Potential impacts of anthropogenic nutrient enrichment on coral reefs in the South China Sea: evidence from nutrient and chlorophyll a levels in seawater†

Jing Guo,abcd Kefu Yu,abcd Yinghui Wang,abc Ruijie Zhang,abc Xueyong Huangabc and Zhenjun Qinabc

Anthropogenic nutrient enrichment is considered to be one of the causes resulting in coral reef decline. In order to better understand the trophic status and to further explore the potential impacts of nutrients on the coral reef decline in the South China Sea (SCS), we investigated the nutrient and chlorophyll a (chl a) distributions in the surface water of reef areas across latitudes from 9° to 22° of the SCS. The results showed that nutrient and chl a concentrations in coastal reefs were obviously higher than those in the central and southern basin. Meanwhile, the investigation of two long-distance transects revealed an inshore-offshore nutrient decreasing trend. However, some offshore coral reefs, such as Yongxing Island, Huaguang Reef and Huangyan Island, were exceptions with relatively higher concentrations than in the surrounding reefs because of the ever-increasing human activity. Compared to other coral reefs worldwide, the nutrient concentration in reef regions of the northern and central SCS was obviously higher than that in healthy coral reefs, approaching that in unhealthy reef areas, which suggested that the present nutrient concentration may reach a risky level. Field survey showed a high ratio of macroalgal cover and coral cover in these reefs, and the significant correlation between the nutrient level and macroalgal cover indicated that elevated nutrients resulted in the phase shift from coral-dominated to macroalgal-dominated reef areas. On the other hand, a significant positive correlation between chl a in lagoons and the volume of lagoons indicated that the structural properties of large lagoons could enhance retention of nutrients and promote the growth of macroalgae, and human disturbance may aggravate the macroalgal overgrowth. Overall, anthropogenic nutrient enrichment has caused negative impacts on coral reefs of the SCS, such as regional macroalgal blooms in coastal reefs and disturbed remote reefs.

Environmental significance

Anthropogenic nutrient enrichment is a major problem which causes the degradation of coral reefs worldwide. This pollution may have led to a negative impact on the coral reefs in the South China Sea (SCS), where coral reefs have been undergoing serious decline in the past few decades. Therefore, it is critical to better understand the potential impacts of nutrient enrichment on coral reef decline. This study reports the investigation of the spatial distribution of nutrients and chlorophyll a and ecological cover parameters in the surface water of reef areas across latitudes from 9° to 22° of the SCS. The results showed that anthropogenic nutrient enrichment resulted in macroalgal blooms and further caused the degradation of coral reefs in some coastal and remote reef areas. Thus, this problem should be paid more attention for coral reef resource management.

1 Introduction

Coral reefs, which are thought to be one of the most typical but vulnerable marine ecosystems, have suffered serious degradation worldwide. The reason has been considered to be global climate change and excessive human disturbance, such as ocean acidification, overfishing, and eutrophication. In some regions, anthropogenic nutrient enrichment resulted in the degradation of environmental conditions for coral reef health. Human activities around coral reefs usually result in an elevated input of nutrients into reef waters, which can theoretically disturb the normal
growth of corals and eventually lead to coral reef decline through various routes. The most famed case study on coral reef decline because of macroalgal blooms, probably due to eutrophication, is that of Kaneohe Bay, Hawaii, in the 1970s and early 1980s. A similar phenomenon also occurred in Reunion Island, the Florida Keys and the Gulf of Eilat, where nutrient enrichment led to a phase shift from abundant coral to abundant macroalgae. All these macroalgal blooms occurred with a DIN ranging from 1.13 to 3.32 μmol L⁻¹ and an SRP ranging from 0.14 to 0.36 μmol L⁻¹. On the other hand, the result of simulated cultivation experiments indicated that elevated nutrient concentrations could have negative impacts on corals’ reproductive success, calcification rates, skeletal density or linear extension. Therefore, direct and indirect negative effects on coral reefs can be caused by nutrient enrichment in the water column.

The South China Sea (SCS) is one of the largest and most important marginal seas in the world. Coral reefs are one of the most prominent and typical marine systems in the SCS, extending from Zengmu Reef (3°34′N) near the equator to the Leizhou Peninsula (21°15′–21°20′N), Weizhou Island (20°54′–21°10′N) and the southern Taiwan Peninsula (22°58′–23°42′N) in the northern SCS (NSCS). Coral reefs in the SCS are mostly distributed in nine regions, including Nansha Islands, Xisha Islands, Zhongsha Islands, Dongsha Islands, Hainan Island, Taiwan Island, the Coast of South China, the Coast of Vietnam and the Coast of the Philippines, covering approximately 8000 km². In the past few decades, ecological monitoring data has shown that coral reefs have been undergoing serious decline. For instance, the living coral cover in Daya Bay, the Luohuitou fringing reef (located in the NSCS) and Yongxing Island (situated in Xisha Islands), declined by about 60–80%. The reason for this decline was probably due to increasing human activities. For example, the Luohuitou fringing reef has continually suffered from reef digging, overfishing, aquaculture, coastal construction and diving tourism since the 1960s. These human activities not only led to direct physical damage of coral reefs, but also degraded the water quality of corals’ habitat by causing high turbidity and increasing nutrient levels. However, in the SCS, the impact of nutrient variation on coral reefs is still unclear and has barely been focused on. Therefore, in this context, we conducted this study to understand whether increasing nutrient levels had negative impacts on coral reefs of the SCS.

In order to achieve this goal, we conducted two cruises to investigate the nutrient and chl a distributions in surface waters of reef areas across latitudes from 9–22° of the SCS, including coral reefs in the NSCS (18°–22°N), Xisha Islands (15°–17°N), Huangyan Island (15°N) and Nansha Islands (9–11°N). The aim of this study was not only to better understand the nutritional status and phytoplankton community in the reef waters of the entire SCS, but also to discuss the potential impact of elevated nutrient levels on coral reefs.

2 Materials and methods

2.1 Study area

This investigation involved four large regions, including 15 coral reef areas (Fig. 1). Coastal reef areas in the NSCS covered Daya Bay and Xuwu and Luohuitou fringing reefs. Coral reefs in Daya Bay (22°50′N), Guangdong province, are mainly distributed in some central islands and coastal areas. The Xuwu Coral Reef Reserve (20°10′N) is considered to be the coastal coral reefs with the largest area (14 378.5 km²) and the most diverse coral species. Coral reefs are mostly situated in the neritic region. The Luohuitou coral reef (18°12′N), a typical fringing reef, is located to the south of Hainan Island. The living corals are mainly distributed on the reef slope, where the depth of the water is less than 6 m.

Xisha Islands (15°40′–17°10′N) are located in the northeastern SCS, about 330 km away from Hainan Island. Our survey region includes Qilian Islands (QL), Yongxing Island (YX), East Island (EI), North Reef (NR), Huaguang Reef (HG), Yuzhuo Reef (YZ), Langhua Reef (LH), and Panshi Island (PS). QL is located in the northern part, including ten small islands, and YX and EI are situated in the northeastern part. These are all coral islands formed by coral sands and shells on the reef flat. NR, DR, VR, BR and PK all belong to scattered atolls encompassing small lagoons.

Huangyan Island (HY, 15°07′N), located in the eastern part of the Zhongsha Islands, is surrounded by a long and narrow reef cluster. It is about 890 km away from Hainan Island. It has a triangle-shaped lagoon with an area of about 150 km² and a depth of 10–20 m. Corals are scattered throughout the reef flats and are abundant in the outer reef slopes.

Investigated reef areas in Nansha Islands include Sanjiao Reef (SJ, 10°11′N), Xian’e Reef (XE, 9°22′N) and Xinyi Reef (XY, 9°09′N), all belonging to an enclosed atoll. They are about 1024 km away from Hainan Island. The reef areas of SJ, XE and XY are 10.8, 18.8 and 6.8 km², while the depths of the lagoon are 5–12 m, 5–13 m and 2–5 m, respectively.

Additionally, two transects, extending from an inshore location to an offshore ocean, were designed to explore the nutrient and chl a distribution. One (T1–T1–T8) was from the western Leizhou peninsula to Huangyan Island and the other (T2–1–T2–11) was from southern Hainan Island to Huangyan Island, including some reef areas of Xisha Islands.

2.2 Sampling procedures and analysis

In this study, a total of 127 stations were sampled during May to June of 2015, when the sample sites were influenced by the strong southwest monsoon. In fringing reefs, samples were collected from reef flats and reef slopes. In coral atolls, samples were collected from lagoons and reef slopes. Seawater samples for nutrient analyses were collected at a depth of 2 m using 250 mL Niskin bottles and three replicate samples were taken at each station. Then, the samples were immediately filtered through a 47 mm mixed cellulose ester membrane, stored in polyethylene bottles and frozen at −20 °C until analysis. The surface seawater temperature and salinity were determined with a Conductivity–Temperature–Depth/Pressure (CTD) unit manufactured by Sea-Bird. Dissolved oxygen (DO), pH, turbidity and transparency were also measured with portable devices during seawater sampling. Nutrients (DIN, SRP, and silicate) were determined with a continuous flow analyzer (SEAL QuAAtro).
The precision of this method is about 5% and the detection limit is 0.04 μmol L⁻¹ for nitrate, 0.01 μmol L⁻¹ for nitrite, 0.02 μmol L⁻¹ for SRP, and 0.2 μmol L⁻¹ for silicate, respectively.

Water samples for chlorophyll a (chl a) analysis were immediately filtered through 0.45 μm pore size cellulose acetate filters and then stored at -20 °C. Filters with chlorophyll a were extracted with 10 mL of 90% acetone and stored in a refrigerator for 24 h. After centrifugation (3000 rpm, 10 min), the chlorophyll concentration in the supernatant was measured with a fluorometer.²⁶

2.3 Statistical analyses

A one-way analysis of variance (ANOVA) was used to test the differences of average nutrient concentration among different coral reef areas with SPSS Statistics 19 (IBM Corp., Armonk, NY, USA). Levene’s test, Durbin–Watson’s test, and Shapiro–Wilk’s test were used to assess whether the data met the assumptions of homogeneity, normality, and independence, respectively. Least-significant difference (LSD) was used for post hoc multiple comparisons of significant ANOVA results. The statistical significance level was set at p < 0.05 for all analyses. In addition, redundancy analysis (RDA) was applied to analyze the correlations among environmental factors and coral cover/algae cover with Canoco v. 4.5 (Wageningen University & Research, Wageningen, The Netherlands).

3 Results

3.1 Level and distribution of nutrients and chl a in reef areas of the SCS

The nutrient and chl a concentration varied spatially in the surface water of the SCS reef areas, generally displaying a decreasing pattern with the increasing distance from the mainland (Fig. 2). The highest value occurred in the NSCS, with an average concentration of 2.93 ± 0.49 μmol L⁻¹ for DIN, 0.415 ± 0.13 μmol L⁻¹ for SRP, 14.75 ± 4.72 μmol L⁻¹ for silicate and 1.71 ± 0.18 μg L⁻¹ for chl a. Among three investigated sites in the NSCS, one-way ANOVA results showed that DIN, silicate and chl a levels exhibited a significant difference between LHT and DYB/XW (P < 0.05), while SRP had no difference among the three locations (P > 0.05).

The second investigated region is the coral reefs in Xisha Islands, which are far away from the mainland, approximately 330 km from southeastern Hainan Island. The results revealed that this region was oligotrophic and nutrient and chl a levels were significantly lower than those in the NSCS. However, an exception was found in YX, where nutrient (DIN: 1.98 ± 0.10...

Fig. 1 Sampling sites in coral reefs of the SCS. The investigated area in the entire SCS (a) included Xuwen (b), inshore–offshore transects (c), Daya Bay (d), the Luhuitou fringing reef (e), Huangyan Island (f), Xisha Islands (g) and Nansha Islands (h). The dots in the figures refer to the sampling sites and the two dashed lines referred to the inshore–offshore transects.
μmol L⁻¹; SRP: 0.61 ± 0.01 μmol L⁻¹; silicate: 1.59 ± 0.06 μmol L⁻¹) and chl a (0.67 ± 0.03 μg L⁻¹) concentrations were similar to those in the NSCS. In contrast, water quality was in good condition in the rest of the reef areas.

Huangyan Island, as our target area in Zhongsha Islands, is also distant from the continent, about 890 km from Hainan Island. In our survey, three transects were set to study nutrient distribution in the northern, southern and northeastern part. DIN, SRP and chl a concentrations were the highest in HY02 and the lowest in HY01 (ANOVA P < 0.05), while the highest silicate concentration was in HY03 and the lowest was in HY01 as well.

The most remote survey area is Nansha Islands, which are located in the southern SCS and are around 1600 km from Hainan Island. The nutrient level was relatively low and there was no significant difference among the three reef areas (ANOVA P > 0.05). The total chl a concentration varied widely among the three locations, ranging from 0.14 to 0.59 μg L⁻¹. The average chl a value could be sequenced in the order: SJ > XY > XE (ANOVA P < 0.05).

3.2 Nutrient and chl a distribution in the lagoon and reef slope

Different geomorphological zones in the atolls, such as lagoons and reef slopes, were investigated to explore the distribution characteristics of nutrients and chl a (Fig. 3). It could be found that DIN and chl a concentrations in the lagoon were generally higher than those in the outer reef slopes in all the atolls of the central and southern SCS (ANOVA, P < 0.05). The average DIN in the lagoon was ~1.2 times higher than that in the outer reef slope, while chl a could be 3–6 times higher. A similar

Fig. 2  Spatial distribution of nutrients and chl a in all the reef areas of the SCS. Dissolved inorganic nitrogen (DIN) concentrations (a), soluble reactive phosphorus (SRP) concentrations (b), silicate (Si) concentrations (c), and chlorophyll a (Chl a) concentrations (d) in the surface reef water were analyzed. The numbers in the figure represent the average concentration of each index.
distribution of SRP and silicate was found only in Huangyan Island. There was no significant geomorphological difference in other reef areas.

In order to explore the relationship between phytoplankton biomass and lagoon size, relative data were collected to analyze this correlation. As shown in Table 1, the largest coral atoll (HY and HG) had the highest chl a concentration, while the smallest atoll (SJ) had the lowest chl a concentration. Our results showed that phytoplankton biomass in lagoons was positively correlated with the volume of the coral atolls in the central and southern SCS \( (R^2 = 0.58, p < 0.05) \). This indicated that the lagoon size plays an important role in regulating phytoplankton biomass in coral atolls.

### 3.3 Nutrient and chl a distribution in the transects of the SCS

In this survey, two long-distance transects, extending from the Leizhou peninsula and southern Hainan Island to Huangyan Island, were designed to explore nutrient and chl a distribution from coastal areas to the central basin (Fig. 4). Nutrient contents gradually decreased with the increasing distance from the shore and tended to remain stable in the central basin. This obviously showed that except for DIN of T2-7 in Yongxing Island, the nutrient level was actually low and not significantly different among reef areas, which are located far away from the mainland. Meanwhile, in the central basin, there was an extremely small difference in the nutrient level between coral reefs and non-reef areas.

In contrast, only in the coastal areas and reef regions did the chl a concentration show relatively high values. The maximum chl a content in surface water occurred in southern Hainan Island and was approximately 0.8 \( \mu g \) L\(^{-1}\). The second highest content was about 0.7 \( \mu g \) L\(^{-1}\) in the Leizhou peninsula. Total chl a concentration in coral reefs of the central basin averaged 0.42 \( \mu g \) L\(^{-1}\), which was more than 2 times higher than that in the ambient open ocean, averaging 0.18 \( \mu g \) L\(^{-1}\).

An examination of nutrient and chl a concentration vs. sampling distance from the mainland plots (in Fig. 5) showed that there was a significant negative correlation between nutrient concentration and the distance \( (R^2 > 0.5, p < 0.05) \) and no correlation between chl a concentration and the distance \( (p > 0.05) \). This indicated an obvious nutrient decreasing pattern from the coastal region to the central ocean. Notably, this figure also revealed the exception of two remote reef areas (HY and YX) with relatively high nutrient and chl a levels, probably due to human activities.

### 3.4 Macroalgal cover and living coral cover in coral reefs of the SCS

An ecological investigation was conducted in some coral reefs simultaneously, mainly including the macroalgal/turf cover (MTC) and living coral cover (LCC). These data were published in another paper by a member of our research group.\(^{27}\) Most of the coral reefs had a good growth status in the central and southern SCS, with the LCC higher than 20%. In contrast, coastal reefs and some offshore reefs suffered heavy degradation, with the LCC lower than 12%. It is noteworthy that these degraded coral reefs always have a high MTC, indicating that macroalgal blooms had an inverse impact on coral growth.

Redundancy analysis (RDA) was applied to explore the relationship between the MTC, LCC and environmental factors. Axis 1 explained 89.8% of the total variation and Axis 2 explained 10.2% of the total variation. According to the RDA results (Fig. 6b), several environmental factors significantly influenced the cover status. Firstly, there was an obvious negative correlation between the MTC and LCC, suggesting that strong competition existed between macroalgae and coral reefs. Secondly, nutrients were found to be the most important factor in promoting the MTC, especially SRP. Water transparency and turbidity also influenced the MTC, due to the difference in sunlight attenuation. Temperature, salinity, DO and pH had little impact on cover parameters.

### 4 Discussion

#### 4.1 Sources, distribution and transport of nutrients in coral reef regions

In this survey, all nutrient species in coastal reefs were obviously higher than in offshore reefs. The dissolved nutrient is largely

![Fig. 3 Nutrient and chl a distribution in the lagoon and reef slope of the coral reefs in Xisha Islands, Huangyan Island and Nansha Islands. Concentration data for DIN, SRP, silicate and chl a are mean ± SE. Letters above histograms denote statistical differences among locations (LSD and SNK tests, \( p < 0.05 \)).](image-url)
influenced by human activities in coastal reefs. For example, an estimation of different sources of NH$_4^+$ and TP was conducted in Daya Bay, according to a government report by Huizhou city (http://www.dayawan.gov.cn/pages/cms/dyw/html/news-zfcg). It revealed that nutrient fluxes derived from direct human activities, namely the sum of wastewater and aquaculture (143.2 t per a for NH$_4^+$ and 57.3 t per a for TP), accounted for 44.1% of total NH$_4^+$ fluxes (324.89 t per a) and 46.4% of total TP fluxes (123.34 t per a). Riverine inputs, which are influenced by human activities indirectly, also contributed a lot to the total nutrient fluxes (34.8% for NH$_4^+$ and 42.4% for TP). In addition, the $\delta^{15}N$ values of POM from XW and LHT were 10.30 ± 5.54‰ and 7.06 ± 3.95‰, suggesting that terrestrial-derived sewage also made a great contribution to nitrogen sources in coastal coral reefs. All this indicated the impact of human activities on nutrient levels in coastal reef areas.

In contrast, few human activities occurred in most of the remote reefs, signifying that there were only natural nutrient sources, such as atmospheric deposition, water exchange and internal nutrient regeneration. However, an obvious exception was found in YX and HY, two remote coral reefs. YX is the most eutrophic area compared with other reef areas. In recent years, large-scale constructions and frequent human activities resulted in lots of rubbish and domestic sewage, reaching 1000 t day$^{-1}$ and 300 t day$^{-1}$. A mass of nutrient loads entered into ambient surface seawater through the flushing of rainfall. In HY, the nutrient concentration was high in HY02 located near the lagoon mouth, where fishing vessels always stay and anchor to prepare for fishing activity. During our study period, about 10
medium-sized fishing vessels were observed to stay in the lagoon near the lagoon mouth.\textsuperscript{23} Waste and pollutants originating from sailors were probably discharged into seawater and caused the nutrient increase.

Through the observation on inshore–offshore transects, a significant negative correlation between nutrient contents and distance from the mainland was found. This confirmed that the terrigenous inputs from coastal areas are the primary nutrient sources and the influence of the delivery of terrestrially derived nutrients to the ocean gradually declined with the increasing distance. Therefore, the obvious exception of YX and HY was probably associated to local human activities.

4.2 Larger lagoons are probably more vulnerable to human impacts

In our study, the difference in the nutrient and chl a content between lagoons and reef slopes not only indicated the high productivity in coral reefs, but also suggested that larger lagoons are more vulnerable to human impacts. The positive correlation between chl a concentration in lagoons and the volumes of the coral atolls indicated that the phytoplankton biomass was influenced by the lagoon size. Previous studies stated that the phytoplankton biomass was positively dependent on the residence time of water in coral reef lagoons.\textsuperscript{32,33} Generally, the larger the lagoon, the longer the hydraulic retention time. The structural and functional properties of these lagoons lead to enhanced retention of nutrients within the reef system,\textsuperscript{3} which promotes the growth of phytoplankton. Therefore, phytoplankton overgrowth may develop within the lagoons during intermittent periods when water residence times exceed phytoplankton generation times. Overall, it is hypothesized that phytoplankton overgrowth probably occurs in the atolls with larger lagoons, especially where it is frequently influenced by human impacts (mainly fishing activities), like Huangyan Island and Huaguang Reef.

4.3 The relatively high nutrient level in regional areas may have the potential to damage coral reefs

Nutrient enrichment has been reported to cause coral reefs to decline in some reef regions. Here, a comparison of the nutrient level is made between our study region and other coral reefs to discuss the potential negative impacts of nutrient enrichment. Table 2 reveals that the water quality remained pristine only in the Gulf of Aqaba\textsuperscript{44} and the Great Barrier Reef,\textsuperscript{45} where the state of coral reefs was healthy. Compared with these two regions, DIN in the SCS was approximately 10–20 times higher, indicating that our reef regions were eutrophic. The previous study concluded that the levels of nutrients that may be considered healthy for coral reef ecosystems were approximately 1 mol L\textsuperscript{-1} of DIN and 0.1 mol L\textsuperscript{-1} of phosphate.\textsuperscript{36} As shown in Table 2, it is obvious that the nutrient levels all exceeded this threshold in unhealthy reef regions as well as our study regions. Nutrient concentrations in coral reefs of the NSCS, seemed to be at a risky level, like the southern Bahia\textsuperscript{37} and Caribbean reefs,\textsuperscript{9} where the state of coral reefs is not so healthy due to macroalgal blooms. It was reported that the macroalgal cover reached 50% and the coral cover was only <10% in the reef areas of the southern Bahia.\textsuperscript{37} This situation was similar to the status in DYB, i.e., low coral cover (<10%) and sporadic harmful algal blooms.\textsuperscript{38} The nutrient level in reef areas of the central SCS is similar to that in the Lower Florida Keys\textsuperscript{38} and the Fiji coral coast,\textsuperscript{39} where a phase shift from coral to macroalgae widely occurred. Especially for Yongxing Island, the nutrient level was similar to that in the coastal reef and possibly led to macroalgal overgrowth. These comparisons indicated that the nutrient concentration in our survey region was obviously higher than that in healthy coral reefs, approaching that in unhealthy reef areas, which suggested that the present nutrient level may be a potential threat to coral reefs.

On the other hand, phytoplankton biomass is thought to be a more reliable indicator of the habitat in coral reef ecosystems.\textsuperscript{35,40} Although the chl a threshold for eutrophication in coral reef regions is still under controversial debate, it should range from 0.2 to 0.5 µg L\textsuperscript{-1}.\textsuperscript{36,41} In our study, the chl a concentration was detected to be about 0.6–1.75 µg L\textsuperscript{-1} in degraded coral reefs, obviously higher than the proposed threshold, which indicated that potential eutrophication may occur and may lead to macroalgal blooms. Actually, the results of the field survey showed that the MTC was significantly high in coral reefs where the LCC was very low. In particular, the ratio of the MTC and LCC reached 2.6, 5.4, and 5.3 in LHT, YX and HG, indicating that macroalgae and turf algae significantly dominated these reef areas. RDA results revealed the negative correlation between the MTC and LCC, which suggested that macroalgal blooms could be an important factor causing degradation of coral reefs. Notably, the positive correlation between the MTC and nutrients demonstrated that nutrient enrichment promoted the growth of macroalgae in the degraded coral reefs. All this indicated that the phase shift from abundant coral to abundant macroalgae occurred gradually in these reef areas, due to high nutrient loads. Therefore, anthropogenic nutrient enrichment is an important source of pollution which causes coral reef degradation and should be paid more attention for coral reef resource management.

5 Conclusion

Our survey showed that nutrient and chl a concentrations in coastal reefs and some offshore reefs (Yongxing Island,
Huaguang Reef and Huangyan Island) were high, which was probably due to human activities, such as riverine inputs, aquaculture and sewage discharge. Nutrient levels in the above reefs were comparable to those in other unhealthy coral reefs worldwide. Meanwhile, field survey revealed that macroalgal overgrowth was present in coral reefs which suffered from frequent human disturbance. There was a significant correlation between the nutrient level and macroalgal cover, indicating that elevated nutrient levels resulted in the phase shift from coral-dominated to macroalgal-dominated reef areas. On the other hand, due to the long residence time, macroalgal overgrowth probably occurred in larger lagoons and human activities may aggravate the occurrence of this situation. Based on this evidence, it could be believed that anthropogenic nutrient enrichment has caused a negative impact on coral reefs of the SCS, such as regional macroalgal blooms.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 91428203), the Guangxi Scientific Projects (No. AD17129063 and AA17204074), and the Bagui Fellowship from Guangxi Province of China (2014BGXZGX03).

References

20 M. X. Zhao, K. F. Yu, Q. M. Zhang, Q. Shi and G. Roff, Age structure of massive Porites lutea corals at Luhuitou fringing reef (northern South China Sea) indicates recovery following severe anthropogenic disturbance, *Coral Reefs*, 2014, **33**, 39–44.


