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The 2014 summer coral bleaching event in subtropical Hong Kong

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Abstract

We reported a coral bleaching event that occurred in August-September 2014 in Hong Kong waters based on video transect surveys conducted at eight sites. The bleaching affected eight species of corals with different growth forms. Bleaching at seven of the eight study sites was minor, affecting only 0.4–5.2% colonies and 0.8–10.0% coral-covered area. Sharp Island East, however, suffered from a moderate level of bleaching, with 13.1% colonies and 30.1% coral-covered area affected. Examination of the government's environmental monitoring data indicated that abnormal water quality conditions preceding and during the bleaching event. Follow-up field surveys of tagged colonies showed that 76% of them had fully recovered, 12% partially recovered, and 12% suffered from mortality. These results indicate that the subtropical corals of Hong Kong are not immune to bleaching, and there is a need to study their responses under climate change scenarios. (141 words)

Keywords: global climate change, coral bleaching, high temperature, hypoxia, *Porites*, *Platygyra*

1. Introduction

Coral bleaching refers to coral tissue whitening due to the loss of endosymbiont zooxanthellae or pigments in these symbiotic algae (Glynn, 1983; Hoegh-Guldberg, 1999). Over the last several decades, large-scale bleaching events have been increasing reported in reefs around the world, especially the 1982–1983 events in the Caribbean (Glynn, 1991), the 1997-1998 events in the Indian Ocean, Caribbean, and tropical Pacific (Wilkinson, 1998), and the 2010 events in the Caribbean (Alemu and Clement, 2014) and tropical Pacific (Doshi *et al.*, 2012; Sutthacheep *et al.*, 2012). Such large-scale bleaching incidences have caused mass coral mortality and large scale degradation of reefs. For instance, the 1997-1998 bleaching events have reduced 16% coral cover around the world, with up to 90% loss in coral cover in some reefs in the Indian Ocean (Wilkinson, 1998).

To date, most coral bleaching events have been reported from tropical reefs. Among the few reports of coral bleaching on subtropical reefs, the affected area was usually small and the impact minor (e.g., Loya *et al.* 2001; Celliers and Schleyer, 2002; Dalton and Carroll, 2011; Harrison *et al.*, 2011; Abdo *et al.*, 2012). However, such small-scale bleaching events should not be overlooked due to the following reasons: 1, subtropical corals are living under marginal environmental conditions for reef development with slow growth rates and variable recruitment success, therefore their recovery from bleaching disturbance is expected to be slow (Harrison *et al.*, 2011; Hoey *et al.*, 2011; Yang and Goodkin, 2014); 2, many subtropical coral reefs are already under the threats of multiple anthropogenic stressors (e.g., sewage pollution, tourism and sedimentation due to coastal development), therefore bleaching may interact with these stressors to escalate the damage (Ang *et al.*, 2005; Berger *et al.*, 2011); 3, global climate change may result in more frequent extreme weather conditions that can cause bleaching in subtropical corals, therefore the cumulative bleaching effects should be considered (Berger *et al.*, 2014); 4, rising sea temperatures may cause tropical corals to shift their ranges to subtropical regions, and such species invasion can affect the recovery of bleached subtropical corals (Greenstein and Pandolfi, 2008).

Located slightly south to the Tropic of Cancer (22°10' – 22°30'N), Hong Kong has a subtropical climate with clear seasonal changes in water temperature. In the wet season (May–October), high temperatures (25–29°C) satisfy the conditions for coral community development. In the dry season (November–April), however, low temperatures, sometimes down to 14°C, prevent corals from developing into true reef structures. Nevertheless, compared with many subtropical coral communities, those in Hong Kong are diverse, with 84 species of hard corals (Chan *et al.*, 2005) and 29 species of soft corals (Fabricius and McCorry, 2006; Yeung *et al.*, 2014). In Hong Kong, there have been a few anecdotal reports of coral bleaching since the 1980s, and the damage was usually localized (McCorry, 2002; Ang *et al.*, 2005). The only recorded mass coral bleaching event occurred in 1997, a strong El Niño year (McCorry, 2002). Here we describe a regional-scale coral bleaching event in Hong Kong, analyze some environmental conditions that might have triggered the bleaching, and discuss the consequence of the bleaching event on these subtropical coral communities. Our data could contribute to a better understanding of the resilience of subtropical coral communities to global environmental changes.

2. Materials and Methods

2.1. Study area

The marine waters of Hong Kong can be divided into an estuarine zone in the west, a transition zone surrounding Hong Kong Island, and an oceanic zone in the east (Fig. 1). Along the west-east direction there is a strong gradient of salinity and sedimentation due to the influence of freshwater input from the Pearl River, with a mean annual discharge of 1.06×10^4 m^3 s^{-1} that ranks only second to the Yangtze River among all rivers in China (Zhang *et al.*, 2012). Most of the natural coastlines in Hong Kong are lined with igneous rocks that usually extend less than 10 m below the sea surface. Below the igneous rocks is usually a bottom of silt and clay that can be stirred up easily. These geological and geographical features have limited the distribution of coral communities mainly in the shallow waters of the oceanic and the transitional zones, with those in the oceanic zone being better developed (Hodgson and Yau, 1997; Ang *et al.*, 2005; Chan *et al.*, 2005; Goodkin *et al.*, 2011; Duprey *et al.*, 2016).

2.2. Quantifying substrate composition and coral bleaching

Based on preliminary observations during surveys jointly organized by the Agriculture, Fisheries and Conservation Department, Hong Kong, and Reef Check Foundation that covered 33 sites in the eastern waters, we selected eight sites that had signs of bleaching for more detailed surveys (Fig. 1). The surveys were conducted during day time between 1000 h and 1500 h in August and September 2014. At each site, a rapid underwater inspection was conducted to locate the area with the highest coral cover. Photographs were taken to record the general pattern of coral bleaching. A 100-m transect was laid parallel to the shore on the sea bottom which was 2-5 m below the water surface. A video transect survey was then conducted to quantify the substrate composition and coral bleaching by a diver swimming slowly along the transect at a speed of approximately 10 meters per minute. The video was captured at 24 frames per second with a resolution of 1920×1080 pixels using a Canon S110 digital camera inside an underwater housing. The camera was held with the lens pointing downward, covering approximately 0.75 m wide on the bottom. Due to the low underwater visibility, it was impossible to cover a wider distance.

In the laboratory, substrate composition of each video was quantified using a point sampling technique that involves stopping the video every 4 seconds to record the substrate composition overlaid by 5 fixed points on the computer screen (Hill and Wilkinson, 2004). On average, 835 points from 167 frames from each transect were sampled to provide reliable data on the substrate composition. The substrate was classified according to Reef Check's Instruction Manual (http://icran.org/pdf/MAR-Pages/tourism/Docs/RC%20Instruction%20Manual%20(English).pdf) as rock (hard substrate > 15 cm in the longest dimension), rubble (hard substrate with 0.5–15 cm in the longest dimension), sand (either volcanic or carbonate material < 0.5 cm in diameter), live coral, dead coral, or others (e.g., sponge, mud) (Fig. 1). Live corals were further identified to genus and their bleaching status (i.e., bleached and non-bleached) were determined. Cover of each substrate, expressed in percentage, was calculated by dividing the number of points for the substrate by the total points for all substrates (Fig. 1). Cover for each coral genus (bleached and non-bleached), expressed in percentage, was also calculated by dividing the number of points for the genus by the total points for all corals (Fig. 2).

Each video file was also examined to enumerate coral colonies and determine their bleaching status (Fig. 2). All coral colonies >10 cm in diameter were identified to genus and enumerated. Each colony was inspected to determine the bleaching status (healthy: no obvious pigment loss; slightly bleached: < 25% surface area bleached; moderately bleached: 25-50% tissue bleached; severely bleached: > 50% surface area bleached).

2.3. Environmental parameters

The Environmental Protection Department (EPD) of the Hong Kong Special Administrative Region government runs a territory-wide water quality monitoring program, which conducts regular monthly surveys at 90 stations (http://epic.epd.gov.hk/EPICRIVER/marine/?lang=en). Data from station PM7 in this monitoring network, in the middle of Port Shelter and the vicinities of our coral bleaching survey sites (Fig. 1), were chosen for analysis to understand the potential causes of the 2014 bleaching event. Water temperature, dissolved oxygen (DO), salinity and chlorophyll-*a* (Chl-*a*) concentration data taken monthly from May to December during 2013 to 2015 were compared to determine whether the environmental conditions were abnormal in 2014. Each parameter had readings from the surface (1 m below surface), middle, and bottom (1 m above bottom), allowing the determination of stratification in the water column.

2.4. Recovery from bleaching

To determine whether consequences of the bleaching, we tagged 48 bleached colonies in September 2014 at three sites with representatives of different coral genera (Fig. 3), and examined the tagged colonies in December 2014 and April 2015. At each re-visit, each sighted colony was photographed with a Canon S110 digital camera inside an underwater housing. In the laboratory, the time-series photographs were compared visually to determine the pattern of recovery/mortality.

3. Results

3.1. Substrate composition and coral bleaching quantified by area cover

There were substantial differences in substrate composition among the eight study sites (Fig. 1). Live coral cover varied from 18.7% at Lo Fu Ngam to 76.6% at Sharp Island East; rock cover ranged from 6.1% at Sharp Island East to 61.9% at Pak Lap Tsai; and sand cover from 0.9% at Pak Lap Tsai to 33.3% at Lo Fu Ngam. Sites with high coral cover (i.e. > 50%) were all inside Port Shelter and had low sand and rock cover. In total 18 genera of live corals were identified (Fig. 2). The number of identified genera ranged from 7 at Town Island to 16 at Shelter Island. Coral communities exhibited a clear site-specific coral dominancy pattern. Specifically, Lo Fu Ngam was co-dominated by *Acropora* (22.1%) and *Porites* (26.5%). Sharp Island West was dominated by *Pavona* (87.9%). Sharp Island East was co-dominated by *Porites* (29.0%) and *Pavona* (38.7%). Shelter Island was co-dominated by *Favites* (24.2%), *Platygyra* (39.7%) and Porites (18.0%). Bluff Island was co-dominated by *Acropora* (37.3%) and *Montipora* (17.0%). Town Island was dominated by *Porites* (80.7%). Pak Lap Tsai was co-dominated by *Montipora* (31.5%) and *Porites* (29.7%). High Island Dam was co-dominated by *Montipora* (32.0%), *Platygyra* (16.9%), *Favites* (14.6%) and *Porites* (12.9%).

Bleaching mainly affected six genera of the most common species (*Acropora*, *Montipora*, *Pavona*, *Platygyra*, *Porites*, *Hydnophora*) (Fig. 2). Two other genera (*Leptastrea and Plesiastrea*), when also affected, accounted for only a small percentage of the total bleached coral area or total colony counts. Bleaching, quantified as impacted area over the total area covered by corals, varied greatly among the sites (left column in Fig. 3). At five sites, the bleached area was small (1.2-4.4%). Only at three sites were the bleached area exceeded 5%: 30.6% at Sharp Island East, 10.0% at Town Island, and 7.9% at Bluff Island. At Sharp Island East, *Pavona, Platygyra*, and *Porites* was responsible to 14.5%, 12.4 and 3.5% of the 30.6% bleached area, respectively. At Town Island, *Porites* and *Acropora* was responsible for 9.3% and

0.7% of the 10.0% bleached area, respectively. And at Bluff Island, *Montipora*, *Acropora* and *Platygyra* was responsible for 6.3%, 1.2% and 0.4% of the 7.9% bleached area respectively.

3.2. Coral community composition and bleaching quantified by colony counts

Colony count data (right column in Fig. 3) showed a similar pattern of coral dominancy from the area cover data (left column in Fig. 3). Specifically, Lo Fu Ngam was dominated by *Porites* (35.5%). Sharp Island West was co-dominated by *Pavona* (43.9%) and *Platygyra* (27.3%). Sharp Island East was co-dominated by *Platygyra* (41.4%) and *Pavona* (24.5%). Shelter Island was dominated by *Favites* (40.4%). Bluff Island was dominated by *Acropora* (47.6%). Town Island was dominated by *Porites* (74.6%). Pak Lap Tsai was co-dominated by *Montipora* (29.0%) and *Porites* (35.0%). And High Island Dam was co-dominated by *Favites* (31.1%), *Montipora* (20.2%) and *Porites* (18.8%). Bleaching was mild in general, but there was substantial site difference which varied from 1 colony (0.4%) at Lo Fu Ngam to 83 colonies (13.1%) at Sharp Island East. Sites with higher levels of bleaching (i.e. > 3% colonies) were confined to Port Shelter: 13.1% at Sharp Island East, 3.5% at Sharp Island West, and 5.2% at Bluff Island. The coral genera appeared to have differential susceptibility, with bleaching affecting only one to four genera among ten genera (*Acropora*, *Montipora*, *Pavona*, *Platygyra*, *Porites*, *Hydnophora*, *Leptastrea*, *Plesiastrea, Turbinaria, Psammocora*) at a specific site. Nevertheless, at Sharp Island East, the most severely impacted site, relatively large percentages of *Leptastrea* (4 of 23 colonies, 17.4%), *Pavona* (17 of 156 colonies, 10.9%), and *Platygyra* (59 of 263 colonies, 23.2%) were bleached. Among them, all 4 impacted *Leptastrea*, 16 colonies of *Pavona*, and 38 colonies of *Platygyra* were moderately bleached (25-50% by colony area), and 2 colonies of *Platygyra* were severely bleached (> 50% by colony area).

3.3. Environmental parameters

Several water quality parameters at PM7, the EPD water quality monitoring station in the middle of Port Shelter, were abnormal during the second half year of 2014 that covered the bleaching event in Mid-August to early September, when compared with the same period in 2013 and 2015 (Fig. 4). Specifically, the surface water salinity in mid-May was only 25 psu, being 9 psu lower than the bottom water salinity. In mid-August, the mid-water Chl-*a* concentration was extremely high (14 µg l^{-1}). In mid-July to September 2014, the bottom water was extremely hypoxic (1.2-1.6 mg l^{-1}). Mid-July to early September corresponded to the hottest time of the year, with surface water temperatures ranging from 27.9 to 30.4°C, being 5-6°C higher than the bottom water temperatures, again indicating strong vertical stratification. Compared with 2013 and 2015, the mean surface water temperatures during mid-July to September in 2014 were also slightly higher: 28.3°C in 2013, 29.1°C in 2014 and 27.8 °C in 2015. In fact, only in 2014 was there a temperature reading higher than 30°C (early September). Starting from October as the surface water temperature decreased, the temperature, DO increased and salinity values became very similar between the surface and bottom water, indicating the loss in vertical stratification.

3.4. Recovery from coral bleaching

Of the 48 tagged colonies, 33 colonies were recovered in the follow-up surveys, including 13 colonies of *Platygyra*, 12 colonies of *Montipora*, 4 colonies *Acropora*, 1 colony of *Hydnophora*, 1 colony of *Pavona*, 1 colony of *Cyphastrea*, and 1 colony of *Porites* (Supplementary Fig. S1). We could not evaluate the status of the missing colonies due to the loss of their steel stakes with tag. Among the colonies found, 25 (76%) had fully recovered, 4 colonies (12%) had partially recovered, and 4 colonies (12%) had suffered from mortality. The dead corals included one colony of *Acropora valida*, two colonies of *Montipora peltiformis*, and one colony of *Platygyra carnosa*. The partially recovered corals included three colonies of *M. peltiformis*, and one colony of *P. carnosa*. For those colonies re-sighted in both the December 2014 and April 2015 surveys, the pattern of recovery was identical on both dates, indicating no observable change in coral health status between the two surveys. For *Platygyra*, encrusting filamentous algae had usually developed on the dead colonies or the part of the bleached area that failed to re-generate healthy tissue.

4. Discussion

The anecdotal reports of coral bleaching in Hong Kong since 1981 showed that most of the incidences were mild, affecting only small areas and isolated colonies (McCorry, 2002; Ang *et al.*, 2005). The only well-documented regional scale coral bleaching event occurred in the summer of 1997, during which McCorry (2002) surveyed nine sites across local waters, including six sites across Hong Kong waters for a quick qualitative assessment, and three sites in the eastern waters that suffered from relatively severe bleaching (Coral Beach, Hoi Ha Wan; Sharp Island – corresponding Sharp Island West in the present study; Tung Ping Chau) for quantitative line intercept transect (LIT) survey. She found whole-community die-off at Sham Wan in the southern waters, and bleaching of 15 genera of corals at other sites. At the three LIT survey sites, species in eight genera showed relatively strong signs of bleaching, with > 15% colonies being bleached or recently dead: *Montipora* (82%), *Goniopora* (64%), *Porites* (33%), *Pavona* (27%), *Stylocoeniella* (33%), *Acropora* (17%), *Hydnophora* (17%), and *Lithophyllon*

(17%). *Platygyra*, however, exhibited only a weak bleaching response, with 3% colonies being bleached or recently dead.

Different from the 2007 event, the 2014 summer bleaching event in Hong Kong only affected the Port Shelter area, without causing extensive coral mass mortality throughout Hong Kong waters. Even within the Port Shelter area, seven of the eight survey sites suffered from only minor coral bleaching. We used two methods to show the level of coral bleaching. Although the results were in general consistent, there was some notable difference between the area cover data and colony count data for species with very small or large colonies. For instance, at Sharp Island East, there appeared no *Psammocora* because the colonies were small and they only covered 0.07% of the coral substrate, too small to see in the figure (left column of Figure 3). But the head count data showed that there were 13 colonies of *Psammocora*, representing 2% of the total coral colonies and showed clearly in the figure (right column). In addition, bleaching based on coral covered area might look more severe than based on colony counts due to the fact that most of the genera affected by bleaching, especially *Montipora peltiformis* and *Platygyra* spp., have big colonies covering a much larger area than other genera. Therefore, using colony counts alone would have underestimated the bleaching on genera with larger colonies.

Nevertheless, the percent bleaching by coral covered area (30.6%) as well as colony counts (13.1%) consistently showed that Sharp Island East located in the inner Port Shelter suffered from a moderately level of coral bleaching. Given that Port Shelter is a semi land-locked bay, the poor water exchange with the open South China Sea water could have contributed to the higher severity of bleaching at this site.

The causes of the 1997 and 2014 bleaching events in Hong Kong were apparently different. The 1997 bleaching event happened during an extended period of hyposalinity associated with a heavy annual precipitation of 3,343 mm – the highest over the 131-year history of weather records by the Hong Kong Observatory (http://www.hko.gov.hk/cis/climat_e.htm). The rainfall in June to August 1997 (2,359 mm) reduced the surface water salinity at Hoi Ha Wan and Sharp Island to 19 psu and 20 psu, respectively (McCorry, 2002). That year's unprecedented rainfall coincided with an exceptionally strong El Niño event that also caused coral bleaching in many other tropical reefs (Wilkinson, 1998). Nevertheless, The EPD's water quality data showed that surface water temperatures during the event were not particularly high, and bottom DO levels were not particularly low when comparing the same period in 1996 and 1998, suggesting that hyposalinity was the main cause of bleaching.

The 2014 bleaching event in Hong Kong also occurred in summer, but the triggering factors were more complicated. The total rainfall in May to June was 1,124 mm, being 363 mm higher than the average value between 1981 and 2010 (http://www.hko.gov.hk/cis/climat_e.htm). This high rainfall resulted in a clear stratification of the water column, as shown by the difference between surface and bottom salinity in mid-May to mid-July (Fig. 4). The high Chl-a concentration in the mid-water in mid-August (14 $\mu g\ l^{-1}$), being around 7 times the corresponding values in 2013 and 2015, might indicate high algal biomass. The bottom water in the hottest months of July to September 2014 was hypoxic, and this summer hypoxic period was substantially longer than the corresponding hypoxic period in 2013 and 2015. Taken together, the environmental data showed that hypoxia and high temperature coincided with the 2014 bleaching event, but other environmental factors might have interacted, leading to the development of the stressful conditions for the corals. Nevertheless, because the EPD data were sparse (one datum per month), they should be interpreted with caution.

The 2014 coral bleaching event in Hong Kong was apparently not isolated, but associated a shifting of the Pacific Decadal Oscillation from the cool phase and into the warm phase since 2013 (Fang *et al.*, 2014; Rodgers *et al.*, 2015). Corals in Hawaii were also impacted by bleaching in 2014, with heavy rainfall in Kāne'ohe Bay causing a 22.5% reduction in coral cover in July in an area directly affected by flooding, and subsequently high temperature in September causing a major bleaching event throughout the bay, further reducing coral cover in the freshwater impacted area by 60.0% (Bahr *et al.*, 2015; Ritson-Williams and Gates, 2016). Tagging of 150 bleached colonies showed that only one colony of *Pocillopora damicornis* and two colonies of *Montipora capitata* subsequently died, indicating good recovery of most affected corals (Ritson-Williams and Gates, 2016).

Little is known about the rates and mechanisms of bleaching recovery in Hong Kong corals. McCorry (2002) found that in 1997, except for corals at Sham Wan which were all killed, recovery occurred within 4 – 8 weeks of water salinity returning to normal values, with accompanying rates of mortality depending on the species: some colonies of *Montipora peltiformis* and *Acropora pruinosa* suffered total mortality, whereas *Pavona decussata* typically only suffered partial mortality. Our follow-up surveys of the 2014 summer bleaching event showed that most bleached colonies had already fully recovered in December, roughly three months after the event. Overall, the generally low percentage of bleached corals among the eight study sites except for Sharp Island East and the high percentage (76%) of tagged coral colonies that had fully recovered in the colder months indicated that the event was mild and there was very limited direct impact on the community structure of the coral communities. Nevertheless, the bleaching at Sharp Island East should raise an alarm about the possible consequences on the community structure, given that the level was higher (30.6% coral-covered area), and bleaching had disproportionally larger effects on the most dominant species such as *Pavona decussata* and *Platygyra carnosa.* Moreover, since Hong Kong corals are already threatened by several stressors including recreational diving (Chung *et al.*, 2013; Au *et al.*, 2014), sedimentation associated with coastal development (Wilson and Wong, 1996; Ang *et al.*, 2005), nutrient pollution (Duprey *et al.*, 2016), bioerosion (Dumont *et al.*, 2013; Qiu *et al.*, 2014; Xie *et al.*, 2016) and abnormal coral growth (Sun *et al.*, 2013; Zhang et al., 2017), and that the climate in the 21st century for Hong Kong is hotter and wetter (www.epd.gov.hk/epd/english/climate_change), coral bleaching should not be viewed as an isolated phenomenon. Examining the synergistic effects between stressors can allow for determination of whether controlling certain anthropogenic activities can reduce the potential impact of coral bleaching. Studying the bleaching responses of corals and their symbiotic zooxanthellae (Wong *et al.*, 2016) to environmental stressors both during bleaching events and in laboratory may reveal the resilience of different species of corals and predict the winners of losers to global environmental change (Cunning *et al.*, 2016).

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Supplementary material

Supplementary Fig. S1. Photographs showing the recovery of coral colonies from bleaching.

Photo credit: James Y. Xie

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Figure Legends

Fig. 1. Map of Hong Kong showing estuarine, transition and oceanic zones, and the benthic substrate composition of the eight study sites in the Port Shelter area (1. Lo Fu Ngam; 2. Sharp Island West; 3. Sharp Island East; 4. Shelter Island; 5. High Island Dam; 6. Pak Lap Tsai; 7. Town Island; 8. Bluff Island). Names of three locations discussed in text are indicated with a circled number: ①, Sham Wan; ②, Sharp Island; ③, Hoi Ha Wan. PM7, an EPD water monitoring site whose data were used to analyze the water quality conditions leading to coral bleaching, is located in the middle of Port Shelter (②).

Fig. 2. Representative photographs showing six species of common corals affected by the 2014 bleaching event: *Acropora tumida* (A), *Platygyra carosa* (B), *Porites lutea* (C), *Montipora peltiformis* (D), *Pavona decussata* (E), *Hydnophora exesa* (F). Photo credit: James Y. Xie

Fig. 3. Composition of coral communities at the eight study sites quantified as percent surface area covered by coral genus (left column), with apparently healthy and bleached area shown in blue and white respectively; and the number of coral colonies (right column), with colonies that were healthy or had different levels of damage shown in different colors. Number placed after site name indicates the total number of coral colonies counted at that site.

Fig. 4. Water quality parameters (salinity, Chl-a concentration, dissolved oxygen concentration and temperature) in the water column of EPD monitoring station M7, which is located in the middle of Port Shelter, during May to December 2013, 2014 and 2015.

Figure 1

Figure 1

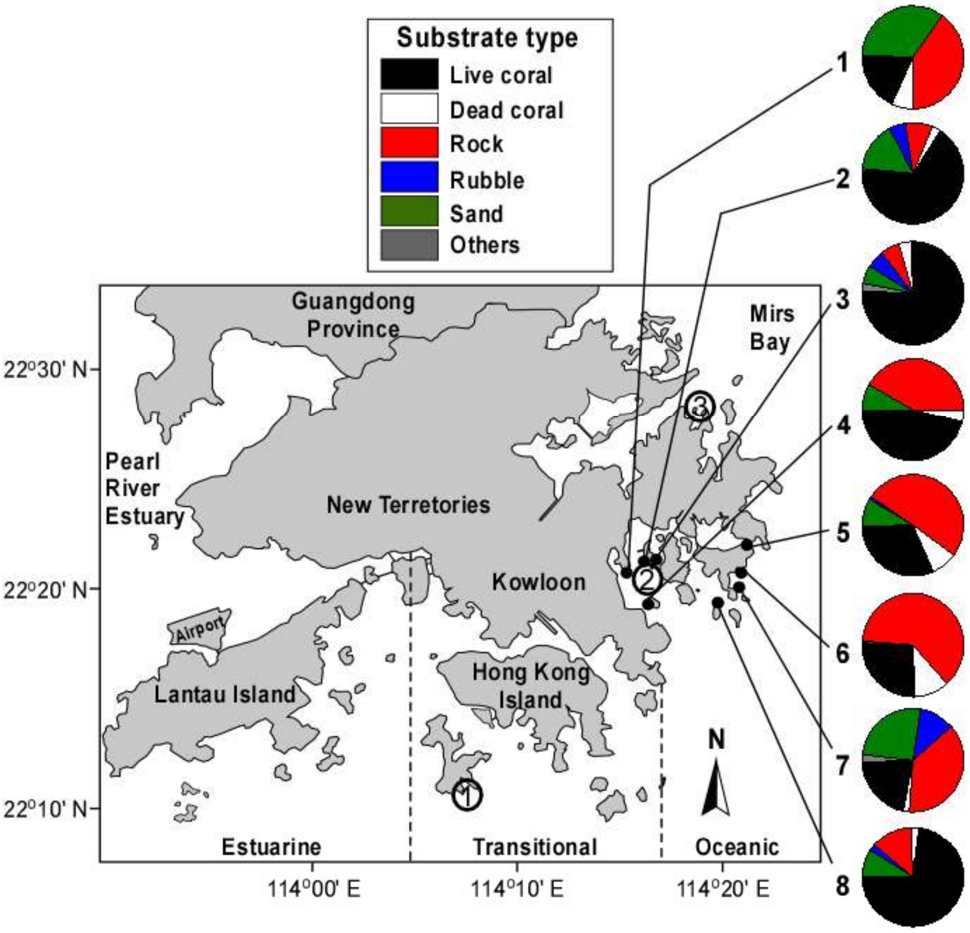

Figure 2

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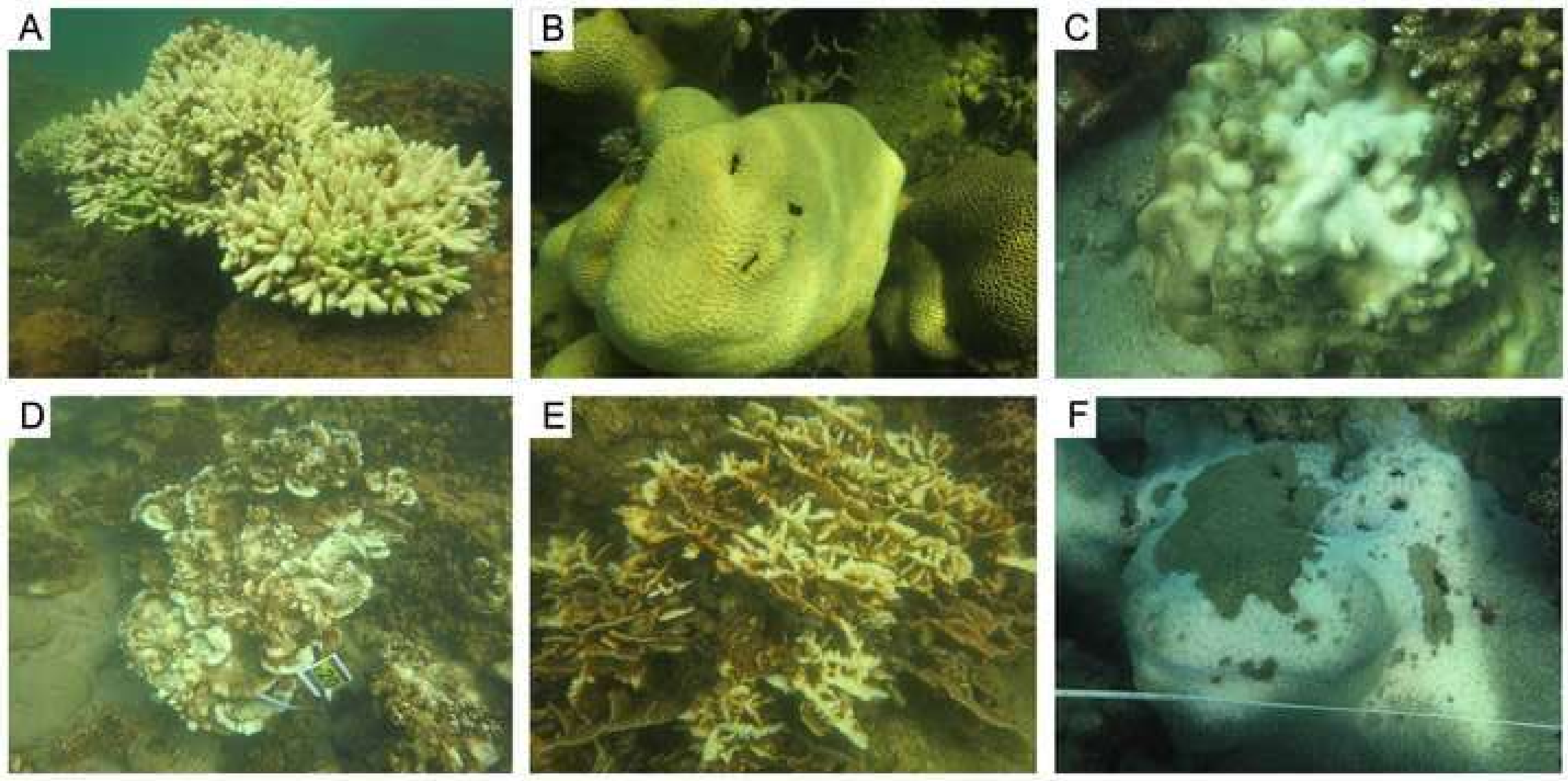

Figure 3

Figure 3

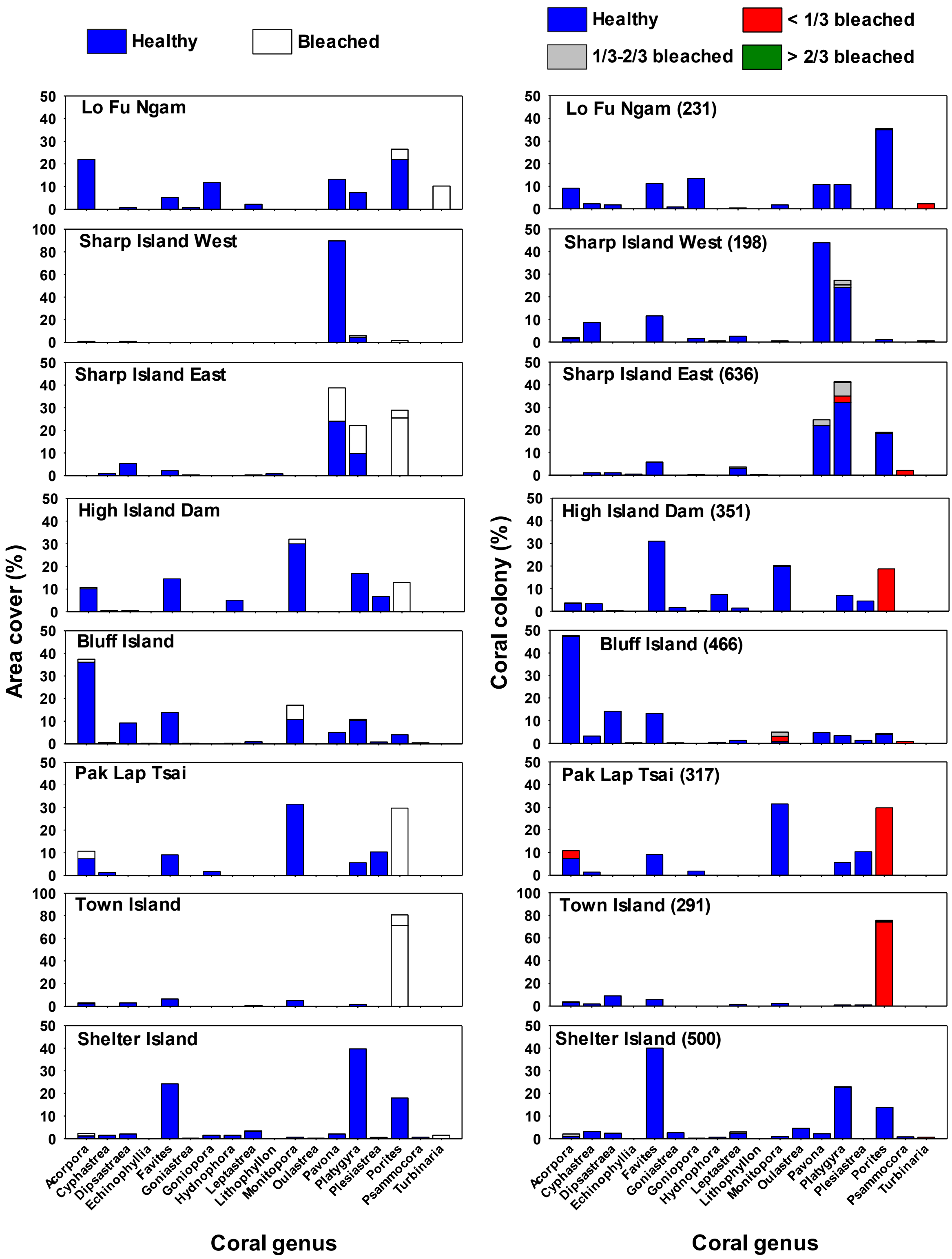

Figure 4

Figure 4