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# Development Trend of Deep-Sea Ecosystem and Marine Protected Areas

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**Abstract:** The types, ecological properties, development problems, and technological needs for studying deep-sea ecosystems are described in this paper. Compared with shallow-sea ecosystems, samples of deep-sea ecosystems are more difficult to collect, fewer data have been generated, and research has been relatively limited. Diverse species that dwell in the deep sea include tubeworms and extreme-thermophilic archaea living around deep-sea hydrothermal vents; mussels and clams that live on sulfate-reducing bacteria in cold spring zones; diverse species found near and on seamounts; cold-water corals that consume planktons; and specialized snailfish found in abyssal layers. These ecosystems are quite different from other ocean ecosystems and are valuable areas to study. Recently, the rapid development of the deep-sea monitoring equipment and other detection devices has provided an excellent opportunity for studying deep-sea ecosystems. Research on deep-sea biodiversity and ecological theory are urgent and practical. Therefore, the following strategies for protecting deep-sea ecosystems are proposed: building a database of deep-sea biology; balancing deep-sea mineral exploring and ecosystem protection; developing theoretical models for deep-sea ecosystems; and accelerating the development of management strategies and legal instruments.

**Keywords:** biodiversity; deep-sea ecosystems; marine protected areas

## 1 Introduction

Oceans deeper than 200 meters account for about 95% of the world's ocean waters and include land slopes, ocean ridges, ocean basins, and trenches. The deep seabed is rich in polymetallic nodules, polymetallic crusts, sulfide deposits, and iron-manganese crusts. Humans have begun to explore the ocean due to a rapid demand for resources. Deep-sea mining has become possible with the rapid development of deep-sea mining technology and a reduction in costs. Although the metabolism and growth of deep-sea organisms are relatively slow, deep-sea ecosystems are the largest biological habitats on the planet, and their biodiversity (genetic diversity, species diversity, community diversity, and ecosystem diversity) is extremely high. The deep sea contains an abundance of new biological resources. The ability to develop and utilize deep-sea resources, while protecting deep-sea biodiversity and ecosystems from damage, has become a major concern for policy makers.

## 2 Deep ocean ecosystem types and research status

Deep oceans are characterized as having high pressure, low food, no light, and are considered nutrient-deficient deserts. In these vast deserts, there are some oasis of life, such as deep-sea hydrothermal areas, cold spring areas, deep-sea cold water coral areas, seamount areas, abyssal areas, and other special ecological environments. These

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ecosystems have species, communities, and ecological associations that differ from the upper ocean, and are valuable for ecological study.

### 2.1 Deep-sea hydrothermal vent ecosystems

Marine scientists discovered deep-sea hydrothermal fluids in the Galapagos Rift in the Eastern Pacific Ocean in 1977 [1] . This discovery triggered discussions about “life originating from deep-sea hydrothermal fluid regions” [2,3], which is considered as one of the most important topics in the life sciences. Currently, about 550 endemic species have been identified in deep-sea hydrothermal vent ecosystems [4]. Those organisms do not rely upon photosynthesis from the upper ocean layers. Chemoautotrophic microorganisms are the primary producers in these deep-sea ecosystems. Secondary producers include tubular worms, mussels, crabs, and fishes (Fig. 1) [5]. The hydrothermal vents are always located around the mid-ocean ridge. The seawater is heated to 350-400 °C after passing through the fissures formed during the cooling of the ocean crust. Because the hydrothermal fluid density is lower than the seawater, it will pass through the rock and form a “black chimney” that is caused by the deposition of various ferrous metal sulfides in the hydrothermal fluid when mixed with seawater The hydrothermal fluid contains a large amount of hydrogen sulfide, which is toxic to most organisms. However, hydrogen sulfide is consumed by some chemoautotrophic microorganisms. Some animals around hydrothermal vents can filter-feed those bacteria, whereas others develop symbiotic relationships with those microorganisms. For example, tube worms that are dominant in the hydrothermal vents do not need to filter and prey, but have evolved a highly specialized organ called a trophosome, which contains many symbiotic microorganisms. These symbiotic microorganisms live autotrophically, supply tube worms with organic matter, and can account for more than 25% of the volume of the worms [6,7]. Tube worms are representative of hydrothermal mouth endemic species and are valuable for life science studies. Hydrothermal vents also contain abundant thermophilic archaea species, such as the “Strain 121” archaea, which has been isolated at depths of 2400 meters along the bottom of the Pacific Ocean. This strain has been found in areas with the highest recorded natural temperatures, and has survived in a 121 °C autoclave [8]. This thermophilic strain may have evolved an effective heat-resistant mechanism to cope with the extremely high temperatures in and around hydrothermal vents by using formate (electron donor) and ferric iron (electron acceptor). Studying these thermophilic microorganisms in deep-sea hot springs has expanded our understanding of the limitations of living in extremely high temperatures. The development of high-throughput sequencing technology provides an opportunity to reveal the adaptive mechanisms in microbial communities living in deep-sea hydrothermal vents. A comparative analysis was conducted of the microbiome metagenome sequence of the Juan de Fuca sulphide “black chimney” and the carbonate “white chimney” called “Lost City” in the central Atlantic. The microbial communities in these two chimneys showed a high abundance of DNA repair-related genes, indicating that these microorganisms needed to evolve a strong DNA repair system in response to the damages caused by harsh conditions, including high temperatures, metal ions, and toxic compounds. In terms of nitrogen metabolism, both microbial communities exhibited significantly different characteristics. The “black chimney” community contained relatively abundant denitrification-related genes, whereas there were significantly fewer of these genes in “white chimney” community [9]. A similar high denitrification rate around the “black chimney” was also revealed by in situ stable isotope probing experiments [10]. These findings demonstrated the distinctiveness and importance of hydrothermal vents in deep-sea ecosystems.

### 2.2 Deep-sea cold spring ecosystem

Fluids flowing under the seafloor-sediment interface contain water, hydrocarbons, hydrogen sulfide, and fine-grained sediments can overflow from the seafloor and change physical, chemical, and biological properties. These processes and products define Cold Spring Ecosystems. Currently, there are thousands of active cold spring areas found globally along the continental margin [13]. The temperature of the cold springs is basically the same as the surrounding sea floor. The overflowed fluid is rich in methane and hydrogen sulfide, and can provide energy sources for chemoautotrophic microorganisms. These microorganisms primarily oxidize methane for energy and are the fundamental levels of cold spring ecosystem food chains. They are distributed in sulfate-methane conversion zones and form plaques ranging in size between several centimeters to hundreds of meters. These methane-oxidizing microorganisms are reliable indicators of the location and size of cold spring fluids [14]. The combined activity of sulfate-reducing bacteria and methane-oxidizing microorganisms results in an anaerobic oxidation of methane in cold spring fluid. Hydrogen sulfide is released by the sulfate-reducing bacteria and becomes a source of energy for chemical autotrophic microorganisms, which increases primary productivity in

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cold spring ecosystems (Fig. 2). According to the degree of attachment to endosymbiotic autotrophic bacteria, the animals at cold springs can be divided into obligate species (such as fungus mats, mussels, tubular worms, and clams), potential obligate species (such as gastropods, limpets, and crabs), and non-obligate species (such as anemones, gastropods, and crustaceans) [15]. Cold spring organisms have extremely high bio-densities, unique biodiversities, rich genetic resources, and unique metabolites with potential utilization values. Cold spring ecosystems have provided opportunities for biologists to discover and study new microbial metabolic pathways and survival strategies.

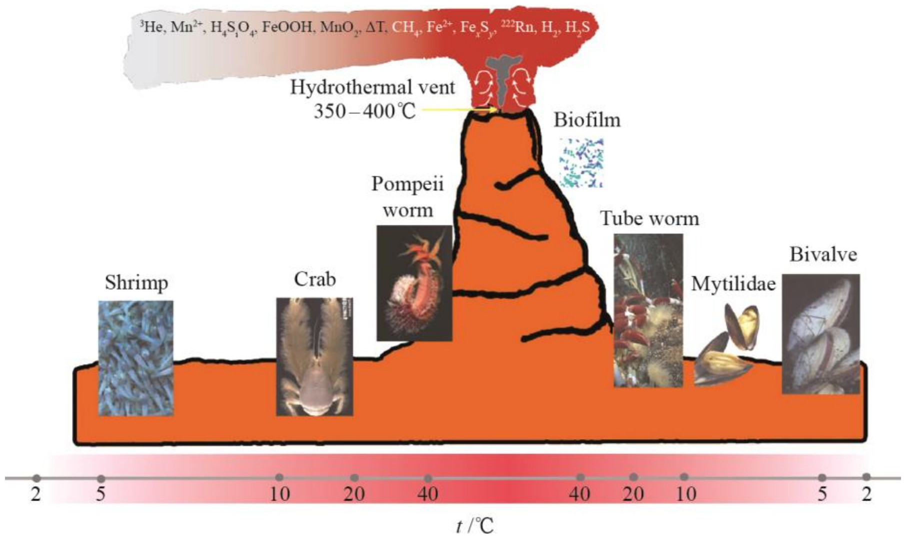


**Fig. 1.** Schematic diagram of the deep-sea hydrothermal vent ecosystem (after Wang et al.[11] and Sievert et al. [12]).

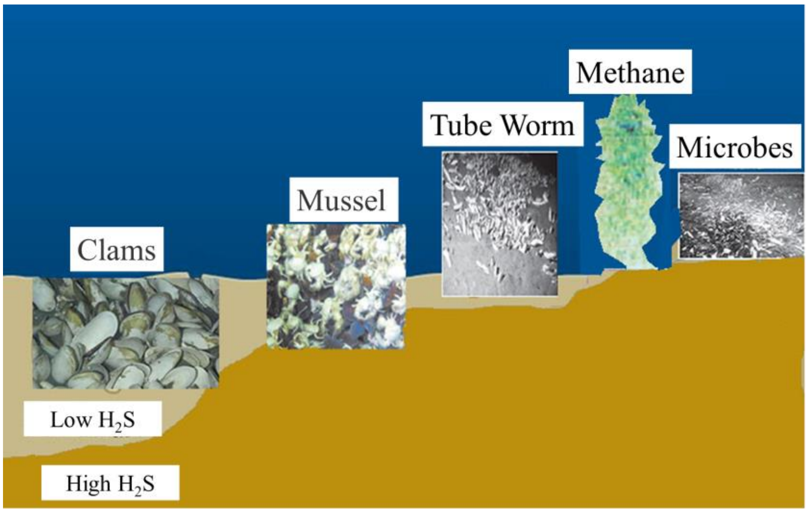


**Fig. 2.** Schematic of deep-sea cold spring ecosystem (after Sahling et al. [16])

## 2.3 Deep-sea cold-water coral ecosystems

Cold-water coral reefs exist worldwide on continental shelves, slopes, and seamounts. In addition to being an important part of deep-sea ecosystems, coral reefs also have high biodiversity and ecological resource values. They have been used for recording long-term climate change. Unlike shallow-sea corals that depend on symbiotic relationships with photosynthetic algae, deep-sea corals feed mainly on plankton and organic matter from the surface. Similar to shallow-water coral reef ecosystems, cold-water coral reef ecosystems are also very vulnerable. Deep-sea fishing, the exploration and extraction of oil and gas resources, deep-sea mining, and ocean acidification caused by global climate change have affected cold-water coral reef ecosystems. Compared with tropical shallow-water corals, less research has been conducted on deep-water cold-water corals. However, with recent developments of deep-sea exploration technology, research of cold-water corals has gradually increased and is becoming an increasingly important area of marine science [17].

### 2.4 Seamount ecosystems

Seamounts are unique habitats in the deep-sea oceans and are widely found in the world's oceans. There are an estimated 25 000 to 140 000 seamounts, covering 28.8 million square kilometers of ocean floor. Seamounts are described as natural laboratories for studying the interaction of marine physical and biological processes [18]. Seamounts can interact with different-scale ocean flows to form complex, multi-scale dynamic processes that include corrective circulation, upwelling (sinking flow), meso-scale vortices, internal waves, and small-scale turbulence. These are independent, multi-scale dynamic processes that affect each other and drive the horizontal and vertical transport of momentum, heat, and nutrients. Thus, the water bodies and seafloor of the mountainous regions have unique ecosystems that are unique from other ocean regions. Typical characteristic organisms living near seamounts are plankton, swimming organisms, and benthic organisms. The mountainous areas will often have higher biomass, abundance [19,20], and diversity [21] than the surrounding ocean ecosystems and ocean basin ecosystems. This phenomenon is called the "Seamount Effect." However, this viewpoint has been challenged recently. In a 20-year systematic survey of different seamounts, researchers found that seamount primary productivity based on chlorophyll concentrations was only a few times higher than the surrounding seas. The few seamounts with high productivity may be an over-estimate, or short-term events [22]. Another view is that the high biomass in seamounts may not be due to local high primary productivity, but is caused by external inputs such as suspended foods, zooplankton, or their predators transported by the currents and seamount terrain. However, the scientists with these viewpoints could not deny that the high productivity characteristics of seamount ecosystems must have a significant impact on the biomass and diversity of seamount microbial groups. Whether seamounts maintain higher productivity than the surrounding seas remains a mystery of the ocean. The primary productivity of the ocean mainly depends on nutrients. How nutrients accumulate and create algal blooms depends on the circulation and vertical mixing of water masses. The high ecological productivity of seamounts is related to two features. The first is if the terrain of the seamounts is shallow enough to generate upwelling that will pass through the pycnocline layer to bring nutrients to the euphotic layer. The second feature is if physical oceanographic processes associated with seamounts cause agglomeration that concentrates surrounding organic matter to form traps. In short, the reason for the high productivity in the seamount remain an open question for further study.

### 2.5 Abyssal ecosystems

Ocean layers deeper than 6000 meters are called abyssal. Due to extreme pressures and isolation from the environment, an abyssal zone environment was thought to be "a pool of stagnant water" where life is scarce. However, during 50 years of study scientists have found the abyssal layer is not static, but is involved in physical oceanographic processes such as deep cyclone and deep ocean circulation patterns, with considerable material input and a rich biodiversity [23–25] For example, in the Atacama Trench, which has a maximum depth of about 8000 meters, the density of small benthic organisms can reach more than 6000 per square centimeter, which is 10 times higher than nearby shallow seabed plains [26]. A similar phenomenon was reported in the Kuril Trench of 10 542 meters [27]. A 35-centimeter long amphipod was captured at 7000 meters in the Kmadek Trench, which is about 10 times longer than its relatives in shallow waters. The size may be due to lack of predators in the trench [28]. Because the abyssal is below the carbonate compensation depth, calcium carbonate exists in a dissolved state and foraminifera with calcium carbonate as the main structural component cannot survive. However, scientists have found a unique species of foraminifera in the abyssal that has adapted to these depths [23]. Chinese scientists used the self-developed "Tianya" and "Haijiao" abyssal landers to capture a super-deep snailfish at a depth of 6 000 meters in the Marialla Trench. Morphological analyses found that the snailfishes were adapted to high pressure environments. Their bones became very thin and had the ability to bend. Their skulls were incomplete and muscle tissues were also very flexible. A genomic analysis revealed that many vision-related genes of those snailfish had been lost. Several genes related to cell membrane stability and protein structure stability were mutated. Those gene-level variations may collectively cause their unique phenotypes and help them to adapt to the extreme abyssal environment [29]. These abyssal-specific species groups are also valuable for studying deep-sea biological diversity.

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## 3 Main problems affecting deep-sea ecosystems

### 3.1 Significant decline in deep-sea biodiversity

In 2003, the International Council for the Exploration of the Sea concluded "the stocks of most deep-sea species may exceed safe biological limits." For example, between 1978 and 1994, the number of several target and non-target species in the Northwest Atlantic decreased by more than 90% [30]. From the mid-1960s to the 1990s, deep-sea fishery production decreased by 0.8 to 1 million tons per year [31]. Since the 1990s, many countries and intergovernmental organizations have recognized the needs to protect vulnerable marine species and habitats, and promote the recovery of depleted populations [32,33]. However, the recovery of deep-sea species with low productivity may require many decades, possibly over a century [34].

Due to the limitations of deep-sea exploration technology, China has just begun to investigate and study deep-sea biodiversity. Fortunately, since the 11th Five-Year Plan period, China has focused on the development of marine technology, with deep-sea development technology achieving unprecedented development. Presently, China already has deep-sea exploration equipment, including atmospheric diving equipment, cable-controlled underwater robots, and 600-meter unmanned and cable-free autonomous underwater robots. It is worth mentioning that the "Jiaolong" 7000-meter manned submersible developed by China is currently the deepest manned submersible that can reach 99% of the world's ocean floor. Another deep-sea submersible, the "Deep Sea Warrior," also successfully completed manned deep-dives in August, 2017. It is worth mentioning that buoyancy materials, deep-sea lithium batteries, and robots associated with the "Deep Sea Warrior" were all developed by China. Its import substitution rate reached to 95%. The application of these deep-sea equipment demonstrates the rapid development in deep-sea exploration technology, and provides the foundation for the future research and protection of deep-sea biological diversity in China. At the legislative level, on May 1, 2016, the *Law of the People's Republic of China on the Exploration and Development of Deep-Sea Seabed Resources* was officially promulgated. This law lists the protection of the deep-sea environment as a special chapter, which has great significance for protecting the diversity of deep-sea species. The promulgation and implementation of this legislation confirmed the general trend of the development of international seabed activities and demonstrated China's responsibility to international concerns.

### 3.2 Ecological problems of deep-sea mining

The exploration and development of deep seabed resources will help humankind meet increasing material demands and spiritual needs. This requires a sustainable development of these resources because exploration can impact marine ecosystems. The operation of high-powered subsea exploration machinery and facilities during exploration will stir bottom sediments, which might block the respiratory organs of large animals and suffocate them. This could also increase the mineral content in seawater and damage coral reefs and microorganisms found in those areas, resulting in some seabed organisms losing breeding and habitat sites. At the same time, the exploration of deep-sea ecosystems using machinery, chemistry, electrolysis, marine corrosion, and lasers can introduce various pollutants into those areas. During the processing of seabed minerals, a large amount of waste may be discarded into the ocean. Pollutants generated by the many ships transporting resources will be discharged directly into the sea and eventually settle into deep-sea ecosystems. The removal of deep-sea resources that are located in areas with complex geological structures and concentrated faulting activities might induce geological disasters such as earthquakes and submarine landslides during the later stages of mining that negatively impact deep-sea ecosystems. Therefore, principles of sustainable development need to be considered for improving the exploration and evaluation of deep-sea ecosystems and for enhancing environmental protection and deep-sea resource monitoring.

The *United Nations Convention on the Law of the Sea* considers seas that are beyond national sovereignty to be the property of all humankind, and any development must be beneficial to all mankind. Specific rules, powers, and responsibilities should be established for seabed mining. Because deep-sea species always live in hotspot regions, setting up ecological reserves has become an effective tool for protecting deep-sea biodiversity and ecosystems. As a result, the coverage of global marine and terrestrial protected areas has expanded. The concept of marine protected areas was first proposed in the World National Parks Congress in 1962. In 1988, the resolution of the Seventeenth Plenary Session of the International Union for the Conservation of Nature in Costa Rica stated that the goals of marine protected areas were to achieve long-term protection, restoration, better understanding and using the world's marine ecological resources. This was to be accomplished through the establishment of protected areas and the management of human activities that affect the marine environment. In 1995, relevant China departments formulated the *Administrative Measures for Marine Nature Reserves*, which implemented conservation-oriented, moderate, and sustainable development, and also strengthened the construction and management of marine nature reserves. The extent of worldwide marine protected areas has almost doubled since 2014 and is now 1.7% of marine areas. The Secretariat of the Convention on Biological Diversity, in conjunction with the United Nations Environment Programme World Conservation Monitoring Centre (WCMC-UNEP) and the United Nations Development Programme (UNDP), stated that by 2020, 10% of the marine environment, especially biodiversity hotspots, should be effectively protected and managed [35].

### 3.3 Impacts of terrestrial pollutants

Rapid socioeconomic development has resulted in many organic pollutants (such as DDT, PCBs, many other pesticides, herbicides, and industrial chemicals) settling into the ocean from runoff, marine aquaculture, chemical spills, and shipwreck accidents. It was once thought that terrestrial pollutants would only affect offshore ecosystems. However, researchers recently found that the concentrations of the above-mentioned persistent organic pollutants in deep-sea fish may be an order of magnitude higher than those of fish living near the surface. Deep-sea waters are considered the ultimate fate of global persistent organic pollutants [36]. The widespread distribution of microplastics in deep-sea sediments is an example of the universality of this phenomenon [37]. Chinese scholars found a large quantity of toxic organic pollutants in the 11 000-meter Mariana Trench Challenger Abyss. The concentrations of some pollutants were higher than in some shallow waters, indicating that persistent organic pollutants had arrived at the deepest part of the world’s oceans. The long-term effects of those pollutants on deep-sea ecosystems have not been evaluated [38].

### 3.4 Impacts of climate change

Increasing global temperatures will stabilize the stratification of the oceans, reducing the deep-sea oxygen supply and the solubility of oxygen in seawater [39–41]. Over the past 20 years, oxygen concentrations in the Indian, Atlantic, and Pacific Oceans have decreased. These regions have distinct oxygen-minimum zones (OMZ), with the horizontal and vertical expansion of OMZ water masses [42]. Ocean ecosystems were severely affected by the loss of oxygen. The hypoxic environment led to significant reductions in biomass and biodiversity [43–45]. In addition, deoxygenation of the upper ocean may have reduced the supply of food to the deep ocean. For example, during the period of low oxygen concentrations in the California cold current, the number of fish in the middle layer was significantly reduced, which led to a 60% decline of deep-sea squid and fish [46,47].

## 4 Essential needs and strategies for deep-sea ecological protection

### 4.1 Establishing databases of deep-sea organisms

In the past few decades, research on marine biodiversity has increased. However, the research has been incomplete, concentrated on only larger groups of individuals, or was concentrated within shallow-water. In the future, a database of deep-sea biodiversity needs to be established through strategic cooperation. Sampling methodologies and data analyses need to be standardized, and a sharing mechanism should be established. Research should be conducted on macro- and micro-organisms. The use of deep-sea detection equipment (such as remotely controlled submersibles and manned deep submersibles) and in situ observation equipment (such as anchor arrays and deep-water gliders) would greatly expand the spatial and temporal understanding of deep-sea biodiversity. At the same time, the use of numerical simulation models can expand the spatial ecological information and develop scientific assumptions for guiding sampling. With the establishment of a deep-sea biodiversity database, it would be possible to track and analyze biodiversity information in different marine environments. A database would provide information for biodiversity hotspot identification, large-scale ecological models, spatial and temporal species migration patterns, and identify how new species are associated with temperature, salinity, and depth. Thus, our understanding of deep-sea biodiversity would be more comprehensive and new scientific strategies can be proposed for the balanced development of deep-sea resource exploration and ecosystem protection.

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### 4.2 Balancing the relationship between the deep-sea resource exploration and ecological protection

The unique characteristics of deep-sea ecosystems will require protection strategies that are quite different from shallow-sea ecosystems [48,49]. Presently, only a few countries and international organizations can scientifically implement deep-sea ecological management, protection, and restoration. In 2007 and 2008, the issue of deep-sea ecosystem protection was put on the agenda at the United Nations General Assembly. Scientists must provide information to help guide the conservation and sustainable management of deep-sea ecosystems. The increase in basic ecological research is essential for designing marine protected areas. However, unlike terrestrial ecosystems, the acquisition of data from deep-sea ecosystems is closely related to the development of deep-sea exploration technologies. Future work that needs to be done includes classifying different deep-sea ecological environments and establishing the relationships between deep-sea species and their habitats. Furthermore, the use of biogeographic distribution models for predicting changes of the deep-sea ecosystems is lacking [49]. The integration of biodiversity/habitat models with other models is important for guiding the establishment of marine protected areas, and the sustainable utilization of deep-sea resources [50].

The continuous development of human society made obvious the contradiction between the development and utilization of resources, and ecological protection. Because this involves many stakeholders, balancing economic development and ecological protection is not an easy task. The success of deep-sea management policies depends on the exchange of public information between stakeholders. Managers need to cooperate publicly with resource users and use scientific research information as a basis to develop and utilize deep-sea resources sustainably.

### 4.3 Developing deep-sea ecological theoretical models

The island biogeographic balance theory is one of the classic theories of ecological research. This theory states that the number of species on an island depends on the area, age, diversity of habitats, the possibility of colonization of new species onto the island, richness of sources, and the balance between the colonization rate of new species and the extinction rate of existing species [51,52]. This theory provides a theoretical basis for establishing biological reserves for protecting the balance between biodiversity and sustainable development and lays a scientific foundation for protecting a reserve’s ecosystem. Currently, the theory is only being validated and applied in terrestrial and shallow-water ecosystems. Research is needed to determine if biodiversity in deep-sea ecosystems also conforms to this theoretical model. Widespread deep-sea ecological environments such as seamounts, cold water coral reef ecosystems, and abyssal layers, are similar to the islands in the above theory. Similar ecological theories can be used to establish the relationships between deep-sea biological diversity and environmental factors (such as habitat area, habitat geology, and habitat water chemical characteristics), and provide guidance for protecting deep-sea biological diversity and the establishment of deep-sea biological reserves. The development of China’s deep-sea exploration equipment makes possible systematic and accurate deep-sea biodiversity surveys and provides opportunities for the development of deep-sea ecological theoretical models.

### 4.4 Accelerating the formulation of management countermeasures and legal documents

Recently, the United Nations accelerated the management of oceans beyond national sovereignty. An international legally binding instrument is being established under the *United Nations Convention on the Law of the Sea* to create “marine biological diversity of areas beyond national jurisdictions (short for BBNJ).” This instrument will include the conservation and sustainable use of marine biodiversity in areas beyond national jurisdictions; marine genetic resources and benefit-sharing issues; zoned management tools for marine protected areas; environmental impact assessments; and marine technology transfer. This instrument is currently under discussion, and once implemented, it will have a huge impact on the development of marine resources in areas beyond national sovereignty. Therefore, in addition to the need for a thorough understanding of the ecological environments, biodiversity and ecosystems in the development of sea areas, there also exists a need to develop mining technologies that avoid harming deep-sea ecological environments.

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