iScience

CellPress
OPEN ACCESS

Review

Conservation of rare and endangered plant species in China

Yue Xu[1,2] and Runguo Zang[1,2,*]

SUMMARY

Rare and endangered plant species (REPs) are facing high danger of extinction, yet a comprehensive and up-to-date review on their conservation in China is still lacking. This paper systematically collected studies and achievements on REPs conservation, including species surveys and monitoring, cause of endangerment, *in situ* conservation, *ex situ* conservation, reintroduction, propagation, conservation legislation, public participation, progress in conservation of wild plant with extremely small populations, and progress in China's implementation of the Convention on Biological Diversity. Although enormous advances have been made in conservation policies and legislations, protection systems, and research, as well as public education and international collaborations, the conservation efficiency is still restricted largely by the conflict between economic growth and biodiversity conservation in China. In order to meet its commitments to the new Post-2020 Global Biodiversity Framework, more work on basic investigation and long-term observation, as well as advanced technologies and application-oriented research on REPs should be carried out.

INTRODUCTION

Biodiversity encompasses the diversity and variability of all life on earth, which plays very important role in the maintenance and sustainable development of human society. However, it is under greater threat than ever before because of global climate change, biological invasion and human activities-induced habitat destruction, environmental pollution, and land-use change.[1] Current extinction rates are orders of magnitude greater than background rates estimated from the fossil record and molecular phylogenies.[2] The ever-increasing loss of biodiversity is threatening unique biota, as well as the functioning and services provided by ecosystems essential for human well-being.[3] However, the major difference between the current mass extinction event and previous ones is that humans are threatened by it, responsible for it, and able to stop it simultaneously.[4]

Owing to its highly heterogeneous geographical and ecological characteristics, China is one of the world's mega-biodiversity countries and is exceptionally rich in plant biodiversity.[5,6] The Catalog of Life China 2022 Annual Checklist (http://www.sp2000.org.cn/) showed that there are 35,214 species of vascular plants in China, representing approximate 10% of the world's diversity of vascular plants. As one of the main centers of origin and diversification for seed plants on Earth,[7] China is profuse in endemic species and phylogenetically primitive taxa.[8] Endemic species account for 52.1% of the total Chinese seed plant species.[9] China also harbors many threatened species because of its long history of human civilization, rapid population growth, and economic development.[10] According to the latest evaluation, 3,879 species, representing 10.84% of all native higher plants in China, have been identified as threatened categories.[11]

Protecting the most deserving species is the primary responsibility of current conservation efforts because of lack of conservation resources, which means effective approaches for the protection of rare and endangered plant species (REPs) are urgently required.[12] Researchers often assess species status to identify whether the species is threatened when determining species that are most worthy of protection. The List of Rare and Endangered Protected Plants in China published in 1987 is the first list focusing on REPs, which includes 388 vascular plants classified to three protection grades.[13] The first list of legally protected plants—the List of National Key Protected Wild Plants in China—is promulgated by the Chinese State Council in 1999 and adjusted in 2021; the newly adjusted list includes 455 species and 40 categories of wild plants. In order to protect the most threatened plant species in China, the State Forestry

[1]Key Laboratory of Biodiversity Conservation of National Forestry and Grassland Administration, Ecology and Nature Conservation Institute, Chinese Academy of Forestry, Beijing 100091, China

[2]Co-Innovation Center for Sustainable Forestry in Southern China, Nanjing Forestry University, Nanjing 210037, China

*Correspondence: zangrung@caf.ac.cn

https://doi.org/10.1016/j.isci.2023.106008

Administration released Implementation Plan of Rescuing and Conserving China's Wild Plant with Extremely Small Populations (WPESP) (2011–2015) in 2012, including 120 species for priority conservation under this program. The International Union for Conservation of Nature (IUCN) Red List of Threatened Species is currently the most widely used system for objective assessment of species' extinction risk.[14] The China Species Red List: Vol. I Red List evaluated the threatening status for 4,408 seed plants using the IUCN Red List Categories and Criteria for the first time; 86% of the assessed species are listed as threatened species.[15] The Ministry of Environmental Protection (MEP) and Chinese Academy of Sciences (CAS) initiated the Red List of China Higher Plants (RLCHP) in 2008. RLCHP used the global IUCN Red List (version 3.1) and guidelines for application at regional and national levels to evaluate the threatening status of 35,784 Chinese native higher plants. A total of 3,879 species are categorized as threatened species, in which 614 species are critically endangered (CR), 1,313 species are endangered (EN), and 1,952 species are vulnerable (VU).[16]

Extinction is irreversible and should not be acceptable. The explicit goal of zero extinction cannot be dismissed in species conservation.[17] The Chinese government highly concerns biodiversity; its experience with ecological civilization (EC) is a great example of how a concerted national effort to mainstream biodiversity conservation by the central and all levels of government can help to realize conservation objectives. EC was proposed in 2007 as an innovative way to reconcile development and nature conservation at the 17th National Congress of the Communist Party of China.[18] EC was then embedded in the country's constitution in 2018 and became the general national development strategy. Under the background of EC, the government has put great efforts into strengthening the effectiveness of biodiversity conservation, including the promulgation of laws, creation of national catalogs of species, evaluation of threatened status of wildlife and setting conservation priorities for them, and use of comprehensive strategies to conserve genetic, species, and ecosystem diversity.[19,20] With China's strong political structure and centralized funding, effective and ambitious national-scale initiatives such as the national Red List evaluation of species, dramatic expansion of protected areas, redline policies to protect biodiversity and ecosystem services, and the network of forest dynamics plots have been launched.[21] By integrating climate, biodiversity, and land-use strategies under national policy frameworks, this kind of "political feasibility" will help to conserve biodiversity[22] and to fulfill the target of zero extinction eventually.

In a global context, China is of vital importance in biodiversity conservation both because of its high species richness and because it is such a significant refuge for many of the species.[23] The Chinese government and associated institutions and communities have made significant efforts to promote biodiversity conservation, especially REPs protection, in the last few decades. Here we try to systematically review the history and current status of REPs conservation in China and summarize its progress and deficiencies, so as to provide support and basis for the future formulation and implement of protection, development, and utilization strategies of REPs. The contents listed here are not exhaustive but an attempt to partly demonstrate the rapid development of REPs conservation in China. We hope the experiences and lessons learned over recent decades also provide useful examples for other countries and regions in biodiversity conservation.

SPECIES SURVEYS AND MONITORING

Plant conservation is suffering from serious gaps in knowledge of baseline data, such as its taxonomy, distribution, ecology, population biology and demography, values, threat, and conservation status.[24] Species surveys and monitoring are fundamental to establish baseline data on biodiversity conservation. In the past several decades, a series of investigations for the whole country were carried out to establish a complete plant inventory since the 1950s. The complete Flora Republicae Popularis Sinicae (80 volumes, 126 books, in Chinese, http://frps.iplant.cn/), Flora of China (49 volumes, in English, http://www.efloras.org/), and the Catalog of Life China are available both in publication and online. China has been a leader in the international effort to digitize and upload museum collections.[21] More than 16.4 million herbarium specimens and 17.8 million color photographs have been digitized and uploaded online (http://www.nsii.org.cn/2017/home.php). To solve the problem of identification of plants, CAS has established the "Plant DNA Bank of China" (https://www.plantplus.cn/dna/), which makes it possible to identify REPs quickly and accurately by DNA barcode. CAS also initiated the Big Earth Data Science Engineering Project (http://www.casearth.com) in 2018, which integrates biodiversity information from the academic communities, decision-makers, conservation practitioners, and the public. Plant surveys on important biodiversity groups have also been conducted. For example, the State Forestry Administration has conducted investigations twice on the National Key Protected Wild Plants during 1997–2003 and 2012–2018. The Ministry of Ecology and

Environment are implementing special investigations on key areas, key species and habitats, and biological genetic resources from 2018 to 2023 through the "Implementation Program for Biodiversity Conservation Major Projects".[25]

Effective biodiversity conservation requires a rapid understanding of how the elements of biodiversity are changing over time. Accumulated monitoring data help to assess the current status and future prospects of REPs and provides suggestions to improve conservation management measures.[6] Using monitoring data to conduct periodical red list assessments in order to better understand the threatened status and threats is also important.[26] For example, a comparison between a new red list assessment of gymnosperm species native to China in 2021 with the earlier assessment released in 2013 showed that 2 families were reduced while 3 genera and 40 species/infraspecies increased in priority.[27] Several biodiversity monitoring networks, the National Forest Inventory (monitoring forest resources and biodiversity with a five-year interval since 1973), China Biodiversity Observation and Research Network (Sino BON, including 24 large forest dynamics plots covering forests from boreal to tropical zones), Chinese Ecosystem Research Network (CERN, including 44 field stations covering all major ecosystems), China Terrestrial Ecosystem Research Network (CTERN, including 202 field stations covering forests, bamboo forests, wetlands, deserts, and cities), and National Ecosystem Research Network of China (CNERN, including 53 well-equipped and developed field stations covering China's main ecosystems), have been established to quantify and understand biodiversity trends.[28,29]

All the above activities together have built the cornerstone of plant conservation research and practice in China through large amounts of data. Nevertheless, several weaknesses should also be addressed. First of all, some key biodiversity areas with high percentage of REPs, such as south slope of the Himalayas and Gaoligong Mountain, are weak or even blank areas for the collection of biological resource inventory. Conducting comprehensive surveys in these regions is urgent, which will provide basic data for protecting cross-border ecological security.[30,31] Secondly, the ratio of data deficient (DD) species in red list assessment of plants is relatively high (13.42% of all higher plants in China[11] versus 7.96% of higher plants in IUCN global Red List [https://www.iucnredlist.org/]). However, categorizing species as DD does not mean that these species are not endangered; in contrast, many of them may be among the most threatened species and require thorough surveys. Thirdly, monitoring is still given low priority in nature conservation because it is often difficult and expensive to implement. Many monitoring programs are poorly designed without a sound ecological basis.[28] The current monitoring network only covers a limited area of land, making it difficult to reflect changes in national biodiversity, especially in key plants such as REPs. And new technologies such as Light Detection And Ranging (LIDAR), remote sensing by drones or small satellites, have not been largely applicated to better understand changes in species dynamics and habitats.[26,32] In order to make biodiversity monitoring in China better serve policy makers and the general public, it is urgent to establish comprehensive survey and monitoring data platforms and promote unified coordination of data gathering.[29] Specifically, top-level design for long-term monitoring system should be built to make the indicators, methods, and guidelines standardized and to enable comparisons between and within sites over time.[30] Fourthly, investigation and monitoring data should be shared, integrated, and analyzed to help guide management decisions and policy.[26] A searchable database about species and population survey information should be set up as a matter of priority. Only in this way can we provide a scientific, reliable, and dynamic basis for biodiversity conservation.[12]

CAUSE OF ENDANGERMENT

Identifying the detailed characterization and distribution of threats faced by species is a crucial step toward estimating the political feasibility of mitigating threats and designing effective conservation strategies. The determination and ranking of biodiversity threats are commonly applied to establish priorities for conservation interventions.[4] Hence, the need to determine threats across species as specifically as possible is urgent. Over the past decades, with the significant progress of conservation genetics and genomics in China, the endangerment history and causes of many REPs have been investigated.[30,33]

The occurrence of most REPs in China can be explained by a combination of intrinsic and extrinsic factors, which lead to declines in species populations and long-term viability.[30] A lot of these plant taxa were probably already rare long before the human activities began to impact the natural ecosystems seriously. There are several intrinsic causes of plant endangerment. Firstly, the evolutionary history of plant species can explain part of their current scarce distribution. China has a high proportion of plant taxa belonging to the oldest taxonomic groups, such as 5,494 bryophytes and pteridophytes and 291 gymnosperms (ca. 25% of the world's total) according to Catalog of Life China. A study revealed that the relict (pre-Quaternary) component at the species and subspecies level is 39.1%[34] for the 243 Chinese endemic genera.[35] When climate became significantly colder and drier during glacial maxima, the distribution of these relic species changed significantly and resulted in range displacement and/or range contraction of plants toward refugia with small and isolated populations.[36] Secondly, some REPs have relatively less diversified morphological features and physiological functions, and their ability to respond to external environmental change is weak.[37] These plants' poor adaptability to the external environment is likely an important contributor to their endangerment, and global climate change may further present threats to their survival. Thirdly, plant's reproductive life cycle consists of phases such as flowering, fruit development, seed production, seed germination, etc. In the case of REPs, however, the cycle may be interrupted at one phase or another due to disruptions at the molecular, biochemical, or physiological levels as a result of ecological changes.[38,39] Some of the constrainting reasons in reproduction in REPs include unbreakable seed dormancy (e.g., *Manglietiastrum Sinicum*[40]), poor seed viability and seed germination (e.g., *Metasequoia glyptostroboides*[41]), inefficient pollen and seed dispersal (e.g., *Bretschneidera sinensis*[42]), poor seed production (e.g., *Manglietia ventii*[43]), and limited seedling establishment (e.g., *Hopea hainanensis*[44]). A very large proportion of REPs encounter these kinds of obstacles to reproductive success, leading to low natural regeneration in the wild.[38]

The above-mentioned intrinsic factors are often enhanced by the impact of extrinsic factors, resulting in negative synergic effects on endangerment.[23] Long history of agricultural activities and human-induced loss of natural habitat in China has caused species decline and losses during several millennia.[10] Rapid increases in human population and urbanization during the last several decades have pushed plants to the brink of extinction or even lead to their extirpation from nature.[30] Threat analysis on Chinese vascular plants found habitat loss and degradation, over-collecting by humans, and intrinsic factors are the three leading threats to angiosperms in China.[16] Similarly, internal attributes of relic and endemic species as well as over-exploitation, habitat loss, and global warming are the main threats to Chinese gymnosperm species.[27] A study on threats to WPESP in China demonstrated that these species were mainly threatened by over-exploitation and habitat fragmentation.[45] The genomic signatures of the critically endangered ironwood tree *Ostrya rehderiana* showed that historical climate change and anthropogenic disturbance jointly caused the continued population size decline in this species.[46] Without question, human activity has been and will continue to be the major threat to plant biodiversity in China.[47]

IN SITU CONSERVATION

The three major techniques for plant conservation are *in situ* conservation, *ex situ* conservation, and reintroduction.[48] *In situ* conservation is defined as "the maintenance and recovery of viable populations of species in their natural surroundings".[49] Although it is considered to be very costly and labor intensive, *in situ* conservation plays a critical role in plant conservation and restoration since it can prohibit the destruction or alteration of a species' habitats,[50] and therefore it is identified as the best method for conserving REPs.[51]

REPs usually need unique and narrow ecological niches; maintaining their existing natural habitats is one of the most important ways to protect them. Protected area (PA) system is the foundation for REPs *in situ* conservation. As a clearly outlined geographical space established in order to achieve long-term conservation of nature and associated cultural values, PA is recognized and managed through legal means.[52] Started from the mid-1950s, ten types of PAs (see Table S1 for the type, definition, number, and area of PAs in China) with a total number of 11,800 and a total area accounted for 18.0% of the whole land area have been established in China by January 2019.[53] The nature reserve system predominates among China's various types of PAs. By 2018, China has established a hierarchical system of nature reserves, which is constituted by 2,750 nature reserves accounting for about 14.8% of its total land area.[54] China has protected about 85% of wild plants and 65% of vascular plant communities through *in situ* conservation techniques.[55]

Previously, nature reserves were facing serious problems of overlapping management, with some nature reserves even involving seven administrative departments.[54] To address this problem, the government tries to reestablish a normative and efficient system for PA management and assessment including three types of protected areas—national parks, nature reserves, and natural parks. National park (NP) in China is defined as "a specific land or marine area approved and managed by the state with clear boundaries, aiming to protect a large area of national representative natural ecosystem and to realize the scientific protection and rational use of natural resources'' (http://www.gov.cn/zhengce/2017-09/26/content_5227713.htm). Through six years' pilot reform, China has officially established 5 national parks in October 2021, covering a total area of about 230,000 km^2 and protecting nearly 30 percent of the key terrestrial wildlife species found in China.[56] Meanwhile, replicable and propagable experience has accumulated, especially on top design, law and regulations construction, and management mechanism of the national park system.[57] These experiences will optimize PAs to cover more key areas for REPs and strengthen ecosystem integrity and structure connectivity.[26] China plans to build 50 to 80 NPs, covering 8-10% of its entire land area. According to the current plan, the most important and representational areas will be included in NPs with the most strict protection,[56] ensuring the long-term survival of key REPs in the ecosystems.[58]

In the draft of post-2020 Global Biodiversity Framework (GBF), the 2030 Action Target 2 calls for ''protect and conserve through well-connected and effective system of protected areas and other effective area-based conservation measures (OECMs) at least 30 percent of the planet.'' There are several OECMs in China, which can serve as promising opportunities to meet post-2020 PA targets.[59] With the aim of protecting important eco-functional areas and ecological sensitive/fragile areas, as well as almost all REPs and their habitats out of the PA system, Ecological Conservation Redline (ECR) was proposed in 2011.[60] As an innovative pathway to expand the area coverage of PAs and conserve biodiversity outside current PAs, ECR covers zones under maximum protection and strictest management.[59] ECR was incorporated into the Environmental Protection Law in 2014 and have become a fully supported national-level ecological protection project.[61] The completed ECR system will expand China's PA system to cover about 25% of its land area, protect more than 95% of China's most valuable ecosystems, all ecologically fragile areas, and 100% of wildlife habitats under state key conservation.[60] ECR delineation had been fulfilled in 15 provinces across China by September 2018, covering 24.9% of the total area in these provinces.[62] Habitats for REPs are usually small patches in fragmented landscapes or located in areas with dense population and frequent human activities. Building mini-reserves with the area less than 1,000 hm^2 in such regions is an effective solution.[63] China has about 50,000 mini-reserves with a total area of about 1.5 million hectares.[64] For example, two mini-nature reserves have been established to protect threatened orchids in Xishuangbanna, Yunan province.[65] The non-commercial forest (NCF) accounts for 41.6% of all forest resources in China, the main purpose of which is to maintain forest ecosystem functions and biodiversity. No commercial harvesting is allowed, and people can only take mild management measures such as tending, thinning, and renewal cutting in NCF.[66] The civil protected areas (CPAs), which are managed by civil institutions, local communities, or individuals, are another *in situ* protection measurement.[67] These CPAs are usually small in size but may contain key habitats for REPs or serve as ecological corridors facilitating species dispersal or migration. Laohegou Nature Reserve in Sichuan province is the first CPA in China, which has become an international-level base for scientific research, biodiversity monitoring, and public education after several years' efforts.[68] China also supplements *in situ* conservation with eco-restoration and eco-compensation. Two of the world's largest initiatives—the Natural Forest Protection Project (1998) and the Grain for Green Program (2000) provide economic incentives for people to protect and restore habitats in support of biodiversity conservation.[26]

Populations and species respond to global change in various ways, including shifts in abundances and ranges, changes in phenology, physiological plasticity, and evolutionary adaptations.[30] Climate change has been proposed to be a threat factor particularly for rare plants with small population sizes, narrow distributions, and specific habitat requirements.[69] The effect of climate change on the distribution area of 68 REPs was estimated in China. Till the year of 2100, distribution area of 17 species will be totally lost, distribution range of 37 species will decline, and 21 species will shift toward higher altitudinal or latitudinal regions under A2 climate change scenario.[70] However, most PAs are selected mainly by the representativeness of current biodiversity, while ignoring the variations in species suitability within PAs in response to future climate and/or land-use changes.[71]

Many studies assessed the effectiveness of current PAs in China for the future planning of biodiversity conservation and found that environmental changes may reduce the efficiencies of PAs for the conservation of target species through significant alteration of species distributions or plant-animal interactions.[72,73] Peng et al.[74] updated the list of threatened woody species in China by adding the conservation status of all native woody plant species under current and future climate and dispersal change scenarios in China. These research works provided important information for improving the performance of PAs under future global change and shedding new light on the priorities for the post-2020 expansion of PAs in China.[73] The sustainable conservation of REPs in rapidly developing and changing environment calls for uniting conservation objectives with addressing climate change and developing nature-based solutions.[22] Gladly, China has drafted mid- and long-term programs and action plans, such as the Proposal of Drawing a ''Red Line'' for Ecological Protection to Mitigate and Adapt to Climate Change, the Beijing Call for Biodiversity Conservation and Climate Change jointly issued by China and France, the China National Biodiversity Conservation Strategy and Action Plan (2011–2030), to provide strong guarantees for combating climate change and biodiversity loss.

Overall, China has made significant progress by implementing the *in situ* conservation and management system.[68] However, we need to have a clear insight into the insufficient conservation efficiency of China's existing PA system. We summarized the reasons and potential solutions of the problems in China's PAs in Table S2. We think those challenges should be paid special attention if China wants to accelerate the construction of an effective PA system.

EX SITU CONSERVATION

Ex situ conservation involves maintenance and breeding of plants under partially or wholly controlled conditions in specific areas outside their natural habitat.[75] Through this approach, the stresses on living individuals due to competition for resource and space can be avoided by providing conditions necessary for a secure life and breeding.[76] For REPs, *ex situ* conservation is essential when their habitats are heavily degraded or fragmented. Data from Botanic Gardens Conservation International (BGCI) showed that 499 plant species *ex situ*-preserved are regionally or globally extinct in the wild.[77] *Ex situ* approaches can serve as a safeguard against rapid environmental change[23] and can extend the time available for conservation research and engagement.[78] *Ex situ* populations can also provide backup for species recovery and reintroduction.[79]

The *ex situ* conservation strategies for plants include botanical gardens, arboreta, seed banks, gene banks, and nurseries.[80] Botanical gardens are the most conventional and effective place for *ex situ* conservation of wild species.[79] Another widely used method of *ex situ* conservation is the collection and storage of seeds under controlled conditions in a ''seed bank''. At present, China has the second largest number of botanical gardens in the world (162 botanical gardens).[81] About 60% of plant species have been protected in those botanical gardens, including 22,104 native species belonging to 2,911 genera and 288 families.[82] Several botanical gardens strongly orient toward REPs in China, providing shelter to the threatened species and carrying out species-oriented conservation programs, such as South China Botanical Garden, Xishuangbanna Tropical Botanical Garden, and Kunming Botanical Garden.[47] A survey on 52 botanical gardens which had the main function of *ex situ* conservation found that 1,754 threatened species are preserved in these botanical gardens, including 252 critically endangered species, 589 endangered species, and 913 vulnerable species.[83] The Chinese botanical gardens had cultivated around 270 species (85% of the species) from the China National Key Protected Wild Plants List by 2015.[84] We collected data of *ex situ* cultivated plants in several main Chinese gardens in Table S3. As the largest seed bank in the whole Asia, 85,046 seed collections of 10,601 species, 24,200 *in vitro* plant collections of 2,143 species, 67,631 DNA material collections of 8,029 species are maintained in the China Germplasm Bank of Wild Species in Kunming by now (http://www.genobank.org). To manage *ex situ* conservation in China, several relevant programs have been launched. CAS has established a 15-year comprehensive *ex situ* conservation program to protect indigenous plants in China; one of the five goals is to enhance botanical garden collections for REPs.[85] The Science & Technology Basic Resources Investigation Program of China is implementing a project to conserve the rare plants in tropical China with *ex situ* conservation methods.[86] The Chinese Union of Botanical Gardens launched a ''Native Plant Full Coverage Protection Program'' (also known as the Zero Extinction Program) in 2013 (https://www.cubg.cn/work/conservation). This program aims to explore the methods and effective ways to protect native plant species in China by conducting plant inventory and conservation in various geographic regions and finally realize the zero extinction of native plants.[87] China has also initiated the construction of National Botanical Garden system since 2021 and officially established the China National Botanical Garden in Beijing and the South China National Botanical Garden in Guangzhou. In the future, may be a ''national *ex situ* conservation system'' can be built and combined with the PA system to form a complete ''national biodiversity conservation system''.[56,80]

China has been developing various types of *ex situ* conservation activities in the past decades; however, there are still some deficiencies in its current *ex situ* conservation system. Firstly, there is a lag in the database and information management in *ex situ* infrastructures. About 6 percent of native species and 12 percent of alien species in botanical gardens have not been identified.[76] Documentation and digitization about biological characteristics, phenological observation, cultivation management, and resource evaluation are far behind the rapid collection of *ex situ* conservated plants, leading to the unhealthy growth of some plants and reduced conservation efficiency.[88] Only 53, 42, and 61 botanical gardens have recorded information of transplanting, reproduction, and phenology of the collected plants, respectively.[82] Secondly, *ex situ* collection in botanical gardens is greatly influenced by traditional introduction and domestication history, as well as plant resources development and utilization orientation in China.[76] While many threatened species often exist in remote places as small and sparsely distributed populations, collecting seeds of common and widespread species is often emphasized in seed banks because they are more easily found.[89] Only 47 species from critically endangered, endangered, and vulnerable categories were conserved in the Kunming seed bank by 2016.[47] Thirdly, genetic diversity is important for the survival, growth, and reproduction of *ex situ* conserved individuals.[90] It is proved that adequate *ex situ* genetic representation of a species may require as many as 30–50 or more individuals sampled from the entire natural distribution range.[91,92] However, a meta-analysis of genetic representativeness of *ex situ* plant collections (approximately 30% of the studied cases were from China) suggested that genetic diversity in *ex situ* plant populations was significantly lower than that in their wild source populations.[92] Take Kunming Botanical Garden for example; although it contains as many as over 7,000 plant species and cultivars, more than 100 species of them have fewer than five individuals.[93] Lastly, seed is easy to collect and store, and cost of seed banking is as little as 1% of the cost of *in situ* conservation.[77] Besides, seeds can represent a range of genetic diversity in the species if collected from different individuals in a population or different populations. Despite these advantages, at least 36% of critically endangered plant species, 35% of vulnerable species, and 27% of endangered species are likely to produce recalcitrant seeds, seeds of which cannot survive the standard drying and/or low-temperature processes involved in seed banking.[94] Besides, although some orthodox species can be dried and frozen, they can only keep viability for less than 10 years.[95] Therefore, cryopreservation at ultra-low temperature (e.g., liquid nitrogen, −196°C) need to be prioritized as a key conservation tool post-2020 to safeguard these "unbankable" species.[96]

The lack of overall planning, unified deployment, and scientific coordination mechanism at the national level has restricted the implementation of the national strategy for *ex situ* conservation in China.[88] A top-down organization and leadership mechanism should be established, and responsibilities of all regarding departments should be clarified to build a network of *ex situ* conservation and research covering major ecological types and REPs in China.[31] Priority in the *ex situ* conservation strategy in China needs to be given to collection of Chinese native flora based on a nationwide inventory of living flora in botanical gardens, especially those vulnerable to climate change and threatened plants.[80] In order to address the genetic and phenotypic changes of *ex situ* plant populations caused by founder effect, genetic drift and inbreeding depression due to the typical small population size in botanical gardens,[79,81] it is necessary to evaluate levels of genetic composition and genetic diversity of the *ex situ* populations and to transplant new individuals to the collections when necessary.[92]

REINTRODUCTION

The accelerating loss of species and natural habitats will not necessarily be halted by current focus of plant conservation on passive protection of fragmented natural habitats.[24] The future of conservation in the Anthropocene lies in conservation-oriented restoration and wide-scale plant reintroductions within and outside the known historical range of the species.[89] Reintroduction refers to "the deliberate establishment of individuals of a species into an area and/or habitat where it has become extirpated with the specific aim of establishing a viable self-sustaining population for conservation purposes".[97] It is the bridge between *in situ* and *ex situ* conservation and the final goal of conservation.[48]

The concept of reintroduction has been widely acknowledged among practitioners and the public in China.[10] Reintroduction procedures and guidelines for REPs have been developed.[98] The Chinese government made a commitment to the Global Strategy for Plant Conservation (GSPC) to implement conservation translocation programs for 6% of the threatened plant species by 2020, which means at least 233 species need to be subjected to reintroduction. By the end of 2019, there were 300 plant reintroduction projects (involving 206 species, 60 families, and 136 genera) in China,[99] indicating that China has already made some progress toward this goal. Liu and Gao[100] found that a total of 55 cases of translocations involving 43 Chinese orchid species of 21 genera were recorded by 2020; among them twenty-five species were classified as threatened.

Several problems and difficulties around the reintroduction of REPs in China should be paid particular attention. First of all, reintroduction is a high-risk and high-cost process in practice, with different species facing diverse difficulties.[101] As a result, the study of reintroduction biology regarding how to restore ecosystems through reestablishment of populations where they occurred naturally before is of great significance.[99] Secondly, many of the REPs are hard to adapt to rapid environmental changes and frequent human disturbances, resulting in the low success rate of reintroduction. The selection of source stocks is critical; long-term reintroduction success will be higher if many individuals with high genetic diversity and divergent responses to environmental stresses from different populations are used.[102] Populations with high genetic diversity can also decrease the risk of genetic diversity decline.[48] Lastly, the importance of assessing the performance of the reintroduction projects based on complete documentation and adequate monitoring is neglected. The status of 222 plant conservation translocation cases involving 154 species was assessed in China. Among them, less than half of the cases had monitoring programs and gathered plant-survival records; the monitoring after planting lasted from 0.3 to 15 years with a mean of 4.9 years. Only thirty percent of the cases had records on whether or not individuals flowered or fruited.[10] It is important to define meaningful, measurable, and comparable criteria for reintroduction success. Because traditional methods by measuring vital rates such as establishment, growth, and fecundity is hard for long-lived species, comparing introduced populations with natural reference populations is advised.[103] Other measures such as population viability analysis, mating systems, and genetic variation are also effective for predicting reintroduction success.[104]

PROPAGATION

Reproduction is of critical importance to population renewal and maintenance of plant species.[105] As mentioned earlier, a large amount of REPs are encountered with some extent of reproductive disturbance, such as unsynchronized development of stamen and pistil, pollen abortion, and embryo sac abortion, leading to decline of species fitness and abundance and even to extinction.[106] Besides, many of their reproductive characteristics, such as pollination, seed growth, and seed distribution mode are incompatible with the changing climate.[37]

Knowledge of reproductive biology is crucial for the effective conservation of REPs.[23] Monitoring and research on reproductive characteristics of REPs protected in botanical gardens and nature reserves should be emphasized to promote their successful propagation and long-term maintenance.[106,107] For example, loss of pollinators and dispersers has greater influence on REPs compared to widely distributed species.[105] Lack of pollinators restricted the reproduction success of four REPs in botanical gardens.[106] Seed-dispersal experiments indicated that hornets play an important role in seed dispersal of *Aquilaria sinensis*; the protection of hornet and moth species should be an effective tactic for conserving *A. sinensis*.[107] Despite critical conservation status, there is limited information relating to propagation of threatened plants.[47] For the 120 WPESP, germination information is available only for 28 species, and storage characteristics are only known for 10 species.[108] Yet, any delay in propagation and breeding research of REPs increases the risk of species extinction.[108]

In recent years, studies on the propagation technology of REPs with low reproductive abilities have made great progress.[109] Artificial propagation of REPs can be used for *ex situ* conservation and reintroduction. Cultivated seedlings can also meet the demands of the commercial market to mediate the conflict between protection and sustainable use of the germplasm resources.[110] Seed propagation is the most efficient way for maintaining genetic diversity in REPs. Because disordered germination is widely observed in REPs, incorporating auxiliary seed treatment into conservation programs is essential.[111] Vegetative propagation methods such as cutting, grafting, and tissue culture are effective supplements for species that are difficult to propagate from seeds.[112] Biotechnological tools, which use living organisms or substances from these organisms to make or modify products for the purpose of improving plants, are necessary for the selection, multiplication, and conservation of the critical genotypes of REPs.[113]

Moreover, propagation base needs to be established in order to provide sufficient seedlings for local protection, *ex situ* protection, and wild reintroduction. Propagation of REPs and other plant species in China is currently done in botanical gardens, national field germplasm nurseries, and plant introduction bases. There are three national plant germplasm resources nurseries with a collection of 64,493 plant resources.[109] Meanwhile, 113 species of REPs have been cultivated mainly with the cultivated area of 1,348,200 ha and 3.4 billion individuals in plant nurseries, germplasm resources bases, and breeding bases.[114]

CONSERVATION LEGISLATION ON CHINAS REPs

A solid and comprehensive legal framework plays an essential role for the adequate protection of biodiversity.[115] China has not formulated specific laws on nature conservation by far, yet there are more than 20 laws, more than 40 administrative regulations, and more than 50 departmental regulations in China related to biodiversity conservation.[25] In addition, there are also some local regulations and legal systems actively supporting REPs conservation in China (see Table S4 for a list of laws, regulations, and legal systems related to REPs conservation). These laws and regulations have provided legal basis for the protection of wild plants and ensured the establishment of a law enforcement and supervision system from the central to the local governments.[8,25,115]

The legislation related to biodiversity conservation is still at the preliminary stage, and there are some defects in the legislation and enforcement system. Firstly, articles of nature conservation are scattered in related statutes and lack unity. There is not a comprehensive law governing biodiversity conservation. Most laws and regulations emphasize the utilization and management of natural resources rather than conservation.[116,117] Secondly, the laws and regulations are often faced to a specific type of natural resource, neglecting other types of resources such as deserts, wetlands, and fresh waters and related REPs. Enhancing conservation laws and legislation on natural ecosystems, wild plant species, and genetic resources is needed.[58,116] Thirdly, legislations lack operability.[115] Rules are more about administrative responsibility rather than civil and criminal; thus, unreasonable penalization of violations often undermines the effectiveness of laws and regulations.[118] Although the rights and duties of conservation related administrative departments have been clearly defined, departments coordination is not explicitly stipulated and becomes an obstacle to overall administration and supervision.[6,117,119]

PUBLIC PARTICIPATION IN CHINAS REPs CONSERVATION

As a country with splendid traditional culture, public participation in REPs conservation has had a long history in China. Fengshui forests have been widely practiced in China for more than 2,200 years, preserving abundant plant species and heterogeneous habitats.[120] There are about 400 “spirit mountains” protected by local communities of Dai nationality in the Xishuangbanna region, Yunnan Province.[8] Species richness of REPs range of 30 km around Tibetan sacred hills in Qinghai was significantly higher than that of outside.[121] More than 35% of the 105 officially protected areas (including nature reserves, forest parks, and scenic spots) in Yunnan are based on different kinds of sacred nature sites.[122]

In recent years, with the widespread publicity to “Beautiful China” and “Ecological Civilization”, the concepts relating to biodiversity has become popular in China, and public actions for the sustainable use and conservation of biodiversity are increasing greatly. The Chinese government has carried out 200,000 plant conservation activities with 180 million participants between 2010 and 2017.[87] Managers and scientists are making great efforts in educating the public about conserving biodiversity, such as the delivery of lectures on natural stories, the editing of nature-related books, and the promotion of creative nature writing.[56] By the end of July 2022, more than 22,800 accounts had been registered on the biodiversity information platform of the Chinese Field Herbarium with more than 17 million field survey photos uploaded (https://www.cfh.ac.cn/). A high proportion of the data were published by nonprofessional public participants, accumulating a large amount of information on species distribution and morphological variation. To date, eight apps and two websites regarding plant identification and vegetation observation have been widely used in China.[87] These pieces of software are expected to provide assistance to policy makers and scientists with high-quality data and to help increase people’s awareness of participation in biodiversity conservation.[123] The popularity of natural history photography in China also confirms the possibility of verification, geolocation, and time-stamping of citizen science observations.[124]

At present, the connections between policy makers, scientists, stakeholders, and the public are still weak.[30] Current contributions of public conservation actions to REPs are limited due to relatively low public participation and weaknesses in data quality control, project management, and information integration.[125] To date, there are only 99,000 checklists to eBird (https://ebird.org/) uploaded by 4,153 observers and

137,797 observations to iNaturalist (https://www.inaturalist.org/) uploaded by 4,947 observers in China. In comparison, the numbers in India are 1.9 million checklists to eBird from 33,000 observers and 512,472 observations to iNaturalist from 14,478 observers. To better increase public activities in ecological conservation and environmental monitoring, improvements are required in financial support, application of new technologies, development of project platforms, and international collaboration.[124,125] Environmental education should be highlighted in local communities where appreciation of the esthetic or ecological value the species possess beyond their practical use is still lacking considerably.[47] We can create a multi-stakeholder coalition for conserving REPs by integrating multidisciplinary approaches and involving local residents.[126]

PROGRESS IN CONSERVATION RESEARCH ON WILD PLANT WITH EXTREMELY SMALL POPULATIONS

As mentioned above, with the characters of extremely small populations (fewer than 5,000 mature individuals in total and less than 500 individuals in each population), restricted habitats, and high risk of extinction, WPESPs have been targeted as conservation priorities in China.[110] This concept has attracted widespread attention since it is comprehensible to government officers, non-conservation scientists, and local communities.[33,127] Many WPESP species have survived for thousands of millennia and exist only in China now, which are acknowledged as part of the shared natural heritage of all mankind.[23] By ensuring their long-term survival, we may have the opportunity to enjoy them, study them, understand them, and even use them.[23]

China launched the implementation plan for rescuing and conserving WPESP in 2012.[128] Various protection programs and actions have been issued by central and local governments since then. 24 provinces and autonomous regions released implementation plans for the conservation of related taxa. Some provinces took prompt action for the conservation of the concerned species, and some released provincial lists and guidelines for conservation action.[127,129] New approaches including population demography, near-situ or quasi *in situ* conservation, and wild reintroduction have been developed quickly.[130] Relevant reports and textbooks have been published, conservation training programs have been launched, and about 10,000 local people and nature reserve staff have been trained.[58] So far, comprehensive surveys and detailed information were available for most species; 103 species are located in nature reserves, 60 species have been protected by forest rangers or local communities, *in situ* or near-situ conservation have been established for about 67 species, *ex situ* conservation have been established for 80 species, artificial propagation has been trialed for 56 species, and reintroduction has been trialed for 26 species.[58,131,132] Through active field research, close integration of *in situ* and *ex situ* approaches, as well as efficient reintroduction and restoration programs, the WPESP program breaks down barriers between high-quality research and practical conservation action to create more successful conservation outcomes.[23]

Despite the above achievements, the goals of the Implementation Plan have only been fulfilled partially. We should realize that conservation of WPESP will be very difficult and time costing, especially because there are few successful examples to follow.[110] A solid theoretical foundation and technical support for the conservation and sustainable utilization of WPESP are still lacking.[133] Periodical assessments need to be performed to confirm the validity of conservation actions.[58] In addition, the amendment and extension of WPESP list should be discussed, paying attention to species with delimitation issues or whose populations exceed expectation after thorough field survey.[133] Overall, WPESP marks a new era of plant conservation in China, where policies on the paper are turned into actions on the ground more efficiently.[118] Experiences from WPESP programs may shed light on REPs conservation globally.

PROGRESS IN CHINA'S IMPLEMENTATION OF THE CONVENTION ON BIOLOGICAL DIVERSITY

As one of the first countries to sign and approve Convention on Biological Diversity (CBD), China is playing a major role in conserving biodiversity and has experienced the evolution of "follower-major participant-active contributor" in implementing the CBD.[134] Within the framework of CBD, the Chinese government has undertaken tremendous actions to conserve and restore the country's vast botanical wealth. Here we use the progress of the implementation on the GSPC in China as an example. China endorsed the GSPC in 2002 and launched its national Strategy for Plant Conservation (CSPC) in 2008.[135] The GSPC China National Report evaluated the status of plant diversity conservation in China from 2011 to 2020 systematically. Overall, mixed progress has been made toward reaching the CSPC targets (see Table S5 for implementation status of each target). Generally speaking, targets related to understanding and documenting existing plant diversity have been achieved before 2018. Targets associated with conservation of plant diversity as well as education and awareness about plant diversity are on track and will be met by 2020. Limited progress has been made in the achievement of targets related to sustainable utilization of wild plant species.[55,87] Constraints to the implementation of the CSPC include limited institutional integration, limited sectorial collaboration and coordination, limited financial and human resources, lack of mainstreaming taxonomic capacity, lack of data (taxonomy, biology, and conservation), and lack of tools and technologies.[136] However, the Chinese government has invested more and more financial resources and labor effort toward implemention of the GSPC.[87]

Despite continued conservation efforts, almost none of the Aichi Targets have been met, extending failure of the previous decade.[137] The 15th Conference of Parties (COP15) of CBD held in Yunnan Province in October 2021 sent a clear signal to the world to change the current development methods in order to better conserve biodiversity. The secretariat of the CBD has released several drafts of the post-2020 Global Biodiversity Framework (GBF) since January 2020, with new goals, targets, implementation and support mechanisms, and enabling conditions. As we discussed earlier, China has greatly improved its policies regarding protection of biodiversity, increased capital investment, strengthened the comprehensive protection systems, enhanced scientific and technological research, promoted public education, and actively participated in international collaborations. China has also released the CSPC 2021–2030 and adopted 18 ambitious targets (see Table S6 for detailed contents of each target). Chinese scientists proposed relevant recommendations to ensure effective implementation of the post-2020 biodiversity targets, including adopting the new targets as the minimum national targets, increasing financial resources for biodiversity conservation substantially, strengthening science-policy interfaces at all levels, and creating a compliance and accountability mechanism based on monitoring systems.[111,138] In general, there is no doubt that China will meet its commitments at the COP15 meeting.

CONCLUSION

Biodiversity is essential to human well-being. Recent events, such as prolonged pandemic, record-breaking climate anomalies, and ravaging forest fires, further highlighted the urgency to halt biodiversity loss. Although massive investments and efforts have been made to conserve plant diversity nationwide, the lists of threatened species are continuing to grow, and habitats are continuing to be lost or degraded. Clearly, the effective conservation of REPs in China still faces great challenges.[24] Biodiversity conservation is inevitably linked with social-economic development, which means biodiversity loss and poverty alleviation are two sides of the same coin.[86] China will always and have to face the conflict between economic growth and biodiversity conservation. A full understanding of this conflict is not only necessary and urgent but also essential for the formulation of effective conservation plans.[25]

This review represents a solid collection of studies on multiple aspects of REPs conservation in China. In conclusion, the Chinese government and associated institutions and communities have devoted tremendous efforts to promote REPs conservation in the last few decades. And enormous advances have been made in developing conservation policies, guidelines, infrastructure, theories, and technologies to protect REPs. In the future, we would like to see more work on basic investigation and long-term observation of changes in REPs, as well as research on origins, distributions, maintenance, and threats of REPs. Advanced technologies, such as high-throughput sequencing, genomics, and remote sensing should be applied to further push additional complementary and synergistic research in biodiversity science.[30] Focusing on application-oriented research would help to provide a scientific basis for formulating strategies for the protection, development, and utilization of REPs in China. We suggest that interdisciplinary conservation efforts, involving government agencies, research institutes, nongovernmental organizations, and local communities, should join together to achieve successful conservation of REPs. As we can see, China is determined to meet its commitments to the new Post-2020 GBF, which would allow China to become a global leader both in biodiversity research and conservation practice in the near future.[124]

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.106008.

ACKNOWLEDGMENTS

This work was supported by the projects of the National Key Research and Development Program of China [2016YFC0503103] and National Natural Science Foundation of China [42271069]. We thank the anonymous reviewers and editors for their comments on the manuscript.

AUTHOR CONTRIBUTIONS

Conceptualization, R.G.Z. and Y.X.; Writing, Y.X.; Funding Acquisition, R.G.Z. and Y.X.; Supervision, R.G.Z.

DECLARATION OF INTERESTS

The authors declare no competing interests.

REFERENCES

1. Mouillot, D., Bellwood, D.R., Baraloto, C., Chave, J., Galzin, R., Harmelin-Vivien, M., Kulbicki, M., Lavergne, S., Lavorel, S., Mouquet, N., et al. (2013). Rare species support vulnerable functions in high-diversity ecosystems. PLoS Biol. *11*, e1001569.
2. De Vos, J.M., Joppa, L.N., Gittleman, J.L., Stephens, P.R., and Pimm, S.L. (2015). Estimating the normal background rate of species extinction. Conserv. Biol. *29*, 452–462.
3. Cardinale, B.J., Duffy, J.E., Gonzalez, A., Hooper, D.U., Perrings, C., Venail, P., Narwani, A., Mace, G.M., Tilman, D., Wardle, D.A., et al. (2012). Biodiversity loss and its impact on humanity. Nature *486*, 59–67.
4. Bellard, C., Marino, C., and Courchamp, F. (2022). Ranking threats to biodiversity and why it doesn't matter. Nat. Commun. *13*, 2616.
5. Chen, L. (1993). Biodiversity in China: Status and Conservation Strategies (Science Press).
6. Volis, S. (2018). Securing a future for China's plant biodiversity through an integrated conservation approach. Plant Divers. *40*, 91–105.
7. Lu, L.M., Mao, L.F., Yang, T., Ye, J.F., Liu, B., Li, H.L., Sun, M., Miller, J.T., Mathews, S., Hu, H.H., et al. (2018). Evolutionary history of the angiosperm flora of China. Nature *554*, 234–238.
8. López-Pujol, J., Zhang, F.M., and Ge, S. (2006). Plant biodiversity in China: richly varied, endangered, and in need of conservation. Biodivers. Conserv. *15*, 3983–4026.
9. Huang, J.H., Ma, K.P., and Chen, B. (2014). Diversity and Geographic Distribution of Endemic Species of Seed Plants in China (Higher Education Press).
10. Liu, H., Ren, H., Liu, Q., Wen, X., Maunder, M., and Gao, J. (2015). Translocation of threatened plants as a conservation measure in China. Conserv. Biol. *29*, 1537–1551.
11. Qin, H., and Zhao, L.N. (2017). Evaluating the threat status of higher plants in China. Biodivers. Sci. *25*, 689–695.
12. Qin, H.N., Jin, X., and Zhao, L.N. (2020). Rare and endangered plants in China. In In Conservation and Reintroduction of Rare and Endangered Plants in China, H. Ren, ed. (Springer), pp. 21–32.
13. State Forestry Administration and Institute of Botany of Chinese Academy of Sciences (1987). List of Rare and Endangered Protected Plants in China, *Vol 1* (Science Press).
14. Duncan, C., Bhm, M., and Turvey, S.T. (2021). Identifying the possibilities and pitfalls of conducting IUCN Red List assessments from remotely sensed habitat information based on insights from poorly known Cuban mammals. Conserv. Biol. *35*, 1598–1614.
15. Wang, S., and Xie, Y. (2004). China Species Red List: Vol I Red List (Higher Education Press).
16. Qin, H.N., Zhao, L.N., Yu, S.X., Liu, H.Y., Liu, B., Xia, N.H., Peng, H., Li, Z.Y., Zhang, Z.X., He, X.J., et al. (2017). Evaluating the endangerment status of China's angiosperms through the red list assessment. Biodivers. Sci. *25*, 745–757.
17. Wiedenfeld, D.A., Alberts, A.C., Angulo, A., Bennett, E.L., Byers, O., Contreras-MacBeath, T., Drummond, G., da Fonseca, G.A.B., Gascon, C., Harrison, I., et al. (2021). Conservation resource allocation, small population resiliency, and the fallacy of conservation triage. Conserv. Biol. *35*, 1388–1395.
18. Xiao, L., and Zhao, R. (2017). China's new era of ecological civilization. Science *358*, 1008–1009.
19. Ma, K., and Wei, F. (2021). Ecological civilization: a revived perspective on the relationship between humanity and nature. Natl. Sci. Rev. *8*, nwab112.
20. Wei, F., Cui, S., Liu, N., Chang, J., Ping, X., Ma, T., Xu, J., Swaisgood, R.R., and Locke, H. (2021). Ecological civilization: China's effort to build a shared future for all life on Earth. Natl. Sci. Rev. *8*, nwaa279.
21. Primack, R.B. (2021). Biodiversity science blossoms in China. Natl. Sci. Rev. *8*, nwab058.
22. Schmidt-Traub, G., Locke, H., Gao, J., Ouyang, Z., Adams, J., Li, L., Sala, E., Shaw, M.R., Troëng, S., Xu, J., et al. (2021). Integrating climate, biodiversity, and sustainable land-use strategies: innovations from China. Natl. Sci. Rev. *8*, nwaa139.
23. Crane, P. (2020). Conserving our global botanical heritage: the PSESP plant conservation program. Plant Divers. *42*, 319–322.
24. Heywood, V.H. (2017). Plant conservation in the Anthropocene – challenges and future prospects. Plant Divers. *39*, 314–330.
25. Wang, W., Feng, C., Liu, F., and Li, J. (2020). Biodiversity conservation in China: a review of recent studies and practices. Environ. Sci. Ecotechnol. *2*, 100025.
26. Huang, G., Ping, X., Xu, W., Hu, Y., Chang, J., Swaisgood, R.R., Zhou, J., Zhan, X., Zhang, Z., Nie, Y., et al. (2021). Wildlife conservation and management in China: achievements, challenges and perspectives. Natl. Sci. Rev. *8*, nwab042.
27. Yang, Y., Zhu, Y., Li, X., Zhang, X., and Yu, B. (2021). An updated red list assessment of gymnosperms from China (Version 2021). Arch. Gynecol. Obstet. *303*, 1599–1606.
28. Mi, X.C., Guo, J., Hao, Z., Xie, Z., Guo, K., and Ma, K. (2016). Chinese forest biodiversity monitoring: scientific foundations and strategic planning. Biodivers. Sci. *24*, 1203–1219.
29. Wu, H., Xu, X., Feng, X., Mi, X., Su, Y., Xiao, Z., Zhu, C., Cao, L., Gao, X., Song, C., et al. (2022). Progress and prospect of China biodiversity monitoring from a global perspective. Biodivers. Sci. *30*, 22434.
30. Mi, X., Feng, G., Hu, Y., Zhang, J., Chen, L., Corlett, R.T., Hughes, A.C., Pimm, S., Schmid, B., Shi, S., et al. (2021). The global significance of biodiversity science in China: an overview. Natl. Sci. Rev. *8*, nwab032.
31. Yang, M., Zhou, J., Zeng, Y., and Sun, M. (2021). Main progress of biodiversity conservation in China and some suggestions for further work. Bull. Chin. Acad. Sci. *36*, 399–408.

32. Hu, T.Y., Wang, N.N., Zhao, X.Q., Mi, X.C., Guo, Q.H., and Ma, K.P. (2018). Advances in biodiversity observation network. J. Remote Sens. *22*, 709–712.

33. Zhou, Y., Li, H., and Ma, K. (2022). Celebrating Biodiversity Science 30th anniversary: a retrospective evaluation. Biodivers. Sci. *30*, 22618.

34. López-Pujol, J., Zhang, F.M., Sun, H.Q., Ying, T.S., and Ge, S. (2011). Centres of plant endemism in China: places for survival or for speciation? J. Biogeogr. *38*, 1267–1280.

35. Ying, T.S., Zhang, Y.L., and Boufford, D.E. (1993). The Endemic Genera of Seed Plants of China (Science Press).

36. Hu, F.S., Hampe, A., and Petit, R.J. (2009). Paleoecology meets genetics: deciphering past vegetational dynamics. Front. Ecol. Environ. *7*, 371–379.

37. Yang, M. (2013). The current situation and protection of China rare and endangered seed plants. Int. J. Environ. Prot. *3*, 29–34.

38. Zang, R.G., Dong, M., Li, J.Q., Chen, X.Y., Zeng, S.J., Jiang, M.X., Li, Z.Q., and Huang, J.H. (2016). Conservation and restoration for typical critically endangered wild plants with extremely small population. Acta Ecol. Sinica *36*, 7130–7135.

39. Saxena, A., Shukla, M., and Saxena, P. (2019). Synthetic seeds: relevance to endangered germplasm conservation. In In Synthetic Seeds: Germplasm Regeneration, Preservation and Prospects, M. Faisal and A.A. Alatar, eds. (Springer), pp. 21–60.

40. Zheng, Y.L., and Sun, W.B. (2009). Seed germination of Huagaimu, a critically endangered plant endemic to southeastern Yunnan, China. Horttechnology *19*, 427–431.

41. Liu, H., Zhu, Y., Liu, X., Jiang, Y., Deng, S., Ai, X., and Deng, Z. (2020). Effect of artificially accelerated aging on the vigor of *Metasequoia glyptostroboides* seeds. J. For. Res. *31*, 769–779.

42. Qiao, Q., Chen, H.F., Xing, F.W., Wang, F.G., Zhong, W.C., Wen, X.Y., and Hou, X.G. (2012). Pollination ecology of *Bretschneidera sinensis* (hemsley), a rare and endangered tree in China. Pak. J. Bot. *44*, 1897–1903.

43. Wang, B., Chen, G., Li, C., and Sun, W. (2017). Floral characteristics and pollination ecology of *Manglietia ventii* (Magnoliaceae), a plant species with extremely small populations (PSESP) endemic to South Yunnan of China. Plant Divers. *39*, 52–59.

44. Lu, X.H., Zang, R.G., Ding, Y., Huang, J.H., and Xu, Y. (2020). Habitat characteristics and its effects on seedling abundance of *Hopea hainanensis*, a wild plant with extremely small populations. Biodivers. Sci. *28*, 289–295.

45. Wang, C., Zhang, J., Wan, J., Qu, H., Mu, X., and Zhang, Z. (2017). The spatial distribution of threats to plant species with extremely small populations. Front. Earth Sci. *11*, 127–136.

46. Yang, Y., Ma, T., Wang, Z., Lu, Z., Li, Y., Fu, C., Chen, X., Zhao, M., Olson, M.S., and Liu, J. (2018). Genomic effects of population collapse in a critically endangered ironwood tree *Ostrya rehderiana*. Nat. Commun. *9*, 5449.

47. Volis, S. (2016). How to conserve threatened Chinese plant species with extremely small populations? Plant Divers. *38*, 45–52.

48. Ren, H., Jian, S., Liu, H., Zhang, Q., and Lu, H. (2014). Advances in the reintroduction of rare and endangered wild plant species. Sci. China Life Sci. *57*, 603–609.

49. Convention on Biological Diversity (CBD) (1992). Convention on Biological Diversity (Text and Annexes (CBD)).

50. Heywood, V.H. (2015). In situ conservation of plant species – an unattainable goal? Isr. J. Plant Sci. *63*, 211–231.

51. Ren, H., Ma, G.H., Zhang, Q.M., and Wen, X.Y. (2020). Reintroduction of *Primulina tabacum* hance, a critically endangered calciphilous perennial herb, in southern China. In In Conservation and Reintroduction of Rare and Endangered Plants in China, H. Ren, ed. (Springer), pp. 111–116.

52. Zhang, L., Luo, Z., Mallon, D., Li, C., and Jiang, Z. (2017). Biodiversity conservation status in China's growing protected areas. Biol. Conserv. *210*, 89–100.

53. Gao, J., Liu, X., Zhou, D., Ma, K., Wu, Q., and Li, G. (2021). Some opinions on the integration and optimization of natural protected areas in China. Biodivers. Sci. *29*, 290–294.

54. Xu, W., Pimm, S.L., Du, A., Su, Y., Fan, X., An, L., Liu, J., and Ouyang, Z. (2019). Transforming protected area management in China. Trends Ecol. Evol. *34*, 762–766.

55. Ren, H., Qin, H., Ouyang, Z., Wen, X., Jin, X., Liu, H., Lu, H., Liu, H., Zhou, J., Zeng, Y., et al. (2019). Progress of implementation on the global strategy for plant conservation in (2011–2020) China. Biol. Conserv. *230*, 169–178.

56. Zhao, W. (2022). Beginning: China's national park system. Natl. Sci. Rev. *9*, nwac150.

57. Li, B., Zhu, Y., Liu, W., Li, S., Fu, M., Ren, Y., Cai, X., and Li, J. (2021). Pilot areas for national park system in China: progress, problems and recommendations. Biodivers. Sci. *29*, 283–289.

58. Yang, J., Cai, L., Liu, D., Chen, G., Gratzfeld, J., and Sun, W. (2020). China's conservation program on plant species with extremely small populations (PSESP): progress and perspectives. Biol. Conserv. *244*, 108535.

59. Choi, C., Shi, X., Shi, J., Gan, X., Wen, C., Zhang, J., Jackson, M.V., Fuller, R.A., and Gibson, L. (2022). China's Ecological Conservation Redline policy is a new opportunity to meet post-2020 protected area targets. Conserv. Lett. *15*, e12853.

60. Gao, J., Wang, Y., Zou, C., Xu, D., Lin, N., Wang, L., and Zhang, K. (2020). China's ecological conservation redline: a solution for future nature conservation. Ambio *49*, 1519–1529.

61. Wu, B., Xie, Y., Li, Y., and Cong, L. (2022). How to delineate and zone protected areas under the scope of ecological conservation redline strategy. Biodivers. Sci. *30*, 213C72.

62. Gao, J., Zou, C., Zhang, K., Xu, M., and Wang, Y. (2020). The establishment of Chinese ecological conservation redline and insights into improving international protected areas. J. Environ. Manage. *264*, 110505.

63. Cui, G.F. (2013). Dictionary of Nature Conservology (China Forestry Publishing House).

64. Tang, X.P., and Luan, X.F. (2017). Developing a nature protected area system composed mainly of national parks. Forest Resour. Manag. *6*, 1–8.

65. Liu, Q., Chen, J., Corlett, R.T., Fan, X., Yu, D., Yang, H., and Gao, J. (2015). Orchid conservation in the biodiversity hotspot of southwestern China. Conserv. Biol. *29*, 1563–1572.

66. Wu, C., Vellend, M., Yuan, W., Jiang, B., Liu, J., Shen, A., Liu, J., Zhu, J., and Yu, M. (2017). Patterns and determinants of plant biodiversity in non-commercial forests of eastern China. PLoS One *12*, e0188409.

67. International Union for the Conservation of Nature (IUCN) (2019). Guidelines for Civil Protected Areas (IUCN).

68. Wang, W., and Li, J. (2021). In-situ conservation of biodiversity in China: advances and prospects. Biodivers. Sci. *29*, 133–149.

69. Vincent, H., Bornand, C.N., Kempel, A., and Fischer, M. (2020). Rare species perform worse than widespread species under changed climate. Biol. Conserv. *246*, 108586.

70. Lv, J.J. (2009). The Impacts of Climate Change on the Distribution of Rare and Endangered Species in China and Adaptation Strategies (Chinese Research Academ of Environmental Sciences). Master' S Thesis.

71. Jones, K.R., Watson, J.E., Possingham, H.P., and Klein, C.J. (2016). Incorporating climate change into spatial conservation prioritisation: a review. Biol. Conserv. *194*, 121–130.

72. Zomer, R.J., Xu, J., Wang, M., Trabucco, A., and Li, Z. (2015). Projected impact of climate change on the effectiveness of the existing protected area network for biodiversity conservation within Yunnan Province, China. Biol. Conserv. *184*, 335–345.

73. Peng, S., Zhang, J., Zhang, X., Li, Y., Liu, Y., and Wang, Z. (2022). Conservation of woody

species in China under future climate and land-cover changes. J. Appl. Ecol. *59*, 141–152.

74. Peng, S., Luo, Y., Cai, H., Zhang, X., and Wang, Z. (2022). A new list of threatened woody species in China under future global change scenarios. Biodivers. Sci. *30*, 21459–21467.

75. Jaisankar, I., Velmurugan, A., and Sivaperuman, C. (2018). Biodiversity conservation: issues and strategies for the tropical islands. In In Biodiversity & climate change adaptation in tropical islands, C. Sivaperuman, A. Velmurugan, A.K. Singh, and I. Jaisankar, eds. (Academic Press), pp. 525–552.

76. Huang, H., and Zhang, Z. (2012). Current status and prospects of ex situ cultivation and conservation of plants in China. Biodivers. Sci. *20*, 559–571.

77. O'Donnell, K., and Sharrock, S. (2017). The contribution of botanic gardens to ex situ conservation through seed banking. Plant Divers. *39*, 373–378.

78. Abeli, T., Dalrymple, S., Godefroid, S., Mondoni, A., Mller, J.V., Rossi, G., and Orsenigo, S. (2020). Ex situ collections and their potential for the restoration of extinct plants. Conserv. Biol. *34*, 303–313.

79. Thomas, G., Sucher, R., Wyatt, A., and Jiménez, I. (2022). Ex situ species conservation: predicting plant survival in botanic gardens based on climatic provenance. Biol. Conserv. *265*, 109410.

80. Wen, X., and Chen, H. (2022). Botanical gardens and ex situ conservation of the wild plant species. Biodivers. Sci. *30*, 22017.

81. Huang, H., and Liao, J. (2022). On China' s national botanical gardens: building a comprehensive system of ex situ conservation of national botanical gardens with task oriented disciplines. Biodivers. Sci. *30*, 222V20.

82. Huang, H. (2018). The Chinese Botanical Gardens (Chinese Forestry Press).

83. Zhao, X., Chen, H., Wu, J., Ren, H., Wei, J., Ye, P., and Si, Q. (2022). Ex situ conservation of threatened higher plants in Chinese botanical gardens. Global Ecology and Conservation *38*, e02206.

84. Jin, X., and Ren, H. (2020). In situ and ex situ conservation of Chinese plants. In In Conservation and Reintroduction of Rare and Endangered Plants in China, H. Ren, ed. (Springer), pp. 33–47.

85. Huang, H., Han, X., Kang, L., Raven, P., Jackson, P.W., and Chen, Y. (2002). Conserving native plants in China. Science *297*, 935–936.

86. Meng, H.H., Zhou, S.S., Li, L., Tan, Y.H., Li, J.W., and Li, J. (2019). Conflict between biodiversity conservation and economic growth: insight into rare plants in tropical China. Biodivers. Conserv. *28*, 523–537.

87. Ren, H. (2021). Progress of the Implementation on the Global Strategy for Plants Conservation in China (Science Press), pp. 2011–2020.

88. Xu, Z.F. (2022). Some opinions to the "Principle of Plan as a Whole" of the constructive system for national botanical gardens. Biodivers. Sci. *30*. https://doi.org/10.17520/biods.2022470.

89. Volis, S. (2018). Plant conservation in the Anthropocene: definitely not win–win but maybe not lose–lose? Encyclopedia Anthropocene *3*, 389–397.

90. Evans, S.M., Sinclair, E.A., Poore, A.G.B., Bain, K.F., and Vergés, A. (2018). Assessing the effect of genetic diversity on the early establishment of the threatened seagrass *Posidonia australis* using a reciprocal-transplant experiment. Restor. Ecol. *26*, 570–580.

91. Hoban, S., Callicrate, T., Clark, J., Deans, S., Dosmann, M., Fant, J., Gailing, O., Havens, K., Hipp, A.L., Kadav, P., et al. (2020). Taxonomic similarity does not predict necessary sample size for ex situ conservation: a comparison among five genera. Proc. Biol. Sci. *287*, 20200102.

92. Wei, X., and Jiang, M. (2021). Meta-analysis of genetic representativeness of plant populations under ex situ conservation in contrast to wild source populations. Conserv. Biol. *35*, 12–23.

93. Chen, G., and Sun, W. (2018). The role of botanical gardens in scientific research, conservation, and citizen science. Plant Divers. *40*, 181–188.

94. Wyse, S.V., Dickie, J.B., and Willis, K.J. (2018). Seed banking not an option for many threatened plants. Nat. Plants *4*, 848–850.

95. Li, D.Z., and Pritchard, H.W. (2009). The science and economics of ex situ plant conservation. Trends Plant Sci. *14*, 614–621.

96. Pence, V.C., Ballesteros, D., Walters, C., Reed, B.M., Philpott, M., Dixon, K.W., Pritchard, H.W., Culley, T.M., and Vanhove, A.C. (2020). Cryobiotechnologies: tools for expanding long-term ex situ conservation to all plant species. Biol. Conserv. *250*, 108736.

97. Maunder, M. (1992). Plant reintroduction: an overview. Biodivers. Conserv. *1*, 51–61.

98. Ren, H., Liu, Q., Li, L.H., and Liu, Z.F. (2019). Introduction to Restoration Ecology, 3rd edn (Science Press).

99. Ren, H., Lu, H., Liu, H., and Xu, Z. (2020). Reintroduction of rare and endangered plants in China. In In Conservation and Reintroduction of Rare and Endangered Plants in China, H. Ren, ed. (Springer), pp. 49–107.

100. Liu, H., and Gao, J.Y. (2020). Orchid conservation translocation efforts in China. In In Conservation and Reintroduction of Rare and Endangered Plants in China, H. Ren, ed. (Springer), pp. 205–224.

101. Zhou, X., and Gao, J. (2012). Reintroduction of rare and endangered plants: theories and practices. Sci. China Life Sci. *55*, 97–98.

102. He, X., Johansson, M.L., and Heath, D.D. (2016). Role of genomics and transcriptomics in selection of reintroduction source populations. Conserv. Biol. *30*, 1010–1018.

103. Menges, E.S. (2008). Restoration demography and genetics of plants: when is a translocation successful? Aust. J. Bot. *56*, 187–196.

104. Monks, L., Coates, D., Bell, T., and Bowles, M.L. (2012). Determining success criteria for reintroductions of threatened long-lived plants. In In Plant Reintroduction in a Changing Climate: Promises and Perils, J. Maschinski and K.E. Haskins, eds. (Springer), pp. 189–208.

105. Sun, W.B. (2013). Conserving Plant Species with Extremely Small Populations (PSESP) in Yunnan: A Practice and Exploration (Yunnan Science and Technology Press).

106. Tang, R., Li, Y., Xu, Y., Schinnerl, J., Sun, W., and Chen, G. (2020). In-situ and ex situ pollination biology of the four threatened plant species and the significance for conservation. Biodivers. Conserv. *29*, 381–391.

107. Chen, Y., Chen, G., Yang, J., and Sun, W. (2016). Reproductive biology of *Magnolia sinica* (Magnoliaecea), a threatened species with extremely small populations in Yunnan, China. Plant Divers. *38*, 253–258.

108. Wade, E.M., Nadarajan, J., Yang, X., Ballesteros, D., Sun, W., and Pritchard, H.W. (2016). Plant species with extremely small populations (PSESP) in China: a seed and spore biology perspective. Plant Divers. *38*, 209–220.

109. Zhou, J., Yang, M., Wen, X.Y., Li, N., and Ren, H. (2021). Strengthen ex situ conservation of plants and promote protection and utilization of plant resources. Bull. Chin. Acad. Sci. *36*, 417–424.

110. Sun, W.B., Liu, D.T., and Zhang, P. (2021). Conservation research of plant species with extremely small populations (PSESP): progress and future direction. Guihaia *41*, 1605–1617.

111. Hu, Y., Wang, M., Ma, T., Huang, M., Huang, G., Zhou, W., Ping, X., Lu, Y., and Wei, F. (2022). Integrated index-based assessment reveals long-term conservation progress in implementation of Convention on Biological Diversity. Sci. Adv. *8*, eabj8093.

112. Sha, D., Yanni, W., Kunlin, W., Lin, F., Lin, L., and Songjun, Z. (2020). Breeding characteristics and artificial propagation of 14 species of Wild Plant with Extremely Small Populations (WPESP) in China. Biodivers. Sci. *28*, 385–400.

113. Janani, H.T., Nishteswar, K., and Verma, A. (2016). Biotechnological tools in the cultivation of medicinal plants. J. Indian Syst. Med. *4*, 42–45.

114. Ministry of Environment Protection of the People's Republic of China (2018). China's Biodiversity: A Country Study (China Environmental Press).

115. Zhou, Z., and Jin, X. (2021). Analysis and suggestions on policies and regulations on conservation and management of wild plants in China. Biodivers. Sci. *29*, 1583–1590.

116. Xue, D. (1998). The legislation, enforcement, and further needs for biodiversity conservation in China. Ambio *27*, 489–491.

117. Xu, N.N. (2010). Study on Legislation of Endangered Species Conservation in China. Doctoral Dissertation (Ocean University of China).

118. Ren, H., Zhang, Q., Lu, H., Liu, H., Guo, Q., Wang, J., Jian, S., and Bao, H. (2012). Wild plant species with extremely small populations require conservation and reintroduction in China. Ambio *41*, 913–917.

119. Zhan, C. (2008). Thinking of the law on protecting the resources of rare and endangered wild plants in China. China For. Econ. *1*, 27–30.

120. Hu, L., Li, Z., Liao, W.B., and Fan, Q. (2011). Values of village fengshui forest patches in biodiversity conservation in the Pearl River Delta, China. Biol. Conserv. *144*, 1553–1559.

121. Zhao, H.F., Zhang, J.X., Se, Y., Zhao, F., Li, R.Q., and Xu, M. (2018). Contribution of mountain worship and sacred hill culture to biodiversity conservation: a case study for Tibetan sacred hills in Qinghai. J. Qinghai Nat. Univ. (Soc. Sci.) *44*, 112–116.

122. Lixin, Y., Shengji, P., and Yu, Z. (2019). Action research on Tibetan sacred nature sites (SNS) conservation in Tibetan community in NW Yunnan. Biodivers. Sci. *27*, 749–757.

123. Xu, Z., Liu, S., Zhao, Y., Tu, W., Chang, Z., Zhang, E., Guo, J., Zheng, D., Geng, J., Gu, G., et al. (2020). Evaluation of the identification ability of eight commonly used plant identification application softwares in China. Biodivers. Sci. *28*, 524–533.

124. Brooks, T.M., and Zhang, X. (2021). Applied biodiversity science in China in the global context. Natl. Sci. Rev. *8*, nwab059.

125. Zhang, J., Chen, S.B., Chen, B., Du, Y.J., Huang, X.L., Pan, X.B., and Zhang, Q. (2013). Citizen science: integrating scientific research, ecological conservation and public participation. Biodivers. Sci. *21*, 738–749.

126. Chen, G., Luo, S., Mei, N., Shen, D., and Sun, W. (2015). Case study of building of conservation coalitions to conserve ecological interactions. Conserv. Biol. *29*, 1527–1536.

127. Sun, W.B., Ma, Y.P., and Blackmore, S. (2019). How a new conservation action concept has accelerated plant conservation in China. Trends Plant Sci. *24*, 4–6.

128. State Forestry Administration (2012). The Implementation Plan of Rescuing and Conserving China' S PSESP (2011–2015) (nonpublic publication).

129. Li, D.Q., and Peng, D.R. (2017). Study on the protection counter measure to extremely small population of wild plant of guangxi. J. Anhui Agr. Sci. *37*, 14806–14807.

130. Yang, W.Z., Zhang, S.S., Wang, W.B., Kang, H.M., and Ma, N. (2017). A sophisticated species conservation strategy for *Nyssa yunnanensis*, a species with extremely small populations in China. Biodivers. Conserv. *26*, 967–981.

131. Zhang, Z., Guo, Y., He, J.S., and Tang, Z. (2018). Conservation status of wild plant species with extremely small populations in China. Biodivers. Sci. *26*, 572–577.

132. Sun, W.B., Yang, J., and Dao, Z.L. (2019). Study and Conservation of Plant Species with Extremely Small Populations (PSESP) in Yunnan Province, China (Science Press).

133. Xu, Y., and Zang, R. (2022). Theoretical and practical research on conservation of wild plants with extremely small populations in China. Biodivers. Sci. *30*, 22505.

134. Qin, T. (2021). The evolution and challenges in China's implementation of the Convention on Biological Diversity: a new analytical framework. Int. Environ. Agreements. *21*, 347–365.

135. The Editorial Committee of "China's Strategy for Plant Conservation" (2008). China's Strategy for Plant Conservation (Sciences and Technology Press).

136. Gratzfeld, G., and Wen, X.Y. (2012). China' S Strategy for Plant Conservation (CSPC)–Progress of Implementation (Botanic Gardens Conservation International).

137. Convention on Biological Diversity (CBD) (2020). Global Biodiversity Outlook 5: Summary for Policymakers (CBD).

138. Xu, H., Cao, Y., Yu, D., Cao, M., He, Y., Gill, M., and Pereira, H.M. (2021). Ensuring effective implementation of the post-2020 global biodiversity targets. Nat. Ecol. Evol. *5*, 411–418.