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Climate variability and massive mortalities challenge giant clam conservation and management efforts in French Polynesia atolls

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ABSTRACT

In 2004, the first no-take area (NTA) dedicated to the conservation of giant clams *Tridacna maxima* was implemented in Tatakoto Atoll, French Polynesia. This NTA protected a unique area worldwide, with extraordinarily high giant clam densities (up to 337 individuals per m^2 on 20-m transect). In 2012, a stock assessment survey revealed a dramatic decrease of the clam population. The reduced densities peaked at 38 ind m^{-2} and the stock in the NTA decreased from 20.1 ± 6.0 million to 1.9 ± 0.55 million clams (mean ± 95% confidence interval). Losses of similar proportions were observed throughout the atoll. Remarkably, the 83% overall loss of this natural resource used daily for consumption and for exports of clam meat to Tahiti Island went unnoticed by the local population. Field clues, including the size of live juveniles attached to the inside of dead shells, pointed to a massive mortality occurring about 3 years before the 2012 survey. Examinations of sea surface temperature satellite data identified a high range of temperature variations before March 2009. In agreement with past and recent events in other atolls, this anomaly is the most likely explanation of the massive loss of giant clams in Tatakoto Atoll, although the exact hydrological and biological secondary mechanisms that occurred in the lagoon remain unclear. The consequences of the massive die-off inside and outside the NTA require new long-term management strategies, by reinforcing the top-down national giant clam management arrangements and by setting flexible management objectives across a network of islands.

1. Introduction

The giant clam *Tridacna maxima* is a quasi-emblematic resource of Pacific Island Countries and Territories (PICTs). It is prized by islanders for its meat, and by visiting tourists and aquarium enthusiasts worldwide for their vivid colors and intricate patterns. *T. maxima* is widely distributed in the Indo-Pacific region, but harvesting pressure proved to be unsustainable in most areas (Othman et al., 2010). As a consequence, *T. maxima* and other Tridacnidae were listed as early as 1985 in the Appendix II of the Convention of Washington, also known as the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). CITES provides an international framework to control the level of international transfers between member countries so that the status of endangered species can be monitored. CITES does not over-rule national laws. National decisions in terms of fishing, protection and stock management cannot be modified by CITES. However, CITES prohibits and authorizes international exports from a country depending on how the resource is managed within the country. For instance, if the exported material comes from aquaculture instead of wild stocks, CITES will authorize the international trade, and will establish adequate quotas.

In French Polynesia, where *T. maxima* is the only species of giant clam (except for limited records of *T. squamosa* in Australes islands see Gilbert et al., 2007), *T. maxima* populations contrast drastically with those in most areas within its distribution range (Green and Craig, 1999). Specifically, remarkable abundance and dominance of *T. maxima* in the eastern Tuamotu archipelago have been recorded since the early 1970s (Salvat, 1972). Densities at Reao and Fangatau atolls have reached 224 and 136 ind m^{-2}, respectively (Salvat, 1972; Andréfouët et al., 2005) and the maximum density ever recorded in the wild was 337 ind m^{-2} on 20-m transect in Tatakoto Atoll in 2004 (Gilbert et al., 2005). The stocks were enormous, e.g., 23.6 ± 5.3 and 88.6 ± 10.5 million clams (mean ± 95% confidence interval) in the 4.05 km^2 Fangatau lagoon and

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11.46 km^2 Tatakoto lagoon, respectively (Gilbert et al., 2006). However, there have been concerns about overfishing in these small lagoons in the past 15 years. Indeed, the demand of Tahiti Island (capital and most populated island, where clams are now rare) led to the import of up to 70 tons of clam meat per year from various Tuamotu and Australes islands in the years 2000–2010. As a consequence, the French Polynesia Fishery Service (now Direction des Resources Marines, DRM) has established several management actions to control and regulate fishing for *T. maxima*. Since 1988, the collection of all individuals smaller than 12 cm has been banned throughout French Polynesia. In addition, specific No-Take-Areas (NTAs) are in the process of being established in several islands. With the agreement of the Tatakoto Atoll inhabitants, the first NTA specifically designed for giant clam protection came into effect in late 2004, only a few months after the initial stock assessment survey (Gilbert et al., 2005). The rationale for the location of the NTA was to protect the largest stock, maximize reproduction potential in an area of high density and promote subsequent dispersal of larvae throughout the lagoon. Larval dispersal was enhanced by selecting a site upstream from the rest of the lagoon relative to the main wind-driven currents.

In parallel, the potential of culturing giant clams in Tatakoto and several other lagoons was assessed by deploying experimental spat collectors (Remoissenet et al., 2009). The high spat collection rates throughout the year in these semi-closed lagoons encouraged DRM to promote future development of commercial harvesting activities based preferentially on cultured giant clams, leaving the wild stock undisturbed. Relying on aquaculture production for international exports in the long term has the advantages of meeting CITES requirements, for both the international meat market and aquarium trade. CITES could authorize larger exports of cultured live clams, while authorizations of exports from wild stocks remain limited. Second, undisturbed wild stocks would promote an "eco friendly" label for the French Polynesia giant clam, as well as clam-related eco tourism activities and restocking using cultured clams (Remoissenet, 2009). Third, using cultured clams could eventually provide a sustainable supply of giant clam meat to the Tahiti market.

Practically, the conservation strategy proposed and implemented by DRM is a set of centralized top-down actions that benefit from bottom-up atoll-scale actions and criteria. Management actions include national-scale measures (e.g., minimum size), and DRM (and on top of it CITES) aims to promote aquaculture and the clam trade where local population want to develop this activity within co-management schemes. However, not all atolls and islands can engage in clam aquaculture because specific habitats and geomorphological features are required. Specifically, *mapiko* (patch reefs made from the accumulation of dead and/or alive clam shells) found in selected atolls determine the suitability of lagoons throughout French Polynesia for clam aquaculture. Without *mapiko* that reveal large natural populations, a lagoon cannot be opened to aquaculture because collection of spat would be too unreliable. This local natural criterion is defined in the national jurisdiction.

By late 2004, all the conditions for sustainable use of the giant clam resource were in place in Tatakoto Atoll, with a specific NTA accepted and understood by local fishermen and inhabitants. In addition, small exports of wild giant clams for the aquarium trade were accepted by CITES in 2011, and six inhabitants had marine grants approved for aquaculture (collecting and rearing) devices. In early 2012, however, a stock assessment revealed that a massive die-off had occurred in the NTA and in the lagoon. There were mounds of empty shells instead of the usually brilliant display of thousands of colorful mantles visible in 2004 (Fig. 1) and until at least December 2008 (Remoissenet, pers. obs.). The amount of dead shells could not be explained by harvesting alone and we concluded that a natural disturbance had occurred in Tatakoto lagoon.

Here, we report the observed losses to the population of *T. maxima* inside and outside the NTA. We present potential climate-driven natural mechanisms that could have led to the massive mortality. Then, we discuss the implications for the management of lagoonal resources affected by massive mortalities. Specifically, we advocate a new management design where objectives need to be established for a network of islands, rather than for islands taken individually.

2. Materials and methods

2.1. Study site

Tatakoto Atoll is a remote semi-closed atoll in the eastern Tuamotu archipelago, located 17.34°S and 138.40°W (Fig. 1), about 1000 km east of Tahiti Island. The lagoon covers 18 km^2 and consists mainly of coral and clam-dominated habitats forming ridges separated by coral sand and mud (Gilbert et al., 2006). The population includes *ca.* 250 inhabitants that traditionally consume clams for subsistence, although this is not the dominant food source. Several families export clam meat and up to 25 tonnes per year have been sent to Tahiti by ships since 2004. Twenty-five tonnes of meat represent around 2.5% of the estimated legal stock (clams > 12 cm) (Gilbert et al., 2006). Tatakoto is an isolated atoll, and no fisherman from outside the atoll can come to harvest the lagoon. Only local villagers collect clams, which would represent a maximum of 100 fishing adults at most in the unlikely event that all of them would fish simultaneously. Harvesting is done by hand, sometimes using a hook. Only the shallowest areas are targeted, by walking along the lagoon and patch reef edges. In Tatakoto, limited fishing is done by snorkelling and none by scuba diving.

The giant clam stock was surveyed in 2004 by snorkelers and scuba-divers, and estimated to be 88.6 ± 10.5 million clams (mean ± 95% confidence interval). Most clams are found in the shallow part of the lagoon (0–6 m depth, covering 11.46 km^2) (Gilbert et al., 2006). Following the stock assessment, the Government of French Polynesia established a 0.5 km^2 NTA in the eastern part of the lagoon (Gilbert et al., 2005). The NTA was the first in French Polynesia, and to the best of our knowledge the first worldwide dedicated to *T. maxima* conservation which was not an informal locally managed marine area.

2.2. T. maxima population assessment

Twenty-nine stations were surveyed during 1 week in January 2012 using six replicate 0.25 m^2 quadrats positioned along two 20 m-long transects, to repeat the 2004 protocol (Andréfouët et al., 2005; Gilbert et al., 2006). Data collection included two types of surveys per station. First, for each station, the two 20-m long transects provided benthic cover data, especially live clams, using the line intersect transect method. Second, the three 0.25 m^2 quadrats per transect were surveyed to assess the density of clams in areas of high clam occurrence. Quadrats were randomly placed within the zone and depth range represented by the transects. Quadrat data served both the population size assessment and also the population structure description because the size of each clam present in each quadrat was measured. Densities are provided hereafter as the density measured in quadrats, weighted by the live clam cover measured on the transect (Andréfouët et al., 2005; Gilbert et al., 2006), thus they are densities per transect.

Stations were surveyed by snorkelling in generally less than 1.5 m of water below the mean low tide level, which is marked by the limit of coral growth and presence of living giant clams. Among these 29 stations, 18 were sampled specifically to compare changes in abundance and size between 2004 and 2012 (Fig. 2).