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REVIEW ARTICLE

Five Decades Behind the Limelight: Crown-Of-Thorns Sea Star Outbreaks Razing the Already Ailing Philippine Reefs

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ABSTRACT

A massive decline in Hard Coral Cover has been observed in the Philippines over the past decades, and Crown-of-thorns Sea star (COTS) outbreaks contribute to this decline. Effectively managing these outbreaks will aid in conserving the country's reefs. However, questions about the extent of the damage caused by outbreaks, the biology of the Philippine COTS, and the nature and triggers of outbreaks dramatically limit the development of effective management. This review presents the existing knowledge of the biology of the Philippine COTS, past and present COTS outbreaks in the country, and current management strategies used to control these outbreaks. An extensive literature search was done to consolidate historical reports of COTS outbreaks from published journal articles, news articles, and personal communication with government agencies and other organizations. Results showed that COTS was reported in the Philippines as early as 1938, but outbreaks have been documented for the past five decades. COTS outbreaks have been consistently reported in the waters of Cebu, Central Visayas from 2002 to 2008 and 2018 to 2021. COTS spawning in the Philippines was reported during the summer months from March to May, but further studies are needed on other aspects of its biology, especially on its morphology, reproductive capacity, larval biology, and feeding capacity. Lastly, a Philippine COTS management program involving the government, the academe, and citizen scientists is urgently needed to monitor COTS outbreaks and minimize its effects on the country's ailing reefs.

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1. INTRODUCTION

The crown-of-thorns sea star (COTS) is notorious as a keystone coral predator. This species contributes to the massive decline in coral cover across the Indo-Pacific region (Fabricius 2013). With this, COTS has been the subject of extensive studies concerning different facets of COTS, from its taxonomy and biology to population control. In the past, COTS was recognized to belong to only a single species, *Acanthaster planci*. However, DNA barcoding revealed the presence of at least four species of COTS (Vogler et al. 2008), with the Philippine COTS belonging to the pan-Pacific clade. The pan-Pacific clade was identified as *Acanthaster* cf. *solaris*, following Haszprunar and Spies (2014) and without recent taxonomic revision. Recent studies that focused on the pan-Pacific COTS revealed two major clades within the Pacific: the East-Central Pacific clade and the pan-Pacific clade. The pan-Pacific clade also includes COTS from Vietnam, Japan, Papua New Guinea, Micronesia, the Marshall Islands, the Great Barrier Reef (GBR), Vanuatu, Fiji, and French Polynesia (Yasuda et al. 2021; Yasuda et al. 2022).

In addition to their taxonomy, another extensively studied aspect of COTS is their capacity for rapid proliferation and the formation of outbreak populations. This phenomenon is closely linked to the interplay between their biology and environmental triggers. COTS are known for their high fecundity and mass spawning, allowing them to proliferate rapidly and in high numbers (Babcock et al. 2016a; Caballes et al. 2021; Pratchett et al. 2021). Over the years, several studies have defined outbreaks differently (reviewed by Pratchett et al. 2014), with definitions highly dependent on the characteristics of the coral reef and the density of COTS a reef can sustain.

Given the position of the Philippines at the core of the Coral Triangle, it is home to some of the most diverse coral reefs in the world. Sites in the Sulu Sea surrounding Palawan have been observed to harbor the most remarkable diversity and populations of reef-building coral species, while sites in the country's northern region were noted for their richness as coral ecoregions (DeVantier and Turak 2017; Licuanan et al. 2017). The country's coral reefs provide economic services to the country's fisheries sector. The total economic value of Philippine reefs is four billion US dollars per year from fisheries, tourism, and biodiversity (Tamayo et al. 2018). Despite their abundance and economic importance, it was found that hard coral cover at a mean of 22.8% across 206 sites between 2014 and 2017, a steep decrease from over 30% cover between 1981 and 2010 (Licuanan et al. 2019), caused by a multitude of ecological and anthropogenic factors such as coral bleaching, harvesting of essential reef species, eutrophication, and infestation of COTS. Sightings and outbreaks of COTS have been reported to be a problem in coral communities and reefs across various provinces in the country over the last decades (see discussion in section 3). The potential for future outbreaks necessitates efforts in monitoring and mitigating COTS for the protection of already highly threatened coral reefs (de Dios and Sotto 2015).

Despite the massive threat that COTS is posing in the country's coral reefs, the biology and ecology of COTS in the country remain poorly studied, particularly the nature, timing, severity, and extent of past and present outbreaks and efficient ways to manage or prevent the occurrence of these outbreaks.

This review presents existing knowledge of the biology, outbreaks, and management of COTS in the Philippines. While most reviews conducted in the past have focused heavily on COTS in the Great Barrier Reef (GBR) and other parts of the Indo-Pacific, this review is the first paper to focus on COTS studies and efforts made in the Philippines. Outbreak reports were collated via literature searches from different published journals and news articles, personal communication with the staff of concerned government agencies, and supplementary information from reef surveys conducted by Reef Check Philippines. Future perspectives on the establishment of a national database for COTS outbreaks and the potential role of citizen science in outbreak monitoring and management are also discussed in this review.

2. Biology of COTS

Extensive research and review articles have been dedicated to studying the biology of the Pacific Crown-of-thorns Sea star (COTS), as evidenced by studies such as Pratchett et al. (2014) and Wilmes et al. (2018). However, it is important to note that most literature on this topic primarily focuses on COTS populations in Australia and Japan. Although no rigorous study was conducted to compare the biology (e.g., morphology, reproduction) of COTS in the Philippines with those found in other regions of the Pacific, many studies have described the general biology, including the general morphology and spawning of the Philippine COTS. Pacific COTS exhibits variable coloration from gray-green to gray-purple with a "bulls-eye" appearance due to two rings of darker papulae (Birkeland and Lucas 1990). COTS collected from several reefs in Zamboanga Del Sur exhibited two color morphs: purple with orange spines and purple with red spines. However, the presence of the "bulls-eye" appearance was not mentioned (Alibon and Madjos 2019; Alibon and Madjos 2020). The size and number of arms of COTS are highly dependent on life stages (Haines 2015). Collected samples of adult COTS from different locations in the country range from 120 to 560 mm in diameter from arm tip to arm tip, with 7–20 arms (see Table 1), consistent with COTS found in other areas of the Pacific (Fabricius 2013; Birkeland and Lucas 1990 as cited in Haszprunar et al. 2017). The arms of COTS are covered with toxic spines 40-50 mm long, which serve as a defense against predators. Tissues overlying the spines contain saponin, a toxic chemical that may inflict painful wounds and other symptoms such as swelling around the wound, nausea, vomiting, and even hemolysis of human red blood cells, with the Pacific species considered to be the most harmful of all the species under the *A. planci* species complex (Moran 1988; Fraser et al. 2000; Haszprunar et al. 2017). In Japan, COTS venom was reported to cause respiratory and liver damage, eventually causing mortality to the person stung (Ihama et al. 2014). In the Philippines, no formal report of extensive injury or death was reported in the past, but there were anecdotal accounts of COTS' sting causing necrosis of infected tissues and fever for days for those sensitive to the toxin. Also, anecdotal accounts from fishermen from Bicol, southern Luzon, mentioned that COTS suddenly blows off its thorns once touched, hence its informal local name, "Granada."

Table 1. Observations of size, number of arms, and depth of occurrence of COTS in various locations in the Philippines.

Location	Diameter (mm)	Number of Arms	Depth (m)	Reference
Samal Island	150-300	9-18	1-18	Bos et al. 2013
Lungui Island, Zamboanga Del Sur	120-270	--	7-8	Alibon and Madjos 2020
Soalogan, Dimataling, Zamboanga Del Sur	185.17-190.5	7-16	3.9-6.4	Alibon and Madjos 2019
Sogod Bay, Southern Leyte	137-324	--	3-12	de Dios et al. 2014
Tubbataha Reefs	130-560	10-20	--	Pan et al. 2010

The inherent life history of COTS contributes to its predisposition to population fluctuations. COTS reproduce sexually, with large females able to release more than 100 million eggs in one spawning season (Babcock et al. 2016a), when male and female individuals aggregate in proximity in a reef to reproduce effectively (Babcock et al. 1994). COTS spawning occurs in months of elevated temperature or when the temperature rises depending on the latitude (Pratchett et al. 2014). In the Philippines, Bos et al. (2013) revealed that gonad maturity and spawning of COTS in Samal Island are highest during the summer months from March to May when sea surface temperature rises above 27°C, the threshold temperature for reaching maximum gonad maturity and spawning for sea stars (Pratchett et al. 2014). Gonado-somatic index (GSI) for male and female COTS increased rapidly from March to May. The highest GSI is recorded during April, with the mean GSI for females at 14.9 and 11 for April 2010 and 2011, respectively. The highest mean GSI recorded for males was 7.7 and 14.8 in April 2010 and 2011, respectively. GSI decreased gradually from April to nearly zero during November, showing an annual reproductive cycle of COTS in the Philippines (Bos et al. 2013). This agrees with Caballes et al. (2021) in the Great Barrier Reef, where the GSI peaks during January and February when the sea surface temperature rises. In New Caledonia, it was found that the peak spawning period for COTS was in December (Hue et al. 2020).

COTS is by far the most notorious coral-eating invertebrate. This is made possible by their large stomach surface area, capable of being everted and wrapped around their prey. Then, proteolytic enzymes are released to digest soft coral tissues and be absorbed by the COTS (Moran 1988; Vogler 2010), enabling a single COTS to consume 150–250 cm2 of live corals per day. The feeding preferences of COTS are affected by multiple facets, including the nutritional value of the coral prey, distribution and abundance of the coral prey, and prior conditioning of each COTS (Moran 1988). In a study by Alibon and Madjos (2019), COTS in the coastal areas of Barangay Saloagan, Dimataling, Zamboanga Del Sur was found to feed in five genera of corals, including Pocillopora, Porites, Acropora, Favites, and Echinopora. Acropora and Pocillopora were the most preferred genera due to their branching and tabular form and higher nutritional value than other coral genera. Porites, even with less nutritional content, are also preferred due to their branching structure and abundance in the area. This result is consistent with the summary made by Pratchett (2014), which revealed that Acropora and Montipora are two of the most preferred coral genera. In contrast, a survey of coral reefs in Kao, Thailand, revealed that the most preferred genera are Fungia and Pavona (Haines 2015), highlighting that coral prey preferences vary between locations across the whole distribution of COTS, influenced by nutritional value, distribution, and abundance of coral species. This feeding behavior was explained using the optimal foraging theory, where the highest growth rate of COTS, both in the field and in controlled aquarium conditions, was achieved when juveniles fed on preferred corals (acroporids and pocilloporids). While the high abundance and encounter rate of Acropora and pocilloporids did not play a significant role in shaping the feeding preferences, alternative prey's relative abundance influenced selectivity (Keesing 2021).

3. Incidents and reports of COTS outbreaks in the Philippines

When in expected numbers, crown-of-thorns sea stars (COTS) are essential in controlling the growth of fast-growing corals, providing room for other benthic invertebrates, and increasing diversity in the reef (Pratchett 2001). However, outbreaks are highly possible due to COTS producing massive numbers of larvae (Birkeland and Lucas 1990). Across the distribution of COTS, the definition of an outbreak varies greatly depending on the size of COTS, the size of the reef cover, and the rate of how fast or slow these sea stars consume corals. Different authors have defined the number of individuals per area to be considered an outbreak. For instance, Pearson and Endean (1969) consider an outbreak with 40 individuals per 20-minute swim in the GBR. Since COTS individuals are relatively smaller in Japan and consume fewer corals per year, the estimated outbreak density is >10 individuals per 15-minute swim (Yasuda 2018). Dumas et al. (2020) consolidated multiple threshold values from several studies and developed a three-level outbreak threshold, which can be used both in professional (individuals per hectare) and non-professional (individuals per ten-minute swim) surveys, namely non-outbreak population (<15 COTS.ha^{-1} or 0-1 COTS.10mins^{-1}), potential outbreak population (15-100 COTS.ha-1 or 2-5 COTS.10mins-1), and confirmed outbreak population (>100COTS.ha^{-1} or >5 COTS.10mins^{-1}). The Department of Environment and Natural Resources - Biodiversity Management Bureau (DENR-BMB), in a memorandum, set preliminary guidance in COTS outbreaks and cited outbreaks as having more than 30 COTS individuals per hectare, or more than one individual seen per 20-minute dive (DENR-BMB 2020).

No available database has consolidated information on COTS outbreaks in the Philippines for the past decades, and the overall damage caused by these outbreaks remains poorly known. Table 2 summarizes information on the provinces affected by COTS outbreaks from a comprehensive literature search from published journals, news articles, websites, and personal communication with concerned government agencies. The first reported observation of COTS feeding on corals was by Alcala (1976) on a reef in Sumilon Island, Southern Leyte. However, as early as 1938, COTS was already reported as “common” in the reefs of Port Galera Bay and Sabang Cove, Mindoro (Vine 1971). The highest number of provinces affected by COTS outbreaks was reported in 2007 (West Philippine Sea: Batangas, Mindoro, Palawan, and Pangasinan; Inner Philippine Sea: Cebu and Bohol; and Celebes Sea: Sarangani). Different areas of Cebu, including well-known tourist and dive spots such as Malapascua, Daanbantayan, Moalboal, Oslob, Camotes Island, and Bantayan Island, have been consistently reported to be infested

Table 2. Consolidated provinces cited to have experienced COTS outbreaks from 1938 to 2022. Data consolidated from published journals, news articles, websites, and government agencies.

Year	Region	Province	Reference
1938	IVA	Mindoro	Vine 1971
1969	IVA	Batangas	Endean and Chesher 1973
	IVB	Mindoro	
1970	I	Pangasinan	Endean and Chesher 1973
	III	Zambales	
	VI	Negros	
1971	IVA	Batangas	Endean and Chesher 1973
	IVB	Marinduque	
		Mindoro	
1985	IVB	Palawan	Nañola et al. 2004 as cited by Magdaong 2014
1998	IVA	Batangas	Nañola et al. 2004 as cited by Magdaong 2014
	IVB	Palawan	Magdaong et al. 2014
1999	IVA	Batangas	White et al. 2001
	VIII	Leyte	Benliro et al. 1999
2000	IVA	Batangas	White et al. 2001

Continuation of Table 2. Consolidated provinces cited to have experienced COTS outbreaks from 1938 to 2022. Data consolidated from published journals, news articles, websites, and government agencies.

Year	Region	Province	Reference
2002	VII	Cebu Negros Oriental	Magdaong et al. 2014
2003	VII	Cebu	Magdaong et al. 2014
	XI	Davao City	Nañola et al. 2004 as cited by Magdaong et al. 2014
2004	IVB	Palawan	Nañola et al. 2004 as cited by Magdaong et al. 2014
	VII	Cebu	Magdaong et al. 2014
2005	VI	Negros Occidental	Magdaong et al. 2014
	VII	Bohol	
		Cebu	
2006	VII	Cebu	Magdaong et al. 2014
2007	I	Pangasinan	World Wildlife Fund 2007
	IVA	Batangas	
	IVB	Oriental Mindoro	
		Palawan	
		Palawan	Tubbataha Reefs Natural Park 2021
	VII	Bohol	Magdaong et al. 2014
		Cebu	
	XII	Sarangani	World Wildlife Fund 2007
2008	IVB	Palawan	Yan 2008
	VII	Cebu	Magdaong et al. 2014
	VIII	Leyte	
	XII	Davao City	Bos et al. 2013
2009	IVB	Palawan	Bos 2009
2012	VIII	Leyte	de Dios et al. 2014
2013	IVA	Batangas	Rabe 2013
2016	VII	Siquijor	Andringa-Davis 2016
2018	VII	Cebu	Dalongeville 2019
2019	IVA	Batangas	The Philippine Star 2019
	VI	Antique	Lena 2019
		Guimaras	
	VII	Cebu	Gonzales 2019; Miasco 2019
	VIII	Southern Leyte	Dimzon et al. 2021
2020	VI	Aklan	Aguirre 2020
		Antique	
2021	III	Zambales	CENRO Zambales 2021a,b,c,d
	IVA	Batangas	Mayuga 2021
	VIII	Cebu	Sitchon 2021
	IVB	Palawan	Laririt 2021
2022	III	Zambales	CENRO Zambales 2022a,b
	VI	Aklan	Aguirre 2022
	IVA	Batangas	DENR CALABARZON 2022a,b
	VIII	Leyte	Bonachita 2022
	XII	Sarangani	Gubalani 2022

by COTS from 2002 to 2008, and in 2018-2021. Even various provinces surrounding and within the Verde Island Passage, which is considered as the center of the center of marine biodiversity, have experienced recurrent COTS outbreaks as early as 1969, including municipalities in Batangas (Balayan Bay - 1969; Mabini - 1999, 2000, 2007, and 2022; Tingloy - 1999, 2000, 2019, and 2022; and Calaca - 2022) and Puerto Galera, Oriental Mindoro (1969 and 2007).

Since 1997, Reef Check Philippines has included COTS in its surveys on coral reef health. A total of 954 surveys in 487 sites were made by Reef Check in the Philippines from 1997 to 2020 (Figure 1). However, since the onset of the global pandemic in 2020, there is limited data for 2020. Integrating the definition of outbreaks adopted by the DENR-BMB (> 20 COTS per hectare), most COTS outbreaks occurred in 2006 when 20 reefs surveyed were in outbreak status. The highest abundance of COTS was recorded in Sogod and Moalboal in Cebu in 2004 and 2008, respectively, and Cebu has been consistently surveyed to have high densities of COTS from 2002 to 2008, consistent with other reports from the literature (see Table 2).

In most areas of the country, the occurrence of outbreaks follows a sporadic pattern. During specific periods, outbreaks can simultaneously impact multiple provinces within a region or islands near each other. These outbreaks can exhibit localized patterns, affecting specific areas, or may occur due to larval recruitment facilitated by water current connectivity. Also, certain provinces, including Cebu, Batangas, and Palawan, have experienced recurring outbreak events in different years. This pattern may be caused by progressive accumulation of COTS, forming breeding populations, or localized recruitment from adjacent reefs or coral communities. However, the lack of studies on these outbreaks prevents quantification of this argument.

Another notable pattern is the increase in the number of reports in particular years. 2006 and 2007 recorded the highest COTS outbreak reports, supported by Reef Check surveys and reports from various agencies and publications. Subsequently, there was another increase in outbreak reports from 2019 to 2022. The rise in COTS outbreaks during these periods can be attributed to anomalously elevated temperatures observed in 2005 and 2016. Historical data from the World Bank Climate Change Knowledge Portal (2021), spanning from 1901 to 2021, demonstrates a consistent upward trend in average annual temperatures in the Philippines. This temperature increase may contribute to favorable conditions for COTS larval survival and the subsequent increase in outbreak events, which may affect more areas in the country. Similarly, in Japan, historical data revealed the poleward migration of the COTS population following the increasing water temperature in temperate areas of the country, supporting the idea that global warming may contribute to the increased occurrence of outbreaks (Yasuda 2018).

Anthropogenic activities also play a crucial role in the increasing occurrence of outbreaks in various areas of the country. Most studies on the

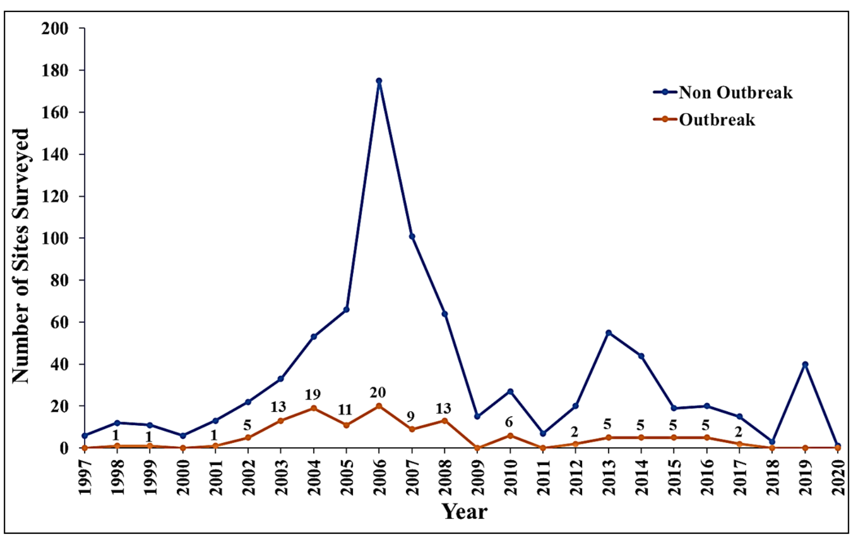

Figure 1. Frequency of COTS outbreaks in the Philippines from 1997 to 2020 from surveys conducted by Reef Check Foundation [accessed 2022 Jun 2]. Available from data.reefcheck.org. Numbers denote the number of reefs in outbreak status per year following the outbreak definition by Fraser et al. (2000).

causes of COTS outbreaks look at the nutrient runoff hypothesis as the main driver of this phenomenon. This hypothesis considers the role of fluctuating water quality in the sudden population explosion of COTS. According to Wooldridge and Brodie (2015), the introduction of nutrient-enriched terrestrial runoff starts a triggering sequence by promoting elevated phytoplankton concentration leading to enhanced COTS larval survival. Given the geographic position of the Philippines, an average of 20 typhoons visit the country annually, making river runoff from higher areas downstream and eventually into the adjacent sea regular. However, unsustainable practices in agricultural, industrial, and residential areas draining water into rivers flowing directly to adjacent coastal areas deliver a considerable concentration of nutrients, which may cause an increased risk of phytoplankton blooms. Dominant anthropogenic activities in particular areas may also trigger localized outbreaks. In Boracay island, for instance, which experienced an outbreak in 2020, poor sewerage and waste management systems in the island may have led to increased nutrient inputs into the adjacent coastal waters, favoring COTS larval survival. In 2016, it was found that several residential and commercial establishments on the island are not connected to the sewerage system, which contributed to the poor water quality in various areas on the island, particularly in areas and months with high tourist density (Limates et al. 2016).

Removal of COTS predators through overfishing and reef degradation is also believed to play a role in eruptions. Various species of coral reef fish and invertebrates have been identified to prey on COTS in both planktonic and benthic phases. However, several of these, such as snappers (Lutjanidae) and emperors (Lethrinidae), are sought and removed by fishers (Kroon et al. 2020). Bos et al. (2011) also documented the polyps of corallimorpharian species *Paracorynactis hoplites* to prey on COTS in the waters of Davao Gulf. Reef degradation and overfishing have been significant problems in the Philippines. Over the last decade, approximately one-third of the country's hard coral cover has been lost (Licuanan et al. 2019). Aside from reef degradation, reef fish diversity in the Philippines also declined alarmingly. For instance, the Central Visayan Region, once ranked highest in reef fish diversity, now ranks lowest in species richness of reef fishes (Nañola et al. 2011). However, Cowan et al. (2017) argued that most of the invertebrate and fish predators of COTS are not targeted by fishers and suggested that instead of the presence of a single species controlling the population of COTS, the suppression of population explosions is a product of collective consumptions by several predators at different life stages of COTS, such as corals and invertebrates consuming larval COTS, and fishes and tritons feeding on matured individuals.

Babcock et al. (2016b) suggested that rather than being triggered by a single cause, outbreaks are affected by coincident biological and physical factors. Increased nutrient concentrations in reefs may not always benefit COTS larval survival. In reefs with fewer larvae of COTS predators, enriched nutrient input will benefit COTS larvae since there will be fewer predators, leading to higher COTS larval survival. However, in coral reefs with high concentrations of larvae of COTS predators, enriched nutrient inputs may be advantageous to these predators, and COTS larval survival will be low. Further, Agustin and Nañola (2013) presented that the spatiotemporal abundance of COTS dramatically relies on environmental conditions and the availability of their preferred food. With this, the overall coral reef characteristics and status contribute to COTS outbreaks by affecting the availability of habitats for COTS predators and habitat and food for COTS.

4. Significance of a national COTS outbreak monitoring database

With the location of the Philippines within the Coral Triangle, as the center of marine biodiversity, and the potential threat of COTS outbreaks to the country's reefs, the development of an efficient management control program is crucial. Outbreak monitoring and population control have been the core of every COTS management effort. Yearly monitoring of outbreaks is crucial to evaluating the spatiotemporal dynamics of outbreaks, evaluating their effects on the reef, and monitoring how fast or slow a reef recovers from an outbreak. For instance, in the GBR, long-term monitoring of COTS outbreaks from its first record in 1962 revealed the southward pattern of outbreaks, consistent with ocean current patterns and temperature changes (CRC Reef Research Centre 2003). Aside from published studies, news articles, and information from government and non-government organizations, there have been no reports of any long-term outbreak monitoring programs initiated in the Philippines. Aside from monitoring, population control is also central to every management effort. Several control measures by chemical injection were implemented in the past, such as injecting copper sulfate into COTS to kill them (e.g., Johnson et al. 1990). However, this method requires technical knowledge as copper sulfate poses risks to the health of other marine life and the overall ecosystem if used indiscriminately (Bruckner 2013). Currently, the most widely used method is injecting an acid, sodium bisulfate, into all the arms of COTS to kill them. Alternatively, Moutardier et al. (2015) introduced vinegar and lime juice as a faster, equally effective, and natural alternative method for killing COTS in the field 12-24 hours post-application. Boström-Einarsson and Rivera-Posada (2016) tested the same method, effectively killing COTS within 24-48 hours. In the Philippines, de Dios et al. (2015) revealed that a hypersaline solution effectively kills COTS within 24 hours, which may serve as a cheaper, equally effective, and more environment-friendly alternative to copper sulfate and other potentially hazardous chemicals used in the past, especially in developing countries like the Philippines.

Despite the availability of alternative outbreak control methods, most efforts still rely on manual extraction of COTS from the reef, where divers individually remove COTS and then bury them ashore. Over the years, numerous COTS extraction efforts have been conducted nationwide. In 2008, over 30,000 COTS were removed from the reefs of Green Island Bay, Palawan (Yan 2008). Gubalani (2022) recently reported that over 175,000 COTS were extracted from Sarangani Bay from October 2021 to June 2022. However, manually extracting COTS from reefs may be counterproductive because COTS may undergo stress-induced release of gametes by male and female individuals, leading to high fertilization rates and even more significant outbreaks. Also, multiple site visits and removal programs should be done regularly since not all individuals can be collected and killed in one collection session (Fabricius 2013).

Efficient COTS management programs require the involvement of all stakeholders, from government agencies, academic institutions, and the people directly or indirectly benefiting from the reefs. The Department of Environment and Natural Resources (DENR), with Executive Order No. 192 s. 1987, mandating it to conserve and manage the country's environment and natural resources will be essential in leading a national program on the management of COTS in the country. The publication of the 2020 memorandum of DENR-BMB on the preliminary guidance for COTS outbreaks is a significant development toward developing a national COTS outbreak management program. Partnerships between the Philippine government and academic institutions will be essential in establishing and implementing science-based standardized methods for outbreak monitoring, reporting, databasing, and population control of COTS, and educating all stakeholders on the biology and ecology of COTS, triggers of outbreaks, and the overall effects of these outbreaks to the reefs and the economy, and raise awareness, especially in coastal communities, which are direct managers of the country's reefs.

Given the extent of the Philippine reefs and the limited resources, monitoring and reporting outbreaks will be challenging. Citizen science is a promising approach in the long term and consistent monitoring and reporting of outbreaks, especially those in more remote locations, by increasing efforts to raise awareness and monitoring for incidences. For instance, in the South Pacific islands of Fiji, Vanuatu, and New Caledonia, private individuals, fishers, and coastal residents who often come across COTS due to their livelihoods accounted for 50.9% of the total reports across these countries. NGOs, research organizations, and small business operators contributed 43% of the reports, while government agencies reported COTS sightings at a rate of 6.2%. In certain areas like the Vanuatuan island Efate, extraction programs were made possible on a community level by NGOs and private businesses as permitted by the central government (Dumas et al. 2020). The case of Romblon Island also emphasizes the importance of citizen science in COTS management. With the help of the Sentro para sa Ikauunlad ng Katutubong Agham at Teknolohiya (SIKAT – Center for the Development of Indigenous Science and Technology) in educating fishers of coastal communities of Romblon on the nature of COTS outbreaks and its correlation on the reef's overall health. The citizen scientists were able to extract 20,000 COTS from their reefs from 2006 to 2007 (Dugan 2013). However, the efficiency of the citizen science approach lies on the proper education of citizen scientists on the nature of outbreaks, correct timing of COTS extraction, proper and standardized monitoring and reporting, and management methodologies.

Given the potential detrimental consequences of COTS outbreaks, the establishment of a national COTS management and control strategy should be devised. Figure 2 presents four recommendations on the management of COTS outbreaks and the roles of each stakeholder. The national COTS management and monitoring system should be composed of four focal functions including: (1) Education campaign on the effects of COTS on coral communities, reefs, the coastal communities, and the country; (2) Strengthening basic research on the biology

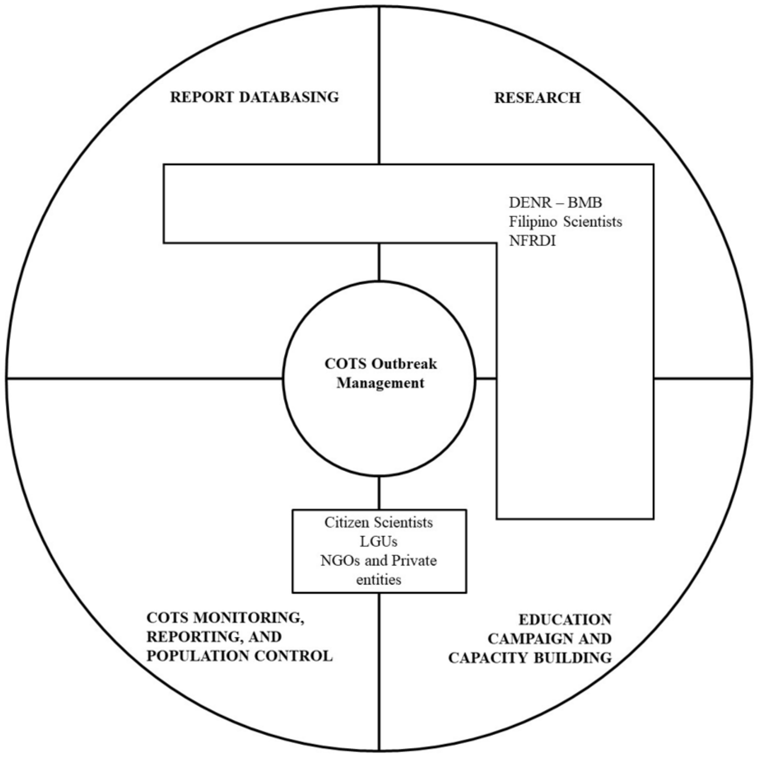

Figure 2. Recommendations on establishing a national COTS management strategy showing its quadrifocal functions. Each quadrant denotes one function. Stakeholders transecting multiple quadrants indicate roles in multiple functions.

and ecology of the Philippine COTS; (3) Capacity building of citizen scientists, local government units (LGUs), non-government organizations (NGOs), and other private entities (e.g., resorts and dive shops) in COTS monitoring, outbreak reporting and management; and (4) Establishing a national database on COTS monitoring and management including a streamlined system from reporting of outbreaks, population control, up to monitoring for potential future outbreaks. The DENR-BMB, being the primary agency for the conservation of coastal biodiversity, should head the program, and take part in population control, education campaign, and research. Filipino scientists and the National Fisheries Research and Development Institute (NFRDI) should further strengthen basic research on the Philippine COTS bridging gaps in the biology and ecology of COTS and triggers of outbreaks, which will immensely help in the formation and continuous improvement of the country's COTS management program. Lastly, citizen scientists, private entities, NGOs, together with LGUs and local DENR arms will be instrumental in constant monitoring, reporting, and population control of outbreaks.

5. Conclusion and future perspectives

Given the extent of the Philippine reefs and the limited resources, monitoring and reporting outbreaks will be challenging. Citizen science is a promising approach in the long term and consistent monitoring and reporting of outbreaks, especially those in more remote locations, by increasing efforts to raise awareness and monitoring for incidences. For instance, in the South Pacific islands of Fiji, Vanuatu, and New Caledonia, private individuals, fishers, and coastal residents who often come across COTS due to their livelihoods accounted for 50.9% of the total reports across these countries. NGOs, research organizations, and small business operators contributed 43% of the reports, while government agencies reported COTS sightings at a rate of 6.2%. In certain areas like the Vanuatuan island Efate, extraction programs were made possible on a community level by NGOs and private businesses as permitted by the central government (Dumas et al. 2020). The case of Romblon Island also emphasizes the importance of citizen science in COTS management. With the help of the Sentro para sa Ikauunlad ng Katutubong Agham at Teknolohiya (SIKAT – Center for the Development of Indigenous Science and Technology) in educating fishers of coastal communities of Romblon on the nature of COTS outbreaks and its correlation on the reef's overall health. The citizen scientists extracted 20,000 COTS from their reefs from 2006 to 2007 (Dugan 2013). However, the efficiency of the citizen science approach lies in the proper education of citizen scientists on the nature of outbreaks, correct timing of COTS extraction, proper and standardized monitoring and reporting, and management methodologies.

Given the potential detrimental consequences of COTS outbreaks, a national COTS management and control strategy should be established. Figure 2 presents four recommendations for the management of COTS outbreaks and the roles of each stakeholder. The national COTS management and monitoring system should be composed of four focal functions including: (1) Education campaign on the effects of COTS on coral communities, reefs, the coastal communities, and the country; (2) Strengthening basic research on the biology and ecology of the Philippine COTS; (3) Capacity building of citizen scientists, local government units (LGUs), non-government organizations (NGOs), and other private entities (e.g., resorts and dive shops) in COTS monitoring, outbreak reporting and management; and (4) Establishing a national database on COTS monitoring and management including a streamlined system from reporting of outbreaks, population control, up to monitoring for potential future outbreaks. The DENR-BMB, being the primary agency for the conservation of coastal biodiversity, should head the program and take part in population control, education campaigns, and research. Filipino scientists and the National Fisheries Research and Development Institute (NFRDI) should further strengthen basic research on the Philippine COTS, bridging gaps in the biology and ecology of COTS and triggers of outbreaks, which will immensely help in the formation and continuous improvement of the country's COTS management program. Lastly, citizen scientists, private entities, and NGOs, together with LGUs, and local DENR arms, will be instrumental in constant monitoring, reporting, and population control of outbreaks.

Finally, it should be emphasized that efficient management of COTS outbreaks is not only limited to the killing or extraction of adult individuals from reefs. It involves a nexus of interdependent factors, including knowledge of the biology and ecology of COTS, the nature and triggers of outbreaks, efficient monitoring, reporting, and population control methodologies, and the involvement of all stakeholders (Figure 2). Initiatives from government and academic institutions will be crucial in conducting research on the biology and ecology of COTS and developing science-based standardized methods for outbreak monitoring, reporting, databasing, and population control of COTS. At the same time, a citizen science approach is a promising tool for long-term and consistent monitoring and reporting of outbreaks across the country, especially in remote areas. Establishing a national database for COTS outbreaks will serve as a baseline for implementing an efficient long-term management strategy for COTS in the country.

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AUTHOR CONTRIBUTIONS

Nicolas JE: Conceptualization, Methodology, Writing – Original draft preparation, review and editing, Visualization. **Pepingco VALO**: Conceptualization, Methodology, Data gathering, Writing – Original draft preparation. **Vince Cruz–Abeledo CC**: Conceptualization, Data gathering, Writing – review and editing, Supervision.

CONFLICTS OF INTEREST

The authors declare no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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