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Long-term Decline of a Fringing Coral Reef in the Northern South China Sea

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ABSTRACT

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The Luhuitou coral reef is a fringing reef at Hainan Island in the northern South China Sea. Since the 1960s, the reef has experienced several significant ecological changes. During that interval, the mean coral cover decreased dramatically from 80–90% in 1962–65 and to just 12% in 2009. In the 1960s, the coral community structure was divided into three well-defined zones: a *Goniastrea* zone and *Montipora* zone (both on the reef flat) and an *Acropora* zone (on the reef slope). However, by 2009, *Porites lutea* became the dominant species on the reef flat, whereas the predominance of *Acropora* on the reef slope weakened significantly. There are few long-established *Porites lutea* colonies present, with approximately 80% being younger than 30 years old. This demographic pattern differs significantly from healthy coral reefs, which are typically dominated by large, well-established (and mature) coral colonies. The long-term decline of the Luhuitou coral reef has most likely been driven as a result of anthropogenic activities, such as overfishing, destructive fishing, reef rock digging, and mariculture and tourism activities. Our study reinforces previous works and highlights the vulnerability of coral reefs to anthropogenic impacts.

ADDITIONAL INDEX WORDS: *Coral reef, decline, human activities, fringing reef, South China Sea.*

INTRODUCTION

Coral reefs are renowned for their spectacular diversity and are an anthropogenically important ecosystem. They support fisheries, tourism, and coastal protection and are highly valued for their aesthetic and cultural significance (Connell, 1978; Done *et al.,* 1996; Moberg and Folke, 1999; Reaka-Kudla, 1997; Smith, 1978). However, these critical ecosystems have experienced severe declines worldwide during the historic period (Hoegh-Guldberg and Bruno, 2010; Lough, 2008). For example, the Great Barrier Reef (Australia) has seen the living coral cover decline from ~50% to only ~20% during 1960–2003 (Bellwood *et al.,* 2004), and the Caribbean coral cover decreased from ~50% to just ~10% between 1977 and 2001 (Gardener *et al.,* 2003).

Our understanding of long-term trends in the "health" of other reefs worldwide is limited by the paucity of long-term ecological monitoring. That is particularly true of coral reefs within the South China Sea, the largest marginal sea of the western Pacific Ocean. Recently, Chen *et al.* (2009) reported a 25-year record showing a significant decrease in living coral cover in Daya Bay (northern South China Sea). Between 1983–84 and 2008, coral cover declined from 76.6% to only 15.3% (Chen *et al.,* 2009). Thus, it is clear that at least some coral reefs within the South China Sea have experienced dramatic changes during the historic period relative to other areas in the western Pacific Ocean (Brown, Clarke, and Warwick, 2002; Edinger *et al.,* 1998). Although sporadic ecological investigations have been carried out at the Luhuitou fringing reef (northern South China Sea) since the 1960s, few studies have attempted to quantify long-term trends in coral ecosystem health in the region. Thus, the aim of this study was to extend the work of Chen *et al.* (2009), both spatially and temporally, to provide a long-term record of ecological monitoring for the region. Our new data sets, based on our recent (2005, 2006, and 2009) surveys coupled with previous observations, now provide one of the longest records of ecological monitoring for any reef within the South China Sea and, as such, allow for more extensive examination of long-term variations in local coral cover.

MATERIALS AND METHODS

Study Site and Local Environment

The Luhuitou fringing reef (Figure 1) is ~3 km long and ~250–500 m wide and is situated adjacent to the Sanya urban area along the southern coast of the Hainan Island. Yu *et al.* (2010) reported the climatic statistics for the region, which, summarised briefly, include the following: the mean annual air temperature is ~25.8 °C (ranging from 24.7 to 27.0 °C); mean annual precipitation is ~1337 mm, with ~90% of rain falling during the wet season (from May to

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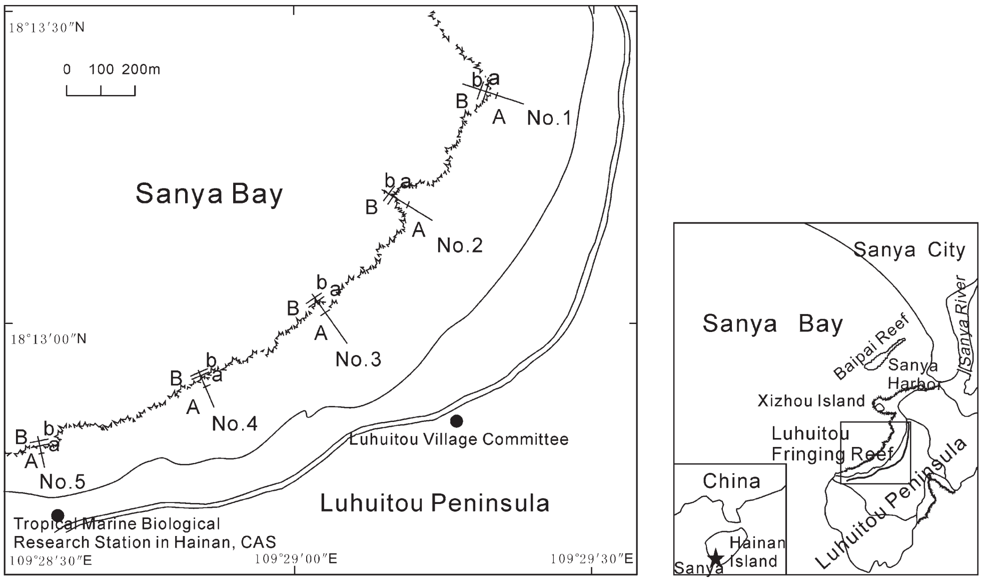

Figure 1. Luhuitou fringing reef location and the location of the permanent transects numbers 1–5. (A) Reef flat; (B) Reef slope. (a) 2-m isobath–transect; (b) 4-m isobath–transect.

October); mean total sunshine duration is ~2478 h/y (ranging from 1751 to 2873 h/y); mean wind speed is 2.4 m/s (ranging from 1.3 to 3.5 m/s); mean monthly seasonal sea surface temperature (SST) varies from a maximum of 29.8 °C in June and a minimum of 22.8 °C in January (yearly mean SST is 27 °C); and the maximum sea surface salinity (SSS) reaches a high of approximately 33.8‰ in April and a low of 32.1‰ in October, with the mean annual SSS being 33.1‰. With such climatic attributes, it is an ideal area for coral reef development. Since 1990, the reef has been zoned within the Sanya National Coral Reef Natural Reserve.

Historical records indicate that the reef had high biodiversity in the past. Zou, Song, and Ma (1975) reported 12 families, 24 genera, and 81 coral species; Xie, Lin, and Li (1981) collected 4 classes, 53 families, and 178 species of molluscs; Zheng (1986) recorded 569 species of fish around Hainan Island,; of which, 296 species appeared on the Luhuitou reef; and Jiang, Li, and Liang (1990) identified 63 algae species in the Luhuitou fringing reef area in 1982–83, with 167 species reported from the broader Hainan Island region.

Previous qualitative observations on the coral community of the Luhuitou reef were made mostly between the 1960s and 1980s (Cai and Li, 1964; Liu, 1998; Naymov, Yan, and Huang, 1960; Pan *et al.,* 1983; Wang, 2001; Xie, Lin, and Li, 1981; Zou, Ma, and Song, 1966; Zou, Song, and Ma, 1975). Quantitative surveys are available mostly for the period between 1996 and present (Yu and Zou, 1996; 1999; Zhang, 2001, 2004; Zhang *et al.,* 2006; Zhao *et al.,* 2008). These data provide an important opportunity to analyze the long-term ecological history of the Luhuitou reef. Significantly, unlike reefs within the centre and south of the South China Sea, Luhuitou reef occurs proximally to a large human population (*i.e.,* Sanya City). Therefore, we are presented with an opportunity to examine potential long-term anthropogenic impact(s) on a coral reef in a single, large, urbanised, and industrialised region.

Field Surveys

Our field surveys were carried out at the Luhuitou fringing reef in 2005, 2006, and 2009. Five permanent, perpendicular coastline transects (Figure 1), labelled numbers 1 to 5 from the north to the south, were set up in 1998 by our research group (Zhang, 2001). These transects, each 80–240 m long (Table 1), covered the area from the upper to lower limits of the coral growth. Two isobath transects were positioned across each permanent transect on the reef slope zone at water depths of 2 m and 4 m (relative to the mean sea level in the Sanya waters). Each isobath transect was 50 m long, with the midpoint cantered at 25 m (Figure 1). A Panasonic NV-GS258 camera (inside an underwater housing) was used to record continuous videos across the five perpendicular transects and the 10 isobaths transects. The 84, 1-m^2 quadrats were established along each perpendicular transect and were photographed using an Olympus C5050 Zoom digital, waterproof camera. For each quadrat, four photographs were taken, with each photograph covering one-quarter of the quadrat area. Video transects and photo-quadrat methods (English, Wilkinson, and Baker, 1997; Foster, Hawkins, and Hardin, 1991) were used to compare different sampling techniques for measuring living coral cover. In addition to examining the quadrats, we also surveyed the surrounding area to identify any coral species that may not have been recorded along the transects. Coral species that were difficult to recognise in the field were sampled and taxonomically identified in the laboratory. We measured the maximum length, (L_{max}), maximum width (W_{max}), and maximum height (H_{max}) of all *Porites*

Table 1. *Detailed information on quadrats and perpendicular transects used in this study.*

	Reef Flat Zone		Reef Slope Zone		Total	
Transect No.	No. of Quadrats	Length of Transects (m)	No. of Quadrats	Length of Transects (m)	Number of Quadrats	Length of Transects (m)
1	7	110	13	130	20	240
2	9	130	11	110	20	240
3	13	120	7	70	20	190
4	8	70	7	70	15	140
5	4	30	5	50	9	80
Total					84	890

lutea corals (n = 1857 colonies) along the transects to examine their relative age distribution.

Data Collection and Treatment

Identification of Coral Species

Species identifications were based on photographs of the transects and on samples following the taxonomic work of Zou, Song, and Ma (1975); Zou (2001); Wallace (1999); and Veron (2000).

Coral Community Analysis

Mean coral cover is commonly used in the assessment of coral reef health (*e.g.,* Jokiel and Rodgers, 2007). The living coral cover of the Luhuitou fringing reef was calculated using the video line-intercept transect method (V-LIT) (English, Wilkinson, and Baker, 1997). The photo-quadrat method (Foster, Hawkins, and Hardin, 1991) was used for quadrat interpretation. We compiled the full image of each 1-m² quadrat by first, joining the four individual photographs, and then, dividing the full image into 10,000 grids (thus, each grid represented 1 cm²) with Adobe Photoshop software. The degree of living coral cover was then calculated from the proportion of live coral colonies that occupied each respective quadrat.

The most dominant coral species were categorized according to their importance values (IVs), which is the sum of their relative abundance (RA), relative coverage (RC), and relative frequency (RF).

$$RA_i = \frac{n_i}{\sum n_i}$$

where n_i is the number of colonies of the coral species i;

$$RC_i = \frac{C_i}{\sum C_i}$$

where C_i is the coverage of the coral species i; and

$$RF_i = \frac{f_i}{\sum f_i}$$ where f_i is the frequency of the coral species i.

The value of IV may range from 0 to 3.00.

Table 2. *Summary of the previous ecological studies on Luhuitou fringing reef.*

Year	Investigators	Study focus	Method	Site	Sources
1958	Sino–Soviet scientists	Coral richness and spatial pattern of coral communities	Field observation and specimen collecting	General reef	Naymov, Yan, and Huang, 1960
1962–65	Zou, Ma, and Song	Coral richness, dominant species and spatial pattern of coral communities	Field observation and specimen collecting	General reef	Zou, Ma, and Song, 1966; Zou, Song, and Ma, 1975
1978	Wang	Coral cover	Transect survey	Fixed transect on reef slope	Wang, 2001
1981	Xie, Lin, and Li	Spatial pattern of coral communities	Field observation	Reef flat	Xie, Lin, and Li, 1981
1983	Scientific Investigation Group of Modern Carbonate Sediment group	Coral cover	Field observation	General reef	Pan *et al.*, 1983
1990	Wang	Coral cover	Transect survey	Fixed transect on reef slope	Wang, 2001
1990–92	Sino–German scientists	Coral diversity	Field observation	General reef	Liu, 1998
1993–94	Yu and Zou	Coral richness, diversity indices	Quadrat survey	Four perpendicular transects	Yu and Zou, 1996; 1999
1998–99	Zhang	Coral cover, coral richness	Quadrat survey	Five perpendicular transects	Zhang,2001
2002	Zhang	Coral cover, coral richness	Liner intercept transect and video liner intercept transect	Five perpendicular transects	Zhang *et al.*, 2006

Porites lutea Age Distribution

The ages of *Porites lutea* corals were calculated using the following formula: $AGE = (L_{max} + W_{max} + H_{max})/3LGR$, where LGR is the mean linear growth rate of *Porites lutea* at the Luhuitou fringing reef (1.1 cm/y was used as the mean LGR here, following previous studies: Nie *et al.,* 1996; Shi, Zhang, and Sun, 2002; Yu and Zou, 1999).

Data from Previous Surveys

A summary of previous ecological studies at the Luhuitou fringing reef is given in Table 2. Such studies covered a range of ecological variables, including coral composition, diversity, living coral cover, and spatial pattern. The results from those previous studies were compared with our newly acquired data sets (based on surveys in 2005, 2006, and 2009), allowing us to construct a long-term ecological history for the Luhuitou fringing reef.

RESULTS

Status of Coral Communities: 2005–09

A total of 13 families, 24 genera, and 69 coral species were identified at the Luhuitou fringing reef during our ecological surveys in 2005, 2006, and 2009 (Table 3). The most dominant coral species, genera, and families were characterized on the basis of their IVs. *Porites lutea* (36.6% IV) was the most dominant coral species, much higher than that of *Acropora hyacinthus* (8.9%), *Porites pukoensis* (6.5%), *Acropora pulchra* (5.6%), and *Montipora digitata* (5.0%). At the genus level, *Porites* (43.8%) was most dominant, followed by *Acropora* (22.9%) (Table 4). Poritidae (48.1%), Acroporidae (33.5%), and Faviidae (10.4%) were the three most dominant families. It should be noted that 25 coral species had IVs less than 1%, including 15 species with values less than 0.5%. This suggests an uneven pattern of coral diversity at the Luhuitou fringing reef.

The average total coral cover across the reef flat varied from (mean ± SE, unless otherwise noted) 3.5% ± 0.7% (V-LIT method) to 5.0% ± 1.4% (photo-quadrat method) (Table 5). Small colonies (<5 y) of *Porites lutea* were the most common coral on the reef flat, occupying, on average, more than 50% of the IVs of all corals in each quadrat (Table 4). This pattern is suggestive of a sparse coral community on the reef flat zone (Figure 2).

The living coral cover on the reef slope appears to have decreased between 2005 (14.8 ± 1.3%), 2006 (12.2 ± 0.8%), and 2009 (12.0 ± 1.8%). During that interval, *Acropora* was the common coral genus, with *A. hyacinthus* and *A. pulchra* being the most common species (Figure 2). *Acropora* (28.3%) was the most important coral genus on the reef slope, followed by *Porites* (26.7%). The IV of *A. pulchra* ranged from 57.1% to 62.0% of all *Acropora* corals in the numbers 3 and 4 transects, respectively, whereas *A. hyacinthus* reached 72.1% of all *Acropora* corals in the number 1 transect.

Temporal Variations of Luhuitou Fringing Reef Coral Species Richness

The earliest introductory ecological investigation on the Luhuitou coral reef took place in 1958, with 17 coral species being reported (Naymov, Yan, and Huang, 1960). More intensive studies took place during 1962–65, when Zou, Song, and Ma (1975) reported a total of 81 coral species on the reef (Table 3). Between 1993 and 1994, Yu and Zou (1996) recorded only 10 families, 21 genera, and 58 species of corals (Table 3), which suggested a loss of 37% of species since the 1960s (Yu and Zou, 1999). Both Zhang *et al.* (2006) and the Sanya National Coral Reef Nature Reserve (2004) reported various coral species on the reef between 1998 and 2002, but their investigations were not focused on an assessment of the reef's coral cover or diversity and, thus, are not representative of the state of the reef's health at that time. Therefore, on the basis of previous studies, we compared our new data from 2005–09 only with that from the studies of 1962–65 and 1993–94 to analyse potential temporal changes of coral species richness. Interestingly, our results show that 29 species identified at Luhuitou fringing reef in the 1960s were not sampled during our most recent investigations. Similarly, 17 species recorded in the 1990s were not observed at Luhuitou reef in 2005, 2006, or 2009. It is uncertain whether those coral species suffered local extinction between those sampling intervals or were absent during recent surveying (Figure 3). Because there have been only minor taxonomic revisions for local coral species during the sampling period (*e.g.,* Veron, 2000 Wallace, 1999; Zou, 2001; Zou, Song, and Ma, 1975), it is unlikely that changing taxonomies have had a significant contribution to the perception and identification of species since the 1950s.

Living Coral Cover

Living coral cover on the reef slope has declined significantly at the Luhuitou fringing reef during the past 50 years (Figure 4). Zhang *et al.* (2006) examined the earliest original reports on the state of the coral reef, as well as interviewed several of the original chief investigators (including professors Zhu Yuanzhi and Zou Renlin), and were able to estimate coral cover to be around 80–90% in the 1960s. On the basis of transect surveys, Pan *et al.* (1983) and Wang (2001) estimated coral cover at *ca.* 60% in 1978–83, decreasing to just 30–40% in 1990 (Wang, 2001). Using quadrat surveys, Zhang (2001) reported a mean coral cover of 41.5% in 1998. Later observations of the five transects in 2002 suggested that the mean living coral cover was about 23.4% (ranging from 5–47% depending on transect) (Zhang, 2004). The Bulletin of Marine Environment Quality of Hainan (2004, 2005, 2006, 2007, 2008) reported coral cover between 12.8% and 23.38% in 2004–08. Our most recent surveys indicate that the mean coral cover was 14.8%, 12.2%, and 12.0% in 2005, 2006, and 2009, respectively. Although our calculations of coral cover were based on different methods than those used in the previous studies, they give roughly similar results (Table 5), suggesting that the results on coral cover from different methods are generally comparable, although there might be some minor difference produced by different investigators. Thus, it is evident that a significant overall decline in living coral cover has occurred at the study site.

Spatial Pattern of Coral Community

There has also been a significant change in the spatial pattern of the coral community at the Luhuitou fringing reef

Table 3. *Temporal records of coral species present on Luhuitou fringing reef.*

Species	1962–65	1993–94	2005–09
Acroporidae			
Acropora			
A. armata (*A. cytherea*)	+	+	+
A. affinis (*A. florida*)	+		+
A. brueggemanni	+	+	+
A. conferta (*A. hyacinthus*)	+	+	+
A. hyacinthus	+		
A. corymbosa	+	+	+
A. decipiens (*A. robusta*)	+	+	+
A. pacifica (*A. robusta*)	+		
A. delicatula (*A. selago*)	+	+	
A. dissimilis (*A. valida*)	+	+	+
A. valida	+	+	
A. formosa	+	+	+
A. haimei	+	+	
A. humilis		+	+
A. millepora			+
A. prostrata (*A. millepora*)	+	+	
A. nasuta	+	+	
A. nasuta crassilabia (*A. nasuta*)	+		
A. pulchra	+	+	+
A. pulchra stricta (*A. pulchra*)	+		
A. tizardi (*A. cerealis*)	+		
A. solitaryensis			+
A. spicifera			+
A. tennis			+
A. insignis			+
Astreopora			
A. myriophthalma	+	+	+
Montipora			
M. aenigmatica		+	
M. circumvallata			+
M. crista-galli (*M. circumvallata*)	+	+	
M. efflorescens			+
M. trabeculata (*M. efflorescens*)	+	+	
M. foliosa	+		
M. fruticosa (M. digitata)	+		+
M. ramosa (*M. digitata*)	+	+	
M. gaimardi	+		
M. hispida	+	+	
M. sinensis (M. monasteriata)	+	+	
M. solanderi	+		
M. striata (M. stellata)	+		
M. truncata	+	+	
M. turgescens			+
M. vietnamensis			+
M. hoffmeisteri			+
Montipora sp	+		
Agariciidae			
Pavona			
P. decussata	+	+	+
P. lata (*P. decussata*)	+		
P. frondifera	+	+	+
P. minikoiensis (*Leptoseris mycetoseroides*)		+	
P. varians	+	+	
P. cactus			+
Pachyseris			
P. rugosa	+		+
P. speciosa			+
Dendrophylliidae			
Turbinaria			
T. agaricia	+		
T. crater	+		
T. peltata		+	+
Faviidae			
Cyphastrea			
C. serailia	+	+	+
Diploastrea			
D. heliopora		+	+
Favites			
F. abdita	+	+	+
F. pentagona	+		+
F. flexuosa			+
Favia			
F. matthaii	+	+	+
F. palauensis	+	+	
F. speciosa	+	+	+
F. veroni			+
F. rotumana			+
Goniastrea			
G. aspera	+	+	+
G. pectinata	+	+	+
G. retiformis		+	+
G. yamanarii	+	+	
Leptastrea			
L. purpurea		+	
Platygyra			
P. crosslandi	+	+	+
P. daedalea			+
P. rustica (*P. daedalea*)	+	+	
P. gracilis (*Leptoria phrygia*)	+	+	
P. ryukyuensis (*P. sinensis*)	+	+	+
P. sinensis			
P. carnosus			+
Echinopora			
E. lamellosa			+
Merulinidae			
Hydnophora			
H. contignatio	+	+	
H. exesa	+	+	+
H. microconos	+	+	+
Merulina			
M. ampliata			+
Scapophyllia			
S. cylindrica	+		
Fungiidae			
Fungia			
F. echinata	+	+	
F. fungites	+		
F. paumotensis	+		
Podabacia			
P. crustacea	+		
Sandalolitha			
S. robusta			+
Mussidae			
Acanthastrea			
A .echinata	+		
Lobophyllia			
L. costata (*L. hemprichii*)	+	+	
L. hemprichii			
L. corymbosa	+		
Symphyllia			
S. agaricia	+	+	+
S. radians			+

Table 3. *Continued.*

Species	1962–65	1993–94	2005–09
Oculinidae			
Galaxea			
G. fascicularis	+	+	+
G. aspera (*G. fascicularis*)	+		
G. lamarcki	+	+	+
Pectiniidae			
Pectinia			
P. lactuca	+		+
Echinophyllia			
E. aspera	+		
Pocilloporidae			
Pocillopora			
P. damicornis	+	+	+
P. brevicornis (*P. damicornis*)	+		
P. danae (P. verrucosa)	+		+
P. verrucosa	+		
P. ligulata	+	+	
Poritidae			
Porites			
P. andrewsi	+	+	+
P. iwayamaensis (*P. rus*)	+	+	+
P. (*Synaraea*)*rus*			
P. lutea	+	+	+
P. pukoensis	+	+	+
P. lichen			+
P. solida			+
Goniopora			
G. duofasciata	+	+	+
G. minor			+
G. columna			+
G. djiboutiensis			+
Siderastreidae			
Psammocora			
P. contigua	+	+	+
P. contigua pulchra (*P .contigua*)	+		
P. nierstraszi			+
Caryophylliidae			
Euphyllia			
E. ancora			+
Total coral species	81 (70)	58 (57)	69 (69)

() indicates species name corrected for synonyms in coral identification.
+ represents the appearance of such coral.

Table 4. *Importance values (IVs) of corals in Luhuitou fringing reef.*

Corals	IV	Percentage of IV
Genera on the whole reef		
Acropora	0.686	22.9
Astreopora	0.025	0.8
Montipora	0.294	9.8
Pavona	0.119	4.0
Turbinaria	0.007	0.2
Cyphastrea	0.025	0.8
Diploastrea	0.008	0.3
Favites	0.091	3.0
Favia	0.017	0. 6
Goniastrea	0.084	2.8
Platygyra	0.089	3.0
Hydnophora	0.008	0.3
Symphyllia	0.009	0.3
Galaxea	0.036	1.29
Pectinia	0.007	0.2
Pocillopora	0.054	1.8
Porites	1.315	43.8
Goniopora	0.126	4.2
Total	3	100
Species on reef flat		
Porites lutea	1.55	51.7
Montipora digitata	0.28	9.4
Porites pukoensis	0.22	7.2
Acropora pulchra	0.20	6.5
Acropora brueggemanni	0.14	4.7
Acropora cytherea	0.12	4.1
Goniastrea aspera	0.10	3.3
Montipora hoffmeisteri	0.08	2.7
…		
Species on reef slope		
Porites lutea	0.65	21.8
Acropora pulchra	0.37	12.4
Acropora hyacinthus	0.25	8.5
Goniopora duofasciata	0.22	7.2
Montipora hoffmeisteri	0.21	6.9
Pavona decussata	0.18	6.1
Astreopora myriophthalma	0.12	4.0
Porites pukoensis	0.10	3.4
Acropora cytherea	0.09	3.1
Platygyra sinensis	0.08	2.7
…		

… include other coral species whose IV is less than that of these common coral species.

during the past 50 years (Table 6). The coral community appears to have been comparatively healthy in the 1960s. Two coral zones were recognized in 1958 (Naymov, Yan, and Huang, 1960): the reef slope, mainly covered by branched staghorn corals; and the reef flat, characterized by abundant, massive corals (*Porites, Favia,* and *Goniastrea*). The reef flat was further divided into a *Goniastrea* zone and *Montipora* zone, based on different dominant coral species, whereas the reef slope was dominated by *A. corymbosa, A. hyacinthus,* and *A. millepora* in the upper subzone and by *A. formosa, A. florida,* and *Porites lutea* in the lower subzone in 1962–65 (Zou, Ma, and Song, 1966). The *Acropora* corals were up to 2 m in diameter, and *Porites* corals grew up to 3–4 m high (Zou, Ma, and Song, 1966).

Xie, Lin, and Li (1981) reported that large, massive corals, such as *Goniastrea* and *Montipora,* which dominated the reef flat before the 1970s, had been replaced by small-sized, massive corals, such as *Porites, Favia, Goniastrea, Platygyra,* and *Montipora*, and a high proportion of algae by the 1980s. *Acropora* corals still dominated the reef slope, but the previous two subzones had disappeared, and the proportion of other massive corals, such as *Porites, Favia, Platygyra,* and *Pavona*, had increased (Pan *et al.,* 1983).

In the early 1990s, only small, sporadic colonies of *Porites* and *Goniastrea* occurred on the reef flat. *Montipora digitata*, the dominant species in the 1960s in this zone, was restricted to the upper rim of the reef slope. Most *Acropora formosa* colonies were found dead, and the overall number of coral species had decreased significantly (Liu, 1998; Zhang, 2001).

Our most recent surveys on the coral community of the Luhuitou fringing reef revealed that the *Goniastrea* and *Montipora* zones, which previously prevailed on the reef flat during the 1960s, had disappeared completely and were

Table 5. *Living coral cover measured with different methods.*

Reef zone	Method	Coral cover (%) in Perpendicular Transects					
		1	2	3	4	5	Average ± SE
Reef slope	V-LIT (isobath transect)	14.1	14.9	16.4	18.0	10.6	14.8 ± 1.3
	V-LIT (perpendicular transect)	14.5	15.7	16.7	18.6	9.9	15.1 ± 1.5
	Photo-quadrat (perpendicular transect)	14.0	16.4	15.2	19.5	7.5	14.5 ± 2.0
Reef flat	V-LIT (perpendicular transect)	1.9	3.8	3.2	5.8	2.8	3.5 ± 0.7
	Photo-quadrat (perpendicular transect)	3.1	9.8	3.9	6.3	2.0	5.0 ± 1.4

V-LIT indicates video-line intercept-transect.

replaced by *Porites lutea*. Although *Acropora* corals were still dominant on the reef slope, their IV was reduced.

Age Distribution of *Porites lutea*

Porites lutea is today the most dominant coral species on the Luhuitou fringing reef. It's massive structure and high density of symbiotic zooxanthellae (Li *et al.,* 2008) allow it to have a strong tolerance to natural and anthropogenic disturbances. The ages of *Porites lutea* corals show that more than 80% of the 488 *Porites lutea* colonies observed along the perpendicular transects in 2006 were less than 30 years old. Older corals (>30 y) were restricted to surrounding deeper waters only (Figure 5). Such an age distribution of *Porites lutea* corals differs significantly from healthy coral reefs, which are typically dominated by large, well-established (and mature) coral colonies (Done, 1999).

DISCUSSION

There is no doubt that the Luhuitou fringing reef has experienced a significant decline in coral cover since the 1960s. Similar, long-term declines have also been observed in many other reefs throughout the world. For example, coral cover on Curaçao in Netherlands Antilles decreased from 52% in 1973 to 22% in 2003 (Nagelkerken *et al.,* 2005); coral cover across the Caribbean reduced from 50% to 10% during the past 30 years (Gardner *et al.,* 2003); and coral cover in the Great Barrier Reef, the best-known, "pristine" coral reefs in the world, has declined from 40% to 20% during past 40 years (Bellwood *et al.,* 2004). A meta-analysis of quantitative surveys of 2667 Indo-Pacific coral reefs indicated coral cover loss of approximately 1% *per* year between 1968 and 2004 and 2% *per* year between 1997 and 2003 (Bruno and Selig, 2007). Because global warming and anthropogenic disturbances are commonly cited as the major causes of

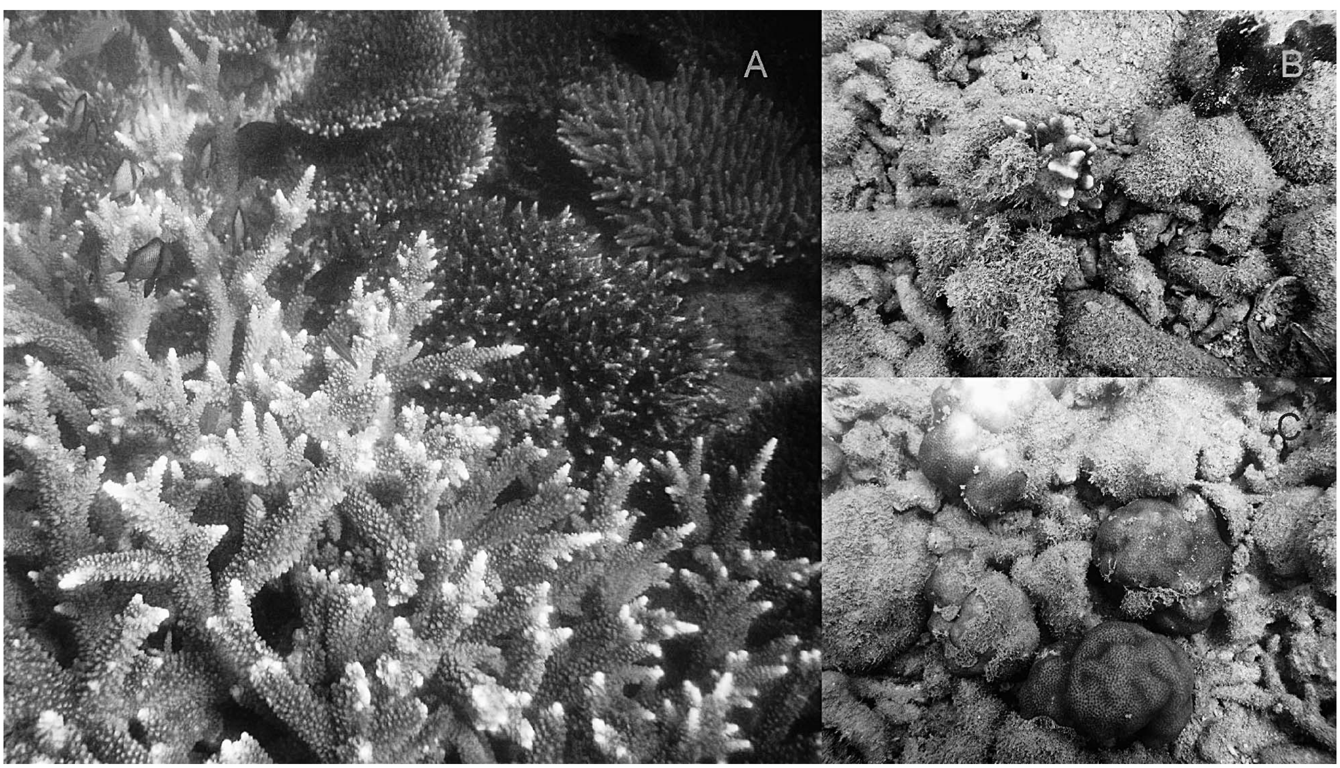

Figure 2. Coral community of Luhuitou fringing reef. (A) Reef slope; (B and C) Reef flat.

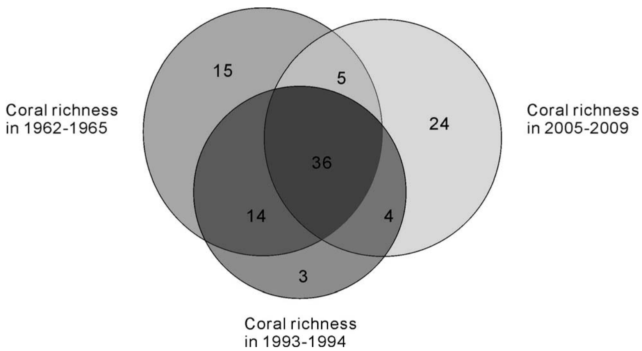

Figure 3. Number of coral species recorded at Luhuitou fringing reef through time, including the number of species common to each sampling period. The total number of species recorded is 101. Of those 101 species, 36 were recorded during each sampling period. Some species (see Table 3) were found exclusively within only one sampling period (*i.e.,* 15, 3, and 14 species in the years 1962–65, 1993–94, and 2005–09, respectively).

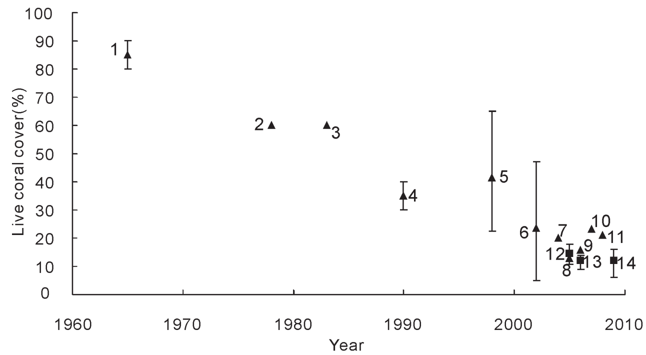

Figure 4. Living coral cover changes between the 1960s and 2009. 1: Estimated from investigations carried out in the 1960s (Zhang *et al.,* 2006). 2: Field investigation in 1978 (Wang, 2001). 3: Field investigation in 1983 (Pan *et al.,* 1983). 4: Field investigation in 1990 (Wang, 2001). 5: Quadrats investigation in 1998–99 (Zhang *et al.,* 2001). 6: Line-intercept transect investigation in 2002 (Zhang, 2004). 7–11: Reports from the Bulletin of Marine Environment Quality (2004, 2005, 2006, 2007, 2008). 12–14: Video-line intercept-transect investigations carried out in 2005, 2006, and 2009. Error bars indicate the range of coral cover.

global coral reef declines (Wilkinson, 2004), it is important to consider such impacts as the possible drivers of coral community changes experienced at the Luhuitou fringing reef.

Potential Climate Change Impacts on Luhuitou Fringing Reef

Global warming, which may lead to bleaching of corals, has been widely blamed as a major cause of global coral reef decline (Wilkinson, 2004). According to the instrumental SST record from the Ying Ge Sea Marine Observation Station (close to the Luhuitou fringing reef), there has been an average local warming rate 0.17 °C *per* 10 years since 1960, consistent with the overall warming trend of the global climate. However, SST warming in this area has actually been more significant in the cooler months of spring and winter, rather than the warmer months of summer and autumn. For example, the lowest SST warming rate in the winter is 0.22 °C *per* 10 years, whereas the highest SST warming rate in the summer is comparatively lower at only 0.14 °C *per* 10 years. Therefore, SST warming has actually favoured coral growth in the northern South China Sea area (Yu, 2005). On the basis of that observation and the fact that SST-induced coral bleaching has never been observed in the area, global warming is unlikely to have been a driving factor in the decline of the Luhuitou fringing reef.

Tropical cyclones may also have destructive effects on coral reefs by destroying the reef structure and causing disturbances to the reef's physical environment (see review of Yu *et al.* [2009] and references therein). Instrumental data show that a total of 49 typhoons swept across the Sanya area during the period AD 1950–2006 (Yu *et al.,* 2010). However, none of those typhoons had a detrimental effect on the Luhuitou fringing reef, most

Table 6. *Evolution of coral community at the Luhuitou fringing reef during the past 50 y.*

	–1969	1970–89	1990–99	2000–09
No. of coral species	8 families, 11 genera, 17 species (Naymov, Yan, and Huang, 1960) 12 families, 24 genera, 81 species (Zou, Song, and Ma, 1975)		10 families, 21genera, 58 species (Yu and Zou, 1996)	13 families, 24 genera, 69 species (2005–2009, this study)
Distribution pattern of coral communities				
Reef flat	*Goniastrea* zone and *Montipora* zone, *G. aspera* and *M. digitata* were its dominant species (Zou, Ma, and Song, 1966)	Reef flat became barren (Xie, Lin, and Li, 1981); Coral colonies reduced in size, and overall less diverse (Pan *et al.,* 1983)	Some *Porites* and *Goniastrea* species grew sporadically; formerly dominant species, *Montipora digitata,* now found only on the upper rim of reef slope (Liu, 1998)	*Goniastrea* zone and *Montipora* zone disappeared completely; *Porites lutea* is now the dominant coral species (this study)
Reef slope	*Acropora* zone, *A. corymbosa, A. hyacinthus, A. millepora* in upper subzones and *A. formosa, A. florida* in lower subzones (Zou, Ma, and Song, 1966)	The boundary of upper and lower *Acropora* subzones disappeared (Pan *et al.,* 1983)	Coral species decreased (Zhang, 2001); but some relatively abundant species remained (Yu and Zou, 1996; Liu, 1998)	Dominance of *Acropora* decreased significantly (Zhang, 2004; Zhang *et al.*, 2006; 2005–2009 this study).

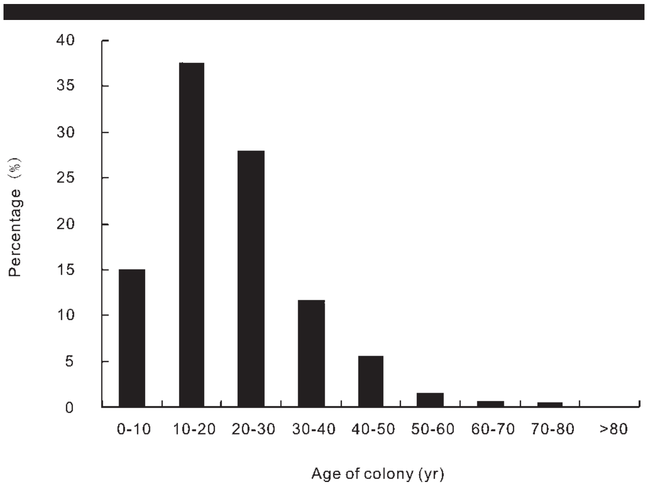

Figure 5. Age distribution of *Porites lutea* corals on Luhuitou fringing reef.

likely because the reef is situated on a leeward coast (Zhang, Yu, and Zhao, 2010).

Cold climate events have been reported as having caused detrimental effects to corals in the northern coast of the South China Sea. For example, nine abrupt winter cooling events caused extensive bleaching and extirpation of mid-Holocene corals along the Leizhou Peninsula, in the northern South China Sea (Yu *et al.*, 2004). In contrast, a recent investigation reported that corals in Daya Bay, northern South China Sea, could survive water temperatures as low as 12.3 °C for at least 6 consecutive days, as observed during a significant extreme cold event that occurred locally in 2008 (Chen *et al.,* 2009). Considering that the lowest SST recorded at the Luhuitou fringing reef since 1960 was 20.4 °C (February 1977), it is unlikely that low winter temperatures have had any significant effects.

Collectively, on the basis of the above observations, it is unlikely that global warming and other extreme weather events have detrimentally affected the Luhuitou fringing reef, at least during the historic period of ecological monitoring.

Potential Anthropogenic Effects on Luhuitou Fringing Reef

Human disturbances, such as overfishing, destructive fishing, increased sedimentary inputs and nutrients, and coastal development, are threatening many coral reefs throughout the world (Fabricius, 2005; Hughes *et al.,* 2003; Pandolfi *et al.,* 2003). The Luhuitou fringing reef, adjacent to Sanya City and Sanya Harbour, plays an important role in providing coastal defence, seafood, recreation, and many other goods and services for local residents and tourists. Sanya City itself has undergone a significant boom period over recent decades, with the local urban population increasing from less than 70,000 in 1984, to more than 260,000 in 2007 (Sanya Statistic Department, 2008).

From the 1970s to the 1980s, coral block mining, overfishing, and destructive fishing (such as blast fishing, cyanide fishing, and electric fishing) occurred on the reef (Hutchings and Wu, 1987; Liu, 1998; Pan *et al.,* 1983), which likely resulted in mass coral mortality and damage to the reef's structure. Since 1990, when the Sanya National Coral Reefs Nature Reserve was established, disturbance from such destructive activities has been reduced significantly. However, some human activities, including blast fishing, anchoring, and trampling, continue in the region, and they appear to be having an ongoing detrimental effect on coral reef recovery (Zhang, 2004). In addition, increased mariculture (pearl oyster, *Eucheuma,* prawn, and abalone) and tourism activities have introduced new stresses to the Luhuitou fringing reef (Figure 6). Local mariculture activities commenced in the 1990s (peaking between 1999 and 2003) and have introduced a vast array of floats, fixed poles, and nets on the reef. In 2003, we observed 14 prawn and abalone cultivation farms around the Luhuitou fringing reef and witnessed the discharge of their sewage directly onto the reef. From 2004 to 2008, scuba diving and other recreational activities expanded on the reef, which resulted in both direct physical damage (such as breaking of branching corals) and indirect influences (such as increased turbidity, changes in wave dynamics, and production of marine debris) to the reef. Corals in the neighbouring Xiaozhou Island and Baipai Reef (Figure 1) have also been severely affected by such disturbances and have almost disappeared during the past decade (Zhang, 2003).

CONCLUSION

The Luhuitou fringing reef in the northern South China Sea has suffered severe declines in both diversity and overall coral cover between 1960 and 2009. Mean coral cover crashed from 80–90% in 1960s to just 12.0% in 2009. More than 80% of the now-dominant species, *Porites lutea*, are less than 30 years old, an age profile typical elsewhere of stressed reefs. Collectively, our results suggest that the local Luhuitou fringing reef coral community has shifted from a flourishing state in the 1960s, to it present comparatively barren state. Such degradations have most likely been driven by direct and indirect local anthropogenic impacts, such as overfishing, destructive fishing, reef rock digging, mariculture (pearl oyster, *Eucheuma*, prawn, and abalone), and local tourism.

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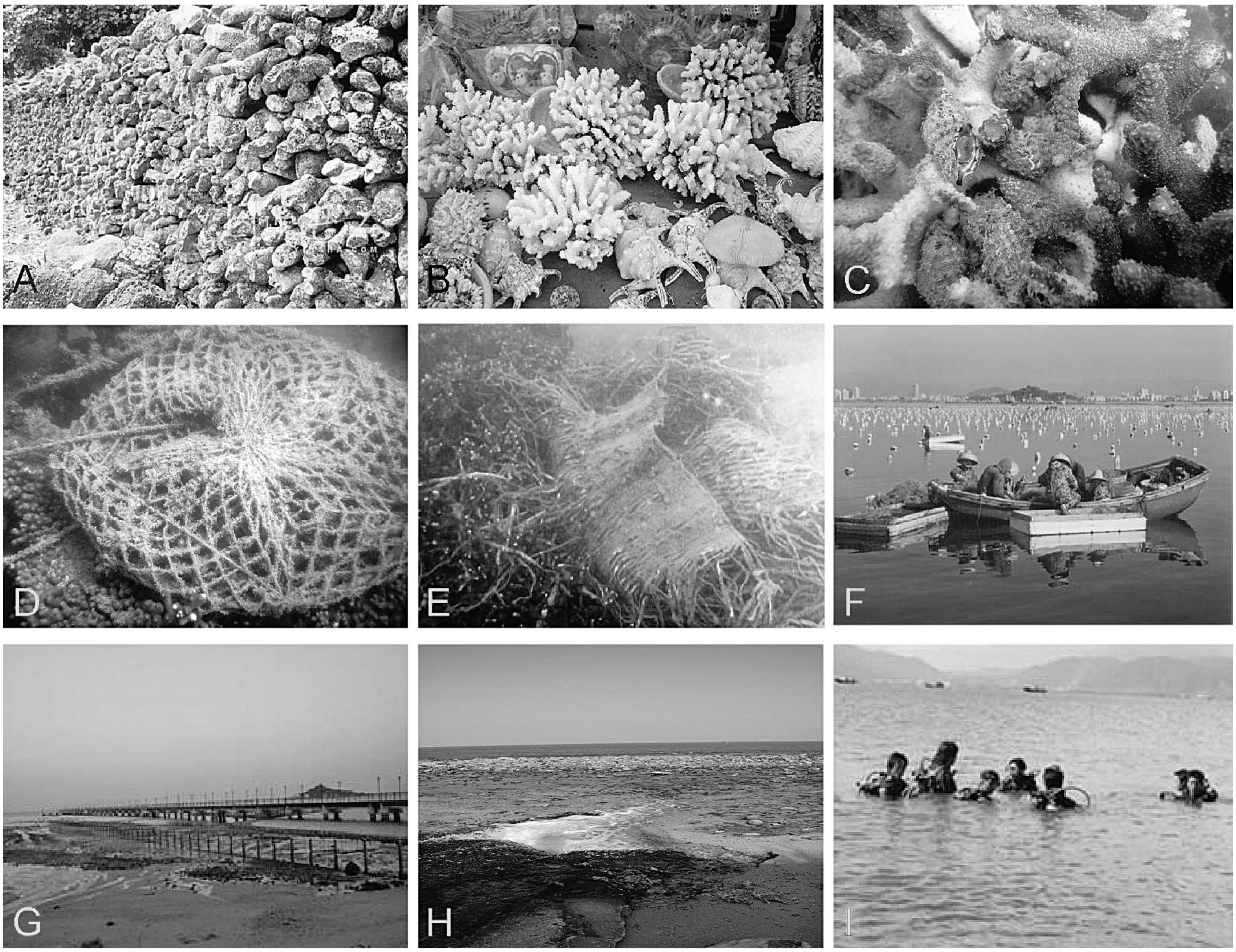

Figure 6. Impacts of various human activities proximal to the Luhuitou fringing reef. (A) Fence built with coral rocks; (B) Commercial corals and shells; (C) Predaceous *Drupella rugosa*; (D) Corals covered by remnant fishing nets; (E) Marine garbage; (F) *Eucheuma* cultivation; (G) Engineering construction; (H) Sewage discharge; and (I) Recreational activities.

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