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Consequences of an uncertain mass mortality regime triggered by climate variability on giant clam population management in the Pacific Ocean

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HIGHLIGHTS

- Quotas were the best management strategy regardless of the mortality regime.
- Climate variability decreased the efficiency of all management scenarios.
- Temporal autocorrelation in natural mortality increased the variability of stocks.

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ABSTRACT

Despite actions to manage sustainably tropical Pacific Ocean reef fisheries, managers have faced failures and frustrations because of unpredicted mass mortality events triggered by climate variability. The consequences of these events on the long-term population dynamics of living resources need to be better understood for better management decisions. Here, we use a giant clam (*Tridacna maxima*) spatially explicit population model to compare the efficiency of several management strategies under various scenarios of natural mortality, including mass mortality due to climatic anomalies. The model was parameterized by *in situ* estimations of growth and mortality and fishing effort, and was validated by historical and new *in situ* surveys of giant clam stocks in two French Polynesia lagoons. Projections on the long run (100 years) suggested that the best management strategy was a decrease of fishing pressure through quota implementation, regardless of the mortality regime considered. In contrast, increasing the minimum legal size of catch and closing areas to fishing were less efficient. When high mortality occurred due to climate variability, the efficiency of all management scenarios decreased markedly. Simulating El Niño Southern Oscillation event by adding temporal autocorrelation in natural mortality rates increased the natural variability of stocks, and also decreased the efficiency of management. These results highlight the difficulties that managers in small Pacific islands can expect in the future in the face of global warming, climate anomalies and new mass mortalities.

1. Introduction

Small insular human communities will have to deal with many difficulties in the next decades to sustain their livelihoods in the face of climate change. In particular, fisheries are predicted to be severely jeopardized by climate variability (Bell et al., 2011). The future state of resources does not only depend on fishing pressure, but is also determined by this difficult-to-predict and

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difficult-to-manage climate variability. Changes are predicted to be unprecedented and projections remain challenging to make. The influence of climate on resources and livelihoods are major issues voiced by all island country leaders at recent international forums on climate change and policy (Bell et al., 2016; Schubert et al., 2017). Tools and models that can provide objective information to support decision-making in a changing climate era are needed.

Theoretical population dynamics and related tools have allowed assessing the sustainability of fisheries and building recommendations for their management. For instance, the management strategy evaluation (MSE) involves using simulation to compare the relative effectiveness of different management approaches for achieving specific management objectives. It has been widely used to assess the effectiveness of management strategies of fisheries, and identify poorly effective strategies that should be eliminated from further consideration (Butterworth et al., 2010; Punt et al., 2014). In practice, MSE involves an operational model (e.g., a population dynamic model) that provide a mathematical representation of the system to be managed, and the fishery that impacts the modelled population (Punt et al., 2014). This operational model can be a population model that allow linking the parameters that affect the life cycle at individual scale (e.g., growth, reproduction, mortality), and apprehend their effect at population level (e.g., stock, recruitment) (Caswell, 2001). The selection of the parameters of the operational model and assess their uncertainty is ideally performed by fitting the model to existing data (Punt et al., 2014). As a result, the recommended management strategies identified by the MSE are usually relevant for the past or present environmental and biological conditions. This means that the operational models implemented in MSE and parameterized with past or present conditions may not be relevant to assess what will happen to populations exposed to future environmental conditions. Unlike temperature latitude fisheries that monitored for stocks, capture sizes, recruitment levels, and other parameters for decades, there is a general paucity of data for tropical reef fisheries. Yet, solutions are urgently needed, as the small scale fisheries of island countries cannot afford waiting decades for data collection before analysing the possible efficiency of management scenarios.

An example of small-scale fishery in demand of management options is the giant clam fishery in the Central Pacific. Giant clams (family Cardiidae, subfamily Tridacninae) are exploited in the Central Pacific for their meat, shell, and for the aquarium trade (Neo et al., 2017; Van Wynsberge et al., 2016; Remoissenet and Wabnitz, 2012). To avoid stock depletion due to increasing commercial exports of meat and shells, all known Tridacninae species were listed in the Washington convention (CITES) in 1985. The trade and export of giant clams between signatory countries are therefore strictly regulated. Considering the wide distribution and relative abundance of one species, *Tridacna maxima*, compared with other giant clam species, *T. maxima* is classified as "lower risk/conservation dependent" (LR/CD) on the IUCN red list of endangered species (IUCN, 2012). The sustainability of giant clam resource appears therefore strongly dependent on historical fishing pressure, management measures, natural productivity, and resistance and resilience of populations to climate change (Black et al., 2011; Van Wynsberge et al., 2016; Neo et al., 2017).

In French Polynesia, the export of a limited number of wild giant clams for the aquarium trade is temporary authorized by CITES (SPC, 2013), provided that stocks are locally managed in a sustainable way. Stock assessments for nine island or atoll lagoons were conducted *in situ* in 2004/2005 (Tubuai and Raivavae islands from Austral Archipelago; and Reao, Pukarua, Napuka, Tatakoto, Fangatau, Tureia and Vahitahi atolls, eastern Tuamotu Gilbert et al., 2006). The spatial characterization of stocks led to the implementation of No Take Areas (NTA) in Tatakoto (Gilbert et al., 2005) and Reao, and supported the development of aquaculture in these two atoll lagoons characterized by a high potential for successful spat collection (e.g., high densities and size structure oriented towards small individuals, Gilbert et al., 2006; Remoissenet and Wabnitz, 2012).

Despite the implementation of management measures and attempt to run sustainably giant clam fisheries, managers have faced a number of failures and frustrations because giant clam abundances have decreased drastically in several lagoons due to lethal environmental conditions at certain time (Adjeroud et al., 2001; Adessi, 2001; Barott et al., 2010; Andréfouët et al., 2013, 2015). Specifically at Tatakoto atoll, Andréfouët et al. (2013) reported a tenfold decrease of stocks between 2004 and 2012. For semi-closed atolls where connections between ocean and lagoon are only possible through few shallow channels usually located in the South part of the atoll rim, Andréfouët et al. (2015) could correlate the occurrence of mortality events with prolonged periods of high temperature, low swell and low wind from the South/South-East. These conditions dry up channels and prevent water renewal, and the lagoon becomes temporary closed and vulnerable to biophysical disturbances (e.g., low water level, high temperature, variability in water salinity and nutrients). Mortality regimes may also be influenced by El Niño Southern Oscillation, with higher risk of giant clam bleaching during El Niño periods (Andréfouët et al., 2017). Other hypotheses were considered to explain the decrease in stocks at Tatakoto (e.g., negative density dependence processes, predation, parasites, pathogen, see Van Wynsberge et al., 2017), but to date the relative importance of these ecological factors remain uncertain.

Beyond the temporal variability of stocks at the atoll scale, spatial differences in density were highlighted between lagoons and within lagoons (Gilbert et al., 2006). Differences in stocks at these scales could be related to differences in habitats, growth, natural mortality, and reproduction, which also varied between lagoons (Van Wynsberge et al., 2017). Indeed, higher mortality rates were reported in semi-closed atolls of Tuamotu archipelago compared with the open lagoon of Tubuai Island in Austral archipelago (Gilbert et al., 2007) and mortality rates varied spatially inside Tatakoto's lagoon (Van Wynsberge et al., 2017).

The high spatial and temporal variability of stocks and life traits complicate management as well as its efficiency over the long run. For example, the NTA at Tatakoto in 2004 was selected initially because of its high giant clam density and potential as a source population for the lagoon (Gilbert et al., 2005). A re-evaluation of stocks in 2012 revealed that this area was the most vulnerable to climatic anomalies (Andréfouët et al., 2013). This event, and other recent observations, have clearly changed the way benthic resource management should be designed in French Polynesian atolls. Specifically, instead of making management recommendations on the basis of presumably stable yields and resource, it seems sensible to take into account the climate-change related disturbances and stochastic processes that also dynamically shape the status of the resource.

Population models were used to make projections of giant clam stocks and compare the relative influence of various management scenarios (Yau et al., 2014; Van Wynsberge et al., 2013). However, no study thus far has compared the efficiency of management scenarios under various regimes of climate-induced mortality. To fill this gap, we integrate several datasets on growth, reproduction, natural mortality and fishing effort previously acquired for two lagoons of French Polynesia (Van Wynsberge et al., 2015, 2017) to build a spatially explicit population dynamics model. We then use the model to address three research questions: (i) Do theoretical models of population dynamics support the hypothesis that giant clam populations have been affected during the past decade by a mass mortality that occurred punctually and suddenly, as expected if triggered by climate variability? (ii) Which management strategies are the most efficient to manage population stocks considering