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Spatial and temporal variations in sediment accumulation and their impacts on coral communities in the Sanya Coral Reef Reserve, Hainan, China

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ABSTRACT

This study investigated the spatial and temporal variations of sediment accumulation and their impacts on coral communities in four sites at two or three depths (3 m, 6 m and 9 m) at the Sanya Coral Reef Reserve by deploying sediment traps on the sea floor during 2007–2009. Rainfall and typhoon events, which appeared to control sediment accumulation in the sea floor of the coral reef, were positively correlated with total sediment and sand-sized (i.e. 63–2000 μm) sediment accumulation. Sediment accumulation rate significantly decreased with the distance far away from the coast in Sanya. The mean sediment accumulation rates in Ximaozhou, Luhuitou and Xiaodonghai during 2007 to 2009 were close to 20 mg cm^{-2} d^{-1}, and they were significantly higher than that in Yalongwan, probably as a result of terrestrial soil erosion caused by strong coast human activities (e.g. coastal construction, dredging and hillside clearing). Correlation analysis revealed that silt-clay-sized sediment accumulation rate was highly negatively correlated with total live coral cover and coral cover in some taxa, such as *Montipora* and branching *Porites*. whereas, *Diploastrea heliopora* was positively correlated with silt-clay-sized sediment accumulation. Correlation analysis also suggested that silt-clay-sized sediment accumulation had a higher efficiency in predicting the spatial variation of total live coral cover in Sanya than did the total sediment accumulation. Based on this investigation, we conclude that high rates of sediment accumulation pose a severe threat to the Sanya Coral Reef Reserve, highlighting the importance of integrated watershed management practices in the Sanya Coral Reef Reserve.

1. Introduction

Coral reefs are productive and diverse ecosystems that provide valuable ecological services such as seafood, recreational possibilities, as well as protection of vulnerable shorelines from storms and wave action (Moberg and Folke, 1999; Oliver et al., 2011). However, the world has lost 19% of the original coral cover, mainly due to damaging activities from catchment areas, combined with over-fishing and global climate change (Wilkinson, 2008; Wilkinson and Brodie, 2011). Over-developed or modified catchments, such as logging, deforestation, cropping, grazing and urban development via enhanced erosion on less vegetated landscapes, will deliver more sediment to the coast coral reef (Oliver et al., 2011; Richmond et al., 2007; Wilkinson and Brodie, 2011; Wolanski et al., 2009). For example, sediment inputs to coral reefs have increased several-fold over the last 150 years in some parts of the world (Cooper et al., 2009). Sedimentation has become one of the most important disturbance factors on the degradation of inshore coral reefs in the world (Hoegh-Guldberg et al., 2007; Rogers, 1990; Smith et al., 2010). Increased suspended sediment concentration in the water column would lead to an increase in seawater turbidity, reduce light availability for zooxanthellae and ultimately decrease the food source for coral colonies (Fabricius, 2005, 2011). Sediment accumulation directly on the coral surface may result in smothering and bacterial infection of coral tissues and lead eventually its death (Hodgson, 1990; Staffordsmith, 1993). Both rejecting sediments settled on the surface by coral and healing damage caused by sediment abrasion on the surface will increase energy demand for coral (Brown et al., 1990; Pastorok and Bilyard, 1985; Rogers, 1990; Staffordsmith, 1993). Exposure to elevated sedimentation for repeated or prolonged periods of time has lead to shifts in the trophic structures of coral reef assemblages,

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reduced coral recruitment, and declining biodiversity due to the loss of sensitive taxa (Fabricius, 2005; Fabricius et al., 2011; van Woesik et al., 1999).

Sediment traps are commonly used as standard tools for monitoring "sedimentation" in coral reef environments (Storlazzi et al., 2011). Some suggest a sedimentation threshold of 10 mg cm^{-2} d^{-1}, with reefs being severely damaged at higher sedimentation rates (Rogers, 1990). The threshold of 10 mg cm^{-2} d^{-1} was also evidenced by some studies (Dutra et al., 2006; Nemeth and Nowlis, 2001; Smith et al., 2008), whereas it was confused in some other study (Muzuka et al., 2010). Chumbe reef with high accumulation of sediments were characterized by high coral cover and high coral diversity in comparison with Bawe reef and sedimentation rate in some site of Chumbe reef fluctuated above the threshold of 10 mg cm^{-2} d^{-1} (Muzuka et al., 2010). Small particles carry more nutrients and pesticides, absorb more light, and cause greater stress and damage to corals than do sediments that are coarse and poor in organic matter (Weber et al., 2006). Sedimentation rate showed a pronounced seasonality (Fernandez and Perez, 2008; Golbuu et al., 2011b; Ismail et al., 2005; Jordan et al., 2010), which was controlled by large amounts of river runoffs in rainy season (Fernandez and Perez, 2008; Ismail et al., 2005) and strong re-suspension caused by wave-induced bottom shear stress in typhoon season (Bothner et al., 2006; Storlazzi et al., 2009). So, re-suspension would significantly cause the coarse particles collected in the traps and increased the accumulation rate in very short time (Bothner et al., 2006), whereas the high sediment accumulation rate probably induced subtle effect on coral reef (Muzuka et al., 2010). So, particle size of the collected sediment may play an important role in determining the validity of threshold of 10 mg cm^{-2} d^{-1} on corals. However, no study evaluated the effect based on field work, especially on long-term monitoring sedimentation data (i.e. >2 years). Some studies found coral community, such as total live coral cover, juvenile coral density and species richness, changed significantly along the pollution or river discharge gradient (Fabricius et al., 2011; Golbuu et al., 2011b; Golbuu et al., 2008). This suggested that spatial distribution of coral community was also an important way to evaluate the particle size effect of collected sediment on corals based on the relationship analysis between coral community and sedimentation rate in different particle size.

Sanya Coral Reef Reserve which located in the southern coast of Sanya City is the national coral reef reserve designated in 1990 for the first time in China. Because Sanya is an eco-tourism oriented coastal city, the income from tourism industry took up 60% for the total Gross Domestic Product (GDP) of Sanay city in 2009 (Li, 2011). Moreover, marine fishery also played a significant contribution to the total GDP of Sanya. This would highlight the importance of the Sanya Coral Reef Reserve in maintaining Sanya marine fishery resources and promoting the sustainable development of Sanya tourism industry. As a result of increased human activities, such as urbanization and coastal development, the coast marine environment and coral reef changed significantly during past 5 decades in Sanya. For example, siltation rates of Sanya Harbor increased from 0.18–1.24 cm/a during past one century to 20–30 cm/a during past one decade and both of the values were markedly higher than the natural siltation rate of 0.14–0.18 mm/a during past 8000a (Wu et al., 1998). Mean live coral cover dropped from about 80–90% in 1960s to 11.24% in 2007 in Luhuitou fringing reef (Zhao, 2008) and from about 80% in 1960s to 26% in 2007 in Ximaozhou Island (Zou et al., 1966). Human activities, such as reef block mining and curios collecting, destructive fishing and over-fishing as well as severe terrestrial sediment runoffs (e.g. sediments, inorganic nutrients and other pollutants) from coastal land and marine farms, caused the fast deterioration of coral reef in Sanya Bay (Li et al., 2012; Zhang et al., 2006). Sedimentation was probably the biggest compounding factor (Lian et al., 2010; Zhang et al., 2006). However, spatial and temporal variations of sediment accumulation rate in Sanya Coral Reef Reserve has not been well investigated yet.

Our objectives of this study were to investigate spatial and temporal variations of sediment accumulation rate, their causes and their impact on coral communities in the Sanya Coral Reef Reserve using sediment traps deployed there. This study was also to evaluate the validity of the threshold of 10 mg cm^{-2} d^{-1} on corals in the Sanya Coral Reef Reserve based on 3 years sedimentation data.

2. Material and methods

2.1. Study site

Sanya Coral Reef Reserve, with a marine area of 85 km^2, was composed of 4 reef zones: (1) Ximaozhou and Dongmaozhou islands (zone 1); (2) west coast of Luhuitou Peninsula and Xiaozhou Island (zone 2); (3) area of the east coast of Luhuitou Peninsula and the Yuling Bay corner, including Dadonghai and Xiaodonghai (zone 3); (4) Yalong Bay including Yezhu Island, Xipai and Dongpai (zone 4) (Fig. 1). Coral reef in Sanya developed from Holocene and was prosperous during 7300–6000 cal.aBP when the biological–geomorphological zones had been formed basically. The modern coral reefs developed at the outer reef flat and reef-front slope (Huang et al., 2007). Zones 1 and 2 receive sewages via Sanya River and the coast runoffs in Sanya Bay. Zone 3 receives Damaoshui River, Hongsha Port and city sewage outfalls in Liudao of Yulin Bay. There is no river discharged into zone 4 directly. Urban sewage in Sanya was 4571×10^4 t/a and dissolved inorganic

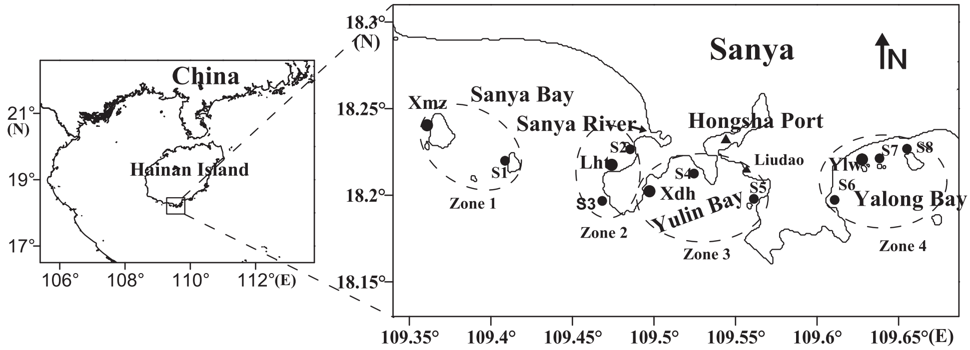

Fig. 1. Study sites in Sanya Coral Reef Reserve. Sediment accumulation rate was monitored for 11 times in totally 11 stations during the time of 2007–2009. Study sites of sedimentation rate: Ximaozhou (Xmz-3, Xmz-6 and Xmz-9), Luhuitou (Lht-3 and Lht-6), Xiaodonghai (Xdh-3, Xdh-6 and Xdh-9) and Yalongwan (Ylw-3, Ylw-6 and Ylw-9). Stony coral community and juvenile coral density were investigated in all of the sites at two or three depths (3 m, 6 m and 9 m) indicated as closed circles.

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nitrogen was 628 t in 2008 (Li, 2011). It was about 30% of the total sewages discharged into Sanya Bay and about 70% discharged into Yulin Bay. Annual sediment load was about 2417 t for Sanya River (Wang et al., 1996) and 789.9 t for Damaoshui River (Chen, 1999). However, only a small amount of sediment flowed into Sanya Bay and Yulin Bay from the two rivers (Wu et al., 1998). Human activities, such as coast construction, dredging, land clearing and tourism, were strong in Sanya Bay and Yulin Bay with the development of the International Hainan Tourism Island in recent years.

The average annual SST in the Sanya Bay was 26.9 °C over the period of 1961–1999. The average monthly SST reached the maximum of 29.5 between May and September and the minimum of 23.2 °C between December and February (Shi et al., 2003). Salinity changed from 31.9 to 33.4 in reef areas (Li, 2011). Sanya is typically controlled by tropical monsoon climate with the northeast wind and waves in winter and the south wind and waves in summer (Zhang et al., 2006). The wet season is typically between May and October accounting for 88% of the annual precipitation (1278 mm). Its tidal cycle is irregular diurnal, with mean tidal height of 1.02 m, mean tidal range of 0.79 m and high tidal height of 1.89 m (Wu et al., 1998).

2.2. Sediment trap

We deployed manually cylindrical sediment traps during 2007–2009 in Ximaozhou (Xmz), Luhuitou (Lht), Xiaodonghai (Xdh) and Xiapi of Yalong Bay (Ylw) at 3 m, 6 m and 9 m above the sea floor at 11 stations in the Reserve (Fig. 1). The trap was made of PVC tubes (tube height = 16 cm, diameter = 4.4 cm, distance from bottom = 50 cm, n = 3–10 tubes per depth). A baffle made of nylon screen of net size (0.8 cm) was placed on the top of each tube which could prevent settling of the swimmers. The height to width ratio of the trap is 3.6, which would minimize capturing resuspended sediment from the bottom and maximized the particulate retention within the trap (Gardner, 1980). The sediment traps were deployed 30–90 days in May, July and December 2007, March, May, July and October 2008, January, April, July and October 2009. Sediment accumulation rate measured with traps placing on the sea floor should be regarded as particle of sediment rain rate to the surface of the coral rather than permanently incorporated into the bottom sediments.

2.3. Sediment analysis

The collected particles were screened with a siever (e.g. 2000 μm for pore size). The particles below the siever were collected by medium speed filter membrane and then dried in an oven at 60 °C for 48 h. Sediment accumulation rate was obtained by weighing the dried sediments (± 0.10 mg) and then dividing by the collection time and the mouth area of collection tubes. The particle size was obtained by a laser particle size analyzer (Mastersizer 2000, Malvern, Britain) with a measurement range of 0.02–2000 μm and a relative error of being less than 3% for three replicated measurements. In this study, sediment accumulation rate was divided into total (i.e. 0–2000 μm), silt-clay (i.e. 0–63 μm) and sand (63–2000 μm) sizes due to the particle size difference for sediment stress on coral colonies (Weber et al., 2006).

2.4. Stony coral community

Two to four replicated 60 m transect line paralleled to the shoreline in zone 1–4 were deployed for investigation of coverage of stony coral community by videos (Fig. 1). Two to three depths (3 m, 6 m and 9 m) were selected at each site (Xmz, Lht, Xdh, Ylw and S1–S8) in accord with the deployment of sediment traps. Line point transect method (LPT) was used to estimate the coverage of stony coral from the videos at 10 cm intervals, yielding 600 points. Stony coral was identified to species level. *Montipora* was divided into foliaceous (also including branching and encrusting) and massive (also including submassive) while *Porites* was divided into branching and massive based on their morphology.

Juvenile coral density was investigated by visual census method (Edmunds et al., 1998). At each depth, juveniles (0.4 cm≤diameter≤5 cm) were carefully counted at least 32 random quadrates (0.5 m × 0.5 m) along each 60 m transect.

2.5. Rainfall and typhoon

Rainfall and wind speed data were obtained from the weather station in Hainan tropical marine biology research station, Chinese Academy of Science. Mean monthly rainfall was 79, 129 and 78 mm during 2007–2009, respectively. The period between May and October was typically rainy season and the rainfall accounted for 95% of the whole year while the remaining period of the year was typically dry. Typhoon data was obtained from the typhoon website of Zhejiang province (http://slt.zj.gov.cn/typhoneweb/). Typhoon in the South China Sea mainly sourced from the west Pacific and appeared during May–November accounting 95% of the total typhoons in a year. Typhoons in South China Sea frequently track from east to west and storm waves occur in July–November in Sanya (Zhang, 2001). Monthly rainfall was significantly correlated with number of typhoons during 2007–2009 (Pearson's correlation, $r=0.531$, $p<0.001$, $n=36$).

2.6. Statistical analysis

Kolmogorov–Smirnov test was used for normality of assumptions. Data that did not meet the assumption were log 2 transformed. Levene's test was used for homogeneity of variance. Three-ways ANOVA was used for total, silt-clay and sand-sized sediment accumulation rate among sites, depths and seasons in the Sanya Coral Reef Reserve. Pearson correlation or Spearman's correlation was used to investigate the relations between sediment accumulation rate and environment variables and coral community (i.e. average data for each zone). Statistical analysis was done using statistical analysis software of SPSS 13.0.

Redundancy analysis (RDA) was used to reveal the relationship between temporal variation of sediment accumulation rate and environment variables (i.e. monthly rainfall, typhoon numbers and wind speed). Principal component analysis (PCA) was used to determine the spatial variation of sediment accumulation rate and differentiate sites in different sediment accumulation rate. The length of these arrows indicated the relative importance of that environmental factor in explaining variation in response variables (e.g. sediment accumulation rate) while the angle between the arrows indicated the degree to which they were correlated. All above analysis was carried out using the statistical analysis package of CANOCO 4.5.

3. Results

3.1. Spatial and temporal variations of sediment accumulation rate

The mean percentage of silt-clay-sized sediments was 63.6 ± 25.3% (mean ± SD), ranging from 8.7% to 99.3%, while the mean percentage of sand-sized sediment was 36.4 ± 25.3%, ranging from 0.7% to 91.3% during the study period. This indicated that the sediments were mainly composed of silt-clay-sized grains. Sand composition of the collected sediments in rainy season was significantly higher than that in dry season (e.g. 49.1% and 27.9%,

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$P<0.001$). For example, sand accounted for more than 90% in a rainy season sediment sample (e.g. June–July 2008 at 3 m in Xmz).

Mean total sediment accumulation rate was 17.3 ± 1.7 mg cm^{-2} d^{-1}, ranging from 0.7 to 126.8 mg cm^{-2} d^{-1}, with the maximum in August–October and the minimum in April–May periods (Fig. 2). Total and sand-sized sediment accumulation rate showed pronounced seasonality with high in summer and autumn and low in spring, whereas it was not pronounced for silt-clay-sized sediment accumulation rate (Figs. 2 and 3, Table 1). Sediment accumulation rate in rainy season (May–October) was significantly higher than that in dry season (November–April) (Table 1).

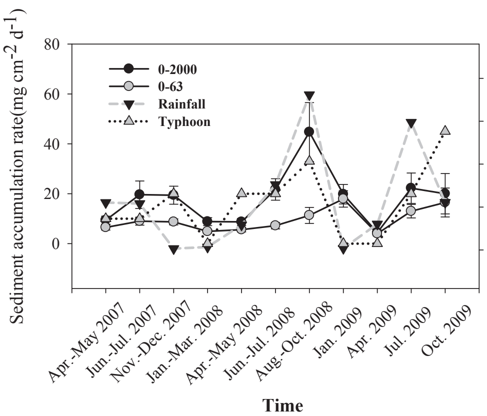

Fig. 2. Temporal variation of total (0–2000 μm) and silt-clay (0–63 μm) sediment accumulation rate and monthly rainfalls and typhoon episode numbers in the Sanya Coral Reef Reserve during the time of 2007–2009 (mean ± SE, $n=11$). Sediment accumulation rate was the average values for the 11 study stations.

Redundancy analysis was carried out using sediment accumulation rate and environmental variables (Fig. 4). Axes 1 and 2 were found to explain 100% of the overall variance (94.5% and 5.5%) of the relationship between sediment accumulation rate and environmental variables. Axis 1 was statistically significant (Monte Carlo permutation test, $p=0.038$). This shows that the first axis is sufficient to explain the sediment accumulation rate–environment variables relationship in the data. Axis 1 of the RDA, namely the sedimentation gradient, represents a high total and sand-sized sediment accumulation rate in the positive direction, which was controlled by rainfall and typhoon episode numbers. The closed

Table 1
Summary of ANOVA for sediment accumulation rate (e.g. 0–2000, 0–63 and 63–2000 μm) among sites, depths and seasons.

Factors	Results of ANOVA		
	0–2000 μm	0–63 μm	63–2000
Site	$F_{3,\,25}=4.92^{**}$	$F_{3,\,25}=7.02^{**}$	$F_{3,\,25}=2.46$
Depth	$F_{2,\,34}=0.099$	$F_{2,\,34}=1.92$	$F_{2,\,34}=0.86$
Season	$F_{1,\,52}=25.93^{**}$	$F_{1,\,52}=7.87^{**}$	$F_{1,\,52}=27.55^{**}$
Site × depth	$F_{1,\,60}=1.14$	$F_{1,\,60}=0.48$	$F_{1,\,60}=2.01$
Site × season	$F_{1,\,78}=0.52$	$F_{1,\,78}=0.51$	$F_{1,\,78}=2.64$
Depth × season	$F_{1,\,87}=0.008$	$F_{1,\,87}=0.60$	$F_{1,\,87}=1.08$
Site × depth × season	$F_{2,\,105}=0.40$	$F_{2,\,105}=0.11$	$F_{2,\,105}=1.86$

** $p<0.01$.

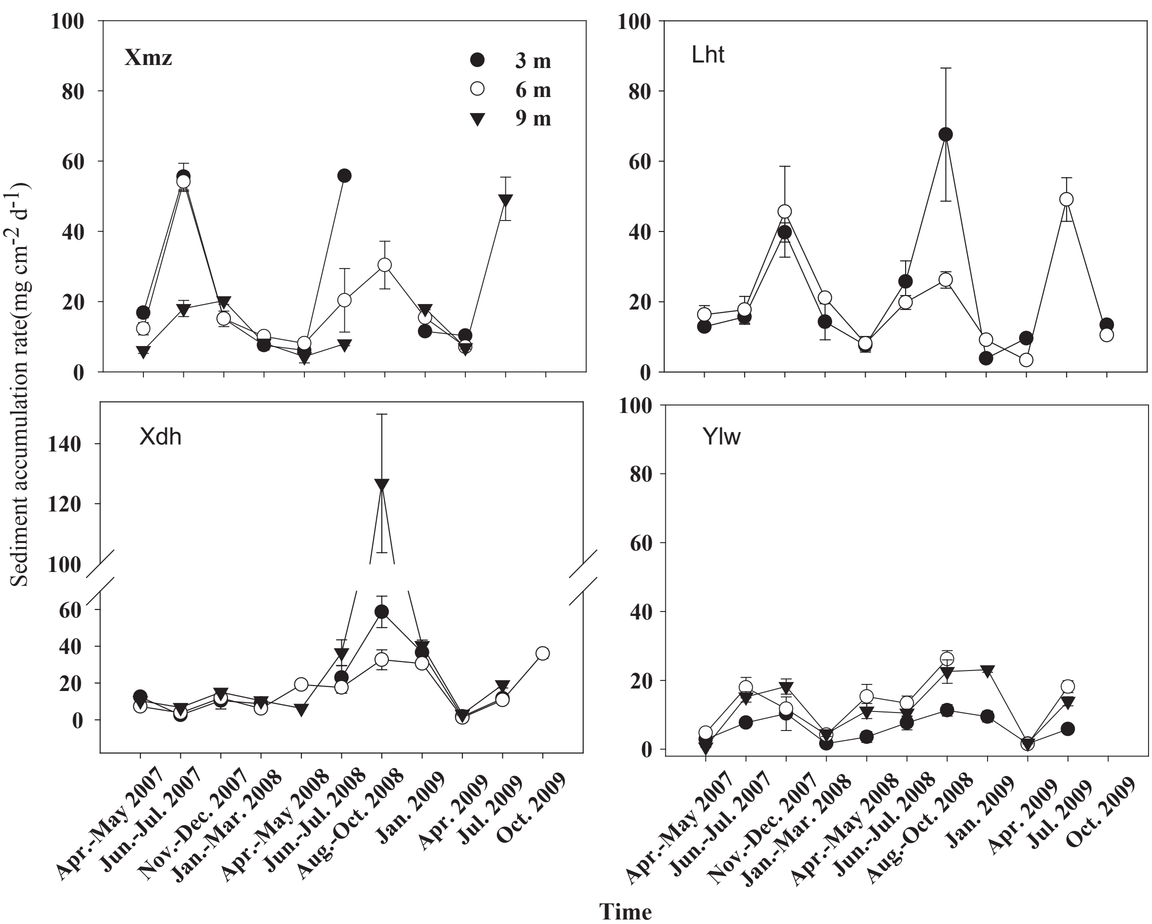

Fig. 3. Temporal variation of total sediment accumulation rate in the Sanya Coral Reef Reserve during the time of 2007–2009 (mean ± SE, $n=1$–11).

circles were located in the positive direction, indicating higher sediment accumulation rate in rainy season.

When a forward selection was performed for the three environmental variables, rainfall was selected first (F=9.013, P=0.006) and then was typhoon episode numbers (F=3.314, P=0.064). However, wind speed was not statistically significant (F=0.333, P=0.626). RDA bioplot shows that total and sand-sized sediment accumulation rate was highly positively related with rainfall and typhoon numbers, whereas, the relations between silt-clay-sized sediment accumulation rate and the amount of rainfalls and typhoon episode numbers were weak. This suggested that silt-clay-sized sediment accumulation rate was not apparently influenced by the amount of rainfall and number of typhoon episodes passing through the study site. Moreover, RDA bioplot also apparently differentiates the sediment accumulation rate in rainy season (close circle) from dry season (open circle) (Fig. 4). Correlation analysis also indicated significant relations between sediment accumulation rates and rainfalls and typhoon episode numbers in some study sites during this study (Table 2).

Total and silt-clay-sized sediment accumulation rate varied significantly among sites while it was not significant for sand-sized sediment accumulation rate (Table 1, Fig. 5). For example, total and silt-clay-sized sediment accumulation rate in Xmz, Lht and Xdh was significantly higher than that in Ylw. Ordination plot based on PCA can clearly divide the 11 stations into 2 groups (Fig. 6). Group 1, composing of stations from Xmz, Lht and Xdh, represented higher sediment accumulation rate and group 2, composing of Ylw, represented lower sediment accumulation rate. Although sediment accumulation rate was not significantly among depths in the Sanya Coral Reef Reserve (Table 2), total sediment accumulation rate in rainy season showed a clearly distinct trend along the depth gradient (Figs. 5 and 7). Total sediment accumulation

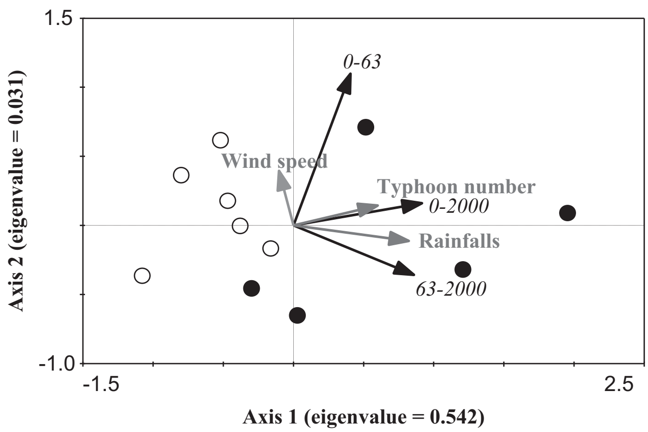

Fig. 4. Ordination plot of mean sediment accumulation rate of the four study sites in Sanya Coral Reef Reserve during the time of 2007–2009 based on redundancy analysis (RDA) shows sediment accumulation rate and environmental variables (e.g. monthly rainfall, typhoon number and wind speed) on axes 1 and 2. Thick red arrows represent environmental variables while thin black arrows represent sedimentation variables. The direction and length of arrows indicate their contribution to variation along those axes. Each circle indicates the sediment accumulation rate for one time. Open circles indicate the time in dry season while closed circles indicate the time in rainy season. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Correlation analysis between sediment accumulation rate (i.e. 0–2000, 0–63 and 0–2000 μm) and environment variables (i.e. rainfalls and typhoon episode numbers) (n=7–11) for the 11 study stations.

Station	Depth	0–2000		0–63		63–2000	
		Rainfalls	Typhoon	Rainfalls	Typhoon	Rainfalls	Typhoon
Xmz	3	0.752*	0.353	0.158	−0.242	0.758*	0.421
	6	0.427	0.265	0.05	−0.193	0.505	0.384
	9	0.658	0.32	0.537	0.102	0.72*	0.539
Lht	3	0.741*	0.483	−0.171	0.433	0.815**	0.412
	6	0.386	0.217	0.577	0.532	0.305	0.127
Xdh	3	0.512	0.529	0.128	0.045	0.634	0.708*
	6	0.263	0.649*	−0.145	0.349	0.606*	0.612*
	9	0.673*	0.601	0.432	0.31	0.692*	0.651*
Ylw	3	0.326	0.555	−0.007	−0.106	0.403	0.757*
	6	0.737*	0.862**	0.577	0.556	0.704*	0.896**
	9	0.27	0.448	−0.126	−0.213	0.517	0.861**

* $p < 0.05$.
** $p < 0.01$.

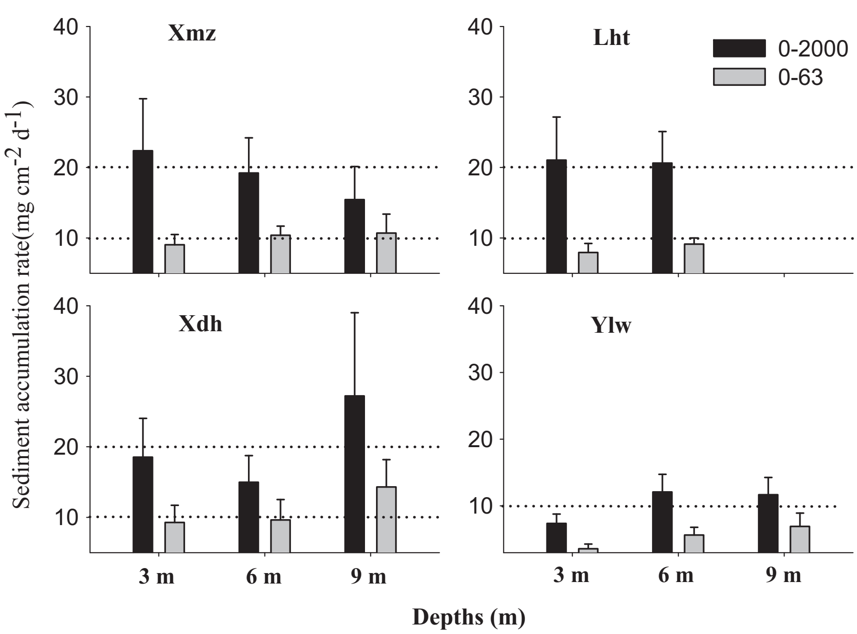

Fig. 5. Spatial variation of total and silt-clay sediment accumulation rate at the depths of 3 m, 6 m and 9 m in the Sanya Coral Reef Reserve (mean ± SE, n=8–11). Sediment accumulation rate was the average values for the 11 monitoring times.

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rate also decreased significantly with the distance far away from the coast (Fig. 8).

3.2. Coral communities and their correlation with sediment accumulation rate

A percentage of live coral coverage and juvenile coral density (e.g. 34.8% and 30 colony cm^{-2}) in Yalong Bay were apparently higher than Sanya Bay and Yulin Bay (Fig. 9). Coral communities in Yulin Bay were significantly degraded, with very low percentage of live coral coverage and juvenile coral density (e.g. 8.7% and 5 colony cm^{-2}). Correlation analysis indicated that total live coral coverage was significantly correlated with total and silt-clay-sized sediment accumulation rate ($p < 0.05$), whereas no correlation were found for juvenile coral density ($p > 0.05$).

Dominant stony coral species were *Galaxea*, *Montipora*, *Porites* and *D. heliopora* in the Sanya Coral Reef Reserve. Correlation analysis indicated that *Pocillopora* and *Platygyra* were significantly negatively related with silt-clay-sized sediment accumulation rate, whereas *D. heliopora* was positively related with silt-clay-sized sediment accumulation rate ($p < 0.05$). Foliaceous *Montipora* and branching *Porites* also showed significantly negative correlation with total and silt-clay-sized sediment accumulation rate ($p < 0.05$).

4. Discussion

4.1. Spatial and temporal variations of sediment accumulation rate and its determining factors

Total sediment accumulation rate changed significantly depending upon the amount of rainfall and typhoon episode numbers in Sanya. Correlation analysis indicated that total sediment accumulation rate significantly correlated with rainfalls in Xmz at 3 m, Lht at 3 m, Xdh at 9 m and Ylw at 6 m, and with typhoon episode numbers in Xdh and Ylw at 6 m (Table 2). Clear decreasing trend for sediment accumulation rate in Xmz and Lht were observed with the distance far away from the coast in rainy season while not clear in Xdh and Ylw (Fig. 7). This suggested that distinct factors

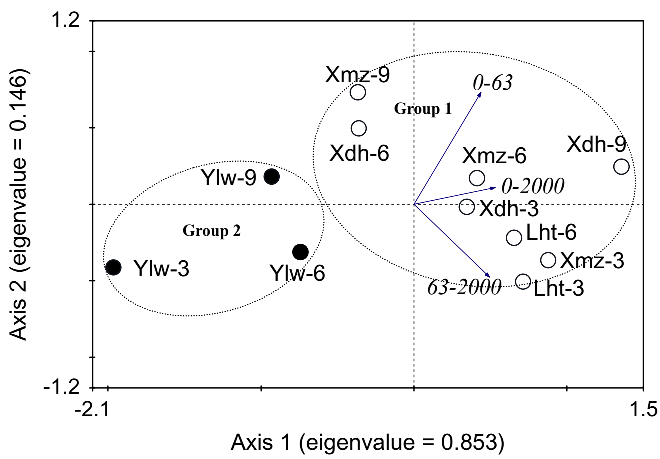

Fig. 6. Ordination plot of the mean sediment accumulation rate from 2007 to 2009 at the 11 monitoring stations based on PCA analysis. Circles indicate each station. Arabic numbers (3, 6 and 9) after the site name mean depth.

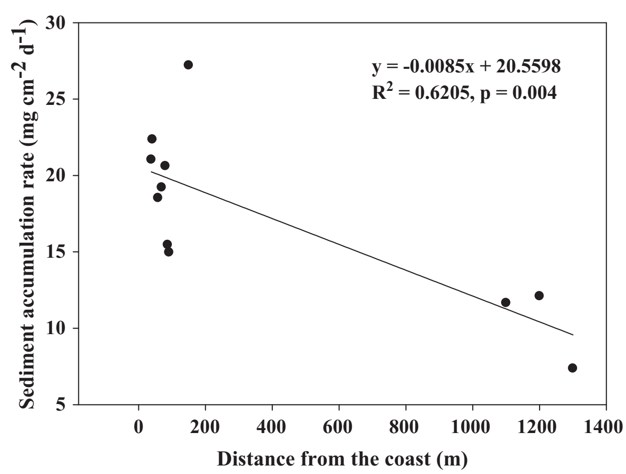

Fig. 8. Regression analysis between the distance far away from the coast and sediment accumulation rate in the Sanya Coral Reef Reserve.

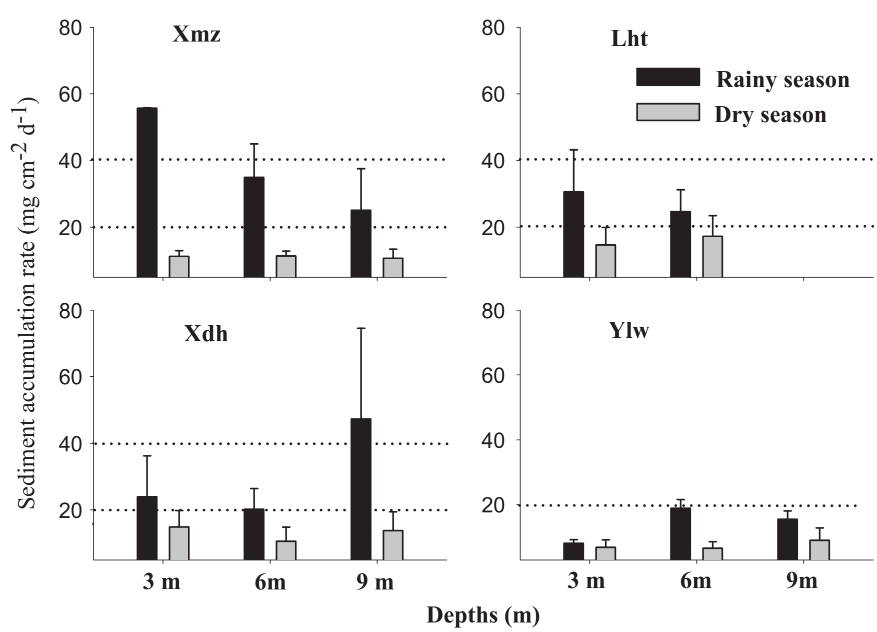

Fig. 7. Spatial variation of total sediment accumulation rate in rainy and dry season at the depths of 3 m, 6 m and 9 m in the Sanya Coral Reef Reserve (mean ± SE, $n = 8$–11). Sediment accumulation rate was the average values for the 11 monitoring times.

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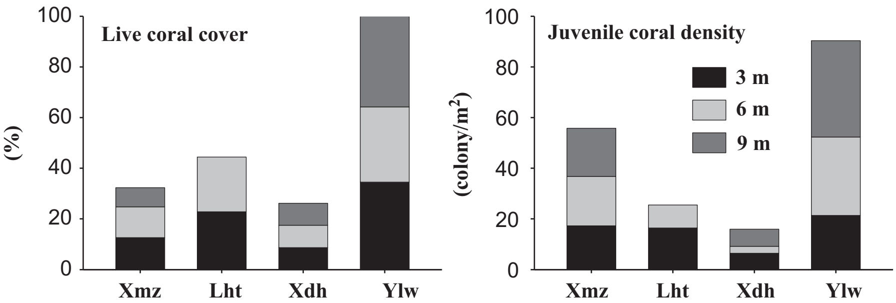

Fig. 9. Spatial variation of coverage of stony coral and juvenile coral density in the Sanya Coral Reef Reserve. The data was averaged in the 4 reef zones from 2–4 sites at each depth.

controlled the seasonal variation of sediment accumulation rate among study sites in Sanya. In all study sites, rainfalls had a pronounced effect upon the seasonal variation of sediment accumulation rate. Large amounts of terrigenous sediments from the coast or river will be discharged into coral reef in rainy season (Fabricius et al., 2007). Especially in Xmz and Lht, the highest mean sediment accumulation rate at 3 m in rainy season indicated a stronger impact from the coast soil erosion with rainfalls (i.e. 40 m from the coast at 3 m). Xmz and Lht are leeward and low wave energy coast while Xdh and Ylw are windward and high wave energy coast (Zhang, 2001). So, typhoon episodes, mostly sourced from the west Pacific and frequently tracked from east to west in Sanya, had a pronounced effect upon the seasonal variation of sediment accumulation rate in Xdh and Ylw. Some studies also found that sedimentation rate was positively correlated with wave-induced bottom shear stress (Bothner et al., 2006; Storlazzi et al., 2009). The rise of bottom shear stress will increase resuspension, then cause large amounts of coarse particles collected in the sediment traps and ultimately make sedimentation rate significantly higher (Bothner et al., 2006; Jordan et al., 2010). For example, the highest sediment accumulation rate (126.7 mg cm^{-2} d^{-1}) during this study was observed at 9 m in Xdh on August–October 2008 and the collected sediment was mainly composed of sand (i.e. 73%). It was in accord with the percentage composition of sand in surface sediment in July 2010 ranging from 70 to 93% in Xdh (Li et al., unpublished data). So, the temporal variation of total sediment accumulation rate in Xmz and Lht were mainly controlled by rainfalls while Xdh and Ylw were controlled by rainfalls and typhoon episode numbers, especially the latter.

Sediment accumulation rate varied significantly among sites in Sanya, which suggesting a strong spatial sedimentation gradient. Sediment accumulation rate also significantly decreased with the distance far away from the coast in Sanya (Fig. 8). The spatial difference in sediment accumulation rate is probably attributable to the impacts from terrigenous inputs (e.g. the coast and river), as reported in other reef zones (Golbuu et al., 2011b; Jordan et al., 2010). In Sanya, sediment accumulation rate in Xmz, Lht and Xdh was significantly higher than that in Ylw. Recently, along with the construction of Hainan Internal Tourism Island, intensive human activities (e.g. ocean engineering activities, dredging, house construction, hillside and coast land clearing) around Sanya Bay and Yulin Bay substantially increase the soil erosion to the adjacent reef areas. High turbidity events lasting for about 2–3 months were observed in Xdh as a result of dumping silts in Yulin Bay and strong hillside clearing in Liudao during September–November 2009, which caused higher sediment accumulation rate (36.0 mg cm^{-2} d^{-1}) than that before the event (Li, 2011). Dominant westward currents in Yulin Bay probably intensify the impacts of pollutants from Hongsha port and city outlets in Liudao on sediment accumulation rate in Xdh. Thus, silt-clay-sized sediment accumulation rate in Xdh was significantly higher than that in Lht and Ylw. Strong human activities (e.g. marine aquaculture, tourism and land fill and clearing) in Xmz (e.g. 2.68 km^2 offshore Island with 4500 citizens) and Lht (e.g. 3 km from Sanya River) might severely increase the sedimentation there. Matured and stable environment condition around Yalong Bay kept the offshore station of Ylw in sediment accumulation rate away from the severe impacts of human activities. So, strong human activities (e.g. coastal construction, dredging and hillside clearing) were the main factors determining the spatial variation of sediment accumulation rate in Sanya Coral Reef Reserve.

4.2. The impact of sediment accumulation rate on coral communities

Total sediment accumulation rates at most stations in Sanya were markedly higher than the "10 mg cm^{-2} d^{-1}" threshold (Rogers, 1990) (Figs. 2 and 3). Many others studies (Dutra et al., 2006; Nemeth and Nowlis, 2001; Smith et al., 2008) evidenced that chronic exposure of higher sediment accumulation rate above the Rogers' value caused severely detrimental effects on coral communities. Mean sediment accumulation rate in Xmz, Lht and Xdh was close to 20 mg cm^{-2} d^{-1} while the value in Ylw just reached the "10 mg cm^{-2} d^{-1}" threshold during the period of 2007–2009, which were apparently higher than the value in many other reef zones, such as 5.0 mg cm^{-2} d^{-1} in Palau (Golbuu et al., 2011b), 2.4 mg cm^{-2} d^{-1} in Kenya (McClanahan and Obura, 1997) and 2.6 mg cm^{-2} d^{-1} at San Cristobai Reef, Puerto Rico (Rogers, 1983). The sedimentation level in Sanya was also evidenced by other environment variables. Turbidity averaged 3.6 NTU and ranged from 1.3 to 8.5 NTU while seawater transparency averaged 3.1 m and ranged from 1.9 to 4.9 m in the whole Sanya Coral Reef Reserve during two monitoring in 2010 (Li, 2011). This suggested that sedimentation in Xmz, Lht and Xdh was severe and the sediment accumulation rate in Ylw was in critical value.

High sedimentation in Sanya significantly correlated with live coral coverage and some coral taxa. This suggested that sedimentation significantly impacted the spatial distribution of coral communities. Total percentage of live coral cover and juvenile coral density in Xmz, Lht and Xdh were apparently lower than that in Ylw. Coral reef in Ylw was in relatively good condition and the coral cover and juvenile coral density (e.g. 34.8% and 30 colony cm^{-2}) was higher than other inshore coral reef ecosystem (Golbuu et al., 2011b). *D. heliopora* was one of the most tolerant coral species while foliaceous *Montipora* and branching *Porites* were very sensitive to sedimentation. During the dumping silts event in Xdh in 2009, *D. heliopora* was the only species which was not impacted by the high turbidity event and mainly distributed in the deep marginal region (Li, 2011). The high tolerance of the species to sedimentation probably attribute to its massive morphology and rejection capacity to sediment burial (Staffordsmith, 1993; Staffordsmith and Ormond, 1992). In this study, *Montipora foliosa* only appeared at 2 sites in Yalong Bay (i.e. $<2\%$ at S7 and 22.7% at S8), where it were less impacted by terrigenous inputs and human activities. The sensitivity of foliaceous *Montipora* and branching *Porites* to sedimentation were probably because of their small polyps and foliaceous features, which was considered as less tolerant for corals as a result of sediment deposition and tissue smothering (Fabricius et al., 2007; Golbuu et al., 2008; Philipp and Fabricius, 2003). Because *Acropora* was regarded as reliable indicator species for reef condition (Golbuu et al., 2008; Greer et al., 2009; Guzner et al., 2007), very low coverage of the species (i.e. $<1\%$) in most sites of Sanya indicated very poor reef condition there. Based on above result, we concluded that the threshold of 10 mg cm^{-2} d^{-1} on corals in the Sanya Coral Reef Reserve based on 3 years sedimentation data was effective.

4.3. Sedimentation stress on coral surface and its prediction on potential changes of coral cover in Sanya

Some laboratory experiments found that silt-sized sediment stressed more on stony coral than coarse particles (Piniak, 2007; Weber et al., 2006). In this study, our results also approved of this opinion based on field work. Firstly, silt-clay-sized sediment accumulation rate was strongly negatively correlated with total live coral cover and coverage of some coral taxa (i.e. *D. heliopora*, foliaceous *Montipora* and branching *Porites*, etc.), where weak correlation were found for total and sand-sized sediment accumulation rate (Fig. 10). Moreover, temporal variation of total live coral cover was significantly correlated with silt-clay-sized sediment accumulation rate in Xdh, however, not significant with total and sand-sized sediment accumulation rate (Li et al., unpublished data). The above opinion was also supported by other study. For example, negative relationships were also found between terrigenous sedimentation rate and the richness of adult and juvenile corals in Palau (Golbuu et al., 2011b).

High re-suspension during rainy or typhoon season will lead to higher percentage of coarse particles in the collected sediments. So, the higher sediment accumulation rate probably does not indicate the real sedimentation stress on coral surface (Bothner et al., 2006; Storlazzi et al., 2011). In this study, silt-clay-sized sediment accumulation rate showed less seasonality and was less impacted by rainfalls and typhoon episode numbers. Silt-clay-sized sediment is mostly sourced from the coast, especially the soil erosion from the hillside and coast construction. This was supported by the rate earth elements analysis on surface sediment in Xiaodonghai Reef (Wang et al., 2011) and the percentage of acid-in-dissolved matter in collected sediment in 2009 during this study (e.g. 66–78%) (Li et al., unpublished data). Delta C^{13} of total organic matter in collected sediment in Sanya in 2009 during this study showed ocean sources (e.g. −20‰, Li et al., unpublished data), which suggested that only small amount of riverine particulates were discharged into coral reef directly from the river (Wu et al., 1998). Based on the above results, we suggested that silt-clay-sized sediment accumulation rate was more reliable in predicating the sedimentation stress on corals. Silt-clay-sized sediment accumulation rate in Ylw was 5.4 mg cm^{-2} d^{-1} while the total sediment accumulation rate reached the threshold (e.g. 10 mg cm^{-2} d^{-1}). So we suggested that 5–6 mg cm^{-2} d^{-1} might be a threshold for silt-clay-sized sedimentation rate and chronic exposure of higher sediment accumulation rate above the value probably caused severely detrimental effects on coral communities.

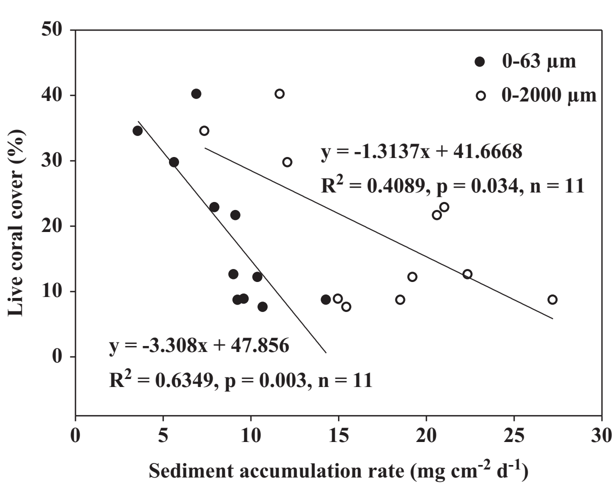

Fig. 10. Regression analysis between coverage of stony coral and total (0–2000 μm) and silt-clay (0–63 μm) sediment accumulation rate.

Regression analysis showed that silt-clay-sized sediment accumulation rate showed higher efficiency than total sediment accumulation rate in predicting the spatial variation of total live coral cover (Fig. 8). When silt-clay-sized sediment accumulation rate reached 6 mg cm^{-2} d^{-1}, the model predicted that coral cover was 28%; when silt-clay-sized sediment accumulation rate reached 10 mg cm^{-2} d^{-1}, the total coral cover will become half of the value in 6 mg cm^{-2} d^{-1} (i.e. 14.8%). When silt-clay-sized sediment accumulation rate reached 14.5 mg cm^{-2} d^{-1}, stony coral probably could not survive. The present model provides some reference information to know the potential changes of coral cover in response to intensified sedimentation as a result of many compounding factors (e.g. global warming, over-fishing and explosive fishing, eutrophication and outbreak of predators, etc.) impacting coral communities in the Sanya Coral Reef Reserve (Li, 2011; Li et al., 2012; Lian et al., 2010; Zhang et al., 2006).

5. Conclusions

Three-years of monitoring of short-term sediment accumulation rate deploying sediment trap in the water column (i.e. 3, 6, and 9 m above the sea floor) in the Sanya Coral Reef Reserve yielded scientific understanding on the cause of the increased sediment accumulation over the coral surface. Rainfall amount and number of typhoon episodes provided a significant amount of coarser sediments (sand-sized) by increasing sediment yield from the watershed and re-suspended bottom sediments by enhancing wave stress. However, silt-clay-sized sediment appears to be introduced mainly from the land clearing coast. Sediment accumulation rate in most sites of Sanya exceeded the "10 mg cm^{-2} d^{-1}" threshold and silt-clay-sized sediment, in particular, posed threat to the survival of coral communities (i.e. stony coral and juvenile coral). *D. heliopora* appeared to be rather tolerant but foliaceous *Montipora*, branching *Porites Acropora*, *Pocillopora* and *Platygyra* were very vulnerable to the higher silt-clay-sized sediment accumulation in the Sanya Coral Reef Reserve.

This study also showed that silt-clay-sized sediment accumulation rate was more effective indicator for sedimentation stress on coral surface than the total size (e.g. <2000 μm). We also argued that 5–6 mg cm^{-2} d^{-1} might be a threshold for silt-clay sedimentation. Linear model predicted that total coral cover might become half of the value in 6 mg cm^{-2} d^{-1} when silt-clay-sized sediment accumulation rate reached 10 mg cm^{-2} d^{-1}. When silt-clay-sized sediment accumulation rate reached 14.5 mg cm^{-2} d^{-1}, stony coral probably could not survive. Therefore, sediment accumulation rate of 5–6 mg cm^{-2} d^{-1} was suggested here as a new threshold value for silt-clay-sized sediment for posing threat to coral community. For maintaining Sanya marine fishery resources and the sustainable development of Sanya tourism industry, integrated watershed management practices (e.g. sustainable forestry, stabilizing hill slopes and reasonable coast construction) in the Sanya Coral Reef

Reserve was urgent and silt-sized sediment input to the Coral Reserve should be controlled less than a threshold value of 5–6 mg cm^{-2} d^{-1}.

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