REVIEW

Regime shifts and resilience in China's coastal ecosystems

Ke Zhang

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Abstract Regime shift often results in large, abrupt, and persistent changes in the provision of ecosystem services and can therefore have significant impacts on human wellbeing. Understanding regime shifts has profound implications for ecosystem recovery and management. China's coastal ecosystems have experienced substantial deterioration within the past decades, at a scale and speed the world has never seen before. Yet, information about this coastal ecosystem change from a dynamics perspective is quite limited. In this review, I synthesize existing information on coastal ecosystem regime shifts in China and discuss their interactions and cascading effects. The accumulation of regime shifts in China's coastal ecosystems suggests that the desired system resilience has been profoundly eroded, increasing the potential of abrupt shifts to undesirable states at a larger scale, especially given multiple escalating pressures. Policy and management strategies need to incorporate resilience approaches in order to cope with future challenges and avoid major losses in China's coastal ecosystem services.

Keywords Ecosystem services · Climate change · Tipping point · Social–ecological systems · Fisheries

INTRODUCTION

Regime shifts are defined as large, abrupt, and persistent changes in the structure and function of ecosystems, usually leading to drastic changes in the provisioning of ecosystem services and, therefore, creating significant

impacts on economy and society (Scheffer and Carpenter 2003; Folke et al. 2004). Once a threshold is crossed, it becomes disproportionately difficult and expensive to reverse or restore to the previous state (Scheffer et al. 2012). Regime shifts in coastal and marine ecosystems are increasingly observed at multiple scales worldwide (Möllumann et al. 2015), ranging from the shifts in coral reefs (Hughes 1994) and kelp forests (Steneck et al. 2013) in the Caribbean, to the collapse of coastal oceanic fisheries and plankton communities in the North Pacific (Hare and Mantua 2000), the North Sea (Kirby and Beaugrand 2009), the Baltic Sea (Lindgren et al. 2009), and the Black Sea (Daskalov et al. 2007). Most marine ecosystem regime shifts typically result from complex interactions of multiple drivers; some of which gradually undermine ecosystem resilience (e.g., overfishing), while the others (e.g., acute climate event such as a cyclone or tsunami) give the final impulse for abrupt change (Möllumann and Diekmann 2012; Anthony et al. 2015). In addition to multiple drivers, feedback mechanisms always play a key role in regime shifts by stabilizing undesirable states and hampering the restoration of degraded ecosystems (Nyström et al. 2012). Policy makers around the world face the pressing challenge of incorporating knowledge of regime shift dynamics and characteristics into ecosystem management, in order to maintain coastal marine ecosystems in safe operating spaces, within which society can thrive from local to planetary scales (Rockström et al. 2009; Dearing et al. 2014).

China's coastal environment has experienced unprecedented deterioration within only a few decades, both in magnitude and speed, due to rapid economic development. The coastline of mainland China runs 18 000 km from the mouth of the Yalu River on the China–Korea border in the north, to the mouth of the Beilun River on the China–

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Vietnam border in the south (Liu 2013). These coastal areas and 348 090 km² of seas support nearly half of China's population and 75 % of its major cities (He et al. 2014). The coastal GDP reached 3129 billion US dollars in 2013 compared to only 5 billion dollars in 1952. These accelerating drivers (Fig. 1) have caused dramatic coastal ecosystem change within a relatively short time period. For instance, approximately 80 % of coral reefs and mangrove swamps have disappeared, and 57 % of wetlands have shrunk since the 1950s in China's coastal areas (Hughes et al. 2013; Murray et al. 2014). Adverse socio-economic and ecological consequences of overexploitation of coastal ecosystem have already emerged (Ma et al. 2014).

Despite huge efforts by the central government to reduce these adverse impacts, the overall situation of the coastal ecosystem continues to worsen (Cao and Wong 2007; He et al. 2014). Policy and management practices that ignore the nonlinear dynamics of complex systems are one set of factors that contribute to these failures (Tong et al. 2014). In this context, critical questions for scientists, managers, and resource users alike include: What is the current state of the China's coastal ecosystems from a dynamics perspective; have they already crossed a major threshold; and, if not, how close are they to crossing a threshold if a business-as-usual path continues? Unfortunately, information about regime shifts in China's coastal ecosystems is rare. One reason for limited research on regime shifts is data availability, due to insufficient date coverage for standard analysis developed for regime shift detection (deYoung et al. 2008). However, there is an increasing number of papers discussing these dramatic changes in

China's coastal marine ecosystems, both qualitatively and quantitatively, which include relevant information about the dynamics of ecosystem change. A review and synthesis that addresses the aforementioned questions and their potential implications is needed and timely.

The key objective of this paper is to synthesize and summarize regime shifts in China's coastal marine ecosystem through the twentieth century based on empirical evidences published in both international and Chinese journals. An exhaustive summary of all regime shifts is beyond the scope of this paper; instead, I highlight the most important emerging issues currently facing China's coastal regions. Next, I discuss the temporal consequence of different regime shifts and their possible connections. Finally, I provide suggestions and recommendations for incorporating resilience approaches in China's coastal ecosystem research and management.

REGIME SHIFTS

Shift to eutrophic states

Clear evidence of eutrophication in China's coastal areas starts from 1970s (Fig. 2). Monitoring data indicate that nutrient concentrations have significantly increased between the 1960s and 1980s in the Yellow Sea (Liu et al. 2008). Long-term palaeoecological records (1900–2008) indicate accelerating eutrophic process since 1975 with a significant increase of total organic carbon and total nitrogen (Wang et al. 2013). Phytoplankton assemblages

Fig. 1 Multiple drivers in China's coastal regions since 1950. The magnitude of drivers increased significantly, especially during last 30 years. The data are scaled from 0 to 10, and 10 means the maximum strength of each driver. The original data value range and unites, as well as data sources, can be found in [electronic supplementary material](#)

Fig. 2 Regime shifts in China's coastal ecosystems. **a** Shift from oligotrophic state to eutrophication state around the 1970s. Change of dinoflagellates' sterol concentration (blue diamond) indicates a shift of phytoplankton communities due to eutrophication in Bohai (Liu et al. 2013b). The number of harmful algal blooms (HAB) (red circle) in China's coastal areas increased obviously since 1970s (He et al. 2014). The hypoxic area (green triangle) expands quickly in Changjiang Estuary within last 10 years (Zhu et al. 2011). **b** Principle component analysis of catch fish in China shows fish community shift around 1980s, and mean trophic level also declined during this period (Supplementary materials). **c** Macroalgal blooms since 2008 in the Yellow sea (Table S3). **d** Inshore coral reef coverage in China's coastal region (Hughes et al. 2013). The gray dash lines within each panel are used to symbolically indicate different ecosystem states

shift from diatom-dominant to dinoflagellate-dominant species as a result of the eutrophication transition during the 1970s in different parts of the Yellow Sea (Liu et al. 2010, Liu et al. 2013b). Increasing harmful algal blooms (HABs) are direct results of eutrophication. The scale and magnitude of HABs started to increase rapidly from the 1970s, and the frequency increased three times every 10 years (Yan and Zhou 2004; Wang and Wu 2009). In 1977, a devastating HAB event in the Bohai Sea covered an area of 560 km² and lasted 20 days, causing serious damage to local fishery and mariculture with huge economic losses. More than 322 documented HAB events are recorded between 1952 and 1998. In 2003 alone, the State Oceanic Administration of China (SOA) reported 119 HAB events impacting a cumulative area of 14 550 km² (SOA 2004).

Eutrophication and related microalgal blooms can lead to hypoxic conditions in the coastal marine ecosystem. In the East China Sea, sudden increases in low-oxygen-tolerant foraminifera microfossils since the 1970s suggest that there has been an increase in hypoxic events (Li and Zhang 2012). Observational data show the spread of hypoxic water gradually extended eastward along the continental shelf at the rate of 3.12 km per year during the period from 1975 to 1995, and phytoplankton, zooplankton, and zoobenthos species decreased significantly (Ning et al. 2011). Although hypoxic conditions have occurred previously without anthropogenic nutrient enrichment, the impacted area was probably much smaller than today (Wang et al. 2014). Survey data demonstrate that hypoxic areas outside the Yangtze estuary covered more than 12 000 km² in 2003, which is considered the world's largest hypoxic zone (Chen et al. 2007). Long-lasting hypoxic events can result in successively larger changes in ecosystem functioning, as well as changes in species, biomass, and abundance, often with threshold-like shifts (Villnäs et al. 2012). Hypoxic states can usually be sustained through a positive feedback loop between nutrient release and phytoplankton abundance, during which sediments release nutrients that fuel phytoplankton and further reinforce hypoxia (Conley et al. 2009).

Fish community shifts

The coastal fishery in China has been exploited for thousands of years. Although large changes in fish stocks have occurred ever since the start of marine fishing (Jackson et al. 2001), the recent century, especially after the establishment of new China in 1949, witnessed unprecedented fishing activities both in magnitude and intensity (Table S1). The total marine catch increased from 0.6 million tons in 1950 to 13.6 million tons in 2011. Principle Component Analysis of key marine catch species in China indicates a marked

stepwise increase around 1980s, which indicates a shift from high trophic species to low trophic species (Figs. 2, S1). In Bohai Sea, survey data analysis suggests that there has been a rapid shift of dominant species from highly valued, high-trophic-level, large-sized demersal species with complicated age structures (Liu and De Mitcheson 2008) to low-value, low-trophic-level, small-sized pelagic species with simple age structure (Jin et al. 2013, Shan et al. 2013). In the East China Sea, the mean trophic level has decreased from 3.5 in 1965 to 2.8 in 1990 and the trophic structure of marine catches has shifted to low-trophic-level species since 1974 (Zhao et al. 2005). The large yellow croaker population has still not recovered from the collapse that started in the 1980s even with continuing restoration effort to boost the species (Chen and Fan 2001; Xu and Liu 2007; Liu and De Mitcheson 2008). Current fisheries in the Bohai Sea are mainly composed of crustacean and mollusc, also suggesting another possible structural shift in recent years. Although the government has implemented a series of policies to boost the collapsed fisheries, there are still no obvious signs of recovery (Goldstein 2013). Top predator growth and recruitment can be negatively affected by predation on eggs and larvae of predators, competition for zooplankton prey, and size-dependent growth (Li and Zhang 2012). These prey–predator feedback loops could contribute to stabilizing the collapsed fish communities, impeding recovery.

Shift to jellyfish-dominant states

A significant increase in jellyfish blooms has been observed from the late 1990s. Since then, jellyfish blooms have become an annual event in the Bohai Sea, Yellow Sea, and East China Sea (Dong et al. 2010) (Table S2). *Cyanea capillata* has increased from 0.41 % in 1998 to 85.47 % in 2003 of the total samplings for fisheries in the Yangtze estuary (Xian et al. 2005). The abundance and frequency of blooms of small jellyfish also increased after 2000 throughout the Jiaozhou Bay (Yellow sea), and the dominant species show a significant shift since 2000 (Sun et al. 2011). Jellyfish blooms are a nuisance to local fisheries, tourism, and coastal power plant operations. Multiple explanations have been suggested as possible drivers of the increase of jellyfish blooms in coastal marine ecosystems, including the depletion of predators and competitors of jellyfish through overfishing, eutrophication of coastal waters, increasing numbers of artificial structures associated with coastal development, and climate change (Duarte et al. 2013). Model results suggest that mutual competition and predation between large jellyfish and pelagic fish form positive feedback loops that contribute to jellyfish blooms in the East China Sea (Jiang et al. 2008). Overly abundant jellyfish can consume fish eggs and larva and could exert a top-down effect on pelagic fish recruitment through direct

predations as well as competition for zooplankton (Roux et al. 2013). As jellyfish become more abundant, their recruitment output increases, generating blooms and feedbacks at ever larger scales. These interacting feedback mechanisms, between jellyfish and small pelagic fishes, can result in the stability of jellyfish-dominant states, which may be difficult to reverse (Nyström et al. 2012).

Shift to macroalgae-dominant states

Macroalgal blooms started to increase along the shores of industrialized countries in the 1970s. However, green tide is a recent phenomenon in China's coastal areas (Table S3). Satellite imagery analysis shows that there were negligible floating macroalgae between 2000 and 2007 (Hu et al. 2010). Massive algal blooms occurred in 2008 (3489 km²) in the open waters of Yellow Sea, and since then the macroalgal blooms have become an annual summer event with increasing spatial and temporal scale, with the 2013 event reportedly reaching a record level (Smetacek and Zingone 2013). In 2008, the world's largest green tide caused aquaculture losses of about 130 million USD, and costs for the emergency response to the green tide, before the 2008 Beijing Olympic games in Qingdao, were estimated to be 320 million USD (Ye et al. 2011). Coastal eutrophication is the obvious explanation for the increase in macroalgal blooms. Yet, it is difficult to attribute the cause of green tides completely to eutrophication because massive green tides are a new phenomenon, while coastal eutrophication has been present in the Yellow Sea for decades (Liu et al. 2013c). The underlying mechanisms that stabilize systems in macroalgae-dominant states are complex. Several possible feedback mechanisms are proposed that reinforce the seaweed-dominant state. One is the self-organization character of seaweed species: the over-winter seed sources (propagules) reserved in the sediment from previous blooms offer opportunities for successive, and larger, blooms the following year (Ye et al. 2011; Liu et al. 2013a, c). Nutrient deposited in sediment following degradation of dead seaweeds can be returned to the surface by vertical mixing, which forms the sediment nutrient pool available for algal growth. As a result, seaweed can continue to proliferate and maintain a eutrophic state, even if nutrient input level is reduced substantially (Yabe et al. 2009; Smetacek and Zingone 2013).

Coral reef ecosystem regime shifts

Coral reef ecosystems in China have undergone dramatic transitions within the past decades, from thriving coral states to macroalgae-dominant or nearly barren states. About 80 % of the coral cover on fringing reefs along China's mainland and around Hainan Island has been lost

since the 1960s (Hughes et al. 2013) (Fig. 2). For instance, in the Luhuitou fringing reefs, coral cover declined from 90 % in 1960s to less than 12 % in 2009, and the dominant coral reef species has shifted from *Goniastrea* and *Montipora* to *Porites lutea* on reef flat, while the predominance of *Acropora* on the reef slope weakened significantly (Zhao et al. 2012). The recent mass occurrence of sea cucumber, with a density of 1000 individuals per square meters and covering half of the reefs in Luhuitou possible, indicates another regime shift (Zhang et al. 2014). In the Dongsha atoll, a survey in 1998 found that over 90 % of the reef and its inhabitants had disappeared and were replaced by filamentous algae or macroalgae (Li et al. 2000). High coral cover and grazing of macroalgae promote the production and successful recruitment of juvenile corals, maintaining coral dominance. Otherwise, depletion of herbivores through overfishing promotes dense stands of macroalgae that out-compete corals and inhibit their recruitment (Hughes and Tanner 2000; Elmhirst et al. 2009). Thus, positive feedback mechanisms involving fishing practices can lock coral reef systems into degraded states.

SYNERGISTIC EFFECTS AND CASCADING SHIFTS

Regime shifts in China's coastal ecosystems are increasing and show characteristic temporal patterns. During the 1970s, China's coastal ecosystems shifted to a eutrophic state with increasing HAB and hypoxia events. Fishery communities shifted from demersal species to pelagic species in the 1980s, and recently some communities have shifted further from pelagic species to invertebrate species. Jellyfish-dominant states began in the late 1990s, and macroalgae-dominant states started after 2007. Multiple escalating exogenous drivers cause the increasing number of regime shifts and push different ecosystems into new alternative states, which have been stabilized by the endogenous system dynamics (Fig. 3). Furthermore, different regime shifts can interact with each other, and one single shift in sub-ecosystem could potentially trigger a cascading effect in which multiple regime shifts could be triggered (Kinzig et al. 2006; Pershing et al. 2015). The temporal patterns of the regime shifts in China's coastal ecosystems provide an opportunity to explore their possible connections.

Eutrophication-induced hypoxic conditions not only damage benthic communities, but also reduce reproductive success of top predators and change fish habitats (Zhang et al. 2010). Fish that spawn in hypoxic water layers or demersal-feeding fish suffer losses due to frequently occurring hypoxic events (Carstensen et al. 2014). When the regional fisheries collapsed in the 1980s, due to long-

Fig. 3 System diagrams outlining the linkage and interaction of different ecosystem regime shifts, multiple drivers, and cascading regime shifts. Accumulating shifts in ecosystems can reduce desired system resilience and facilitate other shifts triggered by exogenous drivers or internal interactions. For instance, hypoxic conditions can reduce reproductive success of top predators, and reduced top predator abundances can lead to a cascading increase in phytoplankton (Nyström et al. 2012)

term destructive exploration, the prey–predator feedback superimposed on the anoxia/hypoxia feedback may have together prevented the fish communities from recovering. For instance, survey data indicate that eutrophication and subsequent hypoxia are responsible for the limited recovery of fishery in the trawling-prohibited area of the East China Sea (Gu and Xu 2011; Chang et al. 2012). Meanwhile, overfishing might also have significant impacts on whole marine ecosystem structure and function through trophic cascades (Casini et al. 2009). The removal of top predators by overfishing can increase the vulnerability of ecosystems to coastal nutrient inputs and paves the way for impacts such as eutrophication and algal blooms (Jackson et al. 2001; Lin et al. 2013).

The proliferation of jellyfish, since late 1990s in the Yellow Sea and East China Sea, is facilitated by the reduction of pelagic fish and increasing hypoxia (Dong et al. 2010). Gelatinous plankton can thrive on food that is no longer consumed by fish, and declining fish stocks also reduce predation on gelatinous zooplankton. Survey data analysis suggests an increase of jellyfish that is consistent with the decrease of fish density in the East China Sea and Yellow Sea (Yan and Zhou 2004). Hypoxia could create conditions which favor the growth of jellyfish compared with other species (Zhang et al. 2012; Qiu 2014). Besides increased nutrients (Xing et al. 2015), declining herbivorous fish and zooplankton have reduced grazing pressure, which may have partly contributed the massive macroalgal blooms since 2007 in the Yellow Sea. The positive correlation between jellyfish and chlorophyll a concentration in

the Yellow Sea suggest a cascading effect resulting from the jellyfish grazing on zooplankton that in turn reduce the grazing of zooplankton on phytoplankton (Dong et al. 2012). This has been observed in the Baltic Sea where research revealed that declines in predatory fish promoted blooms of macroalgae with cascading effects down the food web (Eriksson et al. 2009). Additionally, macroalgal blooms could strengthen hypoxic conditions which in turn further degrade the coastal ecosystems (Smetacek and Zingone 2013).

Clearly, interactions among these regime shifts are likely to be far more complex and require more empirical analyses and dynamic model studies to be fully understood. Yet, the internal feedbacks within each shift, and their connections with each other, suggest that synergistic effects could lead to large-scale regime shifts. The feedbacks that stabilize alternative states are not constant; they can change through time, which in theory can facilitate new shifts when the feedback changes (Peters et al. 2004; Yelenik and D’Antonio 2013). Evidence for regime shifts in the highly sensitive, fast-responding coastal ecosystems suggests that some linked elements of the larger system have already been altered. As observed in social–ecological systems of eastern China (Zhang et al. 2015) and elsewhere (Peters et al. 2007), there is an increasing likelihood for internally or externally forced disturbances (e.g., continuing water quality degradation or climate change, respectively) to propagate new interactions between different sectors and across large regions. The evidence presented in this paper suggests that China’s coastal ecosystem might

Fig. 4 Schematic figure shows China's coastal ecosystem shift from a relatively healthy state to a degraded alternative state

have passed a major threshold in the 1970s and is now currently in a transient phase dominated by hypoxia, fewer fish, and frequent algal/jellyfish blooms (Fig. 4). Transient phases of regime shifts are less predictable than stable phases and can be associated with negative impacts (Folke et al. 2010) where ecological responses to stochastic drivers, like climate events, are likely to become less proportionate, less predictable, and less manageable.

INCORPORATING A RESILIENCE APPROACH

Resilience is the capacity of a system to absorb disturbance and re-organize while undergoing changes so as to still retain essentially the same function, structure, identity, and feedbacks (Folke et al. 2004; Walker et al. 2004). Increasing regime shifts in key components of China's coastal ecosystems are symptomatic of the continuous decline of system resilience. Overfishing, nutrient input, habitat modification, and climate change together have created a simplified coastal ecosystem, which can rapidly respond to external influences in an unpredictable way. Loss of resilience, through the combined effects of multiple pressures, can make ecosystems more vulnerable to changes that could have previously been absorbed (Standish et al. 2014) and can increase the possibility that regime shifts might trigger other shifts in the systems. These cascading regime shifts are likely to lead to highly resilient new regimes that are undesirable and often irreversible. Our evidence indicates that the likelihood of more non-linear shifts in the China's coastal ecosystems may increase

as the pressures continue to accumulate, with potentially large social–economic impacts. Management strategies that are focused too strongly on one domain or on one scale are likely to miss the possibility for interactions among regime shifts and the likelihood that a new, resilient, and possibly less-desirable system will emerge (Rocha et al. 2015).

The pressures on coastal ecosystems in China will inevitably increase in the coming decades, both globally through climate change or more locally through overexploitation, biodiversity loss and change, eutrophication, and contamination. For example, the total nitrogen and phosphorous inputs between 2000 and 2050 are expected to increase 30–200 % (Stokal et al. 2014). As a result, abrupt and catastrophic ecosystem shifts are anticipated to increase in strength and frequency. It is, therefore, crucial to incorporate a resilience approach into the management of China's coastal ecosystems, given the escalating and interacting pressures, especially if system resilience continues to decline. Despite extensive restoration efforts and huge amounts of funding, China's coastal ecosystems remain subject to ongoing degradation. For instance, marine pollution has doubled since 2009 and the polluted coastal waters now cover an area of 145 000 km², stretching from Vietnam to Korea (Grumbine and Xu 2013). Large projects aimed at restoring the marine ecosystem have failed or not achieved as much success as expected (Gao et al. 2014). Policy and management strategies based on linear approaches that ignore dynamic interactions normally generate insufficient actions and inevitably lead to more unwanted problems. For instance, some ambitious programs that focussed on only reducing

nutrient input to the Bohai Sea have failed because they did not fully acknowledge the multiple interactions between ecosystems, economics, and society (Tong et al. 2014).

Early integration of a resilience approach into the regulatory structures of China's coastal ecosystem management is needed in order to address the emerging problems associated with complexity and uncertainty. To this end, I propose three major recommendations. First, these complex issues need to be more widely acknowledged through the promotion of more multidisciplinary system research that explores the nonlinear dynamics of ecological systems, especially thresholds and feedback mechanisms that are critical for sustainable coastal development. At present, this kind of research is under-developed across China. Scientists should take advantage of the progress made by the international resilience community and combine it with China's unique social, economic, and ecological contexts in order to test and apply new resilience theories and approaches. Second, improving institutional coordination and co-management of coastal ecosystems is urgently needed. Co-framing problems from a multiple perspective and creating a shared vision are important. This could also be complemented by building comprehensive monitoring and observation systems, improving the sharing of information and transparency between different sectors. Third, the current top-down policy systems in China for coastal management currently lack the vertical integration of ideas and flexibility of action required to cope with uncertainty and change. Adaptive governance is needed to create innovative frameworks that allow for institutional learning and policy reorientation, which can respond promptly and positively to the changing conditions.

CONCLUSION

I summarize and identify regime shifts in China's coastal marine ecosystems, including the shift from oligotrophic state to eutrophic state in the 1970s, from a demersal fish-dominant state to pelagic fish-dominant state in 1980s, from a few-jellyfish state to jellyfish-dominant state in late 1990s, and from a low-macroalgae state to macroalgae-dominant state in 2008. Coral reef ecosystems also show shifts from coral-dominant states to seaweed-dominant or barren states in the last three decades. The temporal pattern of the regime shifts and underlying, reinforcing feedback mechanisms suggest their complex interactions and cascading effect. Escalating pressures in the China's coastal areas could trigger more undesirable regime shifts at large scales as the desired ecosystem resilience continues to decline, which poses a great challenge and threat to the coastal wellbeing and society. Both scientific research and

management strategies should incorporate a resilience approach in order to better cope with future change and uncertainties. Eventually, coastal ecosystem management approaches and tools need to be developed, which account for regime shift dynamics and characteristics, in order to avoid major losses in ecosystem services.

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AUTHOR BIOGRAPHY

Ke Zhang (✉) is a research fellow at the Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University. His research interest lies in understanding the dynamics of coupled social-ecological systems.

Address: Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville, QLD 4811, Australia.

e-mail: ke.zhang1@jcu.edu.au; kezhang01@gmail.com