# Coastal Ecological Security and Future Marine Ecosystem Management Postprint

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## Abstract

Coastal zones represent the most sensitive and most widely concerned areas in the global ocean, providing essential material resource support and spatial environmental security for the existence and development of human society. As understanding of coastal ecosystem functions, services, and values continues to deepen, and in light of significant changes in coastal ecosystems under the pressure of multiple factors such as intensifying human activities and climate change, issues concerning coastal ecosystem health and ecological security have begun to receive heightened attention. However, current understanding of coastal ecological security issues remains insufficient, and systematic assessment efforts are lacking. It is imperative to develop long-term observation and information acquisition capabilities for marine ecosystems, conduct health assessments and change predictions for coastal ecosystems, and provide scientific support for advancing ecosystem-based management.

## Full Text

## Preamble

**Special Topic:** Status and Prospect of Marine Science

**Title:** Ecological Security of Coastal Ocean and Future Marine Ecosystem Management*

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## Abstract

The coastal ocean represents the most sensitive and highly concerned region of the global ocean, providing crucial material resources and spatial environmental support for the existence and development of human society. As understanding of coastal ecosystem functions, services, and values deepens, and in light of significant changes in coastal ecosystems under multiple stressors including recent human activities and climate change, issues concerning coastal ecosystem health and ecological security have begun to receive widespread attention. However, current understanding of coastal ecological security issues remains insufficient, and systematic assessment efforts are lacking. It is necessary to develop capabilities for long-term observation and information acquisition of marine ecosystems, conduct health assessments and change predictions for coastal ecosystems, and provide scientific support for advancing ecosystem-based marine management.

**Keywords:** coastal ocean, ecological security, marine ecosystem assessment, management

The ocean provides extremely important material resource support and spatial environmental guarantee for the existence and development of human society. Currently, more than half of the global population lives in coastal areas, and coastal resources, environment, and space have become important material foundations supporting the sustainable development of human society. Simultaneously, the coastal ocean serves as an intersection zone of different Earth surface spheres, characterized by high productivity and rich biodiversity and habitat diversity, yet it also bears the influence of numerous factors including human activities and climate change, making its ecosystems relatively vulnerable and the most sensitive and highly concerned region of the global ocean [1]. In recent years, coastal ecosystems have undergone significant changes, causing alterations in ecosystem structure and functional degradation, endangering coastal ecological security, and impairing the services provided by coastal ecosystems and human well-being.

China is a major maritime nation, possessing more than 18,000 km of coastline and over 3 million $km^2$ of jurisdictional sea area, featuring the world' s most typical broad continental shelf seas and large river estuaries with massive water and sediment discharge. The Chinese government attaches great importance to marine resource development, marine environmental protection, and maritime rights maintenance, vigorously developing coastline resources, island resources, port resources, coastal wetland resources, marine biological resources, shallow sea oil and gas resources, etc. Along the coastal front and offshore waters, large-scale marine engineering projects such as nuclear power plants, ports, artificial islands, offshore oil platforms, and offshore wind power stations have been constructed, as well as various fishery engineering projects like "marine ranches" and "artificial reefs." However, coastal ecosystems face multiple stressors including land-based pollution, climate change, eutrophication, overfishing, habitat loss, disorderly aquaculture, and species invasion, with the impacts of many influencing factors continuing to strengthen.

Over the past 100 years, the rapid growth of global population, industrial and agricultural production, and fishing activities has exerted unprecedented pressure on the stability of coastal ecosystems. Taking the alteration of biogeochemical cycles of biogenic elements such as carbon, nitrogen, and phosphorus as examples, massive fossil fuel combustion has caused rapid increases in atmospheric CO2 concentration, not only leading to rising seawater temperatures but also exacerbating ocean acidification, and inducing indirect effects such as sea level rise, ocean current changes, strengthened water stratification, and decreased dissolved oxygen concentrations. Between 1980 and 2011, atmospheric CO2 content increased at an average rate of 1.7 ppm per year, and since 2001, this rate has risen to 2.0 ppm per year [8]. It can be expected that the impacts of rising atmospheric CO2 content on seawater temperature and ocean acidification will continue to intensify in the short term.

Driven by fertilizer production demands, reactive nitrogen entering Earth' s ecosystems has increased approximately 20-fold since the late 19th century. In the 1990s, nitrogen entering the environment through fertilizer application and fossil fuel combustion reached 160 million tons, far exceeding terrestrial biological nitrogen fixation (110 million tons) and marine biological nitrogen fixation (140 million tons) [9]. It is estimated that since the late 19th century, global reactive nitrogen flux to the sea has increased by nearly 80%; by 2030, nitrogen flux to global coastal ecosystems will increase by another 10%-20%.

The biogeochemical process of phosphorus is also affected by human production and living activities such as fertilizer application and sewage discharge. Approximately 4-6 million tons of dissolved phosphorus is transported from land to the ocean via rivers annually, which is double the amount under natural conditions [10]. Excessive input of nitrogen and phosphorus nutrients has intensified coastal eutrophication and placed enormous pressure on marine ecosystems.

Under the influence of human activities, climate change, and other factors, coastal ecosystems have undergone many significant changes over the past century, with loss of many important habitats, rising seawater temperatures, and emerging problems such as hypoxia and acidification. Currently, 50% of global salt marshes, 35% of mangroves, 30% of coral reefs, and 29% of seagrass beds have been lost due to destruction. Affected by global warming, sea surface temperatures continue to rise, exacerbating water stratification, which weakens nutrient exchange and may lead to decreased primary productivity in mid- and low-latitude waters. In many coastal sea areas, bottom water hypoxia caused by eutrophication has become very common, imposing enormous stress on many marine organisms, particularly benthic economic animals, and even affecting fishery resources. Ocean acidification impacts primary producers such as coccolithophores and important habitats like coral reefs and oyster reefs, and may even lead to changes in food web structure. In addition to these changes, even more concerning is the increasing risk of sudden ecological disaster events in coastal ecosystems. Typically, ecosystems change gradually, but once environmental factors exceed the ecosystem's carrying capacity, ecosystems may change abruptly, sometimes even experiencing regime shifts that endanger ecological security.

In China, the situation regarding coastal ecological security is extremely grave

[11]. Most coastal estuaries and bay areas face serious eutrophication problems. In the Bohai Sea, southern Yellow Sea, waters adjacent to the Yangtze River Estuary, southeastern coastal areas, and Beibu Gulf, various types of harmful algal bloom issues are prominent. Hypoxia in bottom waters is gradually emerging in waters adjacent to the Yangtze River Estuary and some nearshore areas of the Yellow and Bohai Seas. The area of sub-healthy and unhealthy coastal waters continues to increase, natural coastlines are continuously shrinking, and important habitats for resource organisms such as coral reefs, mangroves, and estuarine areas are being lost. These problems pose serious threats to the socioeconomic development of coastal regions and the health of coastal ecosystems. However, current understanding of coastal ecological security issues remains insufficient, and systematic assessment work is lacking. It is necessary to develop capabilities for long-term observation and information acquisition of marine ecosystems, conduct health assessments and change predictions for coastal ecosystems, and provide scientific support for advancing ecosystem-based marine management.

## 2 Future Marine Ecosystem Management

### 2.1 Strengthening Long-term Observation and Information Acquisition Capabilities for Coastal Ecosystems

Long-term observation and information acquisition of coastal ecosystems are the cornerstones of coastal ecosystem management. Currently, China has established preliminary capabilities in coastal ecosystem observation and capacity building, and the level of marine informatization has been significantly improved. However, considerable room for improvement remains compared with other countries. To strengthen long-term observation and information acquisition capabilities for coastal ecosystems, systematic deployment is needed to enhance long-term, in-situ, and real-time observation capabilities in key sea areas, while simultaneously addressing issues of marine observation data sharing and common use through institutional and systemic mechanisms.

The emergence of coastal ecological security and ecological disaster issues reflects changes in the structure and function of marine ecosystems. Causal relationships in ecosystems often exhibit lag effects, making short-term studies unable to reveal trends over years or decades or explain the causal relationships of these changes [12]. Therefore, obtaining information on long-term changes in coastal ecosystems is extremely important for revealing the causes of coastal ecological disasters and resolving coastal ecological security issues. Among these, distinguishing between climate change and human activities, between long-term pressures and short-term fluctuations, and between controllable and uncontrollable factors is critical, which also falls within the research scope of long-term ecology.

Currently, internationally renowned long-term observation networks such as the International Long-Term Ecological Research Network (ILTER), the U.S. Long-

Term Ecological Research Network (US-LTER), the UK Environmental Change Network (ECN), and the Chinese Ecosystem Research Network (CERN) have achieved many important results in ecosystem long-term changes and demonstration services [13-15]. However, the marine-related components of these long-term ecological research networks cannot meet national needs for solving marine problems. It is necessary to further establish national long-term observation transects and conduct corresponding long-term research work on this basis. In this regard, Japan' s national transects, Europe' s Atlantic observation transects, and the long-term observations by the UK Sir Alister Hardy Foundation for Ocean Science' s Continuous Plankton Recorder provide excellent precedents. China has only established three marine long-term observation stations in Jiaozhou Bay, Daya Bay, and Sanya Bay within the Chinese Ecosystem Research Network. Although different departments and projects have also established coastal observation systems, they fall far short of meeting the needs for long-term observation and research of coastal ecosystems. As coastal ecological problems become increasingly prominent, it is necessary to establish national-level long-term scientific observation transects and networks for China based on existing observation systems, focusing on issues such as coastal ecological security, ecological disasters, and coastal ecosystem assessment. This involves optimizing observation indicators and analytical methods and standardizing data quality control. Through long-term observations, key processes affecting changes in China' s coastal ecosystems can be revealed, assessment methodology systems for coastal ecosystems can be constructed, and measures and countermeasures for preventing and controlling coastal ecological disasters and restoring degraded ecosystems can be proposed.

Early warning and forecasting of coastal ecological security issues are time-sensitive. On the basis of deploying long-term scientific observation networks, it is necessary to enhance real-time, in-situ observation capabilities for coastal ecosystems from both scientific and technological perspectives. This includes developing in-situ sensors for different elements of marine ecosystems, improving observation precision and real-time data transmission capabilities, and enhancing analytical capabilities for real-time observation data. Currently, sensor technology for physical oceanography elements is relatively mature, but chemical oceanography, particularly biological oceanography sensors, still faces technical bottlenecks that cannot meet the needs of marine ecological security early warning and forecasting. How to break through these technical bottlenecks and construct and improve multidisciplinary coupled coastal observation networks is crucial for China' s coastal ecological security and ecosystem management.

Data acquisition and sharing are common concerns across all disciplinary fields. Due to the particularity of marine observation, data sharing is especially important. The U.S. Long-Term Ecological Research Network adopts an open data policy that explicitly specifies how to publish, access, and use long-term observation data, as well as requirements for data users and providers. For China' s marine observation, how to further optimize data management and provide institutional and systemic guarantees to ensure sharing and common use of marine observation data is an issue that requires focused consideration at national and departmental levels.

In summary, regarding coastal information acquisition in China, comprehensive and strategic top-level design is needed to unify marine data standards and establish effective marine data sharing mechanisms. It is necessary to strengthen three-dimensional observation means, conduct intensive observations in key areas, and integrate sensor grid systems; establish real-time online monitoring systems for marine environments, and implement real-time monitoring and disaster early warning and forecasting for typical ecosystems.

### 2.2 Conducting Health Assessment and Prediction Research for Coastal Ecosystems

Coastal ecosystem health assessment is an important pathway for marine management and development utilization. Guided by the "ecosystem approach," it seeks to understand and grasp the health status of the marine environment through scientific cognition, analyze the impacts of pressures such as human activities on the marine environment, provide scientific basis for marine managers and decision-makers, and offer quantified scientific standards for balancing the relationship between marine ecosystem protection and marine economic development, achieving marine environmental protection and restoration, and promoting sustainable development of the marine economy.

Ecosystem health research began in the 1970s and has been widely applied in the assessment of coastal ecosystems such as estuaries and bays in recent years. Focusing on core issues of coastal ecosystem health assessment, such as the definition of coastal ecosystem health concepts, assessment methods, indicators, and standards [16,17], governments and scholars worldwide have conducted theoretical and methodological explorations and extensive research. Compared with other ecosystems, marine ecosystems have open boundaries, more complex structural functions, and specific characteristics in different sea areas. Combined with differing perceptions of ecosystem health, the definition and assessment of marine ecosystem health face various difficulties and challenges.

In recent years, coastal ecosystem health research has evolved from focusing solely on the structural and functional characteristics of ecosystems themselves [18] to gradually developing into multidisciplinary comprehensive research covering ecological, social, economic, human health, and other aspects, while emphasizing marine ecosystem service functions [19,20]. Currently, two methods are most commonly used in marine ecosystem health assessment research and application: indicator species method and indicator system method. The indicator species method monitors one or more indicator species in marine ecosystems along with their physiological, ecological, structural, and functional indicators, analyzes the health status of these species, and thereby monitors and assesses the health status of the entire marine ecosystem [21]. The indicator species method is relatively simple and requires less data, thus being applied earlier in ecosystem health assessment research. Commonly used indicators include the Index of Biological Integrity (IBI), Shannon-Weaver diversity index, A Marine Biotic Index (AMBI), and benthic indices. However, the indicator species method also has problems such as non-unified standards for indicator species selection and unclear indicative effects on ecosystem changes, making it difficult to conduct comprehensive and integrated assessments of the health status of complex coastal ecosystems.

The indicator system method screens and extracts indicators at different organizational levels, dimensions, and scales of marine ecosystems to establish assessment indicator systems that can comprehensively reflect the overall health status of marine ecosystems. As marine ecosystem health research continues to deepen, indicators related to socio-economics, human activities, and human health have also been incorporated into indicator systems. Combined with indicators of marine ecosystems themselves, comprehensive assessments of marine ecosystem health levels and evolution trends are conducted from different perspectives such as ecosystem structure, function, and services. Based on methods from physics, chemistry, biology, ecology, and toxicology, and utilizing new technologies such as computer mathematical simulation, the indicator system method has become the most commonly used assessment method in current marine ecosystem health research. Currently, the main model methods widely applied in indicator system establishment include the Ocean Health Index (OHI) (Figure 1 [Figure 1: see original paper]), the Pressure-State-Response (PSR) conceptual framework and its improved frameworks, and the HELCOM Ecosystem Health Assessment Tool (HOLAS) [22-25].

Coastal ecosystem health assessment research abroad has seen a series of successful programs and plans, particularly with many successful application cases in North America, Europe, and Australia: Canada has conducted systematic assessment studies on Great Lakes ecosystem health since the 1990s [26]; the U.S. Environmental Protection Agency released the 'National Coastal Condition Report' to assess the status of its coastal waters [27]; Australia established an estuarine and marine environmental quality assessment indicator system and subsequently implemented the 'Ecological Health Monitoring Program' [28], conducting assessment studies on water quality and ecosystem health in the Great Barrier Reef region. The European Union' s Water Framework Directive proposed relatively complete technical indicators for marine environmental assessment [29] and further formulated the Marine Strategy Framework Directive, incorporating regular marine environmental monitoring and assessment into dynamic management processes.

Domestic attention to marine ecosystem health assessment has also been increasing, with relevant research being conducted successively and ecosystem health assessments being carried out in multiple coastal estuaries and bays. However, indicator systems currently used in China's coastal ecosystem health assessment research mostly involve borrowing and referencing existing foreign indicator systems with adaptive modifications for application objects. The construction of localized indicator systems targeting the characteristics of China's coastal ecosystems remains in the exploratory stage, and theoretical, methodological, and validation studies on marine ecosystem health assessment still require further improvement and development. Coastal ecosystem health research needs to further deepen understanding of the relationships between human pressures, global change, and the evolution of marine ecosystem structure and function, establish more comprehensive and integrated marine ecosystem health assessment systems, utilize more effective ecosystem assessment and prediction models to support more effective management decisions, understand restoration mechanisms and methods for rebuilding ecological structure and function, and guarantee marine ecosystem service functions through effective protection policies.

### 2.3 Implementing Ecosystem-Based Marine Management

Ecosystem-based management (EBM) was first proposed in the 1960s, with its fundamental concept being to consider solutions to environmental resource problems from ecological, systematic, and balanced perspectives. The proposal of this concept represents a response by scientists to global-scale ecological, environmental, and resource crises. As an interdisciplinary field combining ecology, environmental science, and resource science—a new cross-disciplinary area of natural sciences, humanities, and technical sciences—it not only has rich scientific connotations but also urgent social demands and broad application prospects [12]. In the 1980s, ecosystem-based management achieved certain developments in both basic theory and practical application, gradually forming a complete theoretical-methodological-model system [30,31]. On this basis, the 1992 United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro proposed managing marine resources and human marine development activities from the perspective of entire ecosystems, promoting integrated management and sustainable use of coastal and offshore environments, thus forming the concept of ecosystem-based marine management. Long et al. [32] summarized the development history of ecosystem-based marine management and proposed 15 principles for ecosystem-based marine management. Integrating these concepts, the basic connotation of ecosystem-based marine management is to fully consider the integrity and internal connectivity of marine ecosystems, and based on scientific understanding of marine ecosystem structure and function, conduct comprehensive management of marine development activities and sea area usage to protect marine health and maintain its ecosystem service functions, thereby achieving sustainable utilization of marine resources and sustainable development of the marine economy.

Over the past 20-plus years, ecosystem-based marine management has been gradually accepted by countries worldwide and has developed rapidly. Many successful international cases can serve as references. Australia issued the 'Australia' s Oceans Policy' in 1998, becoming a model for ecosystem-based marine management [33]. A series of U.S. national ocean policy reports have attached great importance to ecosystem-based marine management, with relevant policy documents such as 'Oceans Blueprint for the 21st Century' and 'U.S. Ocean Action Plan' [34]. Meanwhile, a series of ecosystem-based marine management studies have been conducted, covering different countries, sea areas, and disciplinary fields, providing important support in marine ecosystem health assessment, model development, and policy formulation. Among these, research progress has been particularly prominent in ecosystem-based fisheries management [35-38], ecosystem-based coastal zone management [39,40], and marine spatial planning [41-43], offering excellent references for China' s implementation of ecosystem-based marine management.

Ecosystem structure and function are interdependent and mutually restrictive. The management of any specific ecosystem must be consistent with the particular characteristics of that ecosystem. Global-scale assessments cannot meet the needs of national and sub-regional scale decision-makers [12], and one country' s assessment results cannot be used for other countries' governmental decision-making. Therefore, to comprehensively manage and control China' s coastal ecosystems, it is essential to develop ecosystem management strategies based on China' s coastal ocean. China has already recognized the importance of strengthening marine ecosystem protection and restoration for maintaining sustainable development and utilization of marine resources. In the 'National Marine Functional Zoning Plan' issued by the State Council, which addresses five major problems in China's marine resource development and utilization, it is explicitly proposed to respect nature, establish concepts of revering and protecting the ocean, strictly limit development activities within the carrying capacity of marine resources and environment, adhere to point-based development and area-based protection, ensure improvement of marine ecosystem health status, enhancement of marine ecosystem service functions, and restoration and remediation of damaged coastal ecosystems [44].

Correspondingly, Chinese scholars have conducted concept promotion and scientific research on ecosystem-based marine management in recent years. Research sea areas involve Tianjin coastal waters, Jiaozhou Bay, Laizhou Bay, Jiangsu coastal waters, Yellow Sea, East China Sea, and other regions [45-48], focusing mainly on the impacts of reclamation and fisheries and ecosystem-based marine management based on these issues. This indicates that China has begun to attach importance to ecosystem-based marine management, but overall, China has not yet established an ecosystem-based marine management system.

In view of this, to address the urgently needed solutions for ecological security and ecological disaster issues in China' s coastal ocean, it is necessary to select typical sea areas based on observation, research, and assessment, and construct demonstration projects for sustainable development and management of coastal biological (fishery) resources, marine safety demonstration projects for major coastal engineering facilities, and demonstration projects for prediction, forecasting, and prevention and control of coastal ecological disasters, thereby improving the scientificity, precision, and timeliness of major marine affairs decision-making. On the basis of these demonstration projects, further advancement should be made in constructing and applying intelligent expert systems for comprehensive coastal ecosystem risk assessment, building marine big data service infrastructure platforms, establishing a set of models suitable for China' s coastal ecosystem health assessment, and forming efficient and intelligent observation and early warning systems for ecological disasters such as harmful algal blooms, hypoxia, and jellyfish blooms. Close cooperation with coastal government departments and large enterprises should be promoted to advance real-time sharing of observation data and simulation results, support efficient and intelligent marine ecological security management systems, and enhance China' s comprehensive capabilities in coastal resource development and utilization, coastal ecological environmental protection, and ecosystem-based marine management.

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