Strengthening protected areas for biodiversity and ecosystem services in China

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Recent expansion of the scale of human activities poses severe threats to Earth's life-support systems. Increasingly, protected areas (PAs) are expected to serve dual goals: protect biodiversity and secure ecosystem services. We report a nationwide assessment for China, quantifying the provision of threatened species habitat and four key regulating services—water retention, soil retention, sandstorm prevention, and carbon sequestration—in nature reserves (the primary category of PAs in China). We find that China's nature reserves serve moderately well for mammals and birds, but not for other major taxa, nor for these key regulating ecosystem services. China's nature reserves encompass 15.1% of the country's land surface. They capture 17.9% and 16.4% of the entire habitat area for threatened mammals and birds, but only 13.1% for plants, 10.0% for amphibians, and 8.5% for reptiles. Nature reserves encompass only 10.2–12.5% of the source areas for the four key regulating services. They are concentrated in western China, whereas much threatened species' habitat and regulating service source areas occur in eastern provinces. Our analysis illuminates a strategy for greatly strengthening PAs, through creating the first comprehensive national park system of China. This would encompass both nature reserves, in which human activities are highly restricted, and a new category of PAs for ecosystem services, in which human activities not impacting key services are permitted. This could close the gap in a politically feasible way. We also propose a new category of PAs globally, for sustaining the provision of ecosystems services and achieving sustainable development goals.

conservation strategy | threatened species representation | ecosystem services | protected areas | sustainable development

The increase in human population and escalating per-capita impacts over the last century have greatly intensified the threats to Earth's life-support systems (1, 2). People have altered ecosystems in profound ways, including land-cover and land-use change, spread of invasive species, climate disruption, and pollution, causing reductions in biodiversity and key ecosystem services (1).

A central approach to curbing such threats is establishing protected areas (PAs) (e.g., nature reserves, national parks)—geographical spaces where regulations are put in place to limit human impacts and conserve nature (3). The global coverage of PAs has increased from 13.4 million square kilometers in 1990 to 32 million square kilometers in 2014, with a total of 209,000 PAs that cover 15.4% of the world's terrestrial surface and 3.4% of the ocean area (3). The Aichi Biodiversity Targets proposed in 2010 established goals of 17% coverage of terrestrial areas and 10% coverage of coastal and marine areas by 2020, respectively (3, 4). The specific motivations for establishing PAs range from protecting places for hunting and recreation to securing exceptional sites of geologic wonder, natural resources, or biodiversity. Even in the case of biodiversity conservation as a goal, conflicting values can make PA design challenging (5).

Although the definition of PAs by the International Union for Conservation of Nature (IUCN) includes explicit reference to conserving "nature with associated ecosystem services" (6), biodiversity has historically been the dominant goal for PA design, implementation, and management (7). There is now a major shift underway toward broadening the goals of PAs from a dominant focus on biodiversity to one that also encompasses the provision of ecosystem services for human well-being (8, 9). Well-designed PAs can harmonize people and nature and yield improvements in the well-being of both (10). Evidence shows that PAs not only secure biodiversity (11), but also provide ecosystem services such as mitigating climate change (12), and enhance ecosystem resilience (13).

The need for research on how to achieve both biodiversity and ecosystem services is of utmost urgency in China. Many globally important ecosystems occur in China, including boreal and tropical forests, wetlands, grasslands, riparian zones, and marine ecosystems (14). From the 1950s into the 1980s, forest cover was reduced by half in the Yangtze River basin, causing severe soil erosion in 40% of the region (15), which later contributed to massive flooding in 1998 that destroyed nearly 5 million homes

Significance

Following severe environmental degradation from rapid economic development, China is now advancing policies to secure biodiversity and ecosystem services. We report the first nationwide assessment, showing that protected areas (PAs) are not well delineated to protect either biodiversity or key ecosystem services. This serious deficiency exists in many countries. We propose creating a national park system in China to help guide development along a path of green growth, improving the well-being of both people and nature. This involves establishing new, strictly protected PAs for biodiversity and ecosystem services that are highly sensitive to human impacts, as well as a new PA category—in China and ideally worldwide—for integrating biodiversity, ecosystem services, and human activities to achieve sustainable development goals.

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(16). Although ecosystem service policies have restored some forests and their services, biodiversity continues to decline (17).

The principal PAs in China are nature reserves (the most strictly protected PAs, primarily for biodiversity conservation), spanning over 80% of protected areas. By the end of 2014, 2,729 nature reserves had been established, spanning approximately 15% of China's land surface (18). Of them, 428 are national nature reserves (encompassing 9.9% of China's land surface), and the remaining are local reserves. Most nature reserves in China have been established opportunistically, without a clear planning framework to maximize efficiency and representation of conservation targets (19). Previous nationwide assessments of the effectiveness of China's nature reserves have focused on ecological diversity (19), represented in ecoregions. They showed that about half of China's ecoregions have >10% of their land area protected through the reserve system, and most natural vegetation communities are represented in at least one nature reserve. To date, no comprehensive analyses have been done to assess biodiversity and ecosystem services in China's nature reserves, however. This is a notable gap, considering that global-scale research suggests that the spatial overlap between biodiversity targets and ecosystem services is low (20).

We fill this gap by conducting a nationwide analysis of representation of both biodiversity and ecosystem services in China's nature reserves. We overlaid the map of nature reserves with the habitat map of threatened species (including those with IUCN Red List classifications of critically endangered, endangered, and vulnerable) habitat and then the maps of four major regulating ecosystem services (i.e., water retention, soil retention, sandstorm prevention, and carbon sequestration). We chose these four ecosystem services because they are all national priorities for policymakers and fundamental to human well-being. We then recommend a strategy for establishing a comprehensive national park system to remedy the weaknesses in China's PAs.

Results

Habitat Distribution of Threatened Species in China. Due to the integrated impacts of biophysical factors and thousands of years of human development history, threatened species habitats are mainly distributed in mountainous and wetland areas in the different regions of China. Important conservation areas for all threatened species are shown in Fig. 1. These varied significantly among different taxonomic groups. The diversity of plants, mammals, and birds spans most of China, but amphibians and reptiles are concentrated mainly in the south. Our analysis reveals the important conservation areas for each taxon (Fig. 1 *A*–*E*).

Ecosystem Service Distribution in China. The important source areas for water retention, soil retention, and carbon sequestration are distributed mainly in places with forests, shrubs, and wetlands in the north, south, and Qinghai–Tibet regions in China (Fig. 2 and Fig. S1). They are the Khingan, Changbai Mountains, and Loess Plateau in the north region, the Qinling-Ba Mountains, Nanling Mountains, and Jiangnan Hills in the south region, the eastern Tibetan plateau, and Hengduan Mountains in the Qinghai–Tibet region. However, sandstorm prevention is concentrated mainly in the northwestern region, on Mongolia's Ordos Plateau and in Hunshandake.

Representation of Biodiversity and Ecosystem Services in China's Nature Reserves. Our results show that China's nature reserve network currently represents 13.1%, 17.9%, 16.4%, 10.0%, and 8.4% of the habitat for plants, mammals, birds, amphibians, and reptiles, respectively (Fig. 3*A*). The nature reserve network does reasonably well with mammals and birds because their habitat coverage percentages are above nature reserve network's 15.1% coverage of China's total land surface. There is, however, poor capture of the habitat for plants, amphibians, and reptiles. These results are consistent no matter whether we consider the entire habitat or only the most important habitat (the top 20% of habitat, according to importance values in Fig. 1) of each taxon. Considering only the national nature reserves, which cover 9.9% of land area in China, reveals similar results for plants, mammals, amphibians, and reptiles. But the bird habitat coverage inside the national nature reserves was below 9.9% for both entire habitat and important habitat (Fig. 3*B*). These findings indicate that China's national nature reserves focus primarily on mammal protection but lack adequate attention to plants, birds, amphibians, and reptiles.

When separating the species into those with relatively large and small ranges, we found that the nature reserve network does

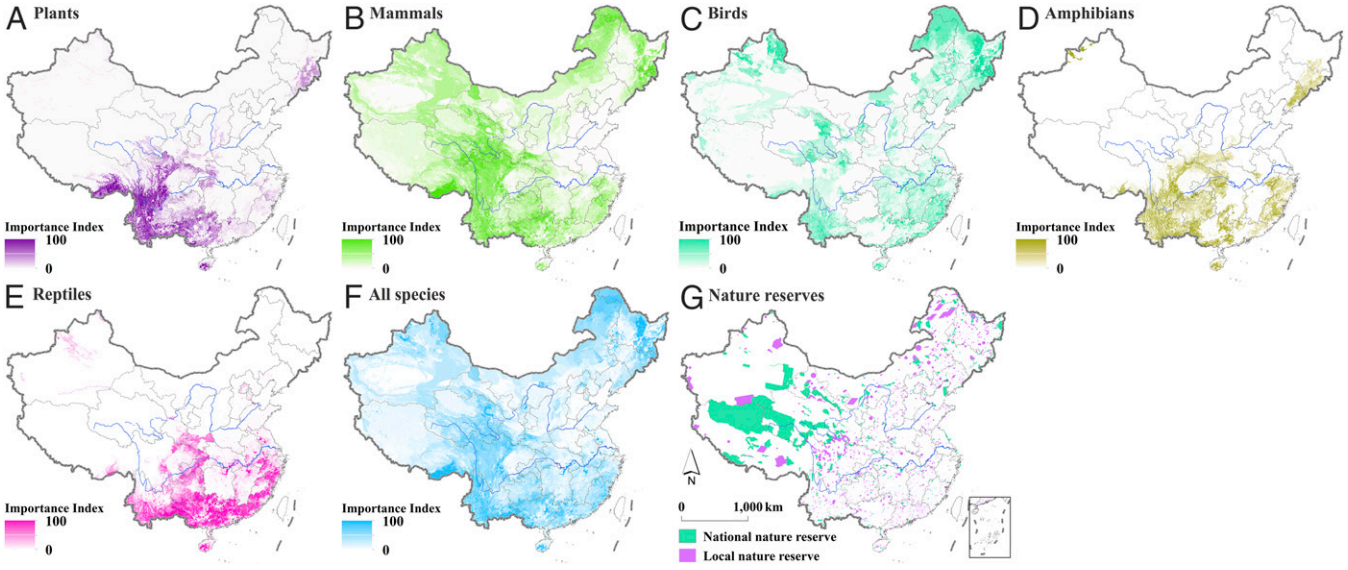

Fig. 1. The importance level of a site for threatened species in China, calculated by summing up potential habitats weighted by IUCN categories (i.e., 3, 2, 1 to categories CR, EN, and VU) for each taxon and for all species in a normalized scale between 0 and 100. *A*–*F* refer to results for plants, mammals, birds, amphibians, reptiles, and all species, respectively. *G* shows the distribution of national and local nature reserves in China. The maps reveal great spatial mismatch of threatened species distributions and nature reserve locations. Nature reserve area is concentrated in the Qinghai–Tibetan region, which has relatively low importance for threatened species.

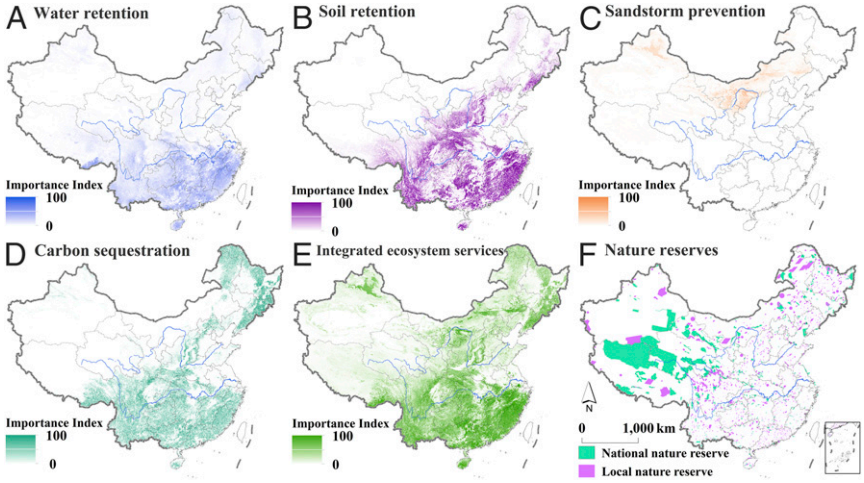

Fig. 2. The importance of ecosystems service source areas in China, showing the spatial mismatch of ecosystems services and nature reserve locations. *A–E* refer to results for water retention, soil retention, sandstorm prevention, carbon sequestration, and integrated ecosystem services, respectively. *F* shows the spatial distribution of China's national and local nature reserves. Sandstorm prevention services originate mainly in north China, whereas the other services originate mainly in east China. Nature reserve area is concentrated in the Qinghai–Tibetan region. Scale 0–100 shows the importance level for each service. Ecosystem service data are from ref. 17.

reasonably well for both large- and small-range mammals. It also does well for large-range birds, many of which are migratory, but not well for small-range birds, although it does reasonably well for the entire bird habitat. For the other three taxa (i.e., plants, amphibians, and reptiles) we find that the entire habitat is not well captured, though small-range species have better representation in the existing reserve network (Fig. S2). The reasons for these patterns are likely several. First, mammals and migratory birds normally have larger ranges than those of plants, amphibians, and reptiles. They are often selected as flagship species for PA establishment. By contrast, plants, amphibians, and reptiles are rarely selected as flagship species. Second, when nature reserves are actually established for plants, amphibians, or reptiles, it is usually because they are threatened—and it is small-range species in these groups that are more often threatened. These small-range species are recently the focus of more conservation attention.

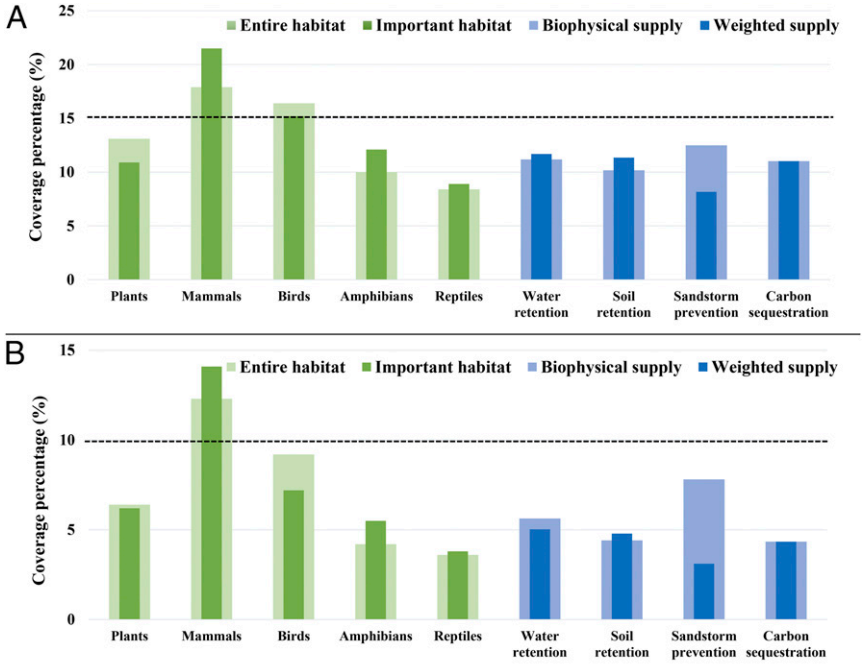

Fig. 3. Comparison of habitat coverage (both entire habitat and important habitat) for threatened species and ecosystem service coverage (biophysical supply and biophysical supply weighted by the number of people benefiting) inside nature reserves in China. (*A*) All nature reserves. (*B*) National nature reserves. These figures reveal that the entire nature network has moderate habitat coverage for mammals and birds and poor habitat capture for plants, amphibians, and reptiles and four key ecosystems services (i.e., water retention, soil retention, sandstorm prevention, and carbon sequestration), in comparison with its coverage of China's total land surface. National nature reserves have moderate habitat coverage for mammals, but poor capture for the other four species and four key ecosystems services. Dashed lines indicate the coverage of all nature reserves (*A*) and national reserves (*B*) relative to China's total land surface.

China's nature reserve network also has a low coverage for the source areas of all four key ecosystem services (Fig. 3). In comparison with the nature reserve network's 15.1% coverage of China's total land surface, it contributes only 11.2% of China's water retention, 10.2% of soil retention, 12.5% of sandstorm prevention, and 11.0% of carbon sequestration. The national nature reserve network contributes only 4.3–7.8% of biophysical supply for the four ecosystem services. The above patterns for all reserves and national nature reserves still hold if we weight the ecosystem service supply by the number of people benefiting.

The low coverage results mainly from spatial mismatch of nature reserve locations with threatened species and ecosystems services distributions (Figs. 1 and 2 and Fig. S1, Table S1, and Table S2). The Qinghai–Tibetan region accounts for 61.2% of the entire reserve area and 75.3% of the national nature reserve area in China. Whereas it encompasses 33.6% of China's mammal habitat, 27.6% of plant habitat and 21.3% of bird habitat, it has a very low proportion of habitat for amphibians (8.5%) and reptiles (4.2%), and only 11.0–14.1% of the entire biophysical supply for the four key ecosystems services. By contrast, the other three regions occupy only 38.8% of the entire reserve area and 24.7% of the national nature reserve area, but encompass over 60% of habitat for threatened plants, birds, and mammals, over 90% of habitat for threatened amphibians and reptiles.

Specifically, the south region encompasses relatively high proportions of habitat for plants (58.0%), mammals (23.6%), birds (29.3%), amphibians (76.6%), and reptiles (87.7%), and 57.7–71.6% of the entire biophysical supply for the three key ecosystem services, excluding sandstorm prevention, as sandstorm usually does not occur in south China; however, it represents only 10.8% of the nature reserve system and 5.3% of national nature reserve system of China. The north region encompasses 27.6% of China's bird habitat, but represents only 13.0% of the nature reserve system and 6.5% of the national nature reserve system. The northwest region covers 56.7% of sandstorm prevention supply but has only 15.0% of the nature reserve area. Large areas of important zones for habitat or ecosystem services in the south (e.g., Nanling and Min-Zhe-Gan Mountains) and north regions (e.g., Changbaishan Mountains and Loess Plateau) are outside the current nature reserve network.

Discussion

We find that China's nature reserve network has a relatively high representation for mammals and birds, but not for plants, reptiles, amphibians, or key ecosystems services. The unit area ecosystem service supply inside all reserves is lower than the average value for China's total land surface. This serious deficiency exists in other countries as well (20). To address this deficiency, we propose to create a new category of PAs for sustaining the provision of ecosystems services for human well-being.

Such a PA category could be beneficial in several dimensions. First, there is no PA type particular to ecosystem services conservation and directly aimed at enhancing ecological security for human beings. Nature reserves are established primarily for biodiversity conservation, not for ecosystem services. Second, important areas for conservation of biodiversity and of different ecosystem services do not always match well. Many places important for ecosystem services are not important for biodiversity conservation (Fig. 4). Nature reserves will not be expanded in those areas, and thus cannot solve deficiencies in ecosystem service conservation. Third, nature reserves are the most strictly managed type of PAs, typically not permitting human use of most of the area within them. For political feasibility of expanding PAs, it is vital to allow some permitted use of natural resources so long as it does not compromise the target ecosystem services. Thus, the new category of PAs for ecosystem services can serve to enhance the balance between protection and sustainable use of natural resources.

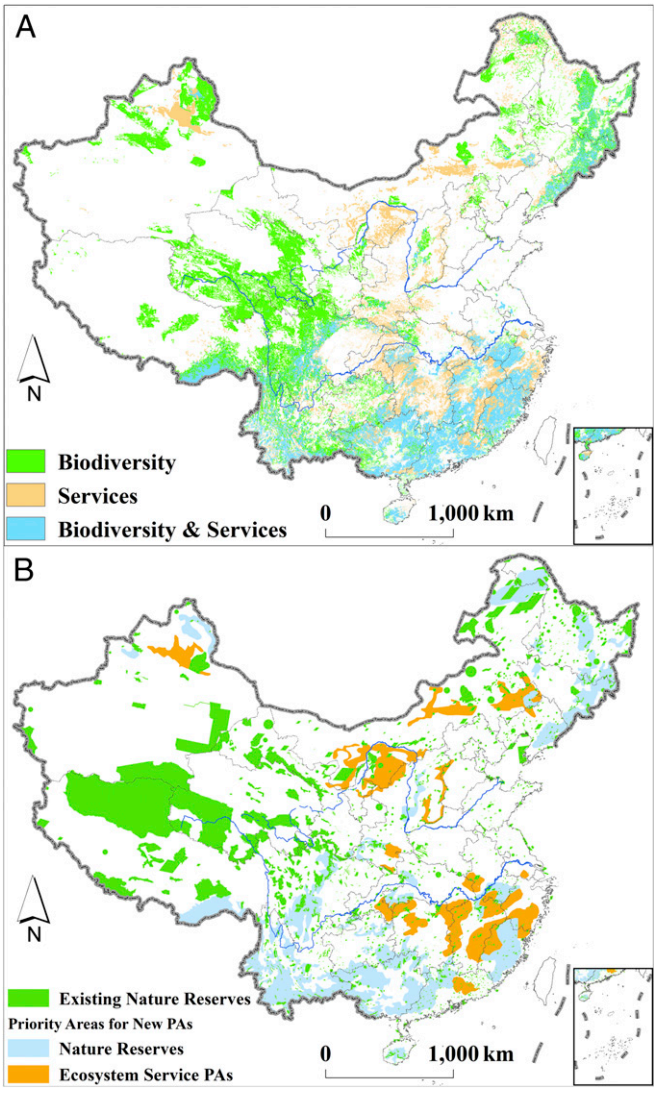

Fig. 4. Priority areas for securing threatened species habitat and source areas of key regulating ecosystems services and application in the design of new PAs. (*A*) Nature reserves with important areas for biodiversity, ecosystem services, and both biodiversity and ecosystem services. Green and tan show important conservation areas for biodiversity and ecosystems services, respectively. Blue shows important areas for conservation of both biodiversity and ecosystem services. Important areas are delineated as those within the top 20% of cumulated area according to the importance index value. (*B*) Priority areas for a comprehensive PA system in China, based on *A*.

We also provide some specific recommendations for China to strengthen the role of the nature reserve network in protecting biodiversity and sustaining ecosystem service supply. These recommendations can be applied to China's emerging national park system. First, we recommend expanding the PA system to cover more area of high priority for biodiversity conservation and ecosystem service provision. New nature reserves need to be established, or existing nature reserves need to be expanded, to encompass important areas for threatened species, particularly focusing on reptiles, amphibians, and plants, given their low coverage inside current nature reserves and need for stricter protection. Important areas such as the lower streams of the Yangtze River, the Min-Zhe-Gan and Wuyi Mountains, Nanling, and west and south Yunnan in the southern region are priority areas for establishment of new nature reserves or expansion of existing ones (Fig. 4).

Second, we recommend establishing clusters of nature reserves in priority areas to reduce serious problems of low habitat connectivity and isolation (typically caused by administration boundaries that inhibit establishing or managing cross-county reserves, for example). Establishing expanded nature reserves in these areas will also protect more source areas of ecosystem services, given the moderately high overlap between biodiversity and regulating services (Fig. 4).

Third, in China we propose to establish a new category of PAs to focus on protection of areas important for the provision of ecosystem services. Human activities inside this category of PAs should be permitted if they do not compromise the provision of key ecosystems services. Places such as the Loess Plateau, Mongolia Ordos Plateau, Eastern Qinling, and middle and south Chongqing are relatively unimportant for biodiversity conservation, but crucial for soil retention, sandstorm prevention, and water retention, respectively (Fig. 4). Such a category of PAs for ecosystem services is likely to get higher support from local governments than nature reserves. For instance, the Qinling Mountains were regarded as key areas for both biodiversity and water-source conservation. After being recognized as a critical source area of China's South-to-North Water Transfer Project (21), more conservation and restoration funding was invested from the local governments than when reserves were only for biodiversity conservation.

In short, based on experience in China and elsewhere, we expect that establishment of PAs—in priority areas defined by both biodiversity and ecosystem service values—will improve the local and national support, effectiveness, and durability of investments in conservation. The priority areas delineated through our analysis span about 30% of the total land surface area, but will encompass 56–78% of important habitat for threatened plants, mammals, birds, amphibians, and reptiles, and contribute 48–56% of the biophysical supply of the four priority ecosystem services.

Our recommendations support conservation policymaking for both biodiversity and ecosystem services. The case of Ecosystem Function Conservation Areas (EFCAs) in China is telling (22). EFCAs have been established through a conservation policy implemented since 2008, with the aim to better protect wildlife habitat and important ecosystem services (i.e., water retention, soil retention, sandstorm prevention, and flood mitigation). To date, however, EFCAs have been implemented separately as a weaker ministry regulation rather than a stronger national law. Besides, other conservation policies such as the Natural Forest Conservation Program (NFCP) and Ecological Public Welfare Forest (EPWF) also provide conservation for natural forests and ecosystem services in the south and north regions. But they are also not national laws. Creating a new PA category of ecosystem services and incorporating the EFCAs, NFCP, and EPWF will significantly enhance long-term institutional support for biodiversity conservation and provision of key ecosystem services.

Finally, the above recommendations may also apply to the development of the first national park system of China. The central government started to pilot an integrated national park system in nine provinces in 2015 (23), aiming eventually to establish a comprehensive, nationwide system to protect important natural ecosystems and wildlife in China and ensure sustainable use of natural resource (24). Our analysis can serve as a basis for this new system. Our suggestion on expanding nature reserves and establishing a new category of PAs for ecosystem services in the priority areas will benefit the balance between strict protection and sustainable use of natural resources, greatly improving biodiversity conservation and also contributing significantly to the ecological security of human society.

Our findings and recommendations in China also apply to many other countries where PAs are not sufficient to provide the long-term protection of biodiversity and ecosystem services to achieve sustainable development. Combining the conservation of biodiversity and ecosystem services will also promote the achievement of the Aichi Biodiversity Target of the Convention on Biological Diversity (7). Further, we recommend establishing a new category of PAs for ecosystem services within the IUCN PA classification system.

Materials and Methods

Nature Reserve Data. We compiled the best available data on nature reserves in China. By the end of 2012, there was a total of 2,669 nature reserves in China, excluding Taiwan, Hong Kong, and Macao, which were excluded due to complications of data availability and administrative differences (25). To evaluate the representation of terrestrial nature reserves, we excluded marine reserves. We excluded reserves which did not have available data. We combined multiple sources of data to delimit the boundaries of the 2,412 terrestrial nature reserves with available data. These reserves cover 15.1% of China's land surface. Data for 713 nature reserve boundaries come from the Ministry of Environmental Protection (MEP), the Nanjing Institute of Environmental Sciences (NIES), and other provincial environmental sciences institutes, including all 363 national-level reserves and 350 local-level reserves. These reserves account for 74.7% of the total area of the 2,412 reserves. Data for an additional 986 nature reserves come from the worldwide dataset on PAs of the United Nations Environment Programme (UNEP) (26). There are 713 remaining reserves without any boundary information. Following Wu et al. (19), we approximated boundaries for these 713 remaining reserves by generating a circular zone with the same size as reported by the MEP using a known point location from NIES as the center (25).

Biodiversity Mapping. To map the important areas for biodiversity conservation, we selected threatened species in the IUCN Red List or China's Red List as indicator species, including categories of critically endangered (CR), endangered (EN), and vulnerable (VU) (27–33). The final selected list contains a total number of 1,534 species, including 955 plants, 152 mammals, 127 birds, 177 amphibians, and 123 reptiles. Distribution information for plants is from the Scientific Database of China Plant Species (34). Range maps for mammals, amphibians, and reptiles are from IUCN (27) and are supplemented using data from Fei et al. (35), and Jiang et al. (36). Range maps for birds are from BirdLife International (37). For details of all species evaluated, see Tables S3–S7.

Because the range maps contained unsuitable habitat, we refined the potential habitat for each species based on specific distribution area, elevational range, and vegetation, as suggested by Li and Pimm (38). Data on specific distribution areas are from the Institute of Zoology, Chinese Academy of Sciences, and supplemented by recent studies (31, 36, 39–50). Ecological requirements on elevation and vegetation for each species are from the Scientific Database of China Plant Species, the IUCN Red List, BirdLife International, and recent studies (36, 40, 48, 50–52). We extracted elevational data using the 90-Meter Digital Elevation Model from the NASA Shuttle Radar Topographic Mission, and vegetation data from the 30-m ecosystems map in 2010 (17).

Important areas for species conservation are identified by summing up weighted potential habitats for each taxon. To describe the relative importance of different IUCN categories, we gave weights of 3, 2, and 1 to categories CR, EN, and VU, respectively. For each taxon, we normalized the summed values separately to the range of 0–100 using the minimum–maximum normalization method (53), with 100 being the most important and 0 being the least important. The overall importance index map for biodiversity conservation used the maximum value of each pixel among the five taxon layers. We defined important habitat for biodiversity conservation as the top 20% cumulated area according to the importance index value (Fig. 1).

Ecosystems Service Mapping. We considered four key regulating ecosystem services: water retention, soil retention, sandstorm prevention, and carbon sequestration, including both biophysical supply and supply weighted by number of people benefiting. Those data are from the national ecosystem assessment project for years 2000–2010 (17). Water retention (soil retention, sandstorm prevention) refers to the water (soil, sand) retained in ecosystems within a certain period (1 y for this study). Water retention was estimated using the water balance equation, revised from the InVEST model (54, 55). In this model, the capacity of water retention is the difference between the amount of precipitation and the sum amount of runoff and evapotranspiration. Soil retention was measured using the universal soil loss equation and InVEST model, indicating the difference between potential and actual soil erosion in ecosystems. The service of sandstorm prevention was mapped using the revised wind erosion equation. Carbon sequestration refers to carbon sequestered by terrestrial ecosystems. By examining the dynamics of biomass carbon storage in China's forest, grassland, and wetland ecosystems, the average annual carbon sequestration was estimated. More detailed information about the four key ecosystem services can be found in ref. 20.

Similar to the importance index of endangered species, we normalized the biophysical supply value into importance index value range 0–100 using the minimum–maximum normalization method (53). We also defined an important area for ecosystem service provision as the top 20% cumulated area according to the importance index value (Fig. 2). The overall importance index map for overall ecosystems service was the maximum value of the four services layers.

Representation Analysis. We used spatial overlap analysis to analyze the representation of nature reserves for protecting threatened species and ecosystems services. If the entire habitat (or important habitat) coverage inside the nature reserves relative to its total habitat area was above the nature reserve coverage of China's total land surface, the reserve network was deemed to have a good representation of threatened species. For the ecosystems services, if biophysical supply (or supply weighted by number of people benefiting) inside the nature reserves relative to its total supply is higher than the nature reserves coverage of China's total land surface, the reserve network was deemed to have a good representation of this ecosystems service. Otherwise, the reserve network was deemed to have a poor representation of threatened species or ecosystems services.

Expansion of the PA System. We consider expanding the PA systems by establishing new nature reserves or expanding existing ones to better cover high priority areas for biodiversity and ecosystem services. These priority areas were delimited by considering the top 20% of habitat for biodiversity conservation and for ecosystem service provision according to the importance index value.

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