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Timing within the reproduction cycle modulates the efficiency of village-based crown-of-thorns starfish removal

Pascal Dumas [a,b,*], Grégoire Moutardier [a], Jayven Ham [c], Rocky Kaku [c], Sompert Gereva [c], Jerôme Lefèvre [d], Mehdi Adjeroud [b,e]

[a] IRD, UMR 9220 ENTROPIE – BP A5, Nouméa, Nouvelle-Calédonie
[b] Laboratoire d'Excellence "Corail", – 58, avenue Paul Alduy, 66860 Perpignan Cedex, France
[c] Fisheries Department of Vanuatu, PMB 9045, Port-Vila, Vanuatu
[d] IRD, UMR 5566 LEGOS – BP A5, Nouméa, New Caledonia
[e] IRD, UMR 9220 ENTROPIE – Université de Perpignan, 52 Avenue Paul Alduy, 66860 Perpignan, France

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A B S T R A C T

In Pacific countries, outbreaks of the crown-of-thorns starfish *Acanthaster planci* (COTS) raise increasing conservation concerns in areas where people heavily depend upon coral reefs for their livelihoods. Small-scale cleanups are often used in an attempt to regulate COTS densities, but their efficiency is challenged by knowledge gaps and the difficulty for the communities to frame their decisions in an ecological perspective. Here, we investigated COTS reproductive seasonality and its potential impact on removals. The spawning period of COTS was documented in two islands of the Vanuatu archipelago using the gonado-somatic index (GSI). Peak spawning occurred one month after the 28 °C threshold was exceeded and was delayed by 2–3 weeks with increasing latitude, theoretically allowing cleanups to be framed within the biological cycle. We demonstrated that subsampling of two/three arms per starfish provide GSI errors <1, a cost-effective strategy to document local spawning patterns. This approach was used during a major cleanup effort that took place during the spawning season, where fishermen removed COTS from a 3.8 km fringing reef. The density drastically dropped from 518.8 to 66.7 ind.ha^{-1} after participants extirpated >4 tons (13,000 starfish). At the end of the removals, GSI was reduced by half when compared to control areas, suggesting that traditional practices may under certain conditions trigger synchronized spawning. More effectively controlling COTS outbreaks will require teaching good ecological practices to avoid potential side-effects, a challenge in countries where a lack of knowledge on COTS does not really foster environmental concerns among local communities.

1. Introduction

Coral reefs provide crucial environmental and economic services to about 500 million people and generate about $30 billion per year in fishing, tourism and coastal protection (Stone, 2007; Wilkinson, 2008; Wilkinson and Souter, 2008). Increasing, widespread coral loss is a major conservation concern, in particular in small Pacific island countries where the coastal communities depend upon coral reefs for their livelihood (Chin et al., 2011). Among the broad range of large-scale disturbances, the coral-eating starfish *Acanthaster planci* ("crown-of-thorns"; COTS hereafter) is a major cause of reef degradation, whose impact is quantitatively comparable to cyclones (Adjeroud et al., 2009; De'ath et al., 2012; Uthicke et al., 2015). While COTS generally occurs at very low densities (typically <1 ind.ha^{-1}), populations can dramatically increase during certain periods, eventually reaching record-breaking levels (e.g. 1515 ind.ha^{-1}, Kayal et al., 2012). These outbreaks represent one of the most significant biotic disturbances for coral reef ecosystems, with coral mortalities leading to significant loss of biodiversity across all biological compartments, reduced structural complexity and a decline in biomass production (Bruno and Selig, 2007; Osborne et al., 2011; Baird et al., 2013). Over a third of Indo-Pacific reefs were recently affected by severe episodes of COTS outbreaks, leading to growing concerns that they are becoming more frequent and more prevalent (Brodie et al., 2005).

In areas where coral reefs form the basis of local subsistence and/or small-scale commercial fisheries, the cascading effects from COTS outbreaks may drastically affect fish and invertebrate resources, thus constituting potential threat to food security and the lifestyle of coastal communities (Sano, 2000; Bell et al., 2009; Pratchett et al., 2011; Ainsworth and Mumby, 2015). Subsequent phase-shifts from highly diverse, aesthetic reefs to more homogeneous underwater landscapes and the presence of highly venomous starfish can also deeply impact the local tourism industry; since 2002, a total of $2.4 million has been

* Corresponding author at: UMR 9220 ENTROPIE - BP A5, Nouméa, Nouvelle-Calédonie.
E-mail address: pascal-paul.dumas@ird.fr (P. Dumas).

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committed to starfish control by the Australian Government in recognition of the damage at key tourism and conservation sites on the Great Barrier Reef (Hoey and Chin, 2004). While a variety of methods have been developed in an attempt to control COTS outbreaks, manual collection followed by disposal is the most commonly used method at the village scale. Starfish are usually removed by local snorkelers using simple, everyday tools such as spears, sticks, hooks, spearguns and flour bags, and then killed in situ, buried or burnt ashore (Fraser et al., 2000). Beyond environmental considerations, these local, small-scale initiatives address very immediate, health- or fisheries-related concerns; as such, they usually receive strong support from regional development or conservation programs. Yet, their efficiency is highly controversial, in particular to protect entire reef systems. Success stories tend to be small in scale, providing only short-term solutions to a complex phenomenon whose ultimate causes are not fully understood (Moran et al., 1988; Kenchington and Kelleher, 1992; Rivera-Posada and Pratchett, 2012). In particular, removal initiatives may be challenged by the great ability of COTS to recolonize cleaned areas, which is modulated by biological, environmental and anthropogenic factors interacting over a range of scales (e.g. reef extent and topography, local/regional connectivity, distance/structure of source populations, available human and financial resources) (Yamaguchi, 1987; Birkeland and Lucas, 1990; Johnson et al., 1990). Framing COTS removals within the reproductive cycle may be a condition for success. COTS are broadcast spawners whose reproduction is known to be concentrated in the summer months, when the sea temperature increases (Lucas, 1973; Moran, 1986). In the Philippines, Bos et al. (2013) thus recommended removing COTS before April, in order to reduce the reproduction success and thus potentially avoid secondary outbreaks in nearby areas. However, comprehensive studies on COTS reproduction patterns are scarce, especially in tropical coral reefs. The exact timing of reproduction may vary considerably with latitudes and eventually locations, calling for simple, robust techniques that allow for routine monitoring of spawning periods (Yasuda et al., 2010). Incorrect timing associated with inadequate removal practices resulting from insufficient knowledge about COTS biology may also incur ecological side effects. Collecting COTS during the reproduction period is often associated with the risk of massive gamete release, as laboratory experiments have shown that synchronized spawning can be triggered by chemical communication between ripe individuals (Beach et al., 1975). Despite very limited field evidence, the idea that stress from unconsidered handling of ripe COTS would provoke massive spawning is pervasive, but quantitative data on the impact of traditional cleanup practices are scarce.

In this study, we investigated COTS reproductive seasonality and its potential impact on the efficiency of village-scale removal initiatives. This work was conducted in Vanuatu, an archipelago from the West Pacific where COTS aggregations are increasingly reported since the last decade (Raubani, 2009). Recently, alarming reports from coastal communities, tourism professionals and NGOs have raised concerns about the geographical extension, intensity and social impact of COTS (Friedman et al., 2008; Dumas et al., 2014a, 2014b). First, we studied COTS reproductive seasonality over one year in two islands with contrasting latitude, in order to determine best potential timing for cleanup. Second, we tested a subsampling approach to provide quick, robust assessments of COTS reproductive status, allowing for easier field monitoring of the spawning period. Last, the ecological impact of small-scale cleanups and associated practices were investigated during a major community effort that took place during the spawning season, so as to derive operational management recommendations at both local (villages, communities) and national levels.

2. Material & methods

2.1. Reproductive seasonality

COTS were sampled monthly over a one-year period at two reef locations across the Vanuatu archipelago (Fig. 1): on the Lelepa reef, 4 km off the northwestern shore of the main island Efate (Shefa province, central Vanuatu), and 250 km further north on the Aore reef, 1.7 km off the southern shore of Santo island (Sanma province). In the context of regional long-term monitoring programs on sea surface temperatures (SST), both islands had been previously equipped with Sea-Bird SBE56 high-accuracy temperature loggers. Loggers were protected in 40 mm∅ PVC pipes drilled with 5 mm holes, and securely installed in 2012 at depths of 6 m (Efate) or 8 m (Santo); the recording frequency was set at 30 min.

At both sites, 20 COTS starfish were collected by snorkelers each month from October 2013 to October 2014 (Efate) and from November 2013 to November 2014 (Santo), after permission was obtained from the customary land owners. Only adult specimens (i.e. with diameter >20 cm, Moran, 1986) were considered. The size (largest diameter of two perpendicular measurements), wet weight and the total number of arms were recorded for each individual. COTS were carefully transported to the nearest marine hatchery and aquaculture facilities of the Vanuatu Fisheries Department (Luganville, Santo Island/Port-Vila, Efate Island) in 100 l containers filled with regularly refreshed seawater, then immediately dissected. Following Conand (1983), sex was determined based on the texture and color of the gonads (white for males and orange for females); the gonads from three randomly chosen consecutive arms were separated and weighed using an electronic scale (accuracy ±0.5 g) to calculate the gonado-somatic index (GSI):

$$GSI(\%) = \left(\frac{\left(\frac{Wg}{3}\right) \times Na}{WT} \right) \times 100$$

Where:
W_T: total weight of the specimen (g)
W_g: cumulated weight for the gonads of three consecutive arms (g);
N_a: total number of arms

Differences in GSI over time were tested using two-way ANCOVAs with Tukey's HSD post-hoc tests when applicable, after data were successfully square-root transformed to meet the assumption of normality. The effects of month were tested for Santo and Efate separately, while controlling for the effects of sex and weight. Correlation between weight and GSI was further investigated using Pearson's correlation moment. Overall differences in water temperature between both islands were tested using daily averaged SST values for the 2013–2014 period. As seasonal patterns are expected to induce greater intra-site variations when compared to inter-site (latitudinal) variations, we used a paired-samples *t*-test to compare SST in Santo vs. Efate.

2.2. Optimization of GSI estimates

Calculating the GSI from the dissection of a limited number of arms may result in biased estimates. We used bootstrap resampling techniques to investigate how increasing the number of arms dissected may affect the accuracy and the precision (sensu Sokal and Rohlf, 1981) of GSI estimates. Seventy random specimens from the COTS collected in Efate for monthly sampling had the gonads from all their arms dissected and individually weighed. In the first step, a reference GSI was calculated for each specimen using the cumulative weight of the gonads from all its arms. In the second step, we used computer-assisted resampling procedures to compute averaged estimates of bias for decreasing numbers of arms. For a given number of arms, the error (bias) was calculated as the mean difference between the reference and the estimated GSI for each