Black Disease (*Terpios hoshinota*): A Probable Cause for the Rapid Coral Mortality at the Northern Reef of Yongxing Island in the South China Sea

Qi Shi, Guo Hui Liu, Hong Qiang Yan,
Hui Ling Zhang

Received: 21 March 2011 / Revised: 27 December 2011 / Accepted: 29 December 2011 / Published online: 24 January 2012

Abstract The northern reef of Yongxing Island, the largest reef island of the Xisha Islands in the South China Sea, was in good condition with significant cover of scleractinian corals until 2002. Surveys in 2008 and 2010, however, found that coral coverage had declined rapidly and severely, implying that catastrophic coral mortality occurred during the past 8 years. A blackish mat was observed covering live and dead corals in both 2008 and 2010 that was identified as an encrusting sponge, *Terpios hoshinota*, by special surface morphology and spicule structure. In addition, spicule residues were found on the surface of long-dead corals, indicating a previous invasion of *T. hoshinota*. *T. hoshinota* is referred to as the “black disease” because it rapidly overgrows and kills corals. Our evidence indicates that outbreaks of black disease are at least partially responsible for the massive coral mortality at the northern reef of Yongxing Island over the past 8 years, although human activities and heat-related coral bleaching cannot be discounted as minor causes for this coral decline.

Keywords Coral mortality · Black disease · *Terpios hoshinota* · Human activities · Coral bleaching · Crown-of-thorns starfish · South China Sea

INTRODUCTION

Degradation of coral reef is a world-wide phenomenon that has accelerated over the past few decades, resulting in massive mortality of scleractinian coral and a rapid decline in total coral coverage (Wilkinson 2004). According to the report of global coral reef monitoring network (GCRMN), the world has effectively lost 19% of the original area of coral reef (Wilkinson 2008). A series of threats are responsible for this widespread damage, including natural

stressors such as coral bleaching, coral diseases, plagues of predators, invasive species, storms, freshwater inundation, seismic events, and volcanic eruptions, and human pressures such as pollution, over-fishing, over-exploitation, modification, and engineering practices (Wilkinson 2004). Global threats (bleaching, disease, and predators) are suspected to increase in frequency and severity coincident with direct human disturbances (Wilkinson 2004).

Degradation of coral communities has been found along many different fringing reefs in China, and the coverage of live coral has declined by about 30–70% over the past few decades (Zhang et al. 2006; Chen et al. 2007; Shi et al. 2007; Huang et al. 2009; Zhao et al. 2010). Surveys provided compelling evidence that coral degradation was primarily the result of human activities, including engineering projects, destructive fishing practices, and pollution (Wang et al. 2006; Zhang et al. 2006; Chen et al. 2007; Huang et al. 2009; Shi et al. 2010). In contrast, little evidence pointed to coral bleaching and coral diseases as major causes for this massive coral mortality.

Yongxing Island (Woody Island) is the largest reef island within the Xisha Islands (Paracel Islands) located in the middle of the South China Sea (Fig. 1a). The coral community was flourishing within the reef as recently as the 1970s and 1980s (Zou 1978; Wang 2001), but was destroyed by harbor construction on the south and west sides and by airfield construction on the east side. Thus, only the northern reef has sustained abundant corals with high coverage into the early twenty-first century (Li et al. 2004; Huang et al. 2006). Our recent surveys, however, reported massive coral deaths and a large decline in coral coverage at the northern reef in 2008 and 2010 that was associated with blackish mats covering both live and dead coral.

This blackish mat was first observed at Guam (Bryan 1973), and was subsequently found on coral reefs around

Fig. 1 The site of Yongxing Island in the South China Sea (a) and survey transects (T1, T2, T3 and T4) at the northern reef of Yongxing Island (b) (Map a is from ReefBase (<http://reefgis.reefbase.org/>); map b is from Google Earth © 2010 Google)

the western Pacific, including Guam, Northern Mariana Island, Western Caroline Islands, American Samoa, the Philippines, Taiwan, and the Ryukyu Archipelago (Plucer-Rosario 1987; Ruetzler and Muzik 1993). The last report of this blackish mat was at Green Island off the southeastern coast of Taiwan in 2006 at a coral reef known to be free of this black mat only a few years earlier (Liao et al. 2007). It

was finally identified as an encrusting sponge named *Terpios hoshinota* that symbiosed with photosynthetic cyanobacteria (Ruetzler and Muzik 1993; Liao et al. 2007). *T. hoshinota* overgrew and killed corals and is now referred to as the “black disease” (Ruetzler and Muzik 1993). It can grow rapidly and widely on substrate (Bryan 1973; Plucer-Rosario 1987; Soong et al. 2009), releases compounds

toxic to other reef organisms (Teruya et al. 2004), and is an aggressive competitor for nutrients (Bryan 1973) and space (Ruetzler and Muzik 1993) on coral reefs. Outbreaks of *T. hoshinota* are now recognized as a major threat to coral communities.

We had surveyed coral coverage and collected samples at the northern reef of Yongxing Island during the summers of 2008 and 2010. In this article, we determined that the blackish mat was *T. hoshinota* and discussed the major cause of massive coral mortality at the northern reef of the Island.

MATERIALS AND METHODS

Study Area

Yongxing Island is a reef island in the Xuande Atoll located in the eastern Xisha Islands at the center of the South China Sea (Fig. 1a). It is about 400–500 km from the Chinese mainland. This island is oval-shaped with an NNW–SSE long axis of 1.8 km and the NNE–SSW short axis of 1.2 km, and occupies a land area of 1.8 km² (Zhao et al. 1999). Yongxing Island shows typical circular geomorphological zones divided into reef foreslope, reef flat, beach, sand barrier, sand mat, and dry lagoon at the island center (Yu et al. 1995). The reef flat usually stretches out 400–800 m with scleractinian coral, mollusks, calcareous algae, and foraminifera residues (Yu et al. 1995). The reef slope is about 25–30 m deep and 100–800 m wide with flourishing corals and developed grooves (Wang 2001). Scleractinian corals of 14 families, 21 genera, and 35 species were found in 1970s (Zou 1978), while 9 families, 14 genera, and 23 species were found in 2002 (Li et al. 2004; Huang et al. 2006). There are two harbors at the southwest side and an airfield on the east side of Yongxing Island (Fig. 1b).

Transect Survey

Line intercept transect is recommended by GCRMN as the standard method for coral reef survey using 20 m line transects. A video line intercept transect expanded the survey to 50 × 0.25 m² belt transects using a video camera and was easier and more representative than line intercept transect (English et al. 1997). In our survey, each transect was a belt of 100 × 0.5 m² that could yield more information on benthic communities. A quadrat frame was designed with 50 cm of marked scales that could be fixed with an underwater digital video camera. During surveys, a scuba diver swam slowly along a transect, put the quadrat frame close to the reef surface, and recorded an uninterrupted real video over the entire transect. The video was

transferred onto computer, and was viewed and analyzed to estimate percent coverage of corals and other benthos (English et al. 1997).

Four transects of 100 m length were established at the northern reef of Yongxing Island, including two transects perpendicular to the coastline at a depth of 2–12 m and two transects parallel to the 4 and 8 m isobath, respectively (Fig. 1b). The position of each transect was controlled by GPS. Four transects were surveyed in July 2008 and August 2010.

Sampling and Analysis

In the surveys from 2008 and 2010, both live and dead corals were covered by a blackish mat resembling the sponge *T. hoshinota* (Fig. 2a, b). This blackish mat was photographed in situ and sampled to analyze its surface morphology and spicule structure. Long-dead corals uncovered from the blackish mat were sampled as well. All samples were placed in sterile 50 ml polypropylene centrifuge tubes at 4°C and transported back to a field station in less than 2 h where they were preserved in 80% ethanol at –20°C until analysis.

A small sample (about 0.1–0.3 g) was picked from the black mat and coverings of long-dead coral and washed twice with distilled water to remove the ethanol and impurities. The cleaned sample was put into a 1.5-ml plastic centrifugal tube with 10% 0.5 ml NCIO solution and incubated for 24 h to digest the samples. After full digestion, the sample was blended with distilled water and centrifuged at 3000 rpm for 5 min. This process was carried out twice to remove digested product and to condense the suspension. The suspension was dripped onto a microscope slide and observed and photographed with a digital camera.

RESULTS

Morphology and Spicule Structure of *T. hoshinota*

The survey demonstrated that blackish mats on the coral were less than 1-mm thick and were gray or dark gray to dark brown and black. A radial canal system structure was observed on the mat surface that contained small osculum at the center of radiating exhalant networks (Fig. 2c). The blackish mat from the northern reef showed similar superficial features with a sponge, *T. hoshinota*, found in Okinawa (Ruetzler and Muzik 1993) and Green Island, Taiwan (Liao et al. 2007).

Spicule is an important skeletal structure in most sponges and is organized into radiating bundles near the ectosomal region (Bryan 1973; Ruetzler and Muzik 1993).

Fig. 2 **a** Coral black disease caused by *T. hoshinota* (1) and dead corals (2) caused by COTS (3) recorded in 2008; **b** coral black disease resulting from *T. hoshinota* invasion (1) in 2010; **c** surface of *T. hoshinota* showing osculum with radiating network (4); **d** spicules

of *T. hoshinota*; **e** spicules of *T. hoshinota* showing lobed head of tylostyle spicule (5); **f** spicule residues of *T. hoshinota* from long-dead coral with fragments of dead coral (all photos taken by Qi Shi)

T. hoshinota has distinctive spicules that can be used to identify this sponge (Ruetzler and Muzik 1993). Under an optical microscope, the blackish mat collected from

Yongxing Island included many long and slender spicules (Fig. 2d) with typical pin-shaped tylostyle (Fig. 2e). The mean spicule length was 323.1 μm (SD = 54.4 μm) as

averaged from 30 randomly selected specimens. The tylostyle spicule exhibited a lobed head with four knobs perpendicular to each other and to the shaft (Fig. 2e). *T. hoshinota* is distinguished by lobed tylostyle spicules (Bryan 1973; Ruetzler and Muzik 1993). Thus, we concluded that the blackish mat encrusting corals in the Yongxing Island belonged to *T. hoshinota*.

A new *T. hoshinota* covering is easy to discriminate in the field and in the laboratory by the superficial morphology and spicule structure. It is difficult, however, to judge whether long-dead corals were killed by *T. hoshinota* because there is no blackish mat, only algae or fragments on the coral surface. If coral had been covered by the sponge, the special spicule would remain on the surface of dead coral when both the coral and *T. hoshinota* died. Ten surface samples of long-dead coral were observed under the microscope, and residues of spicules showing the typical spicule shape of *T. hoshinota* were found in six samples (Fig. 2f). This indicates that some dead corals had been covered by *T. hoshinota* and suffered from black disease in the past.

Coverage of Live Coral and Black Disease

Preliminary underwater observation found that live coral was distributed mainly at the northern reef, was sparse at the eastern reef and scarce or absent at the western and southern reef. At the northern reef, the dominant coral was foliate *Montipora*, while other less numerous corals included *Acropora*, *Pavona*, *Favia*, *Favites*, *Goniastrea*, *Platygyra*, *Galaxea*, *Hydnophora*, *Pocillopora*, and *Porites*. Coral distribution was reduced significantly at greater depths along the reef slope. There was a relative high coverage at depths above 6 m, but progressively less coral below 6 m.

In 2008, the coral coverage along the four 100 m transects (T1–T4) at the northern reef was calculated: 15.0% (T1), 8.0% (T2), 73.1% (T3), and 0.8% (T4) (Fig. 3a). Most of the coral was distributed along the fore portions (0–50 m) of the two perpendicular transects (T1 and T2), and was relatively scarce along the rear portions (50–100 m) of these two transects. This reduction in density toward the rear of the T1 and T2 transects was consistent with the rich coral observed on transect T3 at the 4-m isobath and scarce coral on transect T4 at the 8-m isobath. It was apparent that coral mainly concentrated to the relatively shallow slope and decreased with depth. In 2010, coral coverage along these same transects declined significantly to 1.3% (T1), 0.6% (T2), 4.5% (T3), and 0.3% (T4) (Fig. 3a). The average coverage of coral was 24.2% in 2008 but only 1.7% in 2010 based on the data from these four transects, indicating that the coral community was already in a “degraded condition” (coverage lower than

Fig. 3 Average coverage of live coral (a) and black disease (b) along four transects at the northern reef of Yongxing Island in 2008 and 2010

30%, Mok 2008) at the northern reef of Yongxing Island during 2008 and 2010.

In 2008 and 2010 surveys, black disease caused by *T. hoshinota* was prevalent at the northern reef, but less common at the eastern reef and scarce at the western and southern reef, probably due to the sparse distribution of live corals at these sites. Higher coral coverage will attract *T. hoshinota* to cover and grow. *T. hoshinota* was found growing on different kinds of corals, but mainly on *Montipora*, perhaps because *Montipora* was the dominant coral at the northern reef. *T. hoshinota* was a non-specific invasive species and invaded all dominant species at the coral reef of Green Island, Taiwan (Chen et al. 2009). Studies also showed that *T. hoshinota* grew faster on live coral than on other substrates like dead coral or rock (Bryan 1973; Lin and Soong 2009).

In 2008, coverage of *T. hoshinota* was different along the four transects: 19.9% (T1), 4.4% (T2), 0.4% (T3), and 6.7% (T4) (Fig. 3b). In contrast to the coral coverage, the sponge was distributed mostly on the rear portions (50–100 m) and less prevalent on the fore portions (0–50 m) along transect T1 and T2. It was also scarce along transect T3 at the 4-m isobath, but more common along transect T4 at the 8-m isobath. It was apparent that the invasion of *T. hoshinota* and the outbreak of black disease happened first along the relatively deep slope in 2008. Concomitant with the

decrease in live coral, *T. hoshinota* coverage in 2010 had declined to 3.6% at T1, 2.0% at T2, and 0.7% at T4, but rose from 0.4 to 12.0% along transect T3 (Fig. 3b). Transect T1, T2, and T4 had low coral coverage, and transects T1 and T4 exhibited a higher coverage of sponge than coral in 2008, resulting in a reduction of black disease due to its fast growth rate and reduced growth space on the remaining coral. Transect T3 had the highest coral coverage in 2008, thus providing enough space for *T. hoshinota* growth and resulting in increased sponge coverage along with decreased coral. The average coverage of *T. hoshinota* was 7.8% at the northern reef in 2008 and declined to 4.6% by 2010.

DISCUSSION

Change of Coral Coverage over the Past Decades

Prior to 2002, there were few extensive surveys of coral coverage around Yongxing Island, and even the 2002 survey investigated only four $1 \times 1 \text{ m}^2$ quadrats at the northern reef (Huang et al. 2006). The mean coral cover at the northern reef was 93.5% (Huang et al. 2006), but this is very likely an overestimate because of a few surveyed quadrats. None-the-less, these surveys still reflected healthy coral status at early times and revealed a serious decline in coral coverage over the past decades combining with our survey (Fig. 4). Coral coverage was 90% at the northern reef in the 1980s (Wang 2001), and remained high at 93.5% in 2002 (Huang et al. 2006). Coral coverage declined by about 70% within the 6 years from 2002 to 2008 and continued to decline by around 20% from 2008 to 2010. In general, corals were in good condition (coverage higher than 50%, Mok 2008) at the northern reef until the beginning of the twenty-first century, but were degraded

rapidly in a short time after 2002. It is clear that some stresses introduced during this period resulted in severe coral mortality.

Luhuitou (LHT) Reef located at the south of Hainan Island (Fig. 1a) is a typical fringing reef close to Sanya city and harbor, and has been negatively impacted by human activities, including destructive over-fishing, excessive reef rock diggings, coral collection in the 1970s and 1980s, and by aquaculture and pollutant discharges since the 1990s (Zhang et al. 2006; Shi et al. 2007). Coral coverage has shown a continual decline with a nearly linear trend since the 1960s (Zhang et al. 2006; Zhao et al. 2010). For example, coral cover was about 85% in the 1960s, but declined to 60% by the 1980s, to 35% by the 1990s, and to 12.2% in 2006 where it has since stabilized (Fig. 4). This pattern of change in coral coverage at LHT Reef is quite different from that at the northern reef of Yongxing Island, where decline of coral coverage occurred rapidly in only 8 years.

Major Causes of Coral Mortality

Human Activities

Human activity is regarded as one of main reasons for the decline of coral cover (Wilkinson 2004), especially at fringe reefs like the LHT Reef. In Yongxing Island, two harbors were built at the southwest side in the 1970s and an airfield runway was built at the east side in the 1990s. Construction dredging on the reef flat and slope nearly destroyed the coral communities at the western, southern, and eastern reef. There was no engineering construction at the north side so corals at the northern reef were not influenced directly by construction. Controlled by monsoons, the prevailing winds are from the southwest in summer and from the northeast in winter in the Xisha Islands region, and the sea currents show a similar seasonal pattern (Nie et al. 1997). Owing to the NNW–SSE long axis of Yongxing Island, the southwestern current becomes weak around the island into the northern reef. Moreover, the outstretched airfield runway and a dyke connecting Yongxing Island and Shi Island at the northeast (Fig. 1b) are like barriers to block the southwestern current. Therefore, the northern reef formed a relatively shielded habitat that favors coral growth (Huang et al. 2006). As result of these barrier effects, the turbidity caused by the construction dredging in the southwest and east had little influence on the northern reef, and corals remained in rather good condition at the northern reef with high coverage.

In addition, fishing, coral and shell collecting, and sewage discharge from the island and ships were other human activities that negatively impacted the corals in Yongxing Island (Li et al. 2004). These activities have

Fig. 4 Variation of coral coverage at the northern reef of Yongxing Island since the 1980s (YX Island) (data of 1980, Wang 2001; data of 2002, Huang et al. 2006; data of 2008 and 2010, this article) and variation of coral coverage at LHT Reef (Zhang et al. 2006; Zhao et al. 2010)

continued in recent years, but have not increased due to limited space for population growth and the strict military control of the island. Recent studies found that the seawater around Yongxing Island was of higher quality in terms of heavy metals and nutrient contents than the highest level specified by the National Seawater Standards (Zhou et al. 2007; Wu et al. 2010), indicating no significant seawater pollution around island in recent years. It is difficult to evaluate quantitative loss of coral cover caused by the human activities due to lack of detailed surveys, but the data from the LHT Reef provided a reference. Human activities were mainly responsible for the destruction of the LHT Reef (Zhang et al. 2006; Shi et al. 2007), and coral coverage declined by about 12% between 2002 and 2010 (Fig. 3) (Zhao et al. 2010). The intensity of human activities was weaker in Yongxing Island during this period, so the loss of coral cover caused by human activities should not have exceeded 12% at the north reef of Yongxing Island from 2002 to 2010. Thus, we believe that human impact may have decreased coral cover to some extent, but could not have caused the massive coral mortality observed over this time.

Heat-Related Coral Bleaching

Coral bleaching events can eliminate more than 90% of corals on a reef (Glynn 1984; Wilkinson et al. 1999) and is regarded as an important global stress on corals (Wilkinson 2004). The year 1998 saw the largest coral bleaching and mortality event ever recorded, and it was estimated that 16% of the world's coral reefs were destroyed (Wilkinson 2004). The increasing frequency and spread of coral bleaching events over the past decades are correlated with elevated seawater temperatures, often related to large-scale El Niño events (Glynn 1984; Hoegh-Guldberg 1999; Wilkinson et al. 1999).

In our survey, fishermen from Yongxing Island stated that there was no massive bleached corals found on the reef around the island in the past decade, but this does not mean that bleaching has not had an impact because there have been no regular ecological surveys. A coral bleaching hotspot is a measure of the occurrence and magnitude of thermal stress potentially conducive to localize coral bleaching. A hotspot is a sea surface temperature (SST) anomaly based on the long-term mean SST of the hottest months, and a hotspot exceeding 1°C above the mean of the hottest months is sufficient to cause bleaching stress on corals (Glynn and D'Croz 1990; Goreau and Hayes 1994). The ocean monitoring station at Yongxing Island recorded a monthly mean SST of 29.9°C in the hottest month during 1961–2008 (Fig. 5). Taking the hotspot threshold of 1°C above the mean of the hottest months, the thermal threshold of coral bleaching is 30.9°C at the reef of Yongxing

Fig. 5 Variation of the hottest month SST from the Ocean Observation Station of Yongxing Island. The *dashed line* is the average of the hottest month SST (29.9°C) and *solid line* is the thermal threshold of coral bleaching (30.9°C)

Island. This threshold is higher than peak monthly mean SST recorded in the hottest month during 1960–2008 (Fig. 5) and higher than the 30.3°C average monthly maxima at 47 coral bleaching spots world-wide in 1998 (Lough 2000). In the past decade, only the year 2004 showed a peak summer SST (30.8°C) close to the bleaching threshold of 30.9°C at Yongxing Island (Fig. 5), implying that coral bleaching could have occurred in 2004. Figure 3 shows that coral coverage was still high at about 75% in 2005 and that the loss of coral cover was only about 15% between 2003 and 2005. Even if a coral bleaching episode did occur in 2004, the extent of the bleaching was small compared to the total loss of coral coverage over the past 8 years.

Bleached corals can quickly recover in the absence of continued thermal stress. The GCRMN global status reported that many coral reefs that were severely damaged in the most extensive coral bleaching event in 1998 have demonstrated remarkably rapid recovery since then, and approximately 40% of the lost reefs had recovered by 2004 and approximately three quarters by 2008 (Wilkinson 2004, 2008). In Yongxing Island, SSTs have declined rapidly by about 0.5–1.0°C since 2004, significantly lower than the coral bleaching thermal threshold since 2004 (Fig. 5). If there was coral bleaching in 2004, the bleached coral would have recovered. In fact, the coral coverage has declined continuously since then, implying that some other factors have disturbed coral recovery. Therefore, heat-related coral bleaching may have caused some loss of corals, but is not the main factor responsible for the massive coral mortality at the northern reef.

Crown-of-Thorns Starfish (COTS)

Coral-eating COTS (*Acanthaster planci*) can cause extensive damage to coral communities because the feeding rate of these starfish is greater than the growth, recruitment, and

survival of corals (Chesher 1969). Outbreaks of these starfish have been responsible for the widespread mortality and injury of corals on many reefs in the Indo-Pacific region over the past 40 years (Moran et al. 1988). Particularly in Australia, the COTS is one of the dominant causes of coral mortality responsible for major declines in coral cover over large areas of the Great Barrier Reef (GBR). Swain Reef in the south GBR, for example, has had persistent outbreaks of COTS, resulting in a reduction in average coral cover from 30 to 40% in 1996 down to 10–20% in 2004 (Wilkinson 2004).

COTS were not found around Yongxing Island in 2002 or in previous surveys, and the first local report of COTS was in the Ganquan Island about 90 km southwest of Yongxing Island in 2007 (Li 2007). In 2008, our survey observed COTS at the northern reef of Yongxing Island (Fig. 2a), and some individual corals swallowed by COTS became white and were regarded as another kind of coral bleaching (Fig. 2a). The survey showed that coverage of bleached coral was only 0.1, 0.3, and 0.3% along transects T1, T2, and T3. In 2010, COTS were not found and bleached coral was scarce along all four transects of the northern reef. These observations indicate that COTS did not contribute to the massive coral mortality in Yongxing Island in recent years.

Black Disease (*T. hoshinota*)

Black disease can kill coral rapidly and has been observed in many coral reefs around the west Pacific (Bryan 1973; Ruetzler and Muzik 1993; Liao et al. 2007). In our surveys, both live and dead corals were covered by blackish mats at the northern reef (Fig. 2a, b). This blackish mat was characterized by the typical morphology and spicule structure of *T. hoshinota* (Fig. 2c–e), confirming the existence of the black disease in Yongxing Island. In fact, blackish mat covering corals was first reported at the northern reef in 2002 (Li et al. 2004), but was thought to result from a bacterial infection as little was known about *T. hoshinota* and black disease at that time. Spicule residues of *T. hoshinota* were found on the surfaces of long-dead corals (Fig. 2f), suggesting that corals had been invaded by *T. hoshinota* in the past. A black disease that is well colonized can last for over a decade, occupying the substrates and preventing the recruitment of juvenile corals (Bryan 1973; Plucer-Rosario 1987). It is thus possible that black disease first occurred around 2002 and has lasted for at least 8 years in Yongxing Island.

It is difficult to estimate the total coral losses caused by black disease using only this limited survey and without detailed growth and death data for *T. hoshinota*. Field experiments found that *T. hoshinota* grew faster on live coral than on non-coral substrates (Bryan 1973; Lin and

Soong 2009), so plentiful coral allowed rapid growth of *T. hoshinota* at the northern reef of Yongxing Island. In Green Island, Taiwan, *T. hoshinota* was first found in 2006, and the average loss of coral coverage was 12% within the first year (Liao et al. 2007). It is reasonable to conclude that the large decline in coral coverage was due to the fast-growing and long-lasting sponge *T. hoshinota*. Outbreaks of black disease were the probable major killer that caused massive coral mortality and rapid degradation of the coral community at the northern reef of Yongxing Island over the past 8 years.

It is not clear what caused this outbreak of black disease. Possible environmental factors contributing to such outbreaks including nutrient availability, host specificity, coral coverage, and oceanic currents, and these factors are now being studied (Mok 2008). *T. hoshinota* was found at high levels in polluted and stressed areas caused by coastal overdevelopment at Guam (Plucer-Rosario 1987; Ruetzler and Muzik 1993). At Green Island, Taiwan, *T. hoshinota* was found mainly near shore, closed to human activity and refuse landfills (Chen et al. 2009). However, field investigations have not yet provided evidence to support enhanced *T. hoshinota* growth from sewage discharge around coral reefs (Chen 2009). In Yongxing Island, seawater has remained rather clean around the reef (Zhou et al. 2007; Wu et al. 2010), so it is unlikely that polluted seawater around the island enhanced *T. hoshinota* growth.

The coral reefs where *T. hoshinota* outbreaks have occurred, including the Philippines, Green Island of Taiwan, and the Ryukyu Archipelago (Ruetzler and Muzik 1993; Liao et al. 2007), are located closed to the main axis of the Kuroshio Current in the western Pacific. The Kuroshio Current could play a major role in transporting *T. hoshinota*. A tributary of the Kuroshio Current enters the South China Sea through the Straits of Luzon and joins the southwesterly current in an anticlockwise surface circulation that forms in the South China Sea during winter (Morton and Blackmore 2001). Yongxing Island is located along the southwesterly flow, suggesting that *T. hoshinota* might have been transported by a tributary of the Kuroshio Current from coral reefs in the western Pacific.

CONCLUSIONS

Based on our surveys in 2008 and 2010 and data from previous surveys at the northern reef of Yongxing Island, we conclude that (1) corals were in good condition until the beginning of the twenty-first century but that severe coral mortality has occurred over the past 8 years, (2) human activities and heat-related coral bleaching could have caused some loss of the corals but are not the main cause of this massive coral mortality, and (3) the blackish mat

covering corals at the northern reef was confirmed to be a sponge, *T. hoshinota*, that has invaded the reef before. Thus, outbreaks of black disease were most likely responsible for the massive coral mortality at the northern reef of Yongxing Island over the past 8 years.

Acknowledgments This study was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences (XDA05080300), Important Direction Project of Knowledge Innovation Program of the Chinese Academy of Sciences (KZCX2-YW-138), National Science Foundation of China (40830852 and 41025007), Chinese Ministry of Science and Technology projects (2007CB8015905 and 2006BAB19B03). We thank the anonymous reviewers for their helpful comments on this study.

REFERENCES

- Bryan, P.G. 1973. Growth rate, toxicity and distribution of the encrusting sponge *Terpios* sp. (Hadromerida: suberitidae) in Guam Mariana Islands. *Micronesica* 9: 237–242.
- Chen, C.L.A. 2009. How much we know about coral Black Disease? *Academia Sinica Weekly* 1219 (in Chinese).
- Chen, T.R., K.F. Yu, Q. Shi, S. Li, R. Wang, and M.X. Zhao. 2007. Distribution and status of scleractinian coral communities in the Daya Bay, Guangdong. *Tropical Geography* 27(6): 493–498. (in Chinese, English summary).
- Chen, S.L., C.Y. Kuo, and C.L.A. Chen. 2009. Spatial distribution and temporal variation of the cyanobacteriosponge, *Terpios hoshinota*, and benthos composition on the coral reefs of Green Island. *Journal of National Park* 19: 33–45. (in Chinese, English summary).
- Chesher, R.H. 1969. *Acanthaster planci*: impact on Pacific coral reefs. Final report to US Department of the Interior. Westinghouse Electric Corporation Research laboratories No. 69-951-Ocean-Ra, Pittsburgh.
- English, S., C. Wilkinson, and V. Baker. 1997. *Survey manual for tropical marine resources*, 2nd ed. Townsville: Australian Institute of Marine Science.
- Glynn, P.W. 1984. Widespread coral mortality and the 1982/83 El Niño warming event. *Environmental Conservation* 11: 133–146.
- Glynn, P.W., and L. D'Croz. 1990. Experimental evidence for high temperature stress as the cause of El Niño coincident coral mortality. *Coral Reefs* 8: 181–191.
- Goreau, T.J., and R.L. Hayes. 1994. Coral bleaching and ocean 'hot spots'. *Ambio* 23: 176–180.
- Huang, H., J.S. Lian, X.P. Huang, L.M. Huang, R.L. Zou, and D.R. Wang. 2006. Coral cover as a proxy of disturbance: a case study of the biodiversity of the hermatypic corals in Yongxing Island, Xisha Islands in the South China Sea. *Chinese Science Bulletin* 51(Suppl. II): 129–135.
- Huang, H., B.R. Ma, J.S. Lian, J.H. Yang, Z.J. Dong, Q. Fu, and W. Liang. 2009. Status and conservation strategies of the coral reef in Weizhou Island, Guangxi. *Tropical Geography* 29: 307–318. (in Chinese, English summary).
- Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the world's coral reefs. *Marine & Freshwater Research* 50: 839–866.
- Li, Y.H., X.P. Huang, W.Z. Yue, Y.T. Lin, R.L. Zou, and H. Huang. 2004. Ecological study on coral reef and intertidal benthos around Yongxing Island, South China Sea. *Oceanologia et Limnologia Sinica* 35: 176–182. (in Chinese, English summary).
- Li, Z.L. 2007. Attack of crown-of-thorns starfish in coral reefs of Xisha Islands. *Ocean World* 6: 4. (in Chinese).
- Liao, M.H., S.L. Tang, C.M. Hsu, K.C. Wen, H. Wu, W.M. Chen, J.T. Wang, P.J. Meng, et al. 2007. The "Black Disease" of reef-building corals at Green Island, Taiwan—outbreak of a Cyanobacteriosponge, *Terpios hoshinota* (Suberitidae; Hadromerida). *Zoological Studies* 46: 520.
- Lin, W.J., and K.Y. Soong. 2009. Growth and prevention experiments of *Terpios Hoshinota* surrounding Green Island. *Journal of National Park* 19: 46–57. (in Chinese, English summary).
- Lough, J.M. 2000. 1997–1998: unprecedented thermal stress to coral reefs. *Geophysical Research Letters* 27: 3901–3904.
- Mok, H.K. 2008. Ecological environment in the area along the Kuroshio in Taiwan. *Kuroshio Science* 2-1: 21–27.
- Moran, P.J., R.H. Bradbury, and R.E. Reichelt. 1988. Distribution of recent outbreaks of the crown-of-thorns starfish (*Acanthaster planci*) along the Great Barrier Reef: 1985–1986. *Coral Reefs* 7: 125–137.
- Morton, B., and G. Blackmore. 2001. South China Sea. *Marine Pollution Bulletin* 12: 1236–1263.
- Nie, B.F., T.G. Chen, M.T. Liang, J.L. Zhong, and K.F. Yu. 1997. *The relationship between reef coral and environmental changes of Nansha Islands and adjacent regions*. Beijing: Science Press. (in Chinese).
- Plucer-Rosario, G. 1987. The effect of substratum on the growth of *Terpio*, an encrusting sponge which kills corals. *Coral Reef* 5: 197–200.
- Ruetzler, K., and K. Muzik. 1993. *Terpios hoshinota*, a new cyanobacteriosponge threatening Pacific reefs. *Scientia Marina* 57: 395–403.
- Shi, Q., M.X. Zhao, Q.M. Zhang, H.K. Wang, and L.R. Wang. 2007. Growth variations of scleractinian corals at Luhuitou, Sanya, Hainan Island, and the impacts from human activities. *Acta Ecologica Sinica* 27: 3316–3323. (in Chinese, English Summary).
- Shi, Q., M.X. Zhao, L.Y. Huang, H.Q. Yan, and H.L. Zhang. 2010. Human activities and impacts on coral reef at the Luhuitou fringing reef, Sanya. *Tropical Geography* 30: 486–490. (in Chinese, English summary).
- Soong, K.Y., S.L. Yang, and C.L.A. Chen. 2009. A novel dispersal mechanism of a coral-threatening sponge, *Terpios hoshinota* (Suberitidae, Porifera). *Zoological Studies* 48: 596.
- Teruya, T., S. Nakagawa, T. Koyama, H.M. Kita, and D. Uemura. 2004. Nakiterpiosin and nakiterpiosinone, novel cytotoxic C-nor-D-homosteroids from the Okinawan sponge *Terpios hoshinota*. *Tetrahedron* 60: 6989–6993.
- Wang, G.Z. 2001. *Sedimentology of coral reefs in the South China Sea*. Beijing: Oceanic Press. (in Chinese).
- Wang, L.R., H.T. Zhao, and C.J. Song. 2006. Impact of human activities on coral reef ecosystem at DenglongJiao, Xuwen, China. *Ocean Environmental Protection* 1: 81–85. (in Chinese).
- Wilkinson, C., O. Linden, H. Cesar, G. Hodgson, J. Rubens, and A.E. Strong. 1999. Ecological and socioeconomic impacts of 1998 coral mortality in the Indian Ocean: an ENSO impact and a warming of future change? *Ambio* 28: 188–196.
- Wilkinson, C. 2004. *Status of coral reefs of the world: 2004*. Townsville: Global Coral Reef Monitoring Network and Australian Institute of Marine Science.
- Wilkinson, C. 2008. *Status of coral reefs of the world: 2008*. Townsville: Global Coral Reef Monitoring Network and Reef and Rainforest Research Center.
- Wu, Z.J., D.R. Wang, Y.C. Li, R. Wu, and G.X. Zhang. 2010. The ecological status of phytoplankton in Monitored Xisha Areas. *Chinese Journal of Tropical Crops* 31(6): 1020–1025. (in Chinese, English summary).
- Yu, K.F., C.J. Song, and H.T. Zhao. 1995. The Characters of geomorphology and modern sediments of Yongxing Island, Xisha Islands. *Tropic Oceanology* 14: 24–31. (in Chinese, English summary).

- Zhang, Q.M., Q. Shi, G. Chen, T.C.W. Fong, D.C.C. Wong, H. Huang, H.K. Wang, and M.X. Zhao. 2006. Status monitoring and health assessment of Luhuitou fringing reef of Sanya, Hainan, China. *Chinese Science Bulletin* 51(suppl. II):81–88.
- Zhao, H.T., Q.M. Zhang, C.J. Song, Z. Qiu, X.G. Lin, and J.Y. Yuan. 1999. *Geomorphology and environment of the South China Coasts and South China Sea Islands*. Beijing: Science Press (in Chinese).
- Zhao, M.X., K.F. Yu, Q.M. Zhang, and Q. Shi. 2010. Long-term dynamics of coral cover in Luhuitou Fringing Reef, Sanya. *Oceanologia et Limnologia Sinica* 6: 440–447.
- Zhou, J., D. Yang, Z.C. Peng, S.H. Song, W.J. Zhou, J.F. He, Y. Liu, and G.J. Liu. 2007. The concentrations of dissolved heavy metals in Xisha waters and their influential factors. *Journal of University of Science and Technology of China* 37(8): 1036–1042. (in Chinese, English summary).
- Zou, R.L. 1978. Study on coral in Xisha Island. In *Reports of oceanic biology investigation in the waters of Xisha Islands and Zhongsha Islands, China*. ed. South China Sea Institute of Oceanology, the Chinese Academy of Sciences, 328 pp. Beijing: Science Press (in Chinese).

AUTHOR BIOGRAPHIES

Qi Shi (✉) is a research associate professor at South China Sea Institute of Oceanology, Chinese Academy of Sciences. His research interests include geology, geomorphology and ecology of coral reefs. *Address:* CAS Key Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, No. 164,

Xingangxi Road, Haizhu District, Guangzhou 510301, People's Republic of China.
e-mail: shiqi@scsio.ac.cn

Guo Hui Liu is a doctoral candidate for marine environmental science at South China Sea Institute of oceanology, Chinese Academy of Sciences.

Address: CAS Key Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, No. 164, Xingangxi Road, Haizhu District, Guangzhou 510301, People's Republic of China.
e-mail: sdlgbio@126.com

Hong Qiang Yan is a research assistant professor at South China Sea Institute of oceanology, Chinese Academy of Sciences. His research interests include carbon cycle and ecology of coral reefs.

Address: CAS Key Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, No. 164, Xingangxi Road, Haizhu District, Guangzhou 510301, People's Republic of China.
e-mail: yhq9807@163.com

Hui Ling Zhang is a doctoral candidate for marine geology at South China Sea Institute of oceanology, Chinese Academy of Sciences.

Address: CAS Key Laboratory of Marginal Sea Geology, South China Sea Institute of Oceanology, Chinese Academy of Sciences, No. 164, Xingangxi Road, Haizhu District, Guangzhou 510301, People's Republic of China.
e-mail: zhanghuiling0375@126.com