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Cryosphere Ecosystems: Outpost and Barrier in Global Change

WANG Genxu
Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China

See next page for additional authors

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Abstract

The closely reciprocal feedback between cryosphere and biosphere has constantly been intensified by global change, which strongly affects global management for environment and sustainable development of human-being. From the perspective of basic pattern and function of cryosphere ecosystems, and their response process and adaptive strategy to changing environment, we fully specified distribution patterns of cryosphere ecosystems and how it functioned for earth ecosystems and contributed to human well-being, briefly stated how it is most sensitive, thereby as an indicator to climate change, also pointed out cryosphere ecosystems as barrier function for maintaining biodiversity and increasing productivity, and finally put forward an effective way to facilitate ecosystems health in cryosphere. Totally, the common contents and corresponding study processes in cryosphere ecology were better to be introduced, even essential prospective of cryosphere ecology was included in this paper.

Keywords

cryosphere ecosystems; structure and pattern; carbon stock; biodiversity; effects; regulation

Authors

WANG Genxu, YANG Yan, ZHANG Guangtao, and CHANG Ruiying

Corresponding Author(s)

WANG Genxu [1*]

1 Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China

WANG Genxu Professor of Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (CAS), Director of the Key Laboratory of Mountain Surface Processes and Ecological Regulation, Chinese Academy of Sciences, and Director of the National Field Observation and Research Station of Gongga Mountain Ecosystem.His research focuses on the study of cryosphere ecosystem and global change and ecohydrology.He concurrently serves as the Director of the Ecohydrology Committee of the Chinese Society of Ecology and the Director of the Cryosphere Ecology Committee of the Chinese Society of Cryospheric Science (preparation).He is the editorial board members of many journals including *Journal of Mountain Science*, *Acta Ecologica Sinica*, *Chinese Journal of Plant Ecology*, *Chinese Journal of Applied Ecology*, and also the associate editor of *Mountain Research*.He is the leading principal investigator of 17 projects including National Science Fund for Distinguished Young Scholars of National Natural Science Foundation of China, National Key Project Funds, National 973 Projects, etc.He has published more than 270 papers and 5 monographs.E-mail:wanggx@imde.ac.cn

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Cryosphere Ecosystems: Outpost and Barrier in Global Change

WANG Genxu[1], YANG Yan[1], ZHANG Guangtao[2], CHANG Ruiying[1]

1. Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China;
2. Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China

Abstract: The closely reciprocal feedback between cryosphere and biosphere has constantly been intensified by global change, which strongly affects global management for environment and sustainable development of human beings. From the perspective of basic pattern and function of cryosphere ecosystems, and their response process and adaptive strategy to changing environment, we fully specified distribution patterns of cryosphere ecosystems and how it functioned for earth ecosystems and contributed to human well-being, briefly stated how it is most sensitive, thereby as an indicator to climate change, also pointed out cryosphere ecosystems as barrier function for maintaining biodiversity and increasing productivity, and finally put forward an effective way to facilitate ecosystems health in cryosphere. Totally, the common contents and corresponding study processes in cryosphere ecology were better to be introduced, and even the essential prospect of cryosphere ecology was included in this paper.
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The cryosphere has a feedback effect on global climate change on the basis of its store or release of a large amount of energy and biogenic elements, such as water vapor, methane (CH_4), carbon dioxide (CO_2), and nitrous oxide (N_2O), and also acts on other spheres like biosphere and hydrosphere [1]. The cryosphere is the most sensitive sphere of climate system. Due to climate warming, the ice amount of all cryospheric elements generally in a deficit state, and the energy exchange in phase change leads to the change of material and energy cycle, which results in the changes of various kinds of ecosystems from habitat, composition structure, food web, and distribution pattern. Climate warming has a deeper and wider impact on ecosystems than on other regions. The severe changes of the cryosphere have a great influence on the ecosystems themselves and their service function in the cryosphere, and the changes of the ecosystems have a strong feedback effect on the cryosphere. These actions and reactions, as well as their chain environmental and developmental impacts, are formed in the cryosphere, but their influence is even global. Therefore, cryosphere ecology plays an important role in global management for environment and sustainable development of human beings. Under the background of global change, with the increasing dependence on cryosphere by the sustainable development of human beings, it is urgent to explore the ecosystem protection and sustainable maintenance of service functions in response to the changing environment, starting from the close interaction between cryosphere and biosphere. The discipline of cryosphere ecology emerged at the historic moment and developed rapidly in the upsurge of research on global change and sustainable development.

1 Basic characteristics and functions of cryosphere ecosystems

The cryosphere environment presets special physical, chemical, and biological conditions, and the creatures that adapt to this environment and their relationship with this environment constitute the cryosphere ecosystems. From the perspective of sphere, cryosphere ecology is a discipline that studies the interaction between biosphere and cryosphere. Therefore, it is the basic task of cryosphere ecology to systematically understand the characteristics of biosphere and its ecosystem structure and function in cryosphere.

Generally speaking, with the increase in latitude and altitude, the cryosphere becomes more and more powerful, and the habitat becomes more and more severe, so the complexity and diversity of food web should be significantly reduced. However, even in the Arctic region with extremely high latitude, although its terrestrial primary productivity is very low, there are four nutritional levels of producers (plants), primary consumers (herbivores), secondary consumers (carnivores), and decomposers [2]. This characteristic also can be seen in most areas over 4,000 m above sea level in Qinghai-Tibet Plateau. On the sub-regional scale, the terrestrial biological

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Corresponding author: [（英）通信作者]

communities in the Arctic and Qinghai-Tibet Plateau have various mosaics, which are formed under the joint action of various abiotic factors such as climate, substrate, and hydrological gradient changes. For example, its unique α diversity and community (β) diversity are formed under the effects of the cryospheric elements (snow cover and permafrost) [3,4]. Among the factors based on niche, factors related to landform, thermal gradient, glacier history, frozen soil development history, ocean current in the cryosphere, etc. work together for a colorful habitat environment. For example, in the marine cryosphere environment, ice cover provides unique heterogeneous habitats for Arctic creatures, and there are unique animals and plants at the bottom (secondary bottom habitat) and top (meltwater pool) of the ice surface; even though the marine ecosystem under sea ice is excluded, there is a complete food web structure in ice and snow (Figure 1). In the permafrost regions of the Pan-Arctic continent and Qinghai-Tibet Plateau, ice-related processes such as freeze-thaw cycles and thermokarst have created a dynamic highly heterogeneous spatial pattern in which freshwater lakes and marshes are dotted. This habitat heterogeneity is superimposed on the spatial changes of the various interactions between cryosphere and lithosphere, forming a special highly heterogeneous biodiversity distribution pattern in cryosphere. As a result, there are a large number of regional hotspots with high global biodiversity in Qinghai-Tibet Plateau and the whole Arctic region [5].

In terms of ecosystem function (or importance), besides biological production, energy flow, material circulation, and information transmission which are similar to other ecosystems, cryosphere ecosystems also have their special functions or importance.

(1) Regulation of cryospheric elements. The influence of vegetation on the formation and distribution of frozen soil is universal, and its mechanism is manifested in the influence of vegetation coverage on surface thermal dynamics and energy balance, as well as that on organic matter in surface soil, soil composition, and soil structure. The change of soil organic matter and structure will lead to the change of soil heat conduction, which will affect the soil water and heat dynamic in the active layer (Figure 2). This is a concrete manifestation of the ecological system's strong conservation function for the cryospheric elements, and the same function is also reflected in the role of slowing down the melting rate of sea ice [7]. Due to the special biological environment and habitat characteristics of the cryosphere, different cryospheric elements have different interaction channels, modes, and biological mechanisms on ecosystems. For example, snow cover thickness and melting time not only determine vegetation types and community composition but also play a key role in the ecological characteristics of plants [8]. Glacier ablation can provide more abundant freshwater, nutrients, and organic carbon to the arid area or coastal zone by increasing runoff, thus greatly changing the downstream or marine ecosystem. Permafrost restricts ecosystem type, distribution pattern, productivity, and biodiversity through its influence on water cycle and biogeochemical cycle.

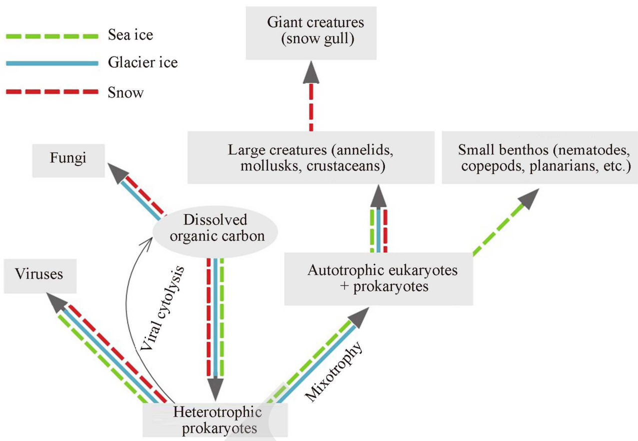

Figure 1 Food web structure in sea ice, glacier ice, and snow environment [6]

(2) Great cold storage effect of carbon and nitrogen stock in ecosystems. In the whole permafrost region of the northern hemisphere, the soil organic carbon stock is approximately 1,672 Pg C within the depth of 3 m, which is equivalent to 50% of the global underground carbon stock [10], so the cryosphere carbon stock occupies an extremely important position in the global carbon balance. Besides, as for the net productivity of Arctic and sub-Arctic vegetation, about 2.47×10^9 t of carbon enters the pedosphere in the form of litter every year. Moreover, lichens and bryophytes widely distributed in the permafrost regions of the Arctic and Qinghai-Tibet Plateau play an important role in nitrogen fixation due to abundant cyanobacteria. In some watersheds in the Arctic region, the annual fixed nitrogen amount can reach 0.8–1.31 kg N/hm^2, accounting for 85%–90% of the total nitrogen input in the watersheds.

2 Response and adaptation of cryosphere ecosystems to global change

Because of the high sensitivity of the habitat elements of the cryosphere to climate change, the cryosphere ecosystems as a whole are the most sensitive biological part of the earth's surface to climate change. At present, most of the things we have learned about the terrestrial ecosystem responding to climate change come from the cryosphere ecosystems. It is the core content of cryosphere ecology to systematically understand the influence and regulation effect of various cryosphere changes on biosphere and the feedback of biosphere to cryosphere.

2.1 Outpost of global change: sensitivity and indication

In the past 30 years, the region with the greatest change in terrestrial ecosystem is the Arctic tundra distribution area, which is manifested in the universal rise of normalized difference vegetation index (NDVI) and biomass increase. The immediate cause of this is the large expansion of shrub and the succession of tundra vegetation communities (Figure 3a). The change in productivity is often related to the change of plant community composition. Therefore, some highland habitats in most tundra areas are covered by more grass and shrubs [11]. While the tundra turns green, the boreal coniferous forest zone turns yellow. The reason for forest degradation is closely related to frozen soil degradation, namely that frozen soil degradation leads to forest vegetation being replaced by wetland meadow vegetation and results in increased drought stress. The succession of plant communities in Qinghai-Tibet Plateau is also very intense. With the degradation of frozen soil, the alpine grassland in Qinghai-Tibet Plateau experienced serious degradation succession in 1980s–1990s and the first five years of the 21st century (Figure 3b). Another indication of the change in ecological sensitivity is the universal and great change of vegetation phenology. In the Arctic region and Qinghai-Tibet Plateau, it has found that the growth of plants is advanced in spring and delayed in autumn and the reproduction phenology changes. This exerts a negative effect on biodiversity. Due to the prolongation of shrub vegetation growth period, the enlargement of shade, and the increase in the thickness of snow interception, a large number of Gramineae species and cryptogams disappeared in Arctic region.

The response of the whole marine cryosphere ecosystems to climate change may be mainly conducted by sea ice retreat. With respect to the sea ice habitat, there are not only food chain cascade reactions within the community but also interactions with aquatic biological communities through organic matter sedimentation and biological migration. Without considering the limitation of nutrients, the effect of sea ice retreat on primary producers of water bodies is definitely positive, while the effect on the ice algae growing on sea ice varies from place to place—the diversity and abundance of ice algae and ice fauna in some areas continue to decrease [12]. For consumers in sea ice habitat, especially animals with long life cycle, the negative effect (such as the reduction of food chain and suitable habitats) is dominant. Arctic marine mammals are considered to be highly sensitive to sea ice changes. Among them, polar bears, narwhals, and, cap seals are considered the most vulnerable species to sea ice changes, because they depend on specific sea ice habitats and have special food chains and predation habits that rely on sea ice habitats [13].

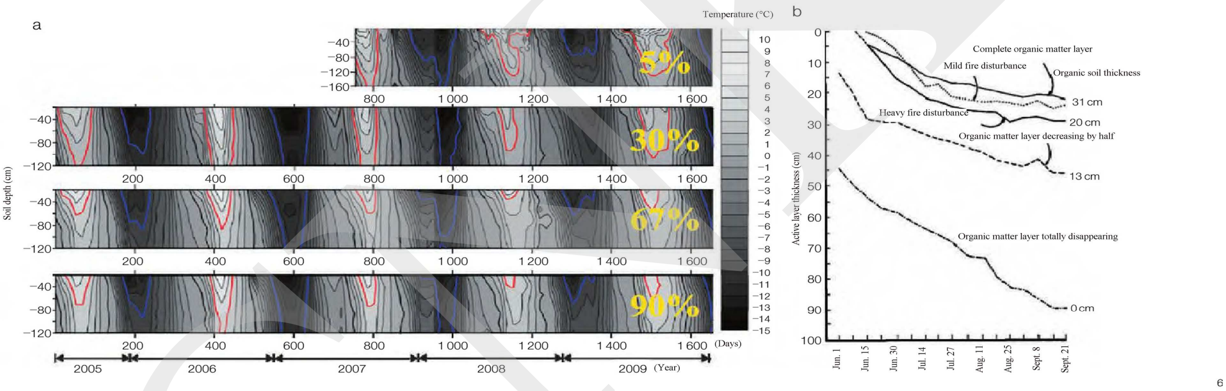

Figure 2 Effects of vegetation cover and soil organic matter change on heat transfer of frozen soil [9]

(a) The isoline map (red line represents the temperature of 4 °C) of temperature change of active layer under different vegetation cover (5%, 30%, 67%, and 90% from top to bottom), and the abscissa is days from 2005 to 2009; (b) effect of change in soil organic matter thickness on the active layer thickness.

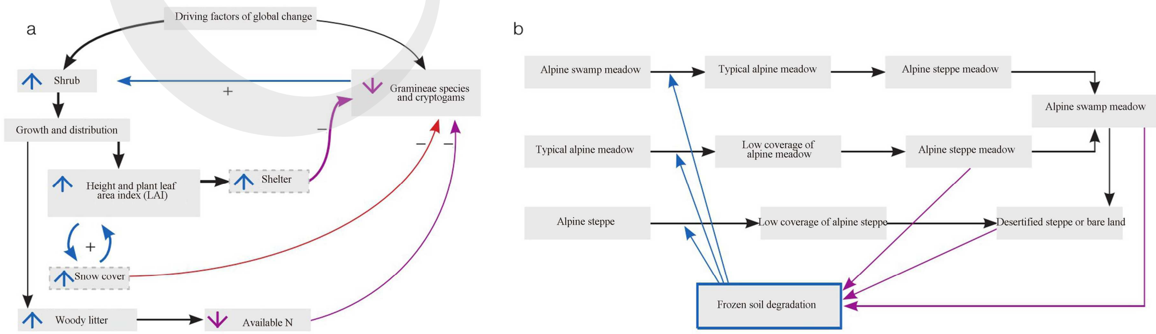

Figure 3 Cascade and feedback effects of ecosystems caused by changes of cryosphere

(a) The warming of Arctic permafrost region leads to shrub replacing tundra vegetation [2]; (b) vegetation community succession caused by frozen soil degradation in Qinghai-Tibet Plateau.

2.2 Refuge for biodiversity

Global change has led to the reduction of biodiversity in most parts of the tropics and temperate zones. However, the existing evidence shows that it is the event with high probability that the biodiversity of high-altitude mountains in the cryosphere area tends to increase, while the probabilities of biodiversity increasing and decreasing of high-latitude cryosphere are almost equal [2]. Because of its diverse climate gradients, the alpine area has the "buffering capacity" to cope with global warming, so as to maintain the refuge of cold habitats. Affected by the decrease in snow cover, glacier retreat, and permafrost degradation, new species habitats appeared in alpine regions, and the original plant community composition and structure also changed quietly [14]. For example, the biodiversity and biomass of alpine vegetation zones above some high-latitude mountain forest lines in Northern Europe increased significantly, and the increasing rate of species richness is enhanced [15]. Temperature rise has shown various impacts on Arctic biodiversity, such as the migration of species in the south to the north, the replacement of tundra areas dominated by mosses and lichens by vascular plants like shrubs in large areas, and changes in plant communities and their related animal populations. Whether in high-altitude mountains or high-latitude Pan-Arctic regions, the productivity of terrestrial ecosystems is increasing significantly almost without exception. Therefore, from the perspective of biodiversity, productivity, and carbon stock, cryosphere at high altitude and high latitude is increasingly becoming a refuge for many species against global warming and plays a very important ecological barrier role.

In the marine cryosphere, the transport of species to the Antarctic and Arctic is significantly enhanced under the condition of sea ice retreat. In the mid-latitude sea area, it has been well proved that organisms move to the Antarctic and Arctic with the distribution of climate warming. With the intensification of warm current invasion, more zooplankton and individuals are transported to deeper sea basins of the Arctic Ocean. In Arctic waters, this northward migration phenomenon is more obvious among zoobenthos and fish. For example, codfish and capelin in polar regions migrated northward, which caused a large number of seabirds to expand northward; the distribution area of common eiders in Greenland extended more than 300 km northward [16].

2.3 Continuously strengthening carbon source trend in ecosystems

Melting of frozen soil will directly or indirectly affect CO_2 emission from soil and sediment by changing temperature, redox state, and organic matter decomposition. A large amount of permafrost carbon stock is lost and emitted under warming will significantly increase the atmospheric greenhouse gas content and form a positive feedback process [17] (Figure 4a). The changes of vegetation (due to the change of hydrological conditions, the mixing of mineral and organic soil, etc.) and microbial community in the area affected by the melting of permafrost will also affect the net greenhouse gas flux. In the Arctic region, from the tundra dominated by Gramineae species with the least disturbance (cold) to the tundra dominated by shrubs with the most disturbance (warm), although the productivity has been greatly improved, the area dominated by shrubs still shows a net loss of CO_2 to the atmosphere. This phenomenon indicates that greenhouse gases in the cryosphere may continue to show net emissions, and the composition of terrestrial biodiversity may determine whether the Arctic will become the source or sink of greenhouse gases [18].

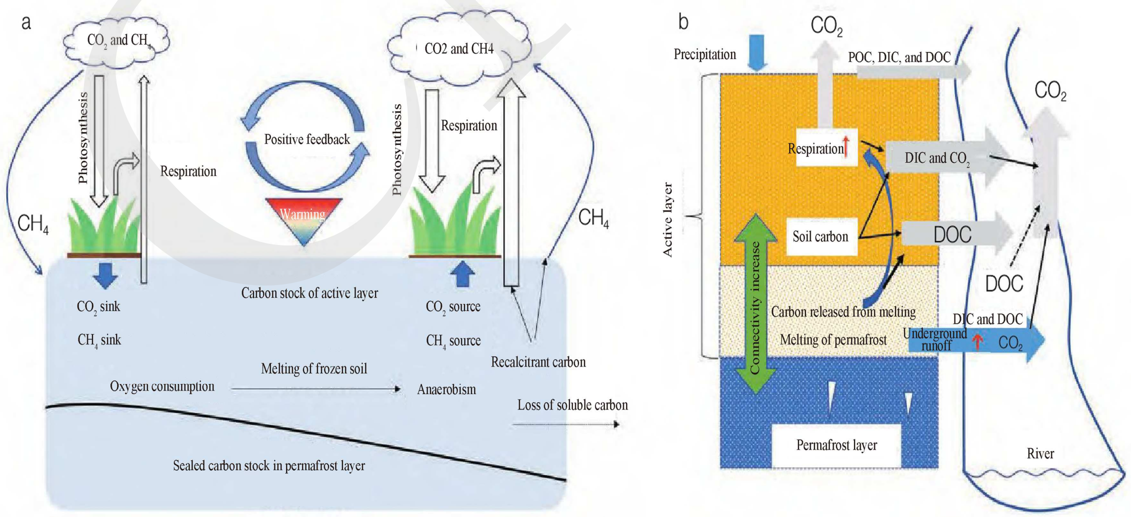

Figure 4 Intensification of carbon emission from cryosphere and carbon output from rivers in cold regions by global climate change

(a) Carbon emission process of terrestrial ecosystem in cryosphere; (b) the process of carbon output from river in cryosphere.

A large amount of carbon stored in frozen soil will be released into rivers and other water bodies along with the degradation of frozen soil (Figure 4b). The degradation of frozen soil caused by warming not only makes more frozen soil carbon enter rivers and lakes with runoff as soluble and granular carbon but also leads to more CO_2 entering rivers through enhancing underground runoff. In the permafrost region of Qinghai-Tibet Plateau, the fluxes of dissolved inorganic carbon (DIC) and dissolved organic carbon (DOC) transported to the downstream areas of Zhimenda Hydrological Station in the source region of Yangtze River are 485 Gg and 56 Gg [19], respectively, and the freezing-thawing process of active layer has a significant effect on the concentrations and fluxes of DIC, DOC, and CO_2 in rivers. The study of rivers in permafrost regions of Pan-Arctic shows that DOC output is controlled by frozen soil coverage and melting layer thickness, and DOC output concentration in areas with high frozen soil coverage is higher than that in areas with low frozen soil coverage [20].

Under the condition of climate warming, the snow cover in the Antarctic and Arctic will turn into ocean or land. On the one hand, this response may cause positive feedback (aggravation) to climate warming, because the ability of seawater to absorb heat is enhanced and the ability to retain greenhouse gases is weakened. On the other hand, the feedback effect may be negative, namely that it delays the trend of climate warming. The retreat of sea ice will stimulate the phytoplankton bloom and lead to the faster growth of benthos. Meanwhile, the collapse of ice shelf leads to more trace elements (mainly iron) entering the ocean, which stimulates the primary productivity and fixes more CO_2. Nevertheless, whether the increase in primary productivity will increase the carbon sink intensity of Arctic Ocean ecosystems is controversial [21].

3 Maintenance and regulation of ecological barrier of cryosphere

Cryosphere is the key area for the protection of species diversity and the maintenance of ecological barrier in the world. In China, nearly two-thirds of the important ecological barrier areas are distributed in the cryosphere. Therefore, the cryosphere plays an important role in the construction and maintenance of ecological barriers and the guarantee of sustainable development in China. Compared with other biological communities on the earth, the characteristics of most biological communities in cryosphere still keep relatively primitive and complete. However, the continuous cryosphere change is increasingly threatening the cryosphere ecosystems. From the perspective of the protection of the global cryosphere ecosystems, more active and effective control measures need to be taken. At present, there are three main control paths developed globally.

(1) Reasonably controlling the ecological pressure of herbivore population. More and more evidence shows that climate and herbivores have potential dual control effects on vegetation community in cryosphere ecosystems as well as main ecotone ecosystem [2]. Animal herbivorous behavior limits productivity and carbon sink of regional ecosystem to a great extent. For example, the eating by a large number of reindeer in the Arctic region leads to serious degradation or even disappearance of lichens on the tundra and tall shrubs on the low riparian plain of the Arctic; the excessive number of *Branta canadensis* leads to the degradation of plant communities in Arctic wetlands [22]. The population of wild herbivores in the Three-river-source National Park of Qinghai-Tibet Plateau has increased rapidly, and the competition between livestock and wild animals on grassland has become increasingly serious. The nutrition interaction in food webs in permafrost regions is very sensitive to the change of cryospheric elements, and the slight change of cryospheric elements may stimulate the drastic response of nutrition competition in food chains. Therefore, how to reasonably control the ecological pressure of herbivores has become a great challenge for the stable maintenance of the cryosphere ecosystems. This kind of control needs to consider both positive and negative impacts of increasing grazing pressure and impacts of other ecosystems with high herbivore density [2].

(2) Strengthening artificial improvement of the structure and productivity of vegetation community. From the composition of species, communities, and nutrient web, the ecosystem structure may determine whether the terrestrial cryosphere ecosystems will become the sink or source of greenhouse gases in the future and whether it will strengthen or weaken regional climate warming [23]. It has long been a consensus that there is significant reciprocal feedback between vegetation coverage change and frozen soil environment. Maintaining high vegetation coverage means high energy absorption, high organic matter content in shallow soil, and abundant litter, and can also effectively resist the interference of rodents, which are beneficial to the protection of frozen soil environment [24]. For the sake of coping with the cryosphere change due to the continuous climate warming, it is necessary to actively explore the optimization scheme of increasing the number of artificially introduced community species (e.g., artificial grassland vegetation community) and artificial vegetation community structure on the basis of further clarifying the optimal representation of community structure, which can not only realize the restoration and improvement of degraded ecosystem structure but also promote the protection of ecosystems to cryosphere environment.

(3) Constructing protection zones on the basis of the ecological carrying capacity of the cryosphere. Although the construction of nature reserves or national parks in the cryosphere is generally considered to be the most effective ecological protection measure, at present, the construction and operation of existing nature reserves and national parks have basically adopted the general traditional ecological

principles, and there is a lack of corresponding measures for the laws of the cryosphere ecosystems themselves. Therefore, it is necessary, on the foundation of the characteristics of ecological functions of cryosphere and the reciprocal feedback between cryospheric elements and ecosystems, to develop the theory and evaluation method of the ecological carrying capacity of the cryosphere on the basis of the sustainable maintenance of the cryosphere environment, and formulate the regional protection planning and ecological service and utilization scheme considering the ecological carrying capacity of the cryosphere. At the same time, through formulating the common code of conduct and the best implementation plan, we should actively develop biological measures suitable for cryosphere environmental protection and manage the cryosphere environment according to the law of ecosystems.

4 Future development trend of cryosphere ecology

(1) Long-term observation system and global shared network combining multi-scale fusion and multi-technology. Considering the huge spatial heterogeneity of cryosphere biological community and its habitats, and the high temporal variability of ecosystem pattern, process, and function caused by the extreme sensitivity of cryosphere to climate change, it is urgent to construct a long-term monitoring network covering all types of cryosphere habitats and ecosystems and form enough representative sample plots that can integrate different scales, so that the key questions about the current situation and future trend of the distribution pattern and function of the cryosphere ecosystems can be solved. Uniform sampling design, measurement methods, and classification standards are adopted to construct a long-term monitoring system with multi-scale fusion under the guidance of unified norms. A three-dimensional comprehensive observation and test platform system of "space, air, and ground" will be developed with a variety of existing advanced technical means and on this basis, the global cryosphere data-sharing network is realized. In this way, the closely interacting and changing biogeochemical and biophysical processes occurring between different cryosphere ecosystems and climate & cryospheric elements can be systematically understood.

(2) Interaction between cryosphere and biosphere and its mechanism. The interaction between cryosphere and biosphere is the most complex process in the interactions of multiple spheres on the earth surface, and there are many unknown fields, such as clarifying the nodes and thresholds of significant changes such as type replacement and structure change of the original ecosystem with the change of cryospheric elements. In the future, it is necessary to understand the influence mechanism of the change of main habitat elements of the cryosphere on the ecosystem, and finally realize the overall understanding of the interaction between the cryosphere and the biosphere and its mechanism [9], including ① the effect of snow cover change on the composition, structure, and function of ecosystems, and the effect and feedback of snow cover change on the biogeochemical cycle; ② the effect of river ice and lake ice change on freshwater ecosystems of lakes and rivers, and the cascade effect on adjacent terrestrial and marine ecosystems; ③ the situation and threshold of interaction between frozen soil and plant ecology under climate change, evolution theory of global change and frozen soil-ecosystem, and terrestrial ecosystem model in cold regions.

(3) Biogeochemical cycle of cryosphere. At present, the main frontier issues in the study of carbon cycle in cryosphere ecosystems are the distinction and contribution of soil heterotrophic respiration, nitrogen cycle and its coupling effect on carbon cycle under environmental change, and the effect of the change of cryosphere geographical process (such as erosion) or soil formation (such as freezing disturbance process) on carbon cycle. In the future, the frontier development direction focusing on the cryosphere carbon cycle mainly includes four aspects: ① the dynamic process and driving mechanism of the cryosphere carbon source and sink; ② coupling effect of carbon-nitrogen biogeochemical cycle in cryosphere; ③ eco-geographical process and freezing disturbance of carbon cycle in cryosphere, including temporal and spatial dynamics and driving mechanism of river carbon-nitrogen transport flux; ④ key geographical processes and scale variability of carbon-nitrogen balance at regional or global scale.

(4) Dynamic simulation of cryosphere ecosystems. At present, researchers are trying to apply some widely used terrestrial ecosystem models to the dynamic simulation of cryosphere ecosystems, but they think too simple about the cryosphere processes, which can hardly describe the evolution of the cryosphere ecosystems. Therefore, in the future dynamic model of the cryosphere ecosystems, it is necessary to strengthen the dynamic simulation based on the dynamic succession mechanism of vegetation in permafrost regions and the quantitative simulation of the carbon-nitrogen-water coupling cycle in the cryosphere, and incorporate the special soil texture and its changes in permafrost regions into the ecosystem model.

(5) Ecological services and ecological security of cryosphere. The structure and pattern of cryosphere ecosystems have changed significantly, and the corresponding effect on regional ecosystem services and ecological security is the weakest field of cryosphere ecology research, which lags behind other related studies in temperate and tropical regions. It is expected that the research on this issue will become the frontier and hot spot in cryospheric science in the future. We should focus on the following five aspects: ① the formation and stable maintenance mechanism of ecosystem services in the cryosphere; ② the assessment and simulation of eco-

system services in the cryosphere; ③ the response of ecosystem services to cryosphere changes and the regulation of regional ecological security in cold regions; ④ the exploration of the regulation strategies and technical system of ecosystem service maintenance and ecological security guarantee in cold regions under the change of cryosphere; ⑤ the establishment of the strategy and mode of ecological security maintenance, management, and conservation of cryosphere.

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WANG Genxu corresponding author, Professor of Institute of Mountain Hazards and Environment, Chinese Academy of Sciences (CAS), Director of the Key Laboratory of Mountain Surface Processes and Ecological Regulation, CAS, and Director of the National Field Observation and Research Station of Gongga Mountain Ecosystem. His research focuses on the study of cryosphere ecosystem and global change and ecohydrology. He concurrently serves as the Director of the Ecohydrology Committee of the Chinese Society of Ecology and the Director of the Cryosphere Ecology Committee of the Chinese Society of Cryospheric Science (preparation). He is the editorial board members of many journals including Journal of Mountain Science, Acta Ecologica Sinica, Chinese Journal of Plant Ecology, Chinese Journal of Applied Ecology, and also the associate editor of Mountain Research. He is the leading principal investigator of 17 projects including National Science Fund for Distinguished Young Scholars of National Natural Science Foundation of China, National Key Project Funds, National 973 Projects, etc. He has published more than 270 papers and 5 monographs. E-mail: wanggx@imde.ac.cn

