Continental Shelf Research 57 (2013) 132–142

Contents lists available at SciVerse ScienceDirect

Continental Shelf Research

journal homepage: www.elsevier.com/locate/csr

Research papers

Land–sea interactions at the east coast of Hainan Island, South China Sea: A synthesis

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ARTICLE INFO

Article history:
Received 19 October 2012
Received in revised form
19 December 2012
Accepted 5 January 2013
Available online 15 January 2013

Keywords:
Hainan
Coastal environment
Ecosystem
LANCET

ABSTRACT

The structure and function of coastal ecosystems is affected by land-based human activities, including changes in water, sediment and pollutant input, as well as land reclamation in coastal areas. Many coastal areas can be considered over-stressed systems as a whole, the ecosystem services of which are strongly impaired. This is particularly important in tropical regions, where the coastal zone is under the influence of a strong climate variability including monsoons and frequent extreme weather events, such as typhoons. During the past decades the continuous development of Hainan's coastal zone and its hinterland, in combination with episodic natural events (e.g., typhoons), caused environmental changes in its coastal ecosystems. However, little is known on the consequences of environmental changes for the biogeochemistry and ecology and, hence, the natural resources of the Hainan coastal ecosystems. The Sino-German inter-disciplinary LANCET (land–sea interactions along coastal ecosystems of tropical China: Hainan) project was designed to address these issues on a local to regional scale and at the same time, to contribute to the global data base in which this type of information from tropical regions is still under-represented. The results obtained from LANCET have been delivered to the local government for an adaptive management at the ecosystem level, and the knowledge is believed to be relevant to other studies of tropical and coastal regions.

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1. Introduction

Land-based human activities such as agriculture, deforestation and/or hydraulic engineering (e.g., dam construction) have altered dramatically riverine hydrology, as well as material fluxes to the ocean, entailing consequences such as eutrophication and changes in community structure (i.e., phytoplankton) of coastal and marine ecosystems (Alongi, 2003; LOICZ, 2005; Jennerjahn, 2012). On a regional scale, coastal ecosystems are often under stress due to sewage disposal, destructive fishing practices, aquaculture and tourism (Fabricius, 2005; Huang, 2005). Natural disasters are other hazards to coastal ecosystems which bear the potential of severe damages; tropical storms and flood events are of particular importance, within this context, in the south and southeast Asian region (World Resources Institute, 2011).

The tropical and subtropical coastal ecosystems of the Asia-Pacific Region are affected by substantial changes in both the land and the coastal sectors. They possess an enormous marine biodiversity, but suffer from impacts from a high population density and rapid economic development, a major result of which are the high material inputs from land-based sources (i.e., rivers). Furthermore, tropical and subtropical coastal ecosystems of the Asia-Pacific region are exposed to the above mentioned climatic and oceanic influences, e.g., monsoons. Therefore, these areas are particularly vulnerable to the combined effects of land-based human activities and ocean-/atmosphere-based extreme events. Similar to other tropical environments, fringing coral reefs and related food-webs in the coastal waters of Hainan are of critical importance for the local communities, because of the goods and services they provide, such as fishery resources, coast protection, tourism etc. However, in Hainan, overfishing and destructive fishing practices (e.g., dynamite and cyanide fishing), coastal engineering and brackish water aquaculture have considerably changed the structure and function of fringing coral reefs which, in extreme cases, have caused the extinction of important marine species (Huang et al., 2006). Therefore, knowledge of the status and functions of coral reefs, as well as of the connectivity between individual coastal habitats, is required to manage ecosystem in a sustainable and adaptive way.

Hydrodynamics and climate-related events in meso- and basin-wide scales can modify the function of coral reefs.

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http://dx.doi.org/10.1016/j.csr.2013.01.004

These need to be understood, in order to discriminate between perturbations caused by changes in climate and oceanography and those caused by regional human activities. Off the east coast of Hainan Island, the monsoon drives the seasonal pattern of coastal circulation in surface waters of the South China Sea, for instance, upwelling in summer and down-welling in winter (Su, 1998; Zhang and Su, 2006). In addition, changes in river discharge and material transport to the ocean, as well as the operation of aquaculture can dramatically alter the hydrographic properties and water chemistry in coral reefs and other coastal habitats.

Coastal and marine ecosystems feature a complex mosaic of food web connections. In particular, coastal waters off Hainan embody diverse habitats, including lagoons and estuaries, sandy beaches, mangroves, sea-grass beds and fringing coral reefs. These habitats are key territories for the socio-economic progress of Hainan Island. Over the last 50–60 years, Hainan's coastal zone and its hinterland underwent considerable changes, due to continuously increasing human activities in combination with episodic natural events (e.g., typhoons); this is especially characteristic following the 1980s when China launched the economic innovation and later the establishment of Hainan Province, in 1988. However, little is known on the extent of environmental changes and the consequences for the biogeochemistry and the ecology of coastal ecosystems. Therefore, the interdisciplinary project LANCET was designed to address these issues on a local to regional scale and, at the same time, to contribute to the global data base in which this type of information from tropical regions is still under-represented.

2. Hainan Island: Environmental and socio-economic settings

Hainan Island is located in the northern part of the South China Sea at 18.10–20.10°N and 108.37–111.03°E and it has a surface area of 35.4×10^3 km^2 (Fig. 1). Its climate is dominated by monsoons, with northeast winds in winter (i.e., November to March) and southwest winds in summer (i.e., May to September), with April and October being the transitions between the two monsoon periods. The annual average temperature of Hainan Island is within the range of 22.8–25.8 °C; rainfall ranges between 961 and 2439 mm yr^{-1}, with ca. 80% of it occurring between May and October, when the southwest winds dominate (Statistical Bureau of Hainan Province, 1994–2011). The landscape of Hainan Island is characterized by mountains in the central part, with the Wuzhishan (Note: "shan" means mountain in Chinese) reaching an elevation of 1867 m above sea level, and hills and alluvial plains in the coastal areas. The vegetation is typical tropical broadleaf forests and grass-forbs communities in the high elevation areas (elevation: $>$500–1000 m), scrub-dominated (e.g., evergreen and deciduous dwarf forest) and cultural crops (e.g., rice, corn and sugarcane) landscapes in the lowlands There are coconut trees along the sandy beaches and mangroves, with muddy sediments in the intertidal coastal areas (Committee of Vegetation Map of China, 2007).

Altogether, there are about 100 rivers with a drainage area of over 100 km^2 each, on Hainan, about 40 of these discharges into the South China Sea; they have a total discharge of ca. 31.0×10^9 m^3 yr^{-1}. In this region, 80–85% of the runoff occurs in the rainy season (Committee of Encyclopedia of Hainan, 1999). Rivers on Hainan have a relative short course (i.e., $<$300–350 km) and hence, a high elevation to length ratio (i.e., H/L). For example, Wanquanhe (Wanquan River) (Note: "he" means river in Chinese), on the east coast of Hainan Island, has a river length of 156.6 km and an elevation difference of 523 m (i.e., $H/L = 3.34 \times 10^{-3}$). Concentrations of 55–197 mg l^{-1} for total suspended matter (TSM) are typical for Hainan rivers, which is relatively low compared to the river systems of mainland of

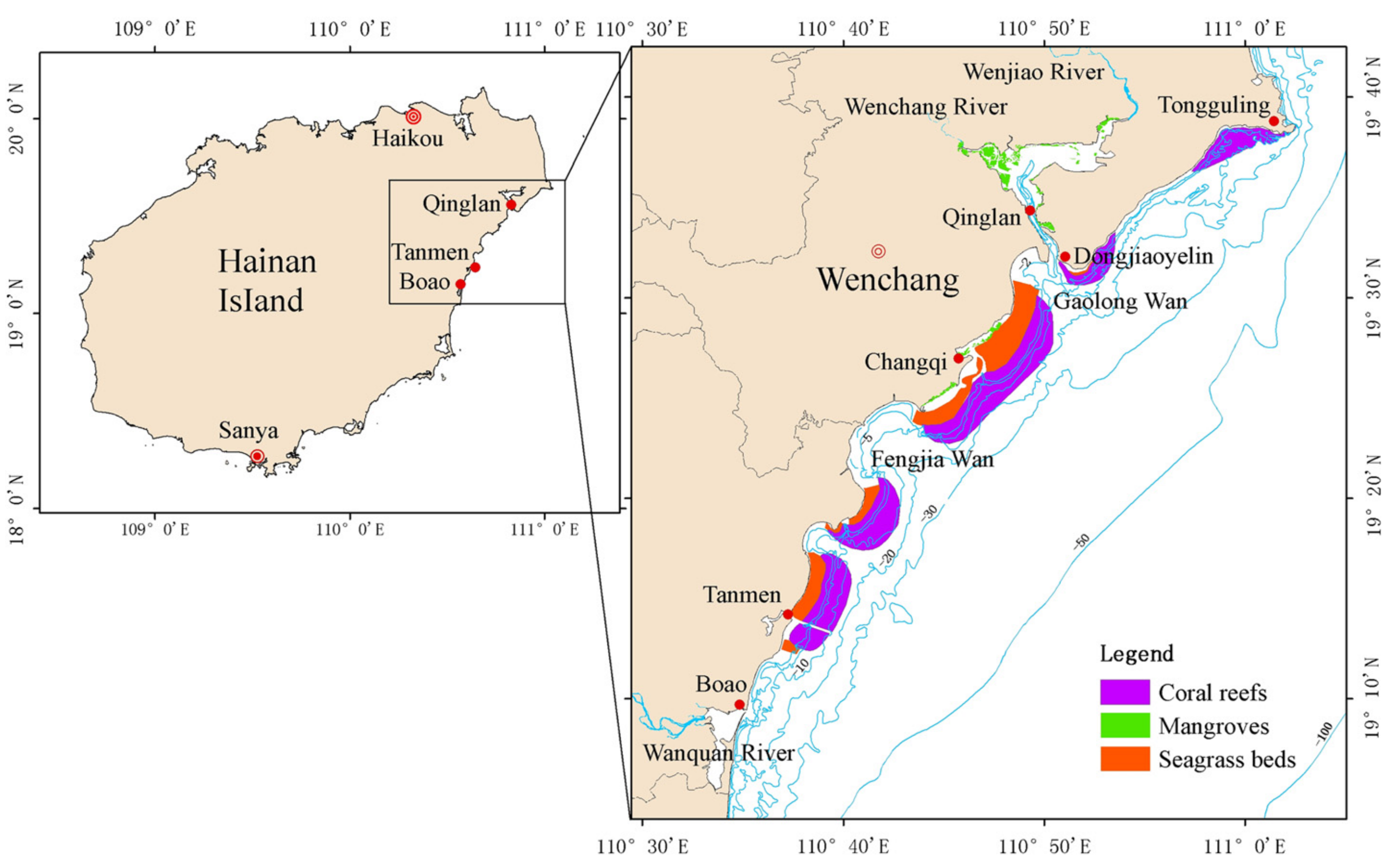

Fig. 1. Study area of the LANCET project, showing the major coastal environments, including mangroves, sea-grass beds and fringing corals.

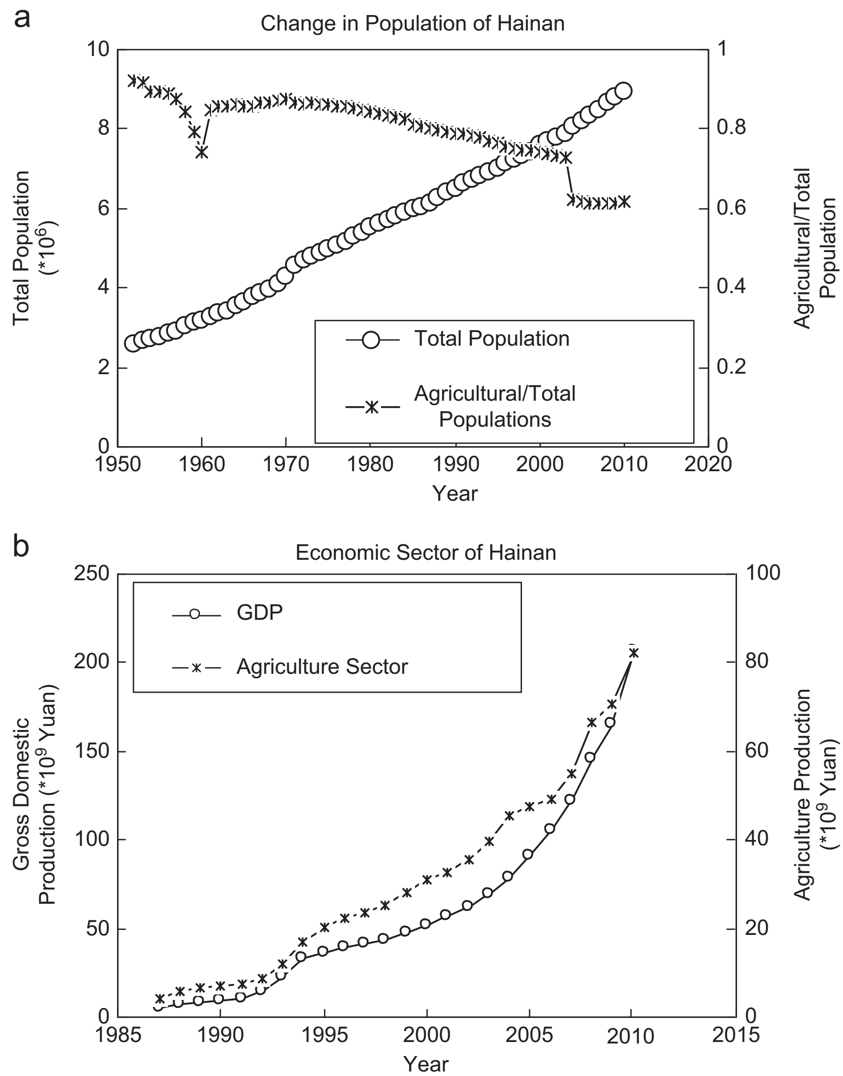

Fig. 2. Change in social and economic aspects of Hainan Island since the 1950s, with population structure (a) and gross domestic product and (b) (Statistical Bureau of Hainan Province, 1994–2011).

China. In the past 3–4 decades, the total riverine sediment load from Hainan amounted to 4×10^{6} t yr^{-1} (Committee of Encyclopedia of Hainan, 1999).

The morphology of the east coast of Hainan Island is characterized by lagoons and tidal channels, sandy beaches and bars, as well as estuaries (Wang et al., 2006). In this region, the tides are characterized by irregular diurnal and semi-diurnal periods. The region is affected frequently by strong cold fronts (i.e., northerly winds) in winter; these may cause intensive vertical mixing in the coastal environment. In the summer, tropical typhoons occur with an average frequency of 8 events yr^{-1} (range: 5–10 events yr^{-1}), over the last five decades (Committee of Data Compilation of Coastal Bays in China, 1999; Shanghai Typhoon Institute, 2006). Historical data show that, within this area, typhoons usually induce heavy rainfalls of up to 500 mm per event and over 50 mm d^{-1} (Shanghai Typhoon Institute, 2006). Due to the monsoon climate, the coastal water circulation off East Hainan is seasonal in character, with northeasterly currents and coastal upwelling in the summer and southwesterly currents in the winter, when the northeasterly winds prevail.

The population of Hainan Island was 2.59 million in 1952, with 92% of the people working in the agricultural sector. In 2010, the population had increased to 8.96 million, whilst the proportion of people working in the agricultural sector dropped to 62% (Fig. 2). The gross domestic product (GDP) of Hainan increased from 5.6 billion Yuan RMB in 1987, to 206.5 billion Yuan RMB in 2010, i.e., more than 30 times greater. The contribution from the agriculture sector dropped from 70 to 80% in the 1980s, to about 40% in 2010 (Fig. 2). The industrial value added another 2.2 billion Yuan RMB in 1987, then increased to 138.1 billion Yuan RMB in 2010. In 1987, the import of goods was 2.5×10^{6} t yr^{-1}, with 5.2×10^{6} t yr^{-1} being exported through cargo ship transportation. This changed to 55.9×10^{6} t yr^{-1} for import and 40.3×10^{6} t yr^{-1} for export, in 2010. The economy of the whole island changed from net export in the 1980s, to net import at the end of the 20th century (Statistical Bureau of Hainan Province, 1994–2011).

The cultivated land of Hainan Island was 344.7×10^{3} ha in the early 1950s, and increased to about 453.3×10^{3} ha in the late 1970s, as a consequence of extensive deforestation for agriculture. In the 21st century, the cultivated area stabilized at $400–440\times10^{3}$ ha (Fig. 3). The cultivation area per capita was about 0.13–0.14 ha in the 1950s and dropped continuously to 0.05 ha per capita in 2010, together with a rapid population rise. The crop production was $1.1–1.2\times10^{6}$ t yr^{-1} in the late 1980s; it reached up to 2.3×10^{6} t yr^{-1} in the late 1990s, then decreased to $1.8–1.9\times10^{6}$ t yr^{-1} in the 21st century (Fig. 3).

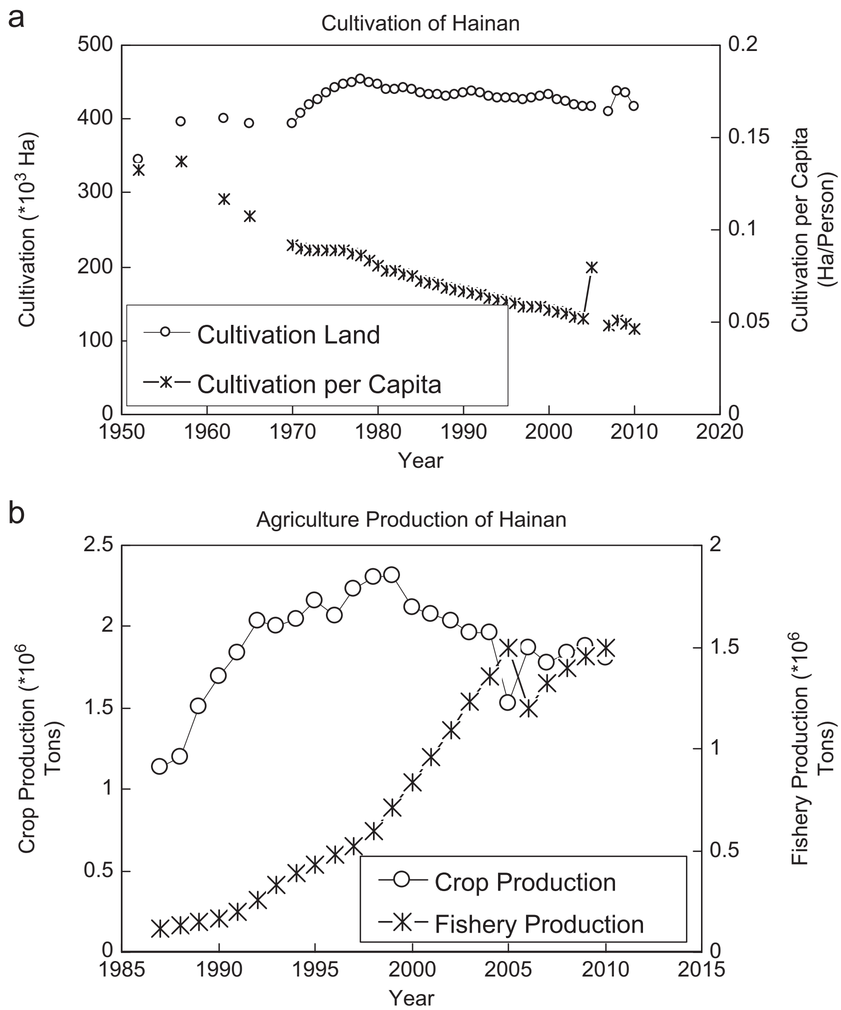

Fig. 3. Evolution of the agricultural sector of Hainan Island over the last 6 decades, showing changes in cultivation land surface (a) and production from crops and fishery activities and (b) (Statistical Bureau of Hainan Province, 1994–2011).

Along with the changes in the agricultural sector, the amount of chemical fertilizer and pesticide applied has also increased over the last 20 years (Fig. 4). For example, in 2010 the application of chemical fertilizers amounted to 327×10^3 t yr^{-1} for nitrogen, 256×10^6 t yr^{-1} for phosphorus, 144×10^3 t yr^{-1} for potassium and 448×10^3 t yr^{-1} for compound fertilizers, respectively. The overall application of pesticides was 17.3×10^3 t yr^{-1} in 2010 (Statistical Bureau of Hainan Province, 1994–2011).

Fishery production increased almost continuously from 0.11×10^6 t yr^{-1} in 1987, to 1.50×10^6 t yr^{-1} in the period between 2005 and 2010 (Fig. 3). Hence, the ratio between fishery and crop productions increased from 0.1 in 1987 to 0.8 in 2010. Moreover, over the last 50 years, there has been a dramatic change in marine fishery production in Hainan Island. The fishery production from the marine sector was 61.9×10^3 t yr^{-1} and 0.21×10^3 t yr^{-1} from aquaculture supply, in 1962; in the first 10 years of the 21st century, the marine fishery production was up to $1.10–1.20\times10^6$ t yr^{-1} and an additional 0.22×10^6 t yr^{-1} from aquaculture supply, with a ratio of aquaculture supply to fishery production of 0.003 in 1962 and 0.19 in 2010 (Fig. 5).

The surface area for marine aquaculture increased from 0.2×10^3 ha in 1957, to 14.5×10^3 ha in 2010. Of Hainan's total surface area used for brackish water aquaculture in 2010, 19.9% were for fish, 62.5% for crabs and shrimps, 8.4% for bivalves and 8.9% for algae and seaweeds (Fig. 6). Another potential human impact on the coastal and marine ecosystems is the change in fishing activities. The total number of fishing boats on Hainan amounted to 8.9×10^3 in 1983 and to 24.8×10^3 in 2010, i.e., a three-fold increase. The fish catch was 12.6 t per ship in 1987 and 60.3 t per ship in 2010 (Fig. 7).

It can be expected that such a rapid growth in the economy and the related changes in the human life style (e.g., structure of society) have impacts on the adjacent coastal and marine ecosystems. The statistics obtained from the Hainan Provincial Government indicate that total industrial wastewater discharge from the whole of the island was 99.5×10^6 t yr^{-1} in 1993; it reduced to 57.8×10^6 t yr^{-1}, in 2010. However, in the meantime, the proportion of direct seaward discharge of industrial wastewater increased from 13.6×10^6 t yr^{-1} in 1993, to 21.9×10^6 t yr^{-1} in 2010. The ratio of direct seaward, to total industrial wastewater discharge, was 0.14 in 1993 and 0.4–0.5 at the beginning of this century (Fig. 8).

Thus, information derived from statistics provided by the Provincial Government indicates that changes in land-based activities (e.g., the application of chemicals in agriculture, seaward discharge of wastewaters), the growth of the aquaculture sector and overfishing can be categorized as major human impacts; these may have altered the structure and functions of the coastal and marine ecosystems of Hainan Island.

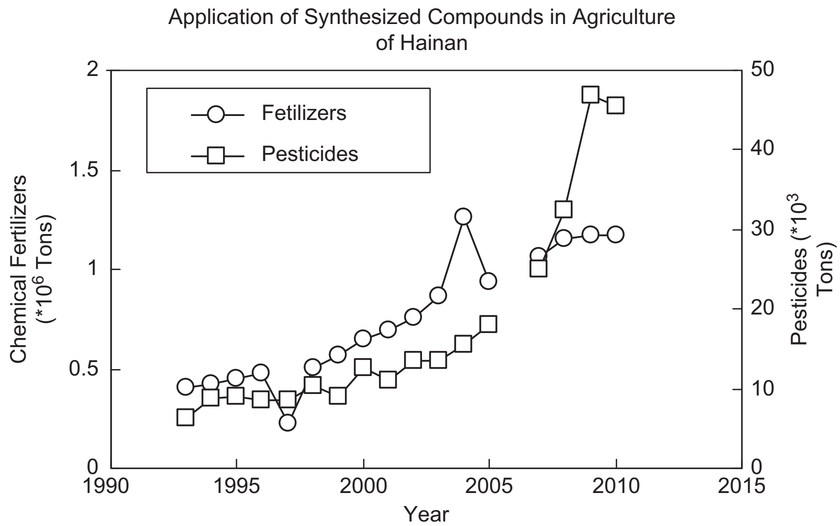

Fig. 4. Application of chemical fertilizers and pesticides in the agriculture of Hainan Island (Statistical Bureau of Hainan Province, 1994–2011).

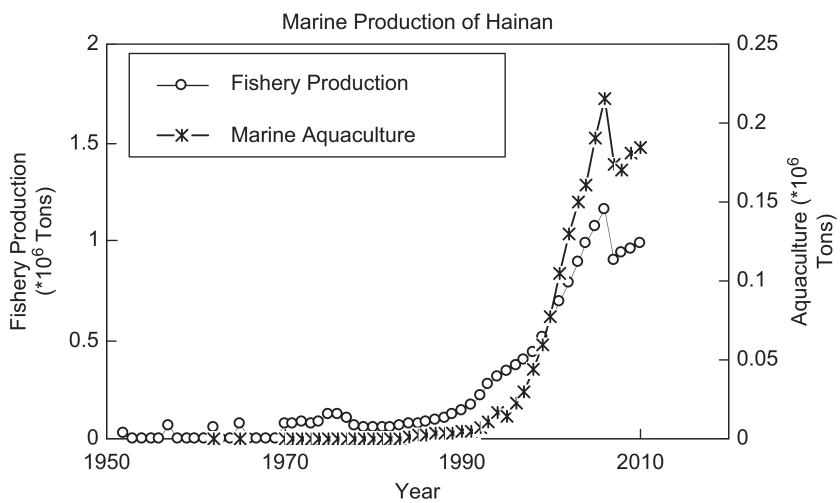

Fig. 5. Comparison of production from fish catch and marine aquaculture (Statistical Bureau of Hainan Province, 1994–2011).

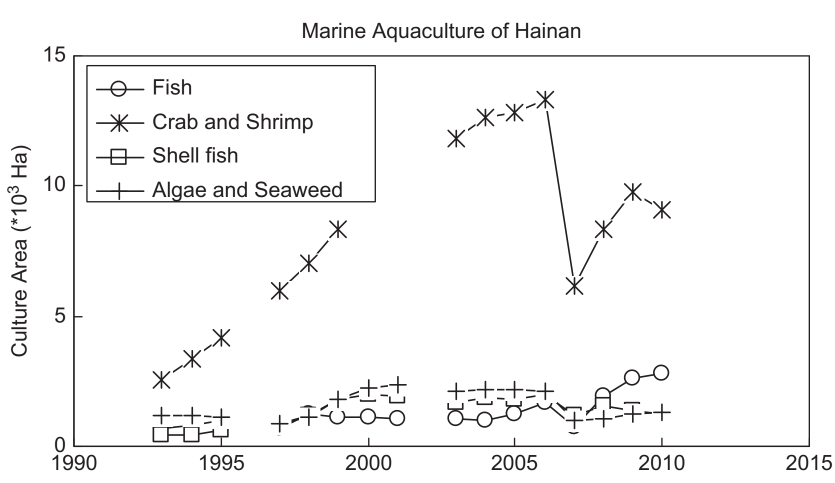

Fig. 6. Proportion of coastal surface areas used for marine aquaculture, including crabs and shrimps, fish, algae and seaweed, and bivalves from Hainan Island (Statistical Bureau of Hainan Province, 1994–2011).

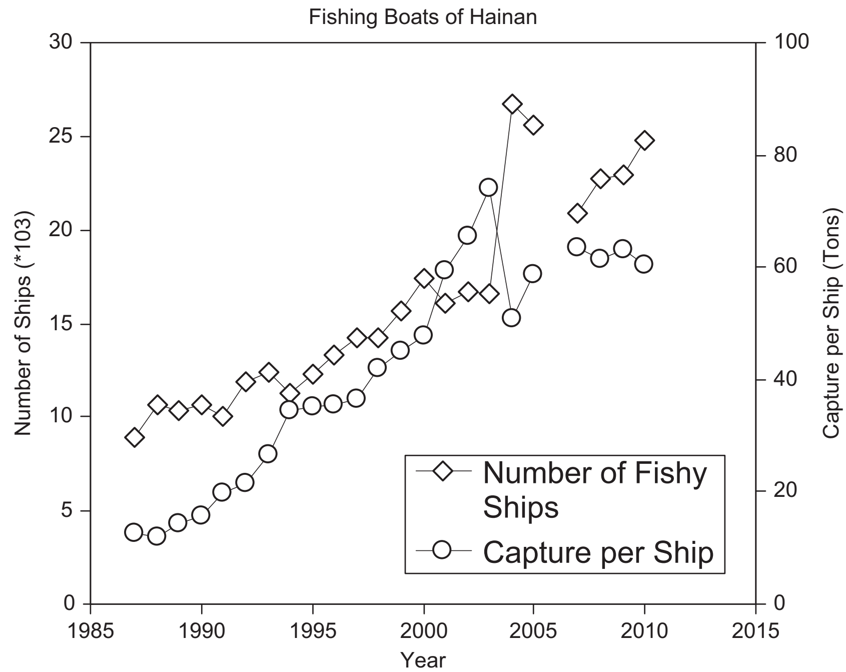

Fig. 7. Number of fishing boats and catch per ship over the last 3 decades (Statistical Bureau of Hainan Province, 1994–2011).

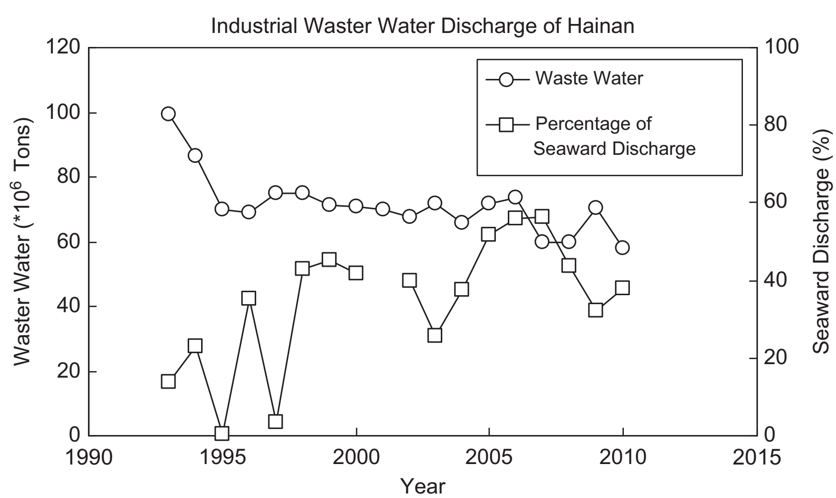

Fig. 8. Trends in industrial wastewater discharges and proportion of direct seaward discharge from Hainan Island (Statistical Bureau of Hainan Province, 1994–2011).

3. The LANCET project

The LANCET (land–sea interactions along coastal ecosystems of tropical China: Hainan) Project (2006–2011) was developed within the scope of a Sino-German cooperation, for improving scientific knowledge on land–ocean interactions in tropical regions, using Hainan as an example. The project was focused on the influences of land-based fluxes and coastal hydrodynamics on the biogeochemistry and ecology of estuaries, coastal bays and other marine habitats (e.g., fringing reefs, mangroves and sea-grass beds); together with their response to external forcings, on a regional scale. Within this interdisciplinary cooperative project, ecological studies included: the investigation of the status of coral reefs and sea-grass beds, as well as the composition of fish assemblages; and their linkages between different coastal habitats. Human impacts were tracked by biogeochemical investigation of pollutants, nutrients and organic matter fluxes. Oceanographic measurements and numerical model studies helped to understand the effects of varying upwelling intensity and changing riverine influx on the physical, chemical and biological properties in the coastal environment (Fig. 9).

The fieldwork of LANCET was carried out on the east coast of Hainan Island, from Tongguling in the north to Sanya in the south; here, several estuaries and coastal lagoons, with mangroves, fringing coral reefs and sea-grass beds are located in the immediate vicinity (Fig. 1). In order to ‘untangle’ the complex interactions at the land–ocean interface in this tropical region (e.g., Hainan Island), LANCET was divided into five cross-linked components, i.e., five subprojects (Fig. 9). Field observations and sample collection were undertaken between 2006 and 2010, covering different monsoon periods (Table 1). The major objectives of the five subprojects are as described below.

3.1. Subproject 1: Present status and regulatory functions of Hainan coral reefs

To understand and assess the present status and regulatory functions of coral reefs and their interdependency with adjacent habitats and external pressures. Knowledge on this topic is crucial to predict resilience, against natural and anthropogenic disturbances.

3.2. Subproject 2: Status of the shallow water fish assemblages

To understand the composition and movement of fish assemblages, between coastal habitats in close proximity, including mangroves, sea-grass beds, sandy beaches and coral reefs. Although some studies have demonstrated connectivity between coastal shallow-water habitats, the understanding of such a connection is still in its infancy, especially in Southeast Asia.

3.3. Subproject 3: Controlling processes and variability of upwelling, adjacent to the Hainan coast

To understand the influence of upwelling on the physical, chemical and biological conditions in the coastal zone offshore of Hainan, with particular emphasis on the interaction between the boundary currents and bathymetry (e.g., topography).

3.4. Subproject 4: Inorganic and organic pollutants in estuarine and coastal environments of Hainan Island

To understand transport, transformation and fate of land-derived pollutants in coastal waters offshore of Hainan. Pollutants are transported mainly in association with natural ligands, colloids and suspended particles, whose composition are usually only poorly known. Analysis of heavy metals and PAHs, together with selected natural components/carriers, was undertaken to understand transport mechanisms from land to the coastal ocean, as well as modification processes; these include changes in redox speciation, transfers between size classes, and the different magnitudes of removal and/or regeneration.

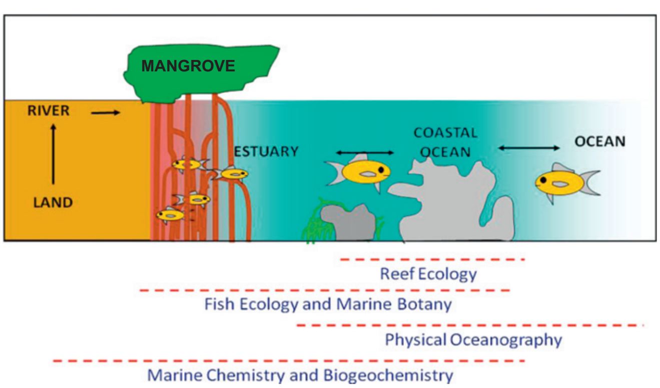

Fig. 9. Conceptual model of LANCET, showing an overview of the habitats of the study. (Adapted from Mumby et al., 2004).

3.5. Subproject 5: Fluxes and transformation of nutrients and organic matter from watershed to the coastal environment off Hainan

To assess the effects of anthropogenically-modified fluxes of land-derived nutrients and organic matter, on water quality, biogeochemistry and the ecology of Hainan's coastal zone. Human intervention on land alters river water quality and the biogeochemistry of receiving coastal waters which, in turn, affect the health and regulatory functions of bordering coral reefs and sea-grass beds. For example, sewage effluents from point and non-point sources alter the natural pattern of riverine carbon and nutrient fluxes, with deleterious effects on coastal habitats.

4. Synthesis of the LANCET results

The 12 articles in this special issue of Continental Shelf Research cover the major aspects of scientific knowledge generated in the LANCET project, e.g., from hydrodynamics and biogeochemistry, to the food web structure and ecosystem function of the east coast of Hainan Island. Here, we summarize and synthesize the results of the project, which are described in detail in the individual articles of this Special Issue.

4.1. Hydrodynamics and sedimentary dynamics

The upwelling offshore the east coast of Hainan Island is the prominent oceanographic phenomenon in the summer, when the southwest monsoons prevail in the South China Sea. The hydrographic observations indicate that upwelled water can reach as close as ca. 5–10 km offshore and as shallow as 5–10 m, sometimes even to the surface under the dominance of southerly and southwesterly winds, bringing up rich inorganic nutrients, relative to the oligotrophic surface waters offshore (Su and Pohlmann, 2009). The distribution and magnitude of upwelling in this region, as derived from field observation and satellite images, can be affected by the water circulation on the continental shelf and the topography, in combination. Moreover, it was found that changes in the hydrographic properties (e.g., temperature and salinity) off the east coast of Hainan Island are related to ENSO dynamics; these can be influenced, in turn, by regional scale variability of the western boundary current system (Su et al., 2012). In summer, the riverine freshwater plumes lead to stratification of the water column, but the plumes are confined to the coastal areas with waters of 20–30 m depth, hence, having only limited impact on the upwelling farther offshore (Su et al., 2011).

Table 1
Field observations within the frame of LANCET, showing the geographic coverage of individual campaigns with information on in-situ measurements and sample collections.

Campaigns	Season	Description of field observations
December 2006	Winter monsoon	Fieldwork was limited to the Wanquan River Estuary, Bamen Bay, and coastal waters with a depth of up to 20 m.
August–October 2007	Summer monsoon	Fieldwork was undertaken simultaneously in the rivers and estuaries, as well as in the coastal environment, up until a water depth of 100 m; tropical cyclones "Franscico" and "Lekima" hit the island during this fieldwork.
July–August 2008	Summer monsoon	Fieldwork was undertaken simultaneously in the rivers and estuaries, as well as in the coastal environment, up until a water depth of 100 m; the tropical storm "Kammuri" passed the region during the fieldwork.
March–April 2009	Transfer period between winter and summer monsoons	Fieldwork was undertaken simultaneously in the rivers and estuaries, as well as in the coastal environment, up until a water depth of 100 m; heavy rainfalls and thunderstorms were encountered during the fieldwork.

Particulate active nuclides (e.g., ^{7}Be, ^{210}Pb$_{ex}$, ^{234}Th$_{ex}$ and ^{137}Cs) were used to denote the character of the sedimentary dynamics on the east coast of Hainan, which is affected by terrestrial fluxes and coastal currents (Huang et al., 2012). Upwelling and coastal currents appear to be the dominant factors controlling the transport and distribution of the surficial sediments, i.e., suspended particles can be transported from south to north, by coastal currents, then carried shoreward by coastal upwelling. Based upon the constant activity (CA) model and ^{210}Pb$_{xs}$ profiles, with depth in sediment cores, the deposition rate is estimated to be 1–4.5 mm yr^{-1}, off the east coast of Hainan (Huang et al., 2012).

4.2. Distribution and behavior of nutrients and trace elements

With regard to dissolved inorganic nutrients, rivers (e.g., Wanquan River) on the east coast of Hainan had moderate nitrate and phosphate levels, but higher concentrations of ammonium and silicate in the aqueous phase, compared to the aquatic systems of the Chinese mainland (Zhang, 2002). In the Wanquan River, 10–30% of total dissolved nitrogen (TDN) consisted of dissolved organic nitrogen (DON). Dissolved organic phosphorus (DOP) accounted for 40–90% of the total dissolved phosphorus (TDP). Molar ratios of dissolved inorganic nitrogen, to dissolved inorganic phosphorus (i.e., DIN/DIP) and dissolved Si/DIN in the freshwater end-member of the Wanquan River Estuary, were 60–90 and 5–10, respectively (Li et al., 2012). In the Wanquan River Estuary, dissolved nitrate and silicate displayed conservative mixing with nutrient-poor seawater, along the salinity gradient, whilst ammonium and phosphate were removed from the water column, most likely in response to uptake by phytoplankton.

In the Wenchang/Wenjiao River and Bamen Bay, nutrient levels of the freshwater end-member displayed seasonal variations. Similar to the Wanquan River Estuary, Bamen Bay is enriched in DIN and depleted in PO_4^{3-}; and the DIN/DIP ratio varied from 60 to 410. In Bamen Bay, DOP represented ca. 65% of TDP and DON accounted for 40–75% of TDN. Dissolved silicate was lower than average levels for other tropical systems (Jennerjahn et al., 2006; Liu et al., 2011). Moreover, NH_4^+ and PO_4^{3-} levels had an estuarine maximum within the salinity range of 5–20 in the Bamen Bay, whereas nitrate and dissolved silicate were removed from the water column by biological uptake (cf. Liu et al., 2011; Herbeck et al., 2012).

Among the trace elements, dissolved arsenic in river water from the east coast of Hainan was 5 nM on average, which is lower than the ca. 15 nM for the open waters of the South China Sea. About 80–90% of the dissolved As was found within the fraction <5 kDa (i.e., "truly dissolved" form), whilst 10–20% were found to be attached to colloids (Balzer et al., 2012). The levels of other dissolved trace elements (i.e., Cd, Cu, Fe, Pb, and Ni) were comparable to those from the mainland rivers of China, except for Fe and Co, which had higher levels (Zhang, 2002). In the estuarine mixing zone, Cu, Co and Ni behaved conservatively along the salinity gradient. Dissolved Fe and Pb showed a negative deviation from the theoretical mixing curve in the estuarine zone, indicating scavenging. Cd displayed a positive deviation from the mixing line, resulting from remobilization and combination with chloride in the water column (Fu et al., 2012). Concentrations of particulate trace elements in rivers from the east coast of Hainan Island are within the same range as those from other systems in China (cf. Fu et al., 2012).

4.3. Sources and distribution of organic matter

Dissolved organic carbon (DOC) concentrations in river waters ranged between 150 and 200 μM, whilst the proportion of particulate organic carbon (POC) in the river was ca. 5% of TSM. A considerable dilution of DOC and POC, together with the dispersal of brackish water plumes offshore, was found (Wu et al., 2012). In the coastal water column, POC was correlated significantly with chlorophyll a. Furthermore, $\delta^{13}C_{org}$ and the OC/TN ratio (i.e., organic carbon/total nitrogen) illustrate that particulate organic matter is a mixture of land-derived and in-situ produced organic materials. Tropical cyclones during the SW Monsoon period in this region induced heavy floods, which were found to play an important role in the export of organic carbon, from the land to the ocean. It was estimated that riverine DOC and POC fluxes to the ocean, induced by a single typhoon event, can account for 10% of the annual flux delivered from this region to the South China Sea (Wu et al., 2012).

Particulate amino acids (AA) and hexosamines were studied, to discriminate between riverine organic matter and in-situ produced labile marine organic matter in coastal waters. A pulsed export of degraded soil organic matter, from the watersheds to the South China Sea following heavy rain falls (e.g., tropical cyclones) in summer, was observed; this is indicated by amino acids and hexosamines compositions. In contrast, a dominance of refractory marine organic matter, in winter and spring, was found in the offshore region (Unger et al., 2012). The production of freshwater organic matter is fueled by anthropogenic nutrients from the catchment areas which, upon entering the coastal environment, can be recycled, consumed and/or stored; eventually, it may affect adversely sea-grass beds and fringing coral reefs (Unger et al., 2012).

Sediment cores collected from a mangrove tidal flat on the east coast of Hainan recorded land use changes over a time span of ca. 100 years. Bulk parameters of organic matter (i.e., POC%, TN%, $\delta^{13}C_{org}$ and δ^{15}N), as well as biomarkers including lignin phenols, fatty acids, alkanes and amino acids (AA), were measured to trace the sources and diagenesis of organic matter. Based upon ^{210}Pb$_{ex}$ chronology and biomarker data, it was found that labile fatty acids were degraded efficiently in the upper parts of sediment cores, corresponding to a deposition phase of 8–10 years, whereas refractory organic components (e.g., lignin phenols) did not show any significant decomposition (Bao et al., 2012). A comparison of AA/lignin phenol ratio from sediments, with those of fresh and terrestrial plants, helped to verify that aquatic organic matter is a significant source of the organic materials in the sediment record. Changes in the composition of lignin phenols in the sediment cores indicate that the contribution of mangrove forests, to the organic matter pool, decreased over the last 3–4 decades; this is related to the extensive deforestation of mangroves and conversion of the area to brackish water aquaculture. This is corroborated by the high δ^{15}N data in the upper part of the sediment core that indicate a high input of sewage and aquaculture effluents (Bao et al., 2012).

4.4. Natural and anthropogenic perturbations of the coastal ecosystem

As mentioned above, brackish water aquaculture is relatively common in the eastern coastal areas of Hainan; it has been estimated that ca. 10 km^2 of the island's surface area is covered by shrimp and fish ponds (Hainan Marine and Fishery Department, 2011). Most of the aquaculture effluents are rich in dissolved nutrients and organic matter and are discharged into the adjacent coastal environment without treatment. Inputs from aquaculture caused eutrophic conditions in the coastal waters of East Hainan and concentrations of nutrients in the water column can exceed the threshold values for 'good water quality' in China. Aquaculture effluents that were discharged into the coastal lagoon of Bamen Bay may have less deteriorating effects to the marine food web, than those emptying directly into open shelf waters. This is presumably due to the filter function of Bamen Bay, that reduces the nutrient export to coastal waters considerably. For comparison, direct discharge of aquaculture effluents into the back-reef areas can be particularly harmful to sea-grass beds and coral reefs, due to eutrophication and habitat competition from an increased algae biomass (Herbeck et al., 2012). Wang et al. (2012) observed that hermatypic coral distributions in fringing reefs off the Eastern Hainan Coast (e.g., Changqi) are affected by radiation and coastal hydrodynamics; the former is regulated by the change in turbidity and the latter by wave propagation from the open South China Sea and wind stress. In near-surface waters (i.e., 2 m water depth), strong wave perturbation prevents the recruitment of larvae, resulting in a low abundance of corals; then corals become more abundant and reach a maximum in distribution at a depth of 5–10 m. Further down the water column, coral communities showed a progressive decrease in abundance, because of light limitation (Wang et al., 2012). The depth at which different forms of corals (e.g., ramose and lumpish corals) reach their peak abundance is determined by the effects of wave action. Waves in shallow waters can generate vertical mixing of water parcels, with different nutrient levels and the resuspension of bottom sediments. High waves (e.g., during the typhoon periods) can break down already damaged corals, but do not destroy the whole of the coral community. On the east coast of Hainan Island, regular and orderly community structure of hermatypic coral is a characteristic of the large-scale spatial distribution pattern of the communities; at small spatial and temporal scales, the microhabitat influences the structure of the community (Wang et al., 2012).

In the fringing reefs off the east coast of Hainan, the overall density of the mobile macro-fauna is low and key functional fish groups are rather limited in the number of species and biomass (Roder et al., 2012). Moreover, mortality and tissue degradation of corals are common and an intensive algal growth was observed. These results suggest that eutrophication and destructive fishing practices are the main drivers of the unfavorable situation for coral survival. Although at the organism level corals are able to cope with these stressful conditions, a shift on the ecosystem level, from a coral reef to a macro-algae dominated community, can be expected in this region if the land-based anthropogenic perturbations continue to increase (Roder et al., 2012).

The overexploitation of marine resources has a great impact on the Hainanese society, together with a change in the traditional fishing techniques (e.g., lift nets), which have been used for many decades, to destructive fishing activities (e.g., dynamite/cyanide fishing). Although the lift-net fishing has less deteriorating influences on the coastal habitats, compared to destructive and mobile fishing methods such as trawling, the non-selective catch by lift-nets can induce a degradation of the community stock at the early life stages of the fish species. This set of conditions is of particular importance during the summer moratorium periods, when offshore fishery by trawls is banned (Krumme et al., 2012).

5. Major findings of LANCET and recommendations for a sustainable management of Hainan's coastal resources

During a final synthesis Workshop in Shanghai, in September 2011, the output of the project was evaluated. Here, we summarize the major findings of LANCET and present recommendations for the sustainable management of Hainan's coastal ecosystems, derived from our newly-acquired understanding of the ecosystem structure and functions, under anthropogenic as well as climate pressures.

5.1. Major findings

- The concentrations of heavy metals in water, suspended particulate matter and sediments from the two riverine systems (i.e., Wanquan River and Wenchang/Wenjiao River) investigated in East Hainan were relatively low; this suggests that no adverse effects on the health of corals and sea-grass beds are expected.
- The effluents from aquaculture facilities, which are located along the NE coast of Hainan, are a major source of nutrient and organic matter pollution; they affect, at least, nearshore coastal waters/back reef areas. Extreme weather events such as typhoons, by inducing strong pulses of freshwater, nutrient and sediment inputs into coastal waters, can amplify the adverse effects of land-derived substances on sea-grass beds and fringing coral reefs.
- Deforestation of mangroves, for the construction of aquaculture facilities, has reduced the buffer functions of this habitat, that could otherwise filter out a large amount of land-derived substances with adverse consequences on sea-grass beds and coral reefs (e.g., loss of nursery grounds and shelter for fish species).
- Eutrophic conditions have been observed in sea-grass beds/back-reef areas and in the immediate vicinity of the river mouths; they enhance the growth of epiphytes, on sea-grasses and corals. Additionally, the decomposition of the high biomass/organic matter produced can induce potential oxygen depletion. Both can impair the performance of sea-grass beds and corals, or even lead to a die-off.
- Overexploitation of fisheries resources is responsible for a low abundance of grazing fish species, which otherwise would control the growth of epiphytes on sea-grass and of filamentous algae in coral reefs.

5.2. Recommendations

- It is suggested that a management of aquaculture facilities is implemented and knowledge is provided for the proper running of the facilities, in order to reduce the input of nutrients and pollutants from aquaculture effluents. A feeding management tailored to the needs of the cultivated organisms, i.e., reduction of feed, may reduce the cost to farmers of feed and may reduce the load of nutrients and organic matter. Furthermore, a treatment of aquaculture effluents should be implemented.
- Since the summer months are the major growth period of juvenile fishes in shallow and inshore nursery grounds, incentives for the artisanal fisheries to reduce fishing down the food-web of the near-shore stocks could be useful. This approach requires that the Local Government addresses the driving aspects of overfishing and mitigates the depletion of inshore resources. Destructive fishing methods, such as dynamite and cyanide fishing should be avoided.
- Additionally, restoration of mangroves in this region needs to be undertaken, because: (i) it would increase coastal protection against physical damage from storms; (ii) it would provide nursery grounds for sea-grass and coral reef organisms; and (iii) sediments, nutrients and other pollutants can be prevented from entering the coastal waters. Monoculture is not recommended as it cannot provide the full services mentioned above.
- Following the expansion of tourism in Hainan Island, sustainability and health of the coastal ecosystems are of major

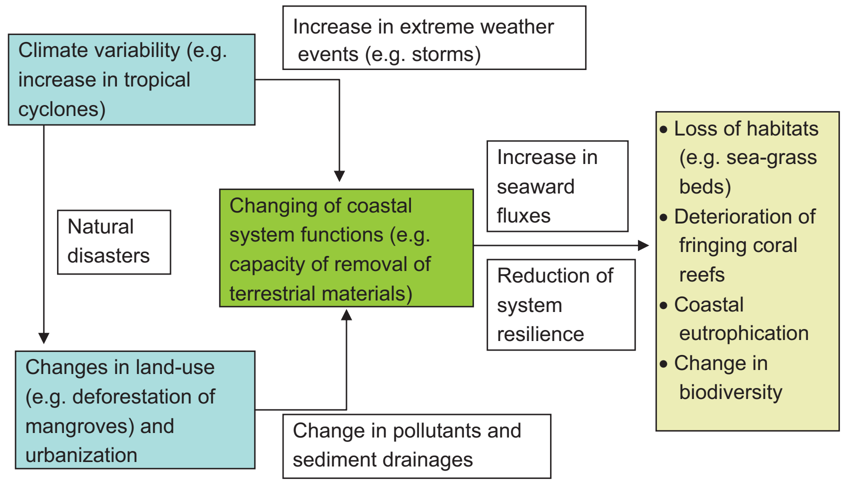

Fig. 10. Conceptual illustration showing how the coastal ecosystems off the East Hainan have been impacted upon by climate variability and human activities. In the Figure, light blue boxes indicate external forcings, the green box means ecosystem response, the yellow box shows the expected consequences to the coastal environment, whilst the white boxes display the known mechanism through which the impact can produce a result. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

economic value and attraction. Hence, conservation of coral reefs, sea-grass beds and mangroves and a sustainable use of their natural resources are mandatory.

In summary, the east coast of Hainan Island is under the combined effects of land-source influx that is modulated by human activities and the marine sector (e.g., coastal circulation); both are impacted upon by the monsoon climate with episodic events (e.g., typhoon) which, in combination, have induced changes in the functions of the adjacent coastal ecosystem (e.g., reduction of buffering capacity for pollutants, because of shoaling of the coastal lagoon) through complex inter-links and forcing—response mechanisms (Fig. 10). From a stakeholder's point of view, there are three other issues to be addressed in future studies, as outlined below.

- Future climate change and the planned economic innovation in the region will impose upon the already over-stressed coastal ecosystem, in the northern part of the South China Sea. Scientists are expected to work with management agencies on the sustainability of the coastal–lagoon–marine system, through 'spatial designing'.
- The coastal engineering construction needs to be designed carefully and managed, to help maintain the buffering capacity of the coastal system (e.g., lagoon), to reduce the direct impact of pollutant drainage from terrestrial sources.
- Monitoring of coastal ecosystems is a critical issue towards the ecosystem-based and adaptive management in tropical regions, such as Hainan; however, this is rather weak, because of lack of infrastructure. With regard to the fringing reefs off East Hainan, the actual monitoring network is not well equipped to provide information about the status of coral reefs, for early diagnostics.

Acknowledgements

The LANCET project was approved at the 13th Meeting of the Joint Steering Committee on Cooperation in Marine Science and Technology, between the State Oceanic Administration (China) and the Federal Ministry of Education and Research (Germany), in 2004. The project was implemented in the period between 2006 and 2011, with financial support from the Federal Ministry of Education and Research of Germany (Fkz. 03F0457 and Fkz. 03F0620), the Ministry of Science and Technology of China (Contract No. 2007DFB20380, for the period of 2008–2010), as well as from the Natural Science Foundation of China (Contract No. 40830850, for the period of 2009–2012). We would like to take this opportunity to express our gratitude to the participants from the University of Hamburg, University of Bremen, Leibniz Center for Tropical Marine Ecology, Ocean University of China, Second Institute of Oceanography, Hainan Provincial Marine Development Plan and Design Research Institute, and East China Normal University, for their contributions to LANCET. We want to thank also the numerous reviewers, whose constructive comments helped us to improve the quality of the individual manuscripts and, hence, of the whole Special Issue. In particular, Prof. Dr. Venugopalan Ittekkot is acknowledged for his initiative role in this LANCET project.

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