Eco-environmental problems in sustainable development of China's coastal zones and development of coastal science: Postprint

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Abstract

Coastal zones constitute not only the most intense land-sea interaction zone extending from land to ocean, but also complex and dynamic Earth surface natural systems, as well as spatial units under the dual influences of high-intensity human activities and global climate change. This article analyzes ten major eco-environmental issues affecting the sustainable development of China' s coastal zones, reviews international coastal scientific research progress and trends against the background of the International Land-Ocean Interactions in the Coastal Zone (LOICZ) program and the International Future Earth Coasts (FEC) program, and briefly describes domestic coastal research progress and gaps. Furthermore, in connection with coastal zone change issues, it explores the research framework, objectives, and content of China' s coastal science and coastal sustainable development, emphasizing that research on land-sea interactions and sustainable development in coastal zones under the pressures of global change and human activities has transcended the traditional scope of geography and oceanography. Based on natural and human factors in coastal zones, it tentatively proposes a "three-zone" concept that divides coastal zones into a "characteristic core zone (strongest interaction zone) - adjacent zone (stronger interaction zone) - peripheral zone (weak interaction zone)" , and points out that coastal science is a comprehensive interdisciplinary science that studies the natural attributes and functions of coastal zones, land-sea interactions, and sustainable development, and is an irreplaceable distinctive discipline for understanding coastal zone laws and supporting sustainable development.

Full Text

Preamble

Special Issue: Coastal Science and Sustainable Development

China possesses 18,000 km of mainland coastline and 14,000 km of island coastline. The 11 coastal provinces, municipalities, and autonomous regions, representing only 13% of the nation' s terrestrial area, concentrate over 50% of large cities, 40% of medium and small cities, 42% of the population, and more than 60% of GDP. Today' s coastal zone serves as both a pillar region for economic development and a "golden zone" for social advancement. Globally, coastal zones also represent the most concentrated areas of economic activity and population, commanding high priority for healthy and sustainable development among all coastal nations and regions. Scientific understanding of the natural and socio-economic patterns of coastal zones is a prerequisite for achieving their healthy and sustainable development. Based on this recognition, *Bulletin of Chinese Academy of Sciences* has specially planned and launched this "Coastal Science and Sustainable Development" special issue, inviting experts from multiple departments and disciplines across China to offer recommendations on China' s coastal scientific research and sustainable coastal development from ecological, environmental, resource, disaster, and management perspectives, aiming to provide scientific support for relevant researchers and decision-makers. This special issue is guided by Researcher Luo Yongming.

Ecological and Environmental Problems in China' s Coastal Sustainable Development and Coastal Science Development

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Abstract

The coastal zone is not only the most intense land-sea interaction zone where land extends toward the ocean, but also a complex and dynamic natural earth surface system, as well as a spatial unit under dual impacts of intensive human activities and global climate change. This paper analyzes ten ecological environmental problems affecting the sustainable development of China' s coastal zone, reviews international coastal scientific research progress and trends against the backdrop of the Land-Ocean Interaction in the Coastal Zone (LOICZ) and Future Earth Coasts (FEC) programs, and briefly describes domestic research progress and gaps. Furthermore, in connection with coastal zone change issues, the paper discusses research ideas, objectives, and contents for China' s coastal science and sustainable development. It emphasizes that research on coastal land-sea interaction and sustainable development under the pressures of global change and human activities has transcended the scope of traditional geography and oceanography. Based on natural and human factors in coastal zones, a "three-zone" concept is proposed, dividing the coastal zone into a "featured core zone (strongest interaction zone)—adjacent zone (stronger interaction zone)—peripheral zone (weak interaction zone)." The paper concludes that coastal science is a comprehensive and interdisciplinary science studying the natural attributes and functions, land-sea interactions, and sustainable development of coastal zones—an irreplaceable discipline for understanding coastal zone patterns and

supporting sustainable development.

Keywords: coastal zone, land-ocean interaction, Future Earth Coasts, coastal science, ecological and environmental problems, sustainable development

The coastal zone refers to the area where land extends toward the ocean. Broadly defined, it is a vast zone radiating from the coastline both seaward and landward, including coastal plains, coastal wetlands, estuarine deltas, intertidal zones, underwater slopes, and shallow continental shelves extending to the shelf edge. Evidently, the coastal zone is a land-ocean interaction zone featuring a unique and dynamic complex natural system with both terrestrial and marine attributes.

Coastal zones offer convenient transportation, dense populations, rapid economic development, and increasingly prominent location importance, making them the most frequent and intensive areas of human activity. Along nearly 500,000 km of global coastlines, over half of the world' s population lives within approximately 60 km of the coast, and two-thirds of cities with populations exceeding 2.5 million are located near tidal estuaries. In China, the total length of mainland and island coastlines reaches approximately 32,000 km, spanning tropical, subtropical, and temperate climate zones. The 11 coastal provinces, municipalities, and autonomous regions cover only about 13% of the national terrestrial area but concentrate more than 50% of large cities, 40% of medium and small cities, 42% of the population, and over 60% of GDP. China's emerging marine economy is growing at an annual rate of 20% [1]. Since the 21st century, nearly 20 national development strategies have been deployed in coastal areas. Today' s coastal zone serves as both a pillar region for economic development and a "golden zone" for regional socio-economic development. Under the national "Belt and Road" development strategy, the coastal zone, as the primary marine economic zone, has become a new engine driving China' s economic development.

Meanwhile, coastal zones face three major impacts: (1) in-situ direct or interactive driving impacts, such as climate change, hydrological changes, population changes, and human activities; (2) land-to-sea impacts, such as reduced sediment input and increased nutrient input; and (3) sea-to-land impacts, such as sea-level rise and increased storm surges. Consequently, China' s and the world' s coastal zones are at the forefront facing severe challenges to sustainable development. At this land-sea interface, with continuous socio-economic development, increasingly more important ecosystem products and services are being used unsustainably, highlighting environmental and resource risks. Under global changes of varying scales, including climate change, coastal zones face ecological and geological disaster crises. How to scientifically prioritize responses to rapid and profound changes occurring in vulnerable coastal zones, and how to predict the unprecedented impacts these changes may have on coastal zones themselves, their biodiversity, and social groups and livelihoods, have become major topics in coastal science and sustainable development research.

This paper analyzes the main ecological environmental problems affecting China' s coastal sustainable development, reviews domestic and international coastal scientific research progress, and explores future needs for China' s coastal science and sustainable development research.

1. Major Ecological and Environmental Problems Facing China' s Coastal Sustainable Development

Coastal zones are both the marine portion influenced by land and the terrestrial portion influenced by the ocean. Climate change, elevated atmospheric CO concentrations, excessive nutrient input, chemical pollution, reduced sediment input, land reclamation, and reclamation are fundamentally altering coastal marine chemistry at rates far exceeding early and recent ecological records at the global scale [2]. The ecological environmental problems emerging in China' s coastal zones (Figure 1 [Figure 1: see original paper]) originate from both land and sea, forming through land-sea interaction processes and under dual impacts of human activities and climate change (Figure 2 [Figure 2: see original paper]). Particularly, current human socio-economic activities have brought unprecedented pressure on coastal ecological environments, making coastal zones one of the world' s three major ecologically vulnerable zones and continuously threatening regional coastal sustainable development. These problems are mainly manifested in the following ten aspects:

1.1 Uncontrolled Growth of Artificial Coastlines and Alarming Loss of Natural Coastlines

Artificial coastlines include groins and jetties, port terminals, reclamation dikes, aquaculture dikes, salt pan dikes, transportation dikes, and seawalls. Over the past 70 years, the length of China' s mainland artificial coastline increased from 3,300 km in the early 1940s to 13,200 km in 2014, with its proportion rising from 18.30% to 67.1%. Coastlines with seaward expansion trends exceed 68%, with an average rate of 24.30 m a ^{1}. Conversely, natural coastline length decreased from 14,800 km in the early 1940s to 6,500 km in 2014, with its proportion dropping from 81.7% to 32.9% [3]. The drastic reduction and spatial fragmentation of natural coastline length have caused severe losses of critical coastal ecosystems and substantially reduced blue carbon storage and sequestration potential.

1.2 Large-Scale Loss of Coastal Wetland Area and Severe Damage to Ecosystem Functions

According to the State Oceanic Administration, between 1990 and 2008, China' s reclamation area of varying scales increased at a rate of 285 km^{2} a ^{1}. By 2009, approximately 65% of mangrove areas had disappeared, and about 80% of coral reefs had been destroyed [4]. Large-scale reclamation not only reduces coastal wetland habitat area and alters hydrodynamics, exacerbating coastline erosion, but also destroys fish spawning, nursery, and feeding grounds while re-

ducing benthic biodiversity and weakening water purification functions, leading to declining ecosystem service functions.

1.3 Intensified Coastal Erosion and Estuarine Siltation, Threatening Coastal Land Resources and Ports

In recent decades, due to various human activities such as unreasonable coastline development, reclamation, and dam construction and water-sediment regulation in upstream river basins, reduced water and sediment input has caused changes in estuarine and coastal hydrodynamic and sedimentary environments. Approximately 70% of China' s sandy coasts and most open muddy coasts suffer from erosion, with eroded sandy coastlines exceeding 2,500 km, particularly severe in estuarine areas and islands [5]. Coastal erosion or landslides lead to loss of tidal flat resources and damage to coastal highways, farmland, and buildings. Instability or siltation of estuaries not only affects maritime traffic but also intensifies coastal urban and rural flooding and accelerates the relocation of seawater desalination intakes, causing significant losses.

1.4 Over-extraction of Coastal Groundwater, Accelerated Seawater Intrusion, Leading to Freshwater Shortage, Soil Secondary Salinization, and Wetland Degradation

In northern China' s coastal zones, unreasonable groundwater extraction has caused large-scale cone of depression, seawater intrusion, and groundwater pollution. Seawater intrusion in China' s coastal zones includes seawater intrusion, saltwater intrusion, and salt tide intrusion. For example, the Bohai Rim region, particularly the Laizhou Bay coast, has become the most severely affected area by seawater intrusion and soil secondary salinization in China, with seawater intrusion area exceeding 10,000 km^2 and soil salinization area reaching 13,500 km^2 [6,7], seriously affecting agricultural production and socio-economic development.

1.5 Oil Pollution from Onshore Spills and Offshore Blowouts, Causing Severe Damage to Coastal and Nearshore Ecological Environments and Fishery Resources

In recent decades, nearly thousands of oil spill accidents have occurred from ships and offshore drilling platforms along China' s coast, with total spill volume reaching 35,000 tons [8]. Coastal oil field exploitation and urban pipeline ruptures have caused occasional bay oil pollution incidents. These nearshore environmental oil pollution problems not only degrade nearshore water quality and destroy marine habitats but also damage biological larvae, fish eggs, and juveniles, affecting marine fisheries and seafood quality [9].

1.6 Frequent Natural Disasters Such as Storm Surges, Floods, and Sea Ice in Coastal Areas, with Increasing Disaster Losses

Coastal zones feature intense land-sea interactions and lack ecological stability, making them prone to frequent natural disasters. Affected by climate change and other factors, storm surges and floods frequently occur in southeast coastal areas, while winter sea ice in the Bohai Sea affects maritime traffic. Analysis shows that during the 40 years from 1949 to 1990, disaster economic losses along China' s coast formed a 100,000 yuan/km² isopleth from north to south along the coastline, constituting a coastal disaster belt. Since the 1990s, extreme weather processes and marine disasters have occurred frequently, with average annual economic losses in coastal areas exceeding 15 billion yuan from various marine disasters. During the "Tenth Five-Year Plan" period, direct economic losses from marine disasters reached tens of billions of yuan, with deaths in the thousands. Economic losses from marine disasters show a clear upward trend overall. Extreme climate events have intensified marine disasters, becoming an important factor constraining China' s coastal economic development [4].

1.7 Obvious Sea-Level Rise Trend, Increasing Potential Ecological and Environmental Risks

Global temperature rise causes ocean thermal expansion and land glacier melting, leading to global sea-level rise. Based on data from 50 tide gauge stations, China' s average sea-level rise rate in recent decades is 1.4–2.0 mm a ^{1}, showing a clear upward trend. Tide gauge data worldwide show that global average sea-level rise in the 20th century was 0.15–0.18 m, with a rise rate of 1.0–2.0 mm a ^{1}. Sea-level rise severely affects coastal ecosystems and biological resources, particularly small islands composed of islets and coral reefs. For China, if sea-level rises by 0.5 m, without any flood control facilities, approximately 40,000 km² of low-lying alluvial plains in eastern coastal areas could be inundated, causing serious impacts on coastal ecosystems, biological resources, land productivity, and water resource systems [4]. Climate change-induced sea-level rise also accelerates coastal erosion [10].

1.8 Intensified Nearshore Eutrophication and Deteriorating Coastal Water Environmental Quality

Through multiple pathways such as river transport, atmospheric deposition, aquaculture input, and waste discharge, large inputs of nutrients and biogenic elements cause intensified nearshore eutrophication, triggering serious nearshore ecological disasters including expanded hypoxic zones, harmful algal blooms, jellyfish, and green tide outbreaks. In 2014, 415 direct ocean discharge sources emitted 6.31 billion tons of wastewater, including 15,000 tons of ammonia nitrogen and 3,126 tons of total phosphorus. In recent years, over 80% of major pollutants in China' s nearshore waters, such as inorganic nitrogen, active phosphate, and petroleum, originate from land-based sources, with total land-based pollutant discharge increasing annually and discharge outlet compliance rate

reaching only 52%. This has caused pollution in nearly 200,000 km² of sea area, remaining high and leaving nearly 70% of nearshore marine ecosystems in sub-healthy and unhealthy conditions. Nearshore water environmental quality is difficult to improve effectively in the short term [11]. Eutrophication problems are particularly prominent in estuaries and waters of large and medium cities (such as Bohai Bay, Yangtze River Estuary, Pearl River Estuary, etc.), not only reducing the recreational and aesthetic value of coastal zones but also directly affecting fishery resources and nearshore ecological security and health.

1.9 Severe Chemical and Microplastic Pollution in Coastal Zones, Threatening Environmental Quality and Seafood Safety

In 2014, the total discharge of four heavy metals (mercury, hexavalent chromium, lead, and cadmium) into the sea was 8.56 tons [11]. In addition to conventional heavy metal pollutants, new types of land-based pollutants have emerged in nearshore water bodies, sediments, and coastal soil environments, such as persistent organic pollutants, antibiotics, radionuclides, and microplastics, whose environmental risks and damages are receiving attention [12]. Some or all of these pollutants are bioaccumulative, toxic, and environmentally persistent, capable of long-distance transport via ocean currents. Some emerging pollutants also have high water solubility (such as perfluorinated compounds, antibiotic drugs, and organophosphate flame retardants), making them more easily transported to nearshore waters via rivers and then to the open ocean via currents, thereby threatening the entire marine ecosystem. Taking the typical emerging pollutant perfluorooctanoic acid as an example, concentrations in the Xiaoqing River basin of the Yellow River Delta' s Laizhou Bay can reach as high as 0.72 mg/L, with concentrations in Laizhou Bay waters reaching 100 g/L. Perfluorooctane sulfonic acid has been listed in the international Stockholm Convention, with its production, use, and disposal controlled by relevant authorities.

1.10 Invasive Alien Species in Coastal Zones, Biodiversity Changes, Frequent Ecological Disasters, and Declining Fishery Resources

The main pathways for alien species invasion in coastal zones include intentional human introduction and unintentional ship transport. Currently, 196 species have invaded China' s coastal zones [13]. Among them, the intentionally introduced aquatic plant *Spartina alterniflora* has caused native plant population growth limitation, biodiversity decline, and weakened ecosystem service functions. Large-scale reclamation not only reduces the area of coastal wetlands such as mangroves, seagrass beds, coral reefs, and muddy tidal flats but also destroys fish spawning, nursery, and feeding grounds, reducing benthic biodiversity and water purification functions. Human activities causing eutrophication have led to frequent ecological disasters such as red tides, jellyfish blooms, and green tides in nearshore waters. Combined effects of climate, ocean, land, and human activities, such as rising seawater temperature, altered hydrodynamics, changed sediment and nutrient input, chemical pollution, overfishing, and recla-

mation, have brought catastrophic consequences to coastal marine ecosystems, leading to sharp declines in biodiversity and fishery resources [14].

Additionally, potential ecological and environmental problems such as tsunamis triggered by possible coastal earthquakes, thermal effects and potential radionuclide leakage risks from nuclear power plant discharges, and ecological environmental issues caused by large-scale coastal and cross-sea projects (such as wind power, cross-sea bridges, port terminals, and offshore drilling platforms) also require attention.

In summary, the current coastal zone is a spatial unit under dual impacts of intensive human activities and global climate change. This space includes complex spatiotemporal changes and multi-process comprehensive effects of terrestrial processes, marine processes, and land-sea interaction processes at the land-ocean interface. These processes have caused serious ecological damage or environmental harm, leading to observable or measurable adverse changes in ecosystem services, human health, and property values, triggering public complaints. This also reminds us that we will face environmental damage assessment and ecological restoration issues [15].

2. Research Progress in Coastal Science at Home and Abroad

2.1 International Coastal Science Research Progress

With the development and utilization of coastal resources and socio-economic progress, the degree of human disturbance and damage to coastal ecological environments continues to increase. Meanwhile, concerns about potential inundation of global coastal low-lying areas and small island nations due to sea-level rise caused by global climate change are growing. To maintain sustainable development and safe survival in coastal zones, countries worldwide, especially developed nations, have established relevant research institutions to conduct extensive and in-depth research on coastal environment, ecology, resources, economy, and management. The international Land-Ocean Interaction in the Coastal Zone (LOICZ) program [16] was launched in the 1990s in response to these needs. The following reflects international coastal scientific research progress and trends through the implementation, progress, and future development of this program.

LOICZ initially focused on horizontal material exchange between land and sea in the coastal zone spatial domain, 不同于 the "vertical" processes emphasized by other International Geosphere-Biosphere Programme (IGBP) projects. Its initial task was to study human activity-induced changes at the land-sea interface in coastal systems, 不同于 climate system changes. At that time, LOICZ' s overall goal was to understand land-ocean interaction dynamics, predict their development, and explore coastal zone responses and coping strategies in the global change process. LOICZ' s scientific plan was accepted by IGBP in 1992

and became one of its core projects.

LOICZ Phase I (1993–2002) aimed to "provide coastal communities with necessary knowledge, insights, and forecasts to support assessment, prediction, and response to global change and regional pressures and their interactions causing coastal zone changes." The program identified four research priorities: (1) material and energy exchange between land and sea; (2) carbon flux and trace gas emissions; (3) impacts of sea-level changes; and (4) human impacts on coastal zone changes. After nearly 10 years of collaborative research using over 200 global stations, LOICZ first provided a global system of nutrient fluxes and metabolism in nearshore waters, solved the problem of land-based driving forces in coastal system function research, and provided estimated values.

LOICZ Phase II (2003–2014) made new plans and structural optimization adjustments. During this phase, LOICZ effectively implemented a "New Science Plan and Implementation Strategy," focusing on questions such as "how coastal zone systems support humanity," "how human activities affect coastal zone systems," and "what regulations and measures are needed to ensure coastal sustainability." In 2005, this strategy was organized around biogeochemical, physical, and human aspects of coastal zone changes into five themes: (1) vulnerability of coastal zone systems and their hazards to society; (2) significance of global change for coastal ecosystems and sustainable development; (3) impacts of human activities on watershed-coastal zone interactions; (4) biogeochemical cycles in nearshore and continental shelf waters; and (5) regulation of land-sea interactions supporting coastal zone system sustainability. The five themes jointly addressed three challenges: (1) scaling up regional scientific research for global science, policy, and management, and scaling down global scientific understanding for regional management and stakeholders; (2) understanding interactions between regional/local and global drivers and pressures; and (3) integrating natural and social science inputs into stakeholder negotiations to enable broad understanding of sustainable coastal use recommendations. Major achievements included biogeochemical budget models, coastal zone typology development, vulnerability and management assessment of declining deltas worldwide, natural disaster and post-disaster recovery experiences, baseline (land-sea boundary) protection measures, socio-ecological system assessment and regional field investigations, lifestyle and future planning impacts on coastal environmental quality and aquatic products, and coastal ocean "ecological economics models."

In 2009, the strategy was redesigned with three priority research themes: (1) linkages between social systems and ecosystems in coastal zones; (2) assessment and prediction of impacts from coastal ecosystem environmental changes; and (3) linkages between coastal zone management and scientific research. Meanwhile, five "scientific hotspots" were established for special coastal zone regions: (1) Arctic coasts; (2) endangered islands; (3) river estuaries; (4) deltas; and (5) urbanization in coastal zones. Major scientific achievements included coastal nutrient biogeochemical fluxes and typology, assessment and prediction of environmental change impacts in nearshore ecosystems, relationships between coastal

megacities and urbanization and coastal zone dynamic changes and risk assessment, adaptation and survival under global change, and assessment of extensive and identifiable impacts from high-latitude climate warming.

The year 2014 marked an important milestone and new starting point for LOICZ. With the conclusion of IGBP and the International Human Dimensions Programme (IHDP) and the proposal of the Future Earth (FE) program, the LOICZ Scientific Committee and regional center directors decided to shift its scientific planning toward Future Earth [17], focusing on understanding the complex processes and their interactions shaping coastal zone systems, strengthening scientific and policy linkages in LOICZ research hotspot regions and global regional centers, continuing to develop core issues of sustainable development and adaptation to global change in coastal zones, and taking a leading role in coastal zones' survival on Earth. In June 2015, a new 10-year (2016–2025) scientific planning framework was proposed, determining three themes: (1) dynamic coasts aimed at improving understanding of coastal zone status, recognizing how natural coasts create coastal civilizations; (2) global development and our coasts, focusing on understanding how ecosystem product and service function development affects human well-being, recognizing how humans govern and transform natural coasts; and (3) achieving transformation toward global coastal sustainability by identifying regulatory pathways and procedures in decision-making transitions, formulating priority actions to motivate social groups to ensure coastal sustainability. Accordingly, LOICZ was renamed the Future Earth Coasts (FEC) program. In July 2016, the FEC Scientific Committee and regional center directors joint meeting was held in Taipei, China, to further discuss implementation plans.

The past 20 years of the international Land-Ocean Interaction in the Coastal Zone (LOICZ) program' s research ideas, implementation experience, and scientific achievements have advanced coastal science and strongly supported sustainable development in global coastal regions. It is believed that the Future Earth Coasts (FEC) program will further enrich coastal science theories and methods and more powerfully support the transformation of coastal social and natural systems toward recoverability and sustainability.

2.2 Domestic Coastal Research Progress

China once synchronized with international efforts by establishing the Chinese Working Group for the Land-Ocean Interaction in the Coastal Zone Program in Qingdao in April 1993, renamed the Chinese Committee for Land-Ocean Interaction in the Coastal Zone in 2005 [18]. Since 2007, the Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, has established the East Asia Regional Office for the LOICZ program. China has participated in parallel tracks of the FEC program, engaging in various scientific activities and conducting inter-regional and international exchange and collaborative research on global coastal zones.

Regarding comprehensive investigation and research on China' s coastal zones, it began with the "National Coastal Zone and Tidal Flat Resources Comprehensive Survey" initiated in the early 1980s. This survey extended 10 km landward from the coastline and seaward to the 10–15 m isobath, covering a total area of approximately 350,000 km² and involving coastal climate, hydrology, geology, geomorphology, soil, vegetation, forestry, biology, seawater chemistry, environmental quality, land use, socio-economics, and many other aspects. The resulting achievements laid the foundation for further research, resource development, utilization, and protection management in China' s coastal zones. More than 10 years later, during the "China' s Nearshore Marine Comprehensive Survey and Evaluation" special project, China' s island and coastal zone basic data were further supplemented and updated, promoting coastal zone informatization work [18]. In recent years, the scientific basic survey on intertidal sediment environmental quality and mapping has provided substantial basic data on coastal zone sediment chemistry and biology.

In terms of coastal science basic theory, methodology, technology, and governance and restoration research, under support from the national "973,""863,"and "Science and Technology Support" programs, departmental public welfare special projects, CAS strategic priority programs, National Natural Science Foundation, international cooperation, and local government projects, Chinese scientists from comprehensive universities and research institutes involved in coastal zone research have made significant progress in estuarine and coastal ocean geomorphology, coastal ecological environment, coastal engineering, coastal information, and sustainable development. These research achievements are mainly reflected in: (1) millennial-scale estuarine evolution patterns, centennial-scale estuarine change processes, estuarine dynamic sedimentation and dynamic geomorphology, estuarine biogeochemical processes, estuarine ecological processes, and estuarine interactions and mutual influences with watersheds and oceans; (2) coastal zone dynamic processes and geomorphology, land-sea and river-sea interactions and coastal ocean geomorphology [18]; (3) coastal zone biodiversity, ecosystem service functions, and ecological disaster mechanisms and prevention; (4) coastal zone environmental pollution processes, monitoring, assessment, prevention, and remediation; (5) sea-level change, storm surges, and natural disaster prevention; (6) digital and information coastal zones; (7) coastal zone engineering survey, design, and safety protection; and (8) coastal zone management, planning, policy, and sustainable development. These research advances have strongly promoted coastal science development and supported China' s coastal sustainable development.

It should be noted that, apart from the more systematic research conducted in estuarine science, coastal ocean geomorphology, land-sea interaction, and ecological disasters, research in other aspects is mostly in the initial stage or limited accumulation phase. China lacks both forward-looking and applied multidisciplinary integrated research projects with themes and plans like the LOICZ program, and top-level design for ecological environmental problems in coastal zone ecological civilization construction and sustainable development, includ-

ing basic theory, methodology and technology, engineering demonstration, and regulatory policy chain-style coastal technology special projects.

3. Discussion on Future Coastal Science and Sustainable Development Research in China

3.1 Coastal Science is an Irreplaceable Featured Discipline for Understanding Coastal Zone Patterns and Supporting Sustainable Development

The coastal zone is a complex and dynamic natural earth surface system, recording the past, displaying the present, and nurturing the future. Its research space depends on the scientific questions to be addressed and is not fixed. Coastal zones are both the marine portion deeply influenced by connected land, featuring tides, currents, waves, sea winds, sea temperature, sea salt, sea ice (such as in Bohai Bay), suspended matter, special substances, and aesthetic appreciation of tourism value, and the terrestrial portion deeply influenced by the connected ocean, providing opportunities for residence, transportation, tourism, fisheries, oil and gas extraction, and offshore activities, while facing risks such as storm surges, floods, tsunamis, coastal erosion, sea-level rise, and seawater intrusion. Therefore, coastal dynamics, marine spatial planning, and coastal management have far exceeded the scope of traditional geography. Although oceanography is an important component of multidisciplinary coastal zone research, fields such as coastal engineering, coastal land use planning and management, coastal freshwater hydrology, coastal climate, sociology, and coastal culture have also exceeded the scope of traditional oceanography. This necessitates constructing coastal zone science' s own integrated land-sea-air-human natural view, holistic view, and socio-ecological system view, developing coastal science. In fact, coastal science has unique research objects (coastal zones), theoretical methods and technical means, problem-solving scheme requirements, and service objectives, making it an irreplaceable featured discipline for understanding coastal zone patterns and supporting sustainable development.

Coastal science, taking coastal zones (coastal land areas, coastal waters, and their land-sea transition zones) as the main research object, is a comprehensive and interdisciplinary science studying coastal zone structure, composition, properties and functions, land-sea interaction processes, mechanisms, effects, and their relationships with human activities and climate change, as well as supporting engineering technologies and management policies for coastal zone sustainable development, involving multiple disciplines including coastal geology, geography, ecology, environment, resources, biology, disasters, information, engineering, economics, and management. In other words, coastal science is the science studying the natural attributes and functions, land-sea interactions, and sustainable development of coastal zones. Its main research includes: (1) natural attributes, land-sea interactions, and evolution patterns of coastal zones; (2) coastal zone changes and countermeasures under intensive human activities; (3)

impacts of global climate change (sea-level rise) on coastal zones and responses; and (4) materials, methods, technologies, and models supporting coastal zone and sustainable development research, as components of earth science, resources, and environmental science.

3.2 Development Objectives and Research Contents of Coastal Science

In terms of overall objectives, addressing the aforementioned ten ecological environmental problems affecting China' s coastal sustainable development (Section 1), the overall goal should be protecting coastal ecological environments, sustainably utilizing resources, and achieving sustainable development, coordinating the relationships among coastal zone resource utilization, economic development, and ecological civilization construction. Through promoting knowledge innovation, technology integration, and integrated management in coastal science, human activity impacts should be minimized and climate change effects mitigated to support the natural recoverability and social sustainability of China' s coastal zones. On one hand, with concepts of land-sea connectivity, sea area connectivity, and global change, natural and social sciences should be integrated from local and regional scales to provide comprehensive knowledge for government and the public. While developing and utilizing coastal resources and developing coastal economies, awareness of protecting and improving coastal ecological environments should be enhanced, and adaptation measures to prevent global climate change should be actively planned. On the other hand, top-level design should be conducted for the main coastal zone change problems, forming chain-style coastal zone technology special projects from basic theory, methodology and technology, engineering demonstration, to regulatory policy. Through establishing national coastal zone technology special projects and stakeholder networks, interdisciplinary and multi-level research should be conducted on the socio-ecological impacts of environmental changes in coastal zones under different bioclimatic zones and economic development levels, clarifying driving factors, dynamics, and effects, understanding coastal zone change patterns, proposing problem-oriented response mechanisms and solutions, and supporting coastal sustainable development.

In terms of recent scientific objectives and research contents, further understanding of coastal land-sea interactions and dynamic changes and their impacts on human socio-economy should be achieved, and the relationship between coastal ecosystem product and service function development and coastal safety and health should be understood to predict coastal sustainability under combined impacts of human activities and global change. Four key scientific problems should be addressed: (1) impacts of human activities and climate change on coastal ecology, environment, and resources; (2) changes in coastal disasters and ecosystems under future sea-level changes; (3) impacts of human development activities on coastal ecosystem products and service functions on land-sea natural systems; and (4) pathways, processes, and indicators for coastal recov-

erability and sustainability. Key research areas include:

(1) Estuarine and coastal sedimentation-erosion and shoreline geomorphological changes under human activity and climate change influences;
(2) Land-sea-atmosphere exchange of biogenic elements and biogeochemical processes in coastal zones;
(3) Coastal biogeography, ecosystems, and their service function changes;
(4) Utilization and protection of coastal tidal flat saline-alkali land, biological resources, and marine energy;
(5) Pollution processes, criteria, and monitoring of emerging pollutants in coastal zones;
(6) Prevention, monitoring, and socio-economic impact prediction of coastal geological and ecological disasters;
(7) Coastal damage assessment, remediation, and sustainable management.

3.3 Land-Sea Integration and Harmonious Coexistence Between Humanity and Nature in Regional Sea Area and Coastal Zone Division Helps Reveal Patterns and Support Sustainable Management

To better understand coastal zone patterns and support sustainable development, two exploratory suggestions are proposed. First, based on bioclimatic zones, regional sea areas, and economic development conditions, it is suggested to divide regional coasts and sea areas, clarifying different regional coastal ecological environmental problems and their solution priorities. Second, through land-sea integration, based on estuarine and coastal geomorphology, runoff and tides, water-sediment and salinity gradients, chemical concentrations, biological species and distributions, sediment dynamics, biogeochemical processes, and the scope and intensity of human economic activities, it is suggested to divide coastal zones into three zones. (1) Featured core zone (strongest land-sea impact zone), from the high-tide line along the coast, intertidal zone to underwater slopes (shallow water below mean low water line or within 6 m isobath). This zone is most strongly affected by runoff, tides, human activities, and climate change, representing the most typical land-sea transition zone. (2) Adjacent zone (stronger land-sea impact zone), extending 3–10 km landward from the high-tide line and seaward from the low-tide line to 15–20 m isobath. This zone is strongly impacted by land or sea, with frequent human activities (e.g., living, aquaculture), distribution of wetlands, saline-alkali land, and salt-tolerant plants on land, and frequent impacts from sea winds and storm surges. In the sea area, gradients of sediment, freshwater, salinity, and pollutants are obvious, with many characteristic marine organisms inhabiting the area. (3) Peripheral zone (weak land-sea impact zone), extending from the landward adjacent zone to coastal plains 50 km or further low-lying areas, and from the seaward adjacent zone isobath to 50 km isobath or further to the 200-nautical-mile exclusive economic zone. The terrestrial area and rivers in this zone can be affected by salt tides and seawater intrusion, while the sea area is physically, chemically, and biologically distinct

from the first two zones but still has considerable human activities (e.g., fishing, offshore activities, economic development), and can be significantly affected by land-source sediment and pollutants or open ocean inputs. It should be noted that this initial proposed division requires further research to clarify its geological and biological indicators and boundaries. It is believed that coastal zone zoning and division will benefit land-sea integration, clarify priorities, and strengthen research on watershed-estuary/coastal/delta-nearshore, watershed-estuary/coastal-bay/island-nearshore, coast-bay-nearshore, and island coast-nearshore linkages under dual impacts of human activities and climate change across different spatiotemporal scales.

3.4 Understanding Coastal Zone Patterns and Serving Sustainable Development Requires Multi-level, Multi-disciplinary Research, Regional Cooperation, and International Exchange

Studying coastal zones as a multi-sphere integrated system of sea-land-atmosphere-life-human interconnections and interactions represents the frontier of coastal science research. Researching such a dynamic and complex natural coastal system and its changes and impacts on sustainability requires comprehensive and interdisciplinary integration of natural and social sciences oriented by problems and policies, requiring integration of science, technology, and management, thereby driving coastal scientific research, technological development, and integrated management. Meanwhile, participation of stakeholders at different levels is needed, as science needs their information and their cognition also needs scientific support. Coastal zones are critical zones for human survival and reproduction in the earth surface system and economic pillar regions for China' s ecological civilization construction and social sustainable development. It is suggested to establish a Chinese Committee for the Future Earth Coasts International Program, strengthen liaison with the international Future Earth Coasts program, promote inter-regional cooperation and international exchange, and open new scientific exploration horizons. Through joint design, collaborative production, and co-dissemination, science and technology and knowledge should be innovated, policies optimized, and effective supervision implemented. This will further promote China' s coastal zone research and coastal science and technology development, maintain or create more vibrant, recoverable, better-serving, safe, and healthy coastal socio-ecological systems, and more powerfully support coastal and even national sustainable development.

Note: Figure translations are in progress. See original paper for figures.