

Benthic shift in a Solomon Islands' lagoon: corals to cyanobacteria

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Abstract. In June 2011 a large phytoplankton bloom resulted in a catastrophic mortality event that affected a large coastal embayment in the Solomon Islands. This consisted of an area in excess of 20 km² of reef and soft sandy habitats in Marovo Lagoon, the largest double barrier lagoon in the world. This embayment is home to over 1200 people leading largely subsistence lifestyles depending on the impacted reefs for majority of their protein needs. A toxic diatom (*Pseudo-nitzschia* spp.) and toxic dinoflagellate (*Pyrodinium bahamense* var. *compressum*) reached concentrations of millions of cells per litre. The senescent phytoplankton bloom led to complete de-oxygenation of the water column that reportedly caused substantial mortality of marine animal life in the immediate area within a rapid timeframe (24 h). Groups affected included holothurians, crabs and reef and pelagic fish species. Dolphins, reptiles and birds were also found dead within the area, indicating algal toxin accumulation in the food chain. Deep reefs and sediments, whilst initially unaffected, have now been blanketed in large cyanobacterial mats which have negatively impacted live coral cover especially within the deep reef zone (> 6 m depth). Reef recovery within the deep zone has been extremely slow and may indicate an alternative state for the system.

Key words: Cyanobacteria, Phase shift, Algal bloom

Introduction

Globally, coastal algal blooms have increased in recent decades and in many areas are considered "harmful" to ecology, human health and economies of coastal areas. Many hypotheses have been formed and tested for this expansion and proliferation of algal blooms, primarily; climate change, ballast water releases and coastal eutrophication (Hallegraeff 1993, Cloern et al 2005). Despite this global trend there are limited documented cases of harmful algal blooms impacting on the tropical Pacific region (Maclean 1975).

The most well known and prevalent human health issue from algae in the Pacific are the benthic dinoflagellates that cause ciguatera poisoning of fish (Skinner et al 2011). However, there are practically no known cases of large-scale water column blooms of *Alexandrium*, *Pyrodinium*, *Pseudo-nitzschia*, *Gymnodinium* that have caused widespread impacts in many other tropical areas globally. The dinoflagellate *Pyrodinium bahamense* var. *compressum* is one of the region's major harmful algae bloom (HAB) species and produces saxitoxins (STX). High densities or 'blooms' of *Pyrodinium* are responsible for paralytic shellfish poisoning (PSP) in several areas in SE Asia, Pacific and Central America (Hallegraeff and Maclean 1989). Diatom species within *Pseudo-nitzschia* genus are also potentially toxic and blooms

have been recorded worldwide but primarily in temperate regions with very few blooms within the tropics.

In addition to toxin production, senescent harmful algal blooms greatly increase biochemical oxygen demand within the water column as individuals sink down. Large biomass associated with blooms can lead to widespread hypoxic or anoxic conditions to occur which are potentially catastrophic for marine fauna within the system depending on the severity and duration of the event.

No long-term environmental monitoring programs exist within this region. Furthermore, there are very few resources locally available to react to such events. Local knowledge represents an important source of information and there has been a long history of small-scale 'red tide' events in sheltered bays within Marovo Lagoon. These events are called "noganoga" in the Marovo language and typically occur on a small-scale (approximately 100 m²). These can result in deaths of planktivorous fish (e.g. mullet) as well as cause diarrhoea, aches, weakness and head spins in humans who consume shellfish during these events. In June 2011, a much more widespread and severe event occurred than those experienced previously. Between June and July a large (> 20 km²) area of discoloured water was observed in Marovo Lagoon followed by the death of thousands of marine fauna.

This paper presents preliminary findings from monitoring both water column and benthic habitats within the affected area. The primary aim of this study was to determine the impact of this event on coral cover of shallow and deep reefs within the affected area.

Material and Methods

Study site description

Marovo Lagoon is a large (750 km²) tropical coral reef lagoon in the Western province of Solomon Islands (Fig. 1 A - D). The study area was a large bay (21 km²) within Marovo Lagoon consisting of shallow reefs and deep channels (> 30 m). Lagoon water temperature varies between 29 – 31°C with little seasonal change. Salinity ranges between 33 – 35 ppt within the embayment depending on catchment runoff events. South-East trade winds generally run from July to October with a monsoon season from December to April. Islands are volcanic in origin with generally steep slopes and this combined with the north facing opening to the study area (Figure 1 D) results in very sheltered conditions. The high water temperature and salinity result in relatively low 100% dissolved oxygen saturation (approximately 6.3 mg L⁻¹ assuming 30 °C and 34 ppt) making these areas especially vulnerable to deoxygenation events.

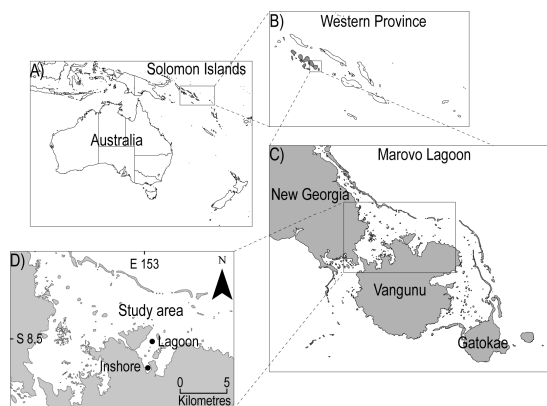


Figure 1: Study area relative to A) Australia, B) Solomon Islands, C) Western Province and D) Vangunu Island, Marovo Lagoon.

Water column sampling

Dirty coloured water and small numbers of dead fish were first reported on 2 June 2011. The situation deteriorated over a 2 week period with widespread death of marine fauna peaking in mid June. On 10 June 2011 locally trained staff used a water quality test kit (World Water Monitoring Day Kit, Alexandria, Virginia, USA) to measure dissolved oxygen levels at inshore and lagoon sites (Figure 1 D).

On 14 June further spot measurements of dissolved oxygen were collected from surface, 4 and 7 m water depth at inshore and lagoon sites using a multiprobe (YSI 600R, Yellow Springs, Ohio, USA). This sampling period is defined as bloom. On 5 July profiles of dissolved oxygen and chlorophyll *a* were collected using another multiprobe (RBR XR-620, Ontario, Canada). This sampling period is defined as one month after bloom initiation.

During both bloom and one month sampling periods, phytoplankton samples were collected at both inshore and lagoon sites using 6 m vertical net tows with a 20 µm phytoplankton net. The net and cod-end were washed with site water to yield a 40 mL sample, this was preserved with Lugol's solution for later microscopic identification. Harmful algal species were identified from 0.1 mL sub-samples placed on a Sedgwick-Rafter cell and counted directly.

Benthic transects

Live/dead coral cover and cyanobacterial cover were classified from digital photo transects of coral reef substrates. At each site three replicate 50 m transects were surveyed with photos taken every 2 m. 25 random points on each digital photos were classified (Kohler and Gill 2006, Albert et al 2008). Transects were conducted on shallow (2 m) reefs and deep (6 m) reefs prior to the bloom (2006), bloom, one month after bloom initiation and 6 months after bloom initiation (December 2011).

Results

In the period 9-12 June 2011 substantial mortality of marine fauna was observed within the affected area (Figure 2 C and D). This included gastropods, bivalves, stingrays, pelagic and reef fish, holothurians, reef and mangrove crabs as well as air-breathing fauna such as turtles (green turtle), dolphins and birds (white tern). Corals, algae and small numbers of small fish appeared to be the only marine organisms that survived the initial bloom event.

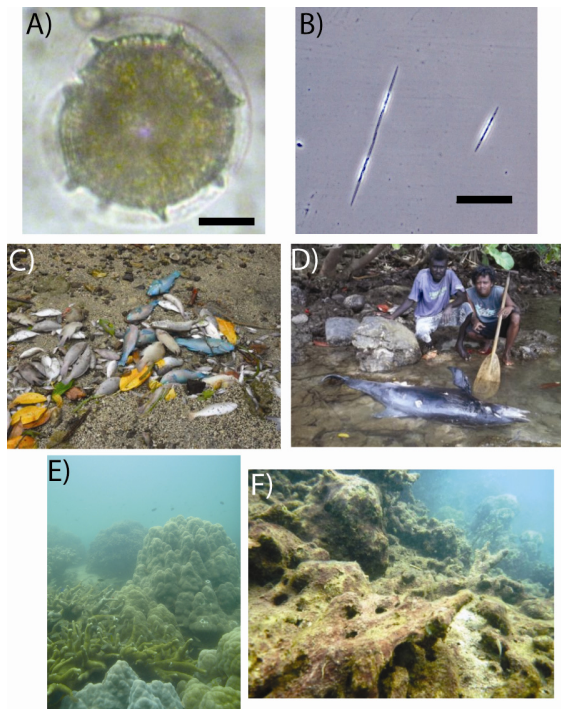


Figure 2: Microscopic images of A) *Pyrodinium bahamense var. compressum* (scale bar 10 µm) and B) *Pseudo-nitzschia spp* (scale bar 50 µm) from field samples. Images of C) fish kill and D) dolphin kill during bloom event. Images from inshore site E) before and F) one month after bloom event showing smothering of reef by cyanobacterial mats.

Water column sampling

Midday surface water testing on 10 June using test kits, revealed dissolved oxygen concentrations $< 1 \text{ mg L}^{-1}$ at both inshore and lagoon sites. These data suggest extremely low dissolved oxygen concentrations were likely throughout the water column at this time.

Spot measurements during and one month after the bloom using multiprobe instruments demonstrate a slight recovery of dissolved oxygen in surface waters (Figure 3 A and B). However, at the inshore site surface dissolved oxygen was still critically low, approximately 2 mg L^{-1} during bloom sampling (Figure 3 A) and less than 1 mg L^{-1} at depths below 4 m for both sites during this time. One month after bloom initiation, further recovery of dissolved oxygen levels was recorded at both sites although midday saturation was still below 100% at both sites (Figure 3 A and B). Rapid declines in dissolved oxygen occurred with depth at both sites and this was associated with an increase in chlorophyll a concentration (Figure 3 A and B). The inshore site recorded extremely high subsurface peak (12 m water depth) in chlorophyll *a* concentration of over 40 µg L^{-1} (Figure 3 A).

Generally the inshore site experienced lower and more prolonged hypoxic/anoxic conditions compared with lagoon site. At both sites a rapid decline of dissolved oxygen concentration was observed with increasing depth except a slight increase in dissolved oxygen was recorded below 10 m at the lagoon site one month after bloom initiation.

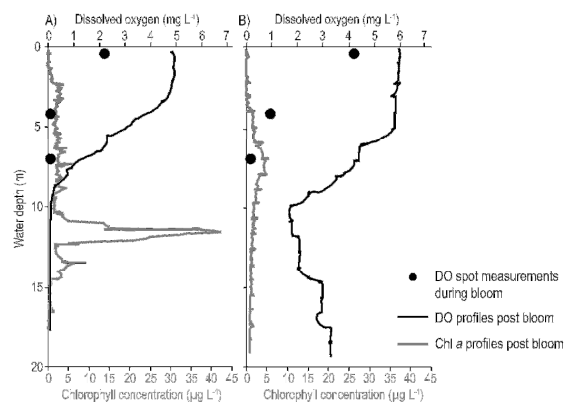


Figure 3: Dissolved oxygen and chlorophyll profiles from A) Inshore and B) Lagoon sites. Spot dissolved oxygen measurements (black dots) collected during the bloom as well as water column profiles of chlorophyll (grey line) and dissolved oxygen (black line) one month post bloom initiation.

Harmful algal bloom species counts

During bloom sampling both inshore and lagoon sites had extremely high numbers of the harmful algal bloom (HAB) species *Pseudo-nitzschia spp* with over 1 million cells L^{-1} recorded during the bloom sampling (Figure 4). One month after bloom initiation extremely high counts were recorded at the inshore site but none identified at the lagoon site. A similar pattern was found with the HAB species *P. bahmense* at the inshore site where high counts were recorded during both sample events. In contrast, counts from the lagoon site did not identify any *P. bahmense* during bloom sampling and relatively low counts one month after bloom initiation (Figure 4). It is important to acknowledge these counts are only for the upper 6 m of the water column and chlorophyll fluorescence peaks were observed deeper than 6 m at both sites (Figure 3 A and B) suggesting these counts may greatly underestimate the true bloom numbers.

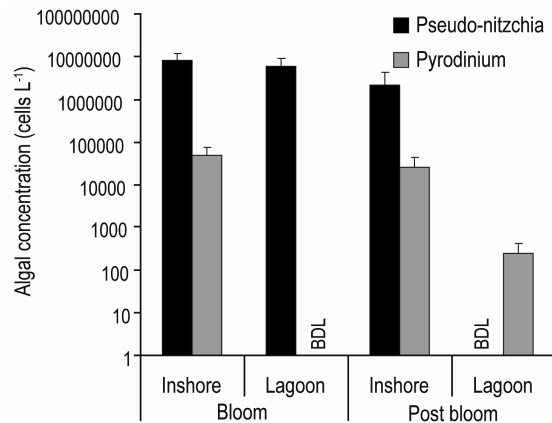


Figure 4: Cell counts for the harmful algal bloom species *Pseudo-nitzschia* spp. and *Pyrodinium bahamense* var. *compressum* during bloom and one month after bloom initiation at inshore and lagoon sites. BDL – below detectable limits (1 cell L⁻¹). Error bars denote standard error.

Reef condition

Surveys of coral reefs during the bloom event compared favourably with pre-bloom transects (Figure 5 A and B). Live coral cover was higher at both shallow and deep transects at the lagoon site compared with the inshore site and little dead coral or cyanobacteria mat cover was recorded. However, a resurvey of both sites just over 2 weeks later revealed dense mats of cyanobacteria covering sand, rubble and live coral with almost 100% cover in the deep reef transects (Figure 5 A and B).

Six months after bloom initiation, live coral cover had still failed to return to pre-bloom conditions. In shallow reefs, cyanobacteria mat cover was greatly reduced with much of coral below these mats dead (Figure 5 A). In deep reefs very little change in cyanobacterial mat cover was found after 6 months and less than 1% live coral cover at either inshore or lagoon sites was recorded.

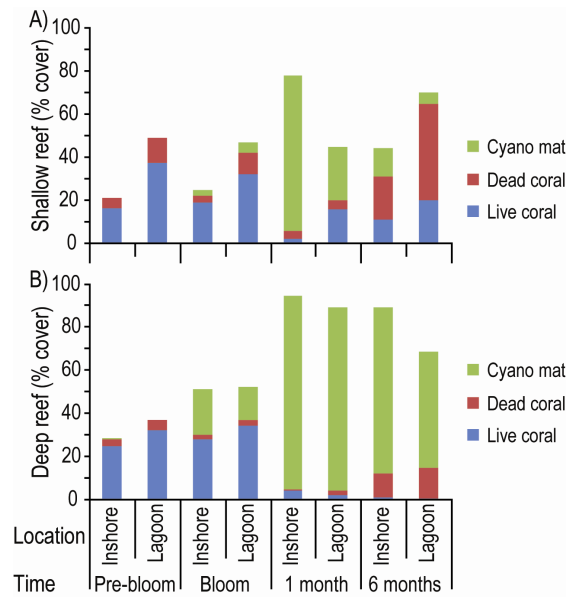


Figure 5: Time history of live and dead coral and cyanobacterial mat percent cover from A) shallow (2 m depth) and B) deep (6 m depth) transects at inshore and lagoon sites.

Discussion

This paper presents the first documented evidence of a large-scale harmful algal bloom in Solomon Islands supporting the trend of increasing harmful algal blooms worldwide (Hallegraeff 1993, Rhodora and Taylor 2001). Whilst coastal algal blooms have been anecdotally reported in the Solomon Islands this event was the largest in area impacted and severity to marine fauna in living memory (based on interviews with 30 elderly fishers at Chumbikopi village in July 2011). The cause of the large-scale loss of marine fauna was likely the prolonged low dissolved oxygen concentrations. The initial test kit sampling suggests the entire water column was anoxic, whilst this evidence is critical in understanding the large scale loss of marine fauna, it is acknowledged the use of test kits yield qualitative data only. However, subsequent quantitative sampling in the weeks following the blooms indeed indicated a prolonged reduction in dissolved oxygen. The hypoxic conditions persisted at depth and inshore compared with surface waters and the lagoon site.

The cause of the hypoxic and/or anoxic conditions was likely due to senescence of the harmful algal bloom as evidenced by the sub-surface chlorophyll peak being associated with strong declines in dissolved oxygen concentration (Figure 3 A and B). This hypoxia likely led to the suffocation of marine organisms across this large area.

The death of air-breathing fauna is more difficult to explain through low dissolved oxygen. Given the

potential for both *Pseudo-nitzschia* spp. and *Pyrodinium bahamense* var. *compressum* to produce powerful toxins, it is likely turtle, dolphin and bird deaths were associated with direct exposure to these toxins in the water column or through consumption of contaminated food.

These anoxic conditions especially in the deeper waters appear to have resulted in a shift in benthic cover from coral to cyanobacteria mats. The rate at which the cyanobacterial mats colonised the benthic environment was surprising (approximately 2 weeks) and the lack of recovery in the deeper reefs is of concern. Removal of this cyanobacterial mat revealed recently dead coral underneath suggesting this smothering was a contributing factor to the death of corals. The persistence of cyanobacterial cover at the deep reefs suggests that subsequent events may result in even faster smothering of shallower benthic surfaces. In addition, some *Porites* spp. corals that were killed by this event were 100-150 years old suggesting the severity of this event was rare. Depending on the rate at which future algal blooms and hypoxic events occur it is conceivable there may be a permanent shift in benthic cover to a cyanobacterial mat (Paul et al 2005, Norstrom et al 2009). This shift will negatively impact local inhabitants as these cyanobacteria dominated systems are unlikely to be as productive fishing grounds as coral reef systems.

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