supported by the fact that the site with the highest numbers of COTS also had the highest proportion of table *Acropora* corals.

A future control programme and monitoring scheme must be put in place while ongoing coral loss can still be reversed. Poison injections have been suggested as the most efficient method of control for COTS. However, a combination of both injections and manual removals may be the most efficient, as Malapascua has a wide variety of people who are passionate about protecting their reefs. Using manual removal alongside poison injection efforts could get more people involved. Poison injections require specialist equipment and training, while manual removals can be carried out by supervised non-specialist and non-diving volunteers. Combining both of these methods could reduce the COTS numbers sufficiently to return the reef to pre-outbreak densities. Once this has been achieved, sites that have a high abundance of table and branching *Acropora* corals should be frequently monitored, as they can be used as indicators to suggest that densities of COTS are climbing too rapidly, showing that repeated action needs to be taken.

Finally, increased survey efforts combined with future research could be used to resolve long-standing queries about the causes of COTS outbreaks, and therefore the best method to manage current outbreaks, while also predicting or even preventing any future outbreaks. Malapascua is a small island and, if an efficient control programme can be implemented and proven to be successful, then the methodology can be utilised on coral reefs across the Indo-Pacific.

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APPENDIX

Table 7. *Taxonomy of the hard corals observed being fed on by COTS and/or identified during benthic surveys around the island of Malapascua.*

Family	Genus	Authority
Acroporidae	*Acropora*	Oken, 1815
Acroporidae	*Alveopora*	Blainville, 1830
Fungiidae	*Cycloseris*	Milne-Edwards & Haime, 1849
Merulinidae	*Cyphastrea*	Milne-Edwards & Haime, 1848
Diploastreidae	*Diploastrea*	Matthai, 1914
Lobophylliidae	*Echinophyllia*	Klunzinger, 1879
Merulinidae	*Echinopora*	Lamarck, 1816
Euphylliidae	*Euphyllia*	Dana, 1846
Faviidae	*Favia*	Milne-Edwards, 1857
Merulinidae	*Favites*	Link, 1807
Fungiidae	*Fungia*	Lamarck, 1801
Euphylliidae	*Galaxea*	Oken, 1815
Agariciidae	*Gardineroseris*	Scheer & Pillai, 1974
Merulinidae	*Goniastrea*	Milne-Edwards & Haime, 1848
Poritidae	*Goniopora*	Blainville, 1830
Fungiidae	*Heliofungia*	Wells, 1966
Merulinidae	*phora*	Fischer von Waldheim, 1807
Acroporidae	*Isopora*	Studer, 1878
Faviidae	*Leptastrea*	Milne-Edwards & Haime, 1848
Agariciidae	*Leptoseris*	Milne-Edwards & Haime, 1849
Lobophylliidae	*Lobophyllia*	Blainville, 1830
Merulinidae	*Merulina*	Ehrenberg, 1834
Montastraeidae	*Montastrea*	Blainville, 1830
Acroporidae	*Montipora*	Blainville, 1830
Pectiniidae	*Mycedium*	Oken, 1815
Lobophylliidae	*Oxypora*	Saville-Kent, 1871
Agariciidae	*Pachyseris*	Milne-Edwards & Haime, 1849
Agariciidae	*Pavona*	Lamarck, 1801
Pectiniidae	*Pectinia*	Oken, 1815
Merulinidae	*Platygyra*	Ehrenberg, 1834
Pocilloporidae	*Pocillopora*	Lamarck, 1816
Poritidae	*Porites*	Link, 1807
Psammocoridae	*Psammocora*	Dana, 1846
Pocilloporidae	*Seriatopora*	Lamarck, 1816
Pocilloporidae	*Stylophora*	Schweigger, 1820
Astrocoeniidae	*Stylocoeniella*	Yabe & Sugiyama, 1935
Mussidae	*Symphyllia*	Milne-Edwards & Haime, 1848
Dendrophylliidae	*Turbinaria*	Oken, 1815

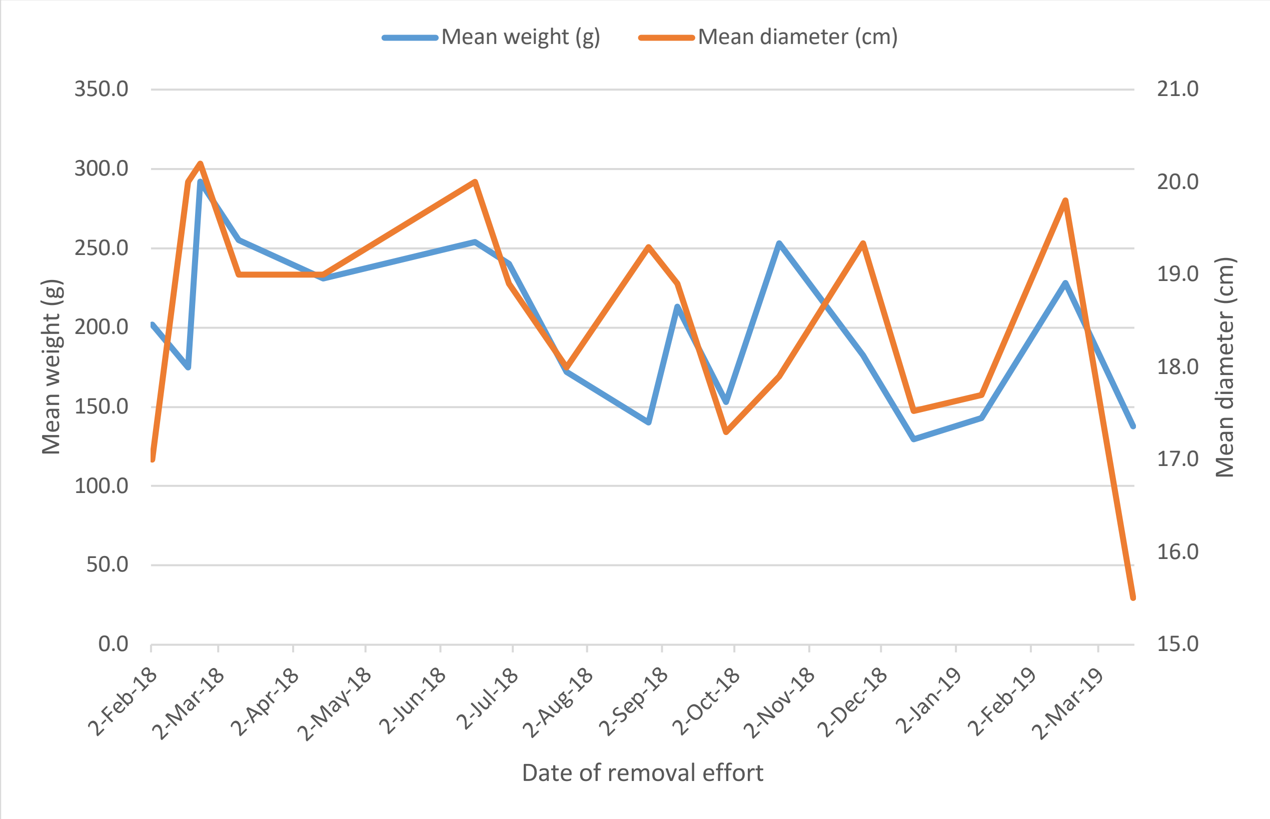

Figure 24. *The mean weight (g) and diameter (cm) of COTS collected from the seventeen manual removal sessions that occurred between February 2018 and March 2019.*