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Important Supporting Role of Biological Specimen in Biodiversity Conservation and Research

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Abstract

Biological specimens are important materials in the field of biological research and non-renewable strategic biological resources. The specimen collection of the Chinese Academy of Sciences (CAS) is the center of conservation, research, and scientific education. It plays an irreplaceable role in the research and protection of biodiversity in China. Biological specimens can provide important information in three dimensions: species, space, and time. The use of different levels of such information supports the research areas of species cognition, biodiversity cataloging, protection and management of endangered species, prevention and control of alien invasion, biodiversity monitoring, and species distribution pattern and biodiversity change. Biological specimens have great potential for biodiversity research and conservation. In the future, the construction and management of specimen resources need to be committed to more comprehensive collection, strengthen the acquisition of in-depth information and the construction of data integration platform, so as to better contribute to the construction of ecological civilization and biodiversity conservation in China.

Keywords

biological specimens; biodiversity; biological collection

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Important Supporting Role of Biological Specimen in Biodiversity Conservation and Research

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Abstract: Biological specimens are important materials in the field of biological research and non-renewable strategic biological resources. The specimen collection of the Chinese Academy of Sciences (CAS) is the center of conservation, research, and scientific education. It plays an irreplaceable role in the research and protection of biodiversity in China. Biological specimens can provide important information in three dimensions: species, space, and time. The use of different levels of such information supports the research areas of species cognition, biodiversity cataloging, protection and management of endangered species, prevention and control of alien invasion, biodiversity monitoring, and species distribution pattern and biodiversity change. Biological specimens have great potential for biodiversity research and conservation. In the future, the construction and management of specimen resources need to be committed to more comprehensive collection and strengthen the acquisition of in-depth information and the construction of data integration platform, so as to better contribute to the construction of ecological civilization and biodiversity conservation in China. **DOI:** 10.16418/j.issn.1000-3045.20210323001-en

Keywords: biological specimens; biodiversity; biological collection

Biological specimens refer to complete or parts of animals, plants, microbes, and ancient creatures, whose biological entities or remains or relics are kept intact or treated specially for long-term conservation, study, research, and display purposes. Biological specimens, in a broad sense, also include other objects or relics related to life activities [1]. Biological specimens are the most authentic and direct manifestations and physical records of creatures in nature. They are widely used in scientific research, popular science exhibitions, biological education, etc., and are important materials in biological research [2,3]. They also play an important role in life science and frontier interdisciplinary fields such as biodiversity protection, pest invasion, global climate change, and evolutionary biology.

Specimens are collected in natural history museums or specimen rooms as records of biodiversity and biological distribution, and they are also important research and educational resources [3–5]. Specimen resources that can be used for research, service, and education are collections of objects and knowledge reserves for understanding species and nature. From the perspective of scientific development, specimens are the basic materials in biosystematics and even biological research as a whole and lay an important basis for human beings to understand and transform nature. They are the most comprehensive representatives of biodiversity and important non-renewable strategic biological resources.

1 Status of biological specimen resources in China

Biological specimen collections and biological collections or museums (hereinafter collectively referred to as biological collections) in China were constructed in the 19th century, started to operate in the early 20th century, and developed after the founding of the People's Republic of China [2]. According to relevant data surveys and statistical analyses, more than 250 biological collections are under normal operation nationwide, with 40 million to 45 million collected specimens in total, and they are mainly affiliated with scientific research institutions, colleges and universities, and natural museums [3]. Among them, biological collections affiliated with China Agricultural University, Northwest A&F University, Southwest Forestry University, Hebei University, Nankai University, South China Agricultural University, and Sun Yat-sen University all have more than 1 million collected specimens, and their total collection size reaches 12.40 million specimens.

The specimen collection of the Chinese Academy of Sciences (hereinafter referred to as "CAS specimen collection") contains the most important and concentrated biological specimen resources in China [2,7]. The CAS specimen collection is a complex of 20 collections based in 19 research

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institutes which are distributed in 13 provinces, autonomous regions, and municipalities across the country. The collected biological specimens are derived from all parts of the country and cover almost all habitat types (including seas), and the collected biological specimen resources include animals, plants, fungi, fossils, etc. The CAS specimen collection is the largest animal, plant, and fungi collection with most specimens in China and even Asia, and it also owns a series of specialized collections that are the largest and most distinctive of their kind in China. The CAS specimen collection is an important center for conservation, research, and scientific education of biological specimen resources in China. It has the largest conservation system and digital data information network of biological specimen resources in China, which also has important international influence. It is also a platform for the integration, sharing, and utilization of biological specimen resources. Therefore, it plays an irreplaceable role in the protection and sustainable utilization of strategic biological resources in China [2]. By late 2020, the CAS specimen collection had stored a total of 22.036 million biological specimens of various types ① (Figure 1), which account for more than half of the total specimen resources in China.

2 Supporting role of specimens in biodiversity research and conservation

Specimens, as a basic material in biological research and a physical carrier and reference of species names, play an important role in promoting the origin and development of various biological disciplines. Scientific discoveries based on collections of specimens have changed the way humans perceive themselves, their environment, and their position in the universe [5,8]. Historically, collections in natural history have been essential resources for studying biodiversity on the earth [4,9], and biological specimens can provide information on biodiversity, taxonomy, and historical distribution of species worldwide. Such specimen information combined with spatial, environmental, and other data can support a wide range of research topics, from ecological and evolutionary perspectives to applications in species diversity, agriculture, and human health. They may provide a scientific basis and detailed evidence for biodiversity conservation, formulation of conservation policies for endangered species, and construction of national ecological security and biosecurity systems [4,8–10].

Since the middle of the 20^{th} century, with the advent of computer technology, specimens and their related information have been digitized on a large scale, which boosts the rapid development of biodiversity research [8]. From the perspective of information technology, information-based specimens mark a breakthrough and innovation in traditional life science, and information data about specimens lays the foundation for the frontiers and integration of life science, information science, and computer science. These data are important derivative resources of biological specimens, which are essential for the sharing of specimen resources, and the development of modern life science. Meanwhile, they are of practical significance to rapidly tracking global climate and environmental changes, identifying and monitoring biological and species diversity dynamically, helping government and scientific research institutions make informed decisions, and serving public education.

2.1 Multi-dimensional information of specimens

A systematic collection of biological specimens is often compared to a library, where specimens are similar to reference books. Moreover, each specimen is unique and provides information in many dimensions: species (biological, genetic, ecosystem diversity), space (place), and time (date) [5]. The value of specimens lies not only in the physical resources and the external morphological characteristics, but also in the temporal and spatial data, historical imprints, and genetic resources, which embodies the supporting role of specimens in biodiversity conservation. When the specimen information in dimensions of species, space, and time is presented and connected to appropriate fields in biological diversity, it becomes clear that the information in different dimensions can support biodiversity research in different fields (Figure 2).

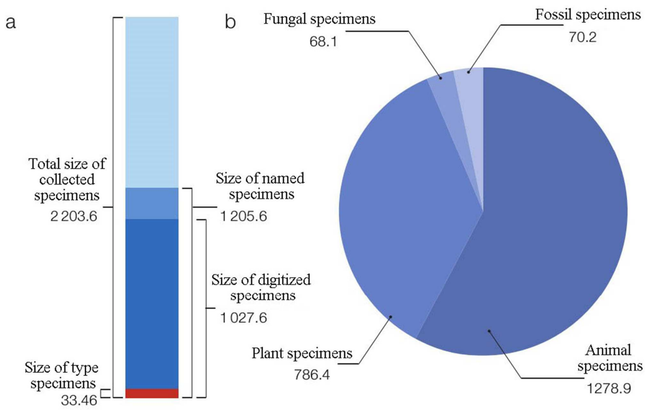

Figure 1 Specimen resources preservation status of the CAS specimen collection (×10,000)

(a) Overall preservation status; (b) Preservation status of various biological groups.

① Data source: statistics of the working committee of the CAS specimen collection (museum).

(1) Species information. Specimens naturally carry not only information about biological species themselves and other derived biodiversity information (including the morphological structures, biological and chemical compositions, and genetic information of various species), but also relevant non-biological information, such as environmental trace elements [11] and environmental pollutants [12] on birds' feathers. To understand nature and its characteristics and laws, human beings need to first name the components of nature. Biological nomenclature has existed since ancient times, but it was not mature until Linné① proposed a biological classification system and invented the "binomial nomenclature" in the 18th century, which allowed people to classify and name various species in a systematical and scientifical manner. In the 19th century, humans began to explore nature on a large scale. Disciplines such as physical geography, meteorology, ecology, biogeography, and the theory of evolution gradually took root, and the development of biology also contributed to the constant perfection and precision of the concept of species. This process was accompanied by massive expeditions worldwide, as well as the collection, preservation, accumulation, and research of specimen resources [8]. Darwin's ② theory of evolution and Wallace's ③ zoogeography would have been impossible if no expeditions were made and no specimens were collected, identified, or studied. Species information can be summarized from studied and named specimens. The species information carried by these specimens is applied to species cognition and biodiversity cataloging, which lays the foundation for research in various fields of life science.

(2) Species information + spatial information. When specimens are collected or obtained, information about spatial distribution, such as locations, latitudes and longitudes, altitudes, and even mountains and rivers, are recorded. Spatial information can reflect the distribution, migration, and other laws of species. In combination with the number of species and historical distribution records, it can be applied to the protection and management of endangered species and the prevention and control of alien species invasion.

(3) Species information + spatial information + temporal information. Specimens also carry temporal information such as the date, time, and season of the collection. In combination with species and spatial information, that information can reveal the distribution pattern and changing laws of biodiversity so as to support biodiversity monitoring and the formulation of conservation strategies. Additionally, climate or geological changes, human activities, and other factors can be integrated to study and explore the geographical distribution pattern of species and the process and mechanism of biodiversity changes.

2.2 Supporting role of specimen information in biodiversity conservation-related fields

2.2.1 Species cognition and biodiversity cataloging

(1) Supporting species cognition. From the perspective of species, specimens are the most important physical evidence for species classification, carriers or records of species names, and important references for identifying unknown species. ① Tracing of new species and discovery of new records. According to the statistics of the working committee of the CAS specimen collection (museum), based on the 20 biological collections of the CAS, an average of more than 150 new species are traced every year. In recent years, a number of important new taxa have been published based on the collections. The followings are some examples. The Chengdu Institute of Biology, CAS, established a new genus of the family Rhacophoridae called *Zhangixalus* [13]. The Institute of Botany, CAS, and other units used the molecular data obtained from the collected specimen materials to establish a family of Wightiaceae [14], which is the sixth angiosperm family published by Chinese scholars. Based on molecular data and collected specimens, the Institute of Zoology, CAS established two new bird families (Elachuridae [15] and Alcippeidae [16]) and one new bird genus (*Parayuhina* [16]) and described one new bird species, *Locustella chengi* [17]. ② Systematic determination of the taxonomic status of species. The

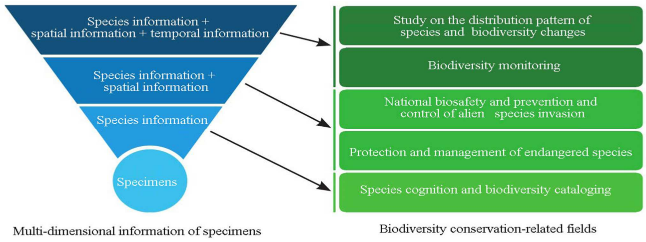

Figure 2 Multi-dimensional information of specimens and its supporting correspondence with biodiversity conservation-related fields

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① Carl von Linné (May 23, 1707–January 10, 1778), a Swedish biologist and founder of the "binomial nomenclature" of animals and plants. He proposed the species classification method of kingdom, phylum, class, order, genus, and species (there was no "family" at that time), which is still in use today.

② Charles Robert Darwin (February 12, 1809–April 19, 1882), a British biologist and founder of the theory of evolution. He published the book *On the Origin of Species* in 1859 and proposed the theory of evolution, which overturned creationism and the theory of species immutability.

③ Alfred Russel Wallace (January 8, 1823–November 7, 1913), a British naturalist, explorer, geographer, anthropologist, and biologist, famous for his theory of "natural selection." He was the founder of zoogeography due to his research and revision of the geographical distribution of animals.

determination of taxonomy is also an important and ongoing task in species cognition. Accumulated specimens are available for the reference of researchers. The CAS species collection offers over 6,000 specimen views for domestic and foreign scholars every year. For example, the Herpetological Museum of the Chengdu Institute of Biology, CAS has the most comprehensive and largest collection of amphibian and reptile specimens in China. By virtue of the collected specimens, researchers can systematically evaluate and revise the classification system and species of Reptilia in China, and further provide the latest taxonomic list of 3 orders, 30 families, 132 genera, and 462 reptile species in China [18].

(2) Supporting biodiversity cataloging. The compilation of biological records is of paramount importance to biodiversity cataloging. The investigation and research of biological resources and the compilation of records reflect the fundamental level of life science in a country [19]. ① State-level cataloging. The compilation and research of various biological records represented by the "three major records" (*Fauna Sinica*, *Flora in China*, and *Spore Plants in China*) have greatly improved the identification rate of biological specimens in China. This fully demonstrates that specimens effectively support the discovery, tracing, determination, and cataloging of species. The "three major records," which have been updated ever since the 1950s, are major systematic projects to figure out the biological resources in China and important landmarks of biodiversity cataloging in China [19,20]. The "three major records" are comprehensive and systematic censuses of China's biological resources using research methods of modern life science. They greatly enhance the knowledge about biological resources in China and promote the rapid development of taxonomy and other biological disciplines. The CAS is an organizer and a main participant in the compilation and research of the "three major records." For example, it takes more than 60 years to compile the *Flora in China*, which won the special prize of National Natural Science Award, and the work includes more than 50 million characters in 126 books and 80 volumes, recording 31,142 plant species of 3,408 genera and 301 families in China. Among them, 110 books of 65 volumes are completed with the participation of experts from the CAS [21], and 80% of the specimens supporting the compilation and research of this work are preserved in the plant collections of the CAS. So far, the *Fauna Sinica* is composed of 113.159 million characters in 163 volumes, recording 39,567 species, 7,844 genera, and 1,043 families of animals in China ①. The *Spore Plants in China* includes 46.29 million characters in 110 volumes, recording 19,414 species, 2,259 genera, and 394 families of spore plants in China ②. During the compilation and research process of the "three major records," most of the specimens collected were preserved in the CAS specimen collection. Meanwhile, each CAS collection also provided a large number of specimens and information consultation services. ② Provincial cataloging. Most of the provinces in China have also completed the compilation of their species catalogs or biological records [20]. The CAS specimen collection also played an important supporting role in this provincial-level compilation work. For example, the collection of the South China Botanical Garden, CAS, provided a large number of specimens for the compilation and research of *Flora in Guangdong*, and this contribution offers insight into the plant diversity in Guangdong. ③ Foreign cataloging. With the advancement of the "Belt and Road" initiative, China has strengthened cooperation with the partnered countries in the research field in recent years, as manifested in a number of joint resource investigations [2]. The collected specimens have supported a series of studies on biodiversity and important achievements, such as the most typical representative *Flora of Pan-Himalaya* [22] and *Flora in Kenya* that is about to be completed and published [23].

2.2.2 Protection and management of endangered species

The protection and utilization of biodiversity have attracted more and more attention in countries across the world, and the public awareness of the significance and the important ecological and application value of wildlife protection is also growing. Specimens and other investigations have shown that the populations and distributions of some species are clearly declining, and a crisis of survival is around the corner. Historical records of specimens have become an important basis for compiling red lists and determining the classification level of endangered species.

(1) Compilation of red lists of endangered species. Some rare and endangered species are seldom seen in the wild, and they only appear in collections, such as *Psephurus gladius* and *Lipotes vexillifer* specimens in the Museum of Hydrobiological Sciences, Institute of Hydrobiology, CAS, and *Cynops wolterstorffi* in the Herpetological Museum, Chengdu Institute of Biology, CAS. Based on the historical distribution information and literature records of the specimens collected by the CAS and related collections affiliated with universities, researchers comprehensively assessed the endangered status of wild vertebrates in China and compiled the *Red List of China's Vertebrates* [24]. In addition, an increasing number of specimen conservation institutions directly participate in the assessment of endangered species.

① Data source: the latest statistics of the Compilation Office of *Fauna Sinica*.

② Data source: the latest statistics of the Compilation Office of *Spore Plants in China*.

For example, the *Red List of China's Biodiversity: Macrofungi* ①, compiled under the leadership of Fungarium of Institute of Microbiology, CAS, is the first official red list of fungi in China and marks China's first endeavor to comprehensively assess the threatened status of macrofungi according to the standard of the International Union for Conservation of Nature (IUCN). The Herpetological Museum, Chengdu Institute of Biology, CAS, participated in the assessment for the *Red List of Reptiles in China*, and conducted research on the biodiversity and threatened status of amphibians and reptiles in China. The assessment has covered the most extensive research objects, provided the most information, and involved the most experts so far. It is of great significance to the research of amphibians and reptiles in China and the protection and utilization of resources [25].

(2) Determination of the classification level of endangered species. Since 2019, the national red insect species assessment team has organized more than 200 insect taxonomists from more than 90 universities and research institutes for surveys or assessments. Based on the collected insect specimens in relevant units across the country, more than 2 million pieces of species information were collected and then used to specially assess the survival, resource accessibility, distribution, and threatened status changes of wild insect species nationwide according to the red species assessment standards of IUCN. The assessment covered 14,549 species, 401 families, 31 orders, and 4 classes of Hexapoda ②. The assessment initially clarifies the number, distribution, and threatened status changes of wild insect species resources in China. Those efforts lay a scientific basis for national-level endeavors to formulate action plans and protection catalogs for protecting the diversity of wild species, conduct background investigations of insect species diversity, and make rational use of insect resources. It also provides basic guidance for relevant scientific research and popular science education and further promotes the *Convention on Biological Diversity* that China makes a commitment to and *China National Biodiversity Conservation Strategy and Action Plan (2011–2030)* ③.

2.2.3 National biosafety and prevention of alien species invasion

Biosafety is an important part of national safety, and national biosafety is the first line of defense and barrier to a country's biosafety. Strengthening port inspections, providing early warnings, and building port quarantine defenses are important guarantees to prevent the invasion of alien species and the spread of animal and plant epidemics. Rapid and effective identification of objects intercepted at ports is the key to accurate law enforcement at ports, and biological specimens are indispensable to the identification of intercepted objects. The identification of species requires reference to existing named specimens, while the identification and discrimination of animal and plant products not only require reference to specimens, but also the DNA information (such as DNA barcode information) based on named species as supporting data. Specimens of invasive alien species have long been used for a series of purposes including species identification, determination of distribution areas, population sources and transmission speed, and assessment of ecological impact [4]. Specimens of invasive species and their sibling species are also key materials for rapid identification and effective prevention of biological invasion [26].

Relying on the biological collections and the collected specimen resources, the CAS carried out a number of important national biosafety projects and established a branch of animal and plant specimen collection for national biosafety, which includes a physical collection and an information base during the 13th Five-Year Plan period. Moreover, the CAS also built a series of data platforms, such as the Information System of Invasive Alien Species of China, DNA Barcode Database of Invasive Alien Species, Quarantine Fungi Database of Imported Plants, and Comprehensive Identification System. Such specimen and species distribution information helped interpret the introduction risk of invasive vertebrates along the "Belt and Road." The suitable habitats for these invasive species to establish populations were predicted based on niche models [27]. Based on existing species distribution and environmental climate factors, efforts were made to analyze and assess the risks of newly intercepted important pests, and the results provided background data for the release of the third and fourth batches of the *List of Invasive Alien Species in China* by the Ministry of Environmental Protection (now "Ministry of Ecology and Environment"). The CAS also cooperated with the customs to monitor invasive alien organisms at ports, where a number of malignant invasive plants that had invaded and spread on a large scale abroad were intercepted and identified, and imported plant epidemics were detected more than 10 times. These results reflect the important supporting role of specimens and the biological information they carry in national biosafety monitoring and prevention of alien species invasion. Building a "sky net" of national biosafety requires prioritized deployment made for the collection and conservation of targeted specimens, construction of rapid detection technologies and identification platforms based on specimens, and also the building of talent pools.

2.2.4 Biodiversity monitoring

Biological research and utilization of biological resources are based on the investigation, collection, and protection of

① http://www.mee.gov.cn/gkml/sthjbgw/sthjbgg/201805/W020180524494623078963.pdf.

② Data source: the national red insect species assessment team.

③ http://www.mee.gov.cn/gkml/hbb/bwj/201009/t20100921_194841.htm.

biological resources, which is of strategic significance due to its influence on the safety of natural resources, social development, and related biological research in China. *China National Biodiversity Conservation Strategy and Action Plan (2011–2030)* lists 10 priorities and actions in biodiversity conservation, including "conducting biodiversity investigations, assessments, and monitoring." Biodiversity investigations, assessments, collection, and protection all rely on the support of classical classification and specimens.

So far, some state-level biodiversity monitoring networks have been established to collect biodiversity data in China [20], and specimens are important data sources that can provide scarce and unique historical records [4,6]. For example, the Institute of Hydrobiology, CAS, has conducted basic investigations of aquatic organisms nationwide since the 1950s, created basic disciplines such as Chinese ichthyology, phycology, and protozoology, and kept the collected specimens in the Museum of Hydrobiological Sciences. In recent years, researchers have used these specimens to conduct a comprehensive assessment of fish diversity in the Yangtze River Basin for the first time and established a DNA barcode reference database [28]. These efforts, along with long-term uninterrupted monitoring of fish in the Yangtze River, have enhanced biodiversity protection in the Yangtze River Basin and realized "ten-year closed fishing" in the Yangtze River.

2.2.5 Research on species distribution patterns and biodiversity changes

(1) Research on species distribution patterns. The distribution of species reflects their living ranges and habitats, and fauna and flora can comprehensively demonstrate the composition and the temporal and spatial distribution of biological species community in a region. Specimens provide reliable and direct information on species distribution. By digitizing the species distribution information, researchers can carry out biogeographical and fauna and flora studies based on the big data of distribution information. China has accumulated rich data for fauna and flora investigations and analyses, division of distribution area types, and biogeography [29,30]. In recent years, with the emergence and application of new biogeographical methods and theories, as well as the establishment of big data analysis models, fauna and flora/diversity pattern studies have developed into a new deeper stage where fauna and flora/pattern phenomena can be interpreted quantitatively and their formation mechanisms can be explored [29]. The followings are some examples. ① In the field of plant diversity research, scientists charted the evolutionary tree of 92% of the angiosperm genera in China and captured more than 1.4 million entries of detailed spatial distribution data based on the collected specimens. They also revealed the evolutionary history of the distribution pattern of angiosperm diversity and identified the "museums" and "cradles" of angiosperm evolution in China. The conservation priorities have been proposed on the basis of identified hot spots of angiosperm phylogenetic diversity in China [31]. ② In the field of insect diversity research, with Hemiptera (an important agricultural and forestry insect group) as an example, the species distribution information based on abundant specimens was used to build a geographic distribution dataset of Hemipteran insects in China. On this basis, a comprehensive diversity pattern analysis was made to test whether there were differences in the effect of different environmental factors on the diversity of Hemipteran insects in different regions. This further led to the proposal of scientific hypotheses, such as the "museum" and "cradle" role of mountainous areas in the evolution of the temporal and spatial diversity pattern of Hemipteran insects [32]. ③ In the field of reptile research, the historical reserves of species collections and abundant morphological information generated from the specimens collected from intensive investigations over the past 10 years, as well as molecular data, were fully used to examine the adaptability and evolution of amphibians and reptiles in Tibet. Moreover, based on the distribution information provided by specimens, a systematic analysis was made on the amphibians and reptiles in Tibet to strongly support the research on the diversity pattern and evolution of these animals [33].

(2) Research on biodiversity changes based on deep mining of specimen information. The uniqueness of specimens also comes from their ability to provide scientific data over a huge time span from millions of years ago to the present, thereby supporting the research on species decline and biodiversity loss [4]. The deep value of specimens can be explored to explain how species adapt to environmental changes based on specimen information at different historical stages and to examine the endangerment mechanism of species in molecular-level research based on collected specimens. Such value is collectively manifested in its ability to promote research on global changes, which have become the focus of modern biological research. However, the absence of biological data spanning the "Anthropocene" limits our understanding of how human factors affect biodiversity and natural resources. A large number of plant, animal, and fungal specimens preserved in biological collections can break this limitation and provide invaluable physical evidence and information for biological research on global changes [34]. Many studies have been conducted in this field abroad, and successful attempts have also been made in China in recent years. For example, the Institute of Botany, CAS, used the collected herbarium specimens of the *Typha* genus to establish a regression equation of plant stomatal index and atmospheric carbon dioxide concentration, and reconstructed the carbon dioxide concentration at the turn of the Tertiary and Quaternary periods. This work was based on the stomatal morphological characteristics of the leaf surface at different time and the environmental carbon dioxide information of the corresponding era. This research also integrated previous data to construct the first global atmospheric carbon dioxide concentration curve in the terrestrial ecosystems over the past 5 million years and further examined the impact of carbon

dioxide on global climate change. The research results are helpful for the government and all sectors of society to understand, consider, and formulate measures to deal with current and future climate warming. This attempt is of theoretical and practical significance [35].

3 Specimen resources for future biodiversity conservation

In recent years, there has been an increasing number of studies on ecological and environmental problems (such as biodiversity changes), and the number of studies using biological specimens in collections from an ecological or environmental perspective has also risen sharply. Specimens show great potential in promoting ecological and environmental research [36]. However, the deep value of specimens has not been fully exploited. We should recognize the importance of specimen resources and believe that they will be increasingly used in biodiversity research and conservation.

3.1 Challenges and trends

The environment is a central concern of human beings in the 21st century [37]. How to master the knowledge of biodiversity on the earth and use it to shape a global environmental system where all creatures live will be a major challenge for mankind [6]. As far as the current rate of species extinction is concerned, there is a pressing deadline to meet this challenge, with so many biodiversity resources to be discovered and so many biodiversity studies to be completed [37]. During the years that have passed in the 21st century, research and methods based on specimen collections have brought about breakthroughs in life science. For example, the digitization of and open access to abundant specimen data and images, the linking of specimen and climate data with phylogenetic research results on a global scale, and the generation of massive genomic data have enabled us to explore major theoretical issues such as evolutionary and diversity patterns [8]. In China, scientific research on biodiversity has developed rapidly in recent decades, with significant progress made in cataloging and monitoring, mechanism and process, threat and strategy. Furthermore, deeper attempts will be made in three directions: applying biodiversity theories to biodiversity conservation practice, strengthening capacity building and application of advanced technologies, and intensifying and expanding international cooperation [20].

Facing these challenges and trends, collections need to make massive improvements for ability enhancement as important entities and information sources of biodiversity. Workers and researchers of specimen collections need to consider how they can cater to biodiversity conservation and research at a consistent pace. Meanwhile, what is equally important is the building of talent pools in basic fields such as the collection, identification, classification, conservation, management, and information mining of specimen resources.

3.2 Actions and outlook

Throughout the development histories of specimen collections and biodiversity science, specimens have been used by means of their information extracted and analyzed. Humans began to classify and name organisms in the 18th century, made large-scale expeditions and accumulated numerous specimens in the 19th century, digitized specimen records and opened up the field of biodiversity in the 20th century, and conducted in-depth data integration and statistical analyses in the 21st century [8]. During this process, we continued to learn, exploit, and utilize species and specimen information. With the advent of various new ideas and technologies, humans are more and more able to obtain information from specimens. In order to address different biodiversity research and conservation problems by virtue of different levels or scopes of information, we can start with information to solve existing problems and meet future challenges as long as our physical resources keep growing.

(1) Making a commitment to the collection of specimens and their related information in a more systematic and comprehensive manner. It is far-reaching for specimen collections to continuously expand the collection, conservation, and scientific and digital management of specimens, and try to cover most biodiversity niches that are still waiting to be discovered, recorded, described, and understood in nature. At the same time, information platforms can be built to acquire massive information about the biodiversity known on the earth and transform such information into scientific and social knowledge [6]. Related technologies can be used to improve the quality of data and reduce errors or deviations. For example, suspected identified specimens can be confirmed through DNA barcoding [20].

(2) Using new technologies and methods to acquire deep information. Although traditional collections of biological specimens are mainly used in biodiversity research, their applications in taxonomic, systematic, and evolutionary biology research are only part of their value [5]. While continuously accumulating and improving the basic information of specimens, specimen collections should closely follow the development trends of biodiversity-related disciplines, dig into the deep information of specimens, and explore new directions for information utilization to further exploit the value of specimen collections and cater to scientific and social development. For example, the stomatal morphology of leaf surfaces [34] and pollutants in feathers of bird specimens [12] can be captured to reveal the law of climate change.

(3) Further strengthening data integration and the construction of sharing platforms. The primary task of specimen collections to meet the biodiversity challenge is to liberate their collected specimens from physical libraries through the

construction of information integration platforms. Only through information technology gathering and data integration, can specimens be used to tackle complex biodiversity problems, and therefore specimen collections can become the cornerstone of global biodiversity solutions [6]. The construction of information platforms can help overcome the limitation of small sample sizes, and online open access is a good way to reduce the costs of data acquisition. In recent years, China has made unremitting efforts in this regard, including investment in the construction of several biodiversity data platforms. In the future, we will continue to strengthen the capacity building of platforms and expand international cooperation and sharing, which is also the development strategy of biodiversity research in China [20].

As the largest biological collection system in China, the CAS specimen collection played a huge supporting role in past biodiversity research and conservation efforts. Now, in collaboration with the major specimen collections in the country, it has taken the lead in building the "National Animal Collection Resource Center" and "National Plant Specimen Resource Center" [2]. While strengthening the construction of these two centers, the CAS specimen collection will lead the collection, preservation, sharing, and utilization of specimen collection and contribute to the construction of ecological civilization and biodiversity research and conservation in China.

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