Response of Biodiversity, Ecosystems, and Ecosystem Services to Climate Change in China: A Review

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Abstract: Climate change is having a significant impact on the global ecosystem and is likely to become increasingly important as this phenomenon intensifies. Numerous studies in climate change impacts on biodiversity, ecosystems, and ecosystem services in China have been published in recent decades. However, a comprehensive review of the topic is needed to provide an improved understanding of the history and driving mechanisms of environmental changes within the region. Here we review the evidence for changes in climate and the peer-reviewed literature that assesses climate change impacts on biodiversity, ecosystem, and ecosystem services at a China scale. Our main conclusions are as follows. (1) Most of the evidence shows that climate change (the increasing extreme events) is affecting the change of productivity, species interactions, and biological invasions, especially in the agro-pastoral transition zone and fragile ecological area in Northern China. (2) The individuals and populations respond to climate change through changes in behavior, functions, and geographic scope. (3) The impact of climate change on most types of services (provisioning, regulating, supporting, and cultural) in China is mainly negative and brings threats and challenges to human well-being and natural resource management, therefore, requiring costly societal adjustments. In general, although great progress has been made, the management strategies still need to be further improved. Integrating climate change into ecosystem services assessment and natural resource management is still a major challenge. Moving forward, it is necessary to evaluate and research the effectiveness of typical demonstration cases, which will contribute to better scientific management of natural resources in China and the world.

Keywords: climate change; biodiversity; ecosystems; ecosystem services; natural resource management

1. Introduction

Biodiversity and ecosystems as natural capital provide services such as provisioning, regulating, supporting, and cultural for human society, and assets play fundamental roles in supporting human well-being [1]. However, climate change poses widespread and increasingly serious global threats to biodiversity and ecosystems [2]. The sixth assessment report of the United Nations Panel on Climate Change (IPCC) clearly pointed out that from the prediction of average temperature change in the next 20 years, the global temperature rise is expected to reach or exceed 1.5 °C; at least until the middle of this century, the global surface temperature will continue to rise [3]. In addition, the increasing frequency and intensity of extreme weather events (such as droughts, heatwaves, and heavy rainfall) will affect 25–40% of the global ecosystem structure and function [4,5], and further affect the supply level of ecosystem services and the human well-being [6].

China is one of the most sensitive and vulnerable regions to climate change [7]. The National Assessment Report on Climate Change (III) pointed out that the average temperature of China's land has increased by 0.9–1.5 °C in the past 100 years (1909–2011) (China's National Assessment Report on Climate Change (III), 2014). It will continue to increase in the next 20 to 100 years, with a temperature increase of 0.5 to 0.8 °C, which is

slightly higher than the average global temperature rise (0.6 ± 0.2 °C) during the same period [7]. Therefore, the precipitation patterns and other bioclimatic factors will change significantly as the global average temperature continues to rise [8], which will have a profound impact on China's natural ecosystems and ecosystem services, and will create huge challenges for natural resource management. Thus, policymakers need to adopt active and flexible response strategies, considering historical and future prospects, in order to achieve sustainable development of ecosystem services.

Based on this, in the context of the National Assessment Report on Climate Change (III) and the Blue Book on Climate Change in China, we have conducted an analysis of the research themes of many scientists and tried to summarize the research on biodiversity, ecosystems, and ecosystem services in China from spatial and temporal scales, (the review includes three components: (i) Biodiversity individuals, populations and species that constitute the ecosystem. (ii) The characteristics and processes of the ecosystem. (iii) the services that the ecosystem provides to support human development). Finally, we cite examples of relevant adaptive actions to reveal the challenges that climate change brings to natural resource management and to propose possible future management strategies, with a view to providing examples for the implementation of natural resource management and sustainable development on a global scale.

2. Data Sources and Analytical Methods

Meteorological data: From the China Meteorological Administration Meteorological Data Service Center (https://data.cma.cn/ (accessed on 6 August 2020)), the monthly meteorological data set was obtained from 1960 to 2019, which covers 613 ground observation stations from 1951 to the present.

Land Use and Land Cover data: Sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/ (accessed on 4 May 2020)). Land use types include six types of cultivated land, forest land, grassland, water area, residential land, and unused land.

China's state poverty counties data: From the official website of the Leading Group Office of Poverty Alleviation and Development (of the State Council), the published list of 665 key counties for national poverty alleviation and development in 2012 (http://www.cpad.gov.cn/ (accessed on 4 May 2020)).

Invasive Alien Species data: Sourced from the Database of Invasive Alien Species in China (http://www.chinaias.cn/ (accessed on 20 March 2020)) and the Ministry of Ecology and Environment of China (http://www.mee.gov.cn/ (accessed on 20 March 2020)).

Literature Retrieval Data: We researched articles published between 1990–2019, which were collected using selective keywords under 'TOPIC' in the database of ISI Web of Science Core Collection. We searched the keywords: (ecosystem, ecosystem service, climate change etc.), and searched a total of 18,323 studies on ecosystems in China (including 5434 studies on the impact of climate change on ecosystems, accounting for about 30%); 4258 studies on ecosystem services in China (including 1042 studies on the impact of climate change on ecosystem services, accounting for about 24%). As needed, we further searched articles related to climate change, and selected 330 articles for detailed review.

3. Results

3.1. Overall Research Trends

We searched a total of 18,323 studies on ecosystems in China (including 5434 studies on the impact of climate change on ecosystems, accounting for about 30%); 4258 studies on ecosystem services in China (including 1042 studies on the impact of climate change on ecosystem services, accounting for about 24%). From 1990 to 2019, the volume of literature on ecosystems and ecosystem services shows an increasing trend (Figure 1A,C), which indicates that people are paying more and more attention to the impact of climate change on ecosystem and ecosystem services (Figure 1B,D). Based on the analysis of 330 literature after filtering and screening, we found that the spatial scale diversity was considered in a

number of studies (Figure 1D), but the terrestrial ecosystem (230 Studies) was significantly more than the freshwater (44 Studies) and the marine (56 Studies) (Figure 1D). The forest and grassland ecosystems in the terrestrial ecosystem were the hot research areas. Although the research covers a large area of China, more attention has been paid to the Qinghai Tibet Plateau (32 studies in Tibet and 20 studies in Qinghai), and the Inner Mongolia Plateau accounts for about 11% (36 studies in Inner Mongolia) (Figure 1E).
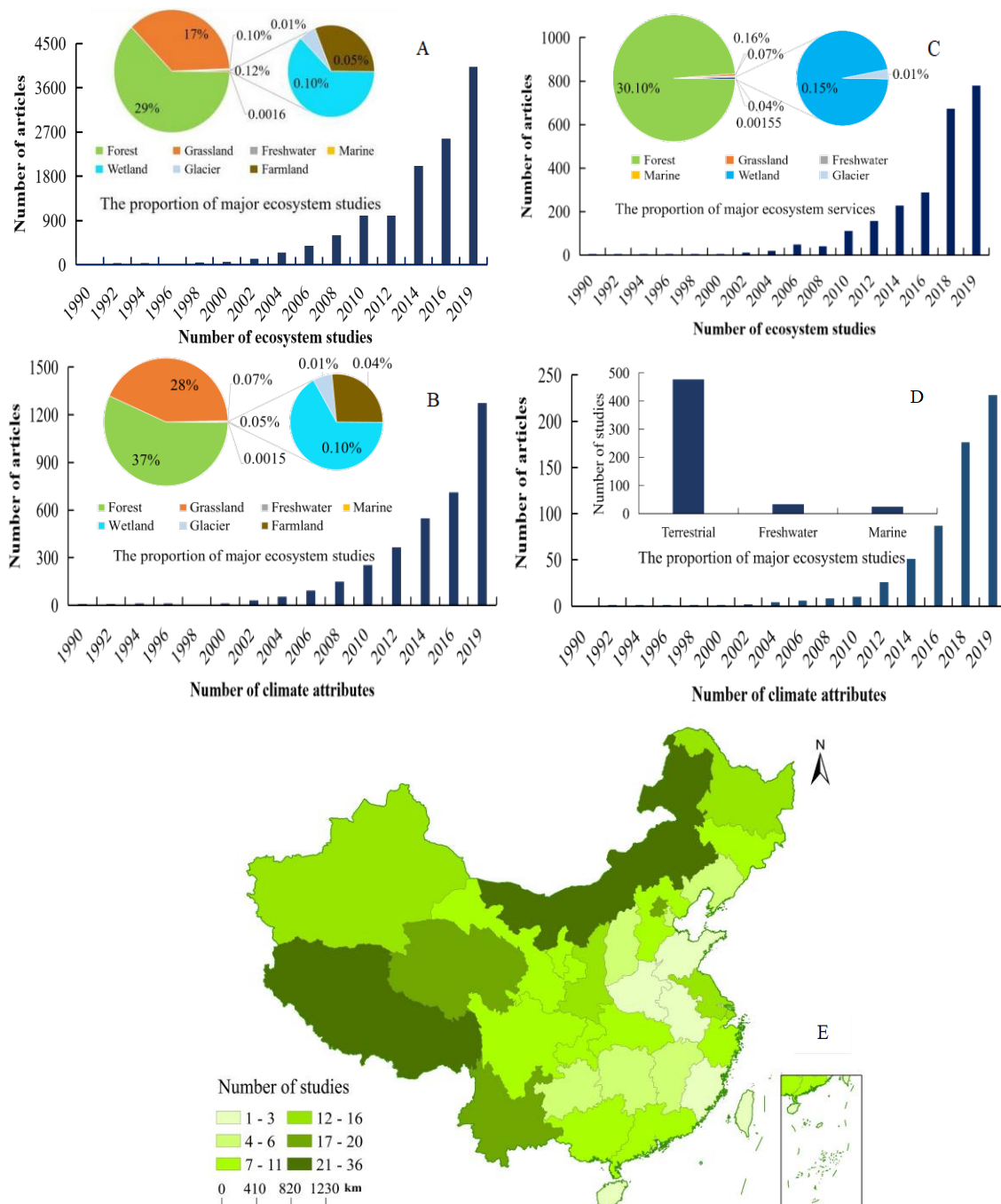

Figure 1. Key attributes of the ecosystem and ecosystem service assessments. (**A**) The number of ecosystem studies and the proportion of major ecosystem studies; (**B**) the number of climate attributes and the proportion of major ecosystem studies; (**C**) the number of ecosystem services studies and the proportion of major ecosystem services studies; (**D**) the number of climate attributes and the proportion of major ecosystem services studies; (**E**) Number of studies in different regions of China. The above data sources are from CNKI.

3.2. Increasing Threat to Biodiversity

The degradation of ecosystems, especially habitat loss, is one of the important reasons for the decline of biodiversity [9]. The relationship between global warming and species diversity has become the focus of research in recent decades [10]. Under the scenario of global warming in the future, climate-sensitive species show a trend of migration to high altitude, high latitude, and westward [11]. Recently, species distribution shifted to a higher altitude at a rate of 11 m per decade, and to a high latitude at a rate of 16.9 km per decade [12]. The extinction risk of high altitude and high latitude species will be further intensified [12]. Therefore, climate change has become the biggest threat to global biodiversity, and research is urgently needed to reveal how species' habitats respond to future climate change.

3.2.1. Phenological Changes

There is a significant correlation between phenology and climate change, and the change of phenology has become the main indicator of species' response to climate change [13]. Under the background of global warming, plant phenology has changed significantly. Such abrupt warming can affect many aspects of vegetation, such as plant composition and diversity, phenology, productivity, biomass, and vegetation fraction [14], and then affect the energy flow, carbon cycle and water cycle of the whole terrestrial ecosystem.

In recent decades, the phenology of plants in China has been strengthened by climate change, and the growing season has been prolonged. The phenological changes of peach showed a more intense trend. The flowering date was advanced by 11.1 days, while the defoliation date was delayed by 8.7 days [15]. According to the Blue Book on Climate in China, from 1963 to 2019, the spring phenophase of representative plants in different regions showed a significant advance trend. For example, Beijing Station (*Magnolia denudata Desr.*), Shenyang Station (*Robinia pseudoacacia* L.), Hefei Station (*Salix babylonica*), Guilin Station (*Liquidambar formosana Hance*), and Xi'an Station (*Acer mono Maxim.*) advanced 3.3 days, 1.4 days, 2.2 days, 2.9 days and 2.5 days, respectively (Blue Book on Climate in China, 2020) (Figure 2).

From different parts of the country, the timings of leaf-out and fruit-set significantly advanced in Qinghai Tibet Plateau in recent years [16,17]. In recent decades, warming in Inner Mongolia Plateau has been much faster than the global warming rate [18], and the increase of temperature impacts grassland phenology significantly [19]. In Northwest China, climate change also impacts crop phenology.

Climate warming leads to the earliness of pseudostem elongation, booting, anthesis, and ripening stages of winter wheat during the 24 years [20]. Compared with terrestrial systems, phenological changes of marine and aquatic habitats in China are less recorded, mainly due to the difficulty in detecting and tracking aquatic organisms.

Under the background of global warming, if the climate continues to warm, the phenological changes and the resulting ecological, agricultural, socioeconomic, and health problems deserve attention. The response of phenology to global warming is becoming a hot spot in the current international global change research, and NDVI is increasingly becoming an important means of vegetation response to climate. At present, many domestic researchers have carried out some work on the response of phenology to climate warming, and the research on the response of vegetation to climate change using NDVI has also been carried out. However, compared with the international research progress, there is still a lot of research work to be further carried out.

3.2.2. Geographical Expansion of Species

Climate change is driving species distribution and abundance changes in terrestrial and aquatic ecosystems [21]. At the same time, future climate change will also have significant changes in the geographical range of species. For example, climate change is threatening the habitat of flagship species and has posed a serious threat to the habitat

of the giant panda (*Ailuropoda melanoleuca*) in recent decades [22]. For plants, warming will threaten the survival of Alpine coniferous forests in Northeast China [23]. The rising trend of Qinghai spruce (*Picea crassifolia Kom.*) and Qilian juniper (*Juniperus przewalskii Kom.*) tree-limit in Qilian Mountains of China is also obvious, with the warming and humidification of the climate [24], the growth of Qinghai spruce in the Qilian Mountains showed an overall upward trend after 2000 [25,26]. It is also found that the rise of Qilian Mountain forests has been relatively obvious in the past 100 years, and the rising rate has decreased from east to west. With the improvement of temperature and moisture conditions, the lower line of forests in some areas has moved down significantly [26,27].
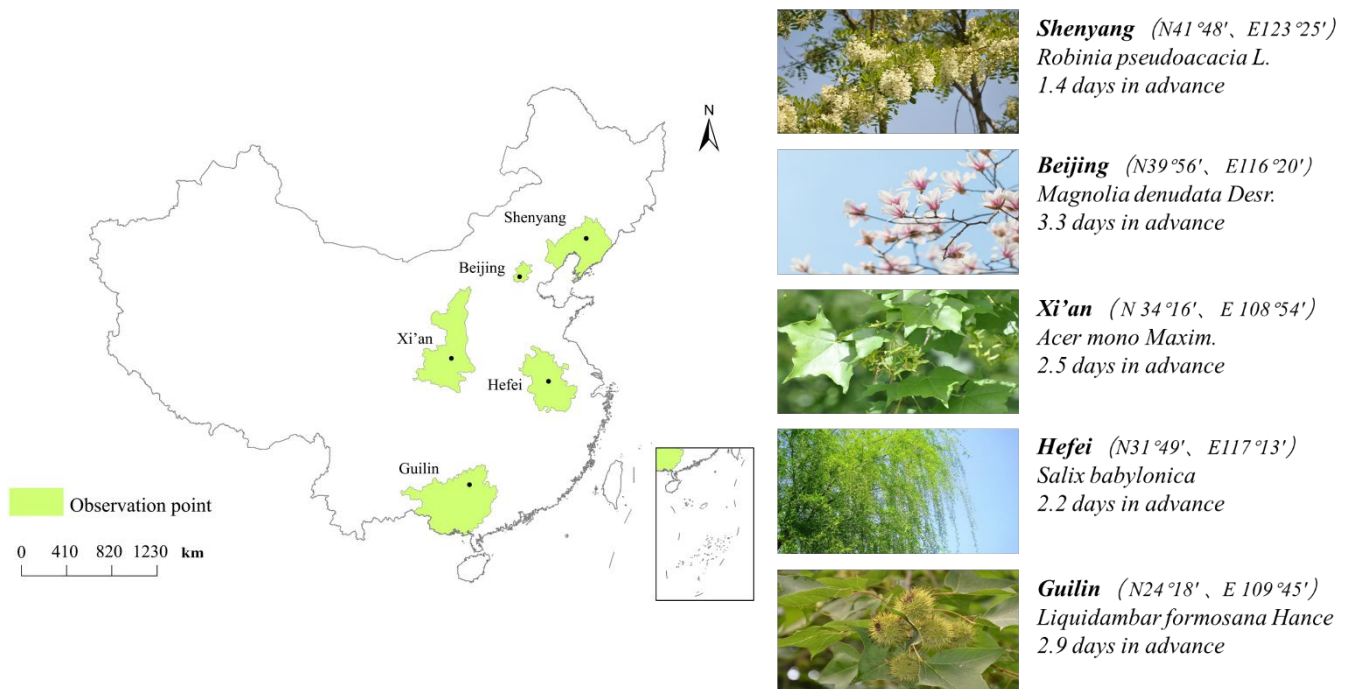

Figure 2. Changes in the initial period of leaf development of representative plants in different regions of China from 1963 to 2019 (*Magnolia denudata Desr.*: The famous flower in China has a flowering period of about 10 days. *Robinia pseudoacacia* L.: Temperate tree species, native to the United States, now widely planted throughout China. *Salix babylonica:* belongs to light-loving and wet-loving plants, producing the Yangtze River Basin and the Yellow River Basin. *Liquidambar formosana Hance*: likes warm and humid trees, which are produced in Qinling Mountains and south of Huaihe River in China. *Acer mono Maxim.*: a deciduous tree with a height of 15–20 m, distributed in Northeast and North China). The data sourced from Chinese Phenological Observation Network (CPON) (http://www.cpon.ac.cn/ (accessed on 6 August 2020)).

Many studies have found that climate warming is changing the habitat range of species all over the world. Driven by climate change, there are three different modes of habitat transfer, includes decrease, increase, and disappearance [28]. For example, the prediction of habitat range of *Polygala tenuifolia* in China shows that the highly suitable habitat area was slowly reduced over time in the context of climate change [29]. For *Haloxylon* (*Haloxylon ammodendron (C. A. Mey.) Bunge*) vegetation in arid areas, warming will lead to the gradual disappearance of habitat in the Balkhash Lake area in the east of Xinjiang [30]. However, for some plants in the Himalaya–Hengduan Mountains, climate warming has increased the habitat range to some extent. The predictions indicate that, under a wide range of climate change scenarios, the distributions of *Cyananthus* and *Primula* will shift upward in elevation and northward in latitude, furthermore, under these scenarios, species will expand the size of their range [31]. In addition, for some crops (*Zingiber*, *Brassica napus* L., *Triticum aestivum* L., *Glycine max (Linn.) Merr*), future climate change may lead to increased habitat area [32].

For some species, climate change has resulted in reductions in population size and, for range-restricted or isolated species and populations, in extinction or extirpation [33,34]. In particular, it may increase the risk of extinction of a plant species with extremely small populations [35]. *Metasequoia glyptostroboides* in southern China, a plant species with extremely small populations that are categorized as critically endangered, facing ongoing habitat fragmentation and degradation, and resultant serious population decline [35,36]. The temperature is an important environmental factor that affects the growth, development, and function of plants. It directly affects the physiological functions of plants, such as photosynthesis, respiration, material transportation, and energy conversion. In the case of global warming, therefore, six wetland plants (*Bruguiera gymnorrhiza*, *Carex doniana*, *Glyptostrobuspensilis*, *Leersiahexandra*, *Metasequoiaglyptostroboides*, *Pedicularis longiflora*) in China are also facing the risk of extinction [35].

3.3. Ecosystems

In previous studies, we found that the ever-changing climate drivers profoundly affect the numbers, compositions, and activities of individuals, populations, and species, which will lead to changes at the ecosystem level. Therefore, we focus on several key ecosystem-level characteristics affected by climate change.

3.3.1. Biological Invasion Accelerates Expansion

The IUCN (International Union for Conservation of Nature) definition is: "*An alien species is a species introduced outside its natural past or present distribution, if this species becomes problematic, it is termed an invasive alien species (IAS)*" (https://www.iucn.org/theme/species/our-work/invasive-species (accessed on 6 August 2020)). The harm caused by biological invasion is alien invasion, which ultimately affects biodiversity, ecosystem services, and human well-being [37]. It is generally believed that many biological invasions are responsible for the extensive changes and even extinction of protozoa [38]. It is known that biological invasion can be attributed to both human activities and climate change, but here we focus on how climate change affects the spread of alien species. The IPCC predicts that extreme temperature and abnormal precipitation patterns in many regions will affect the distribution of local and invasive species [3], and the general warming trend will further expand the geographical range of some species [39].

At present, China has become one of the most serious alien species invasion countries. According to the Bulletin of the State of the Ecological Environment in China 2019, issued by the Ministry of Ecology and Environment, more than 660 alien invasive species have been found in China, an increase of about 30% compared with 10 years ago. Among them, 71 species have caused or are a potential threat to the natural ecosystem and have been listed in the list of alien invasive species in China. Two hundred fifteen alien invasive species have invaded the National Nature Reserve, and 48 of them have been listed in the list of alien invasive species in China (Bulletin on the State of China's Ecological Environment in 2019, 2020, issued by the Ministry of Ecology and Environment) (Figure 3).

At present, the geographical distribution and density of alien species in China tend to decrease from the south and the east to the north and the west [40,41]. How will climate change affect China's future invasion of alien species? A simulation of the range change of invasive species in different climate scenarios found that invasive alien plants may further expand into Northern China [42], for example, future climate change was predicted to result in a shift in the alien invasive weeds in Qinghai and Tibet (regions of higher altitude) as well as Heilongjiang, Jilin, Liaoning, Inner Mongolia, and Gansu (regions of higher latitude) [43]. In China, farmland and forests are mainly distributed in the South and East, while grasslands are mainly distributed in the North and West. Therefore, it will pose a great threat to climate-sensitive terrestrial ecosystems (Agro-pastoral Ecotone in Northern China) [44] (Figure 3). According to this trend, future research should pay more attention to the impact of climate change on species invasion in ecologically vulnerable areas and agro-pastoral ecotone [44] (Figure 3). To prevent and manage biological invasion in China,

we still need to learn from the international biological invasion database and strengthen international cooperation, build and improve China's biological invasion database, and at the same time, speed up the legislation of bio-safety laws.
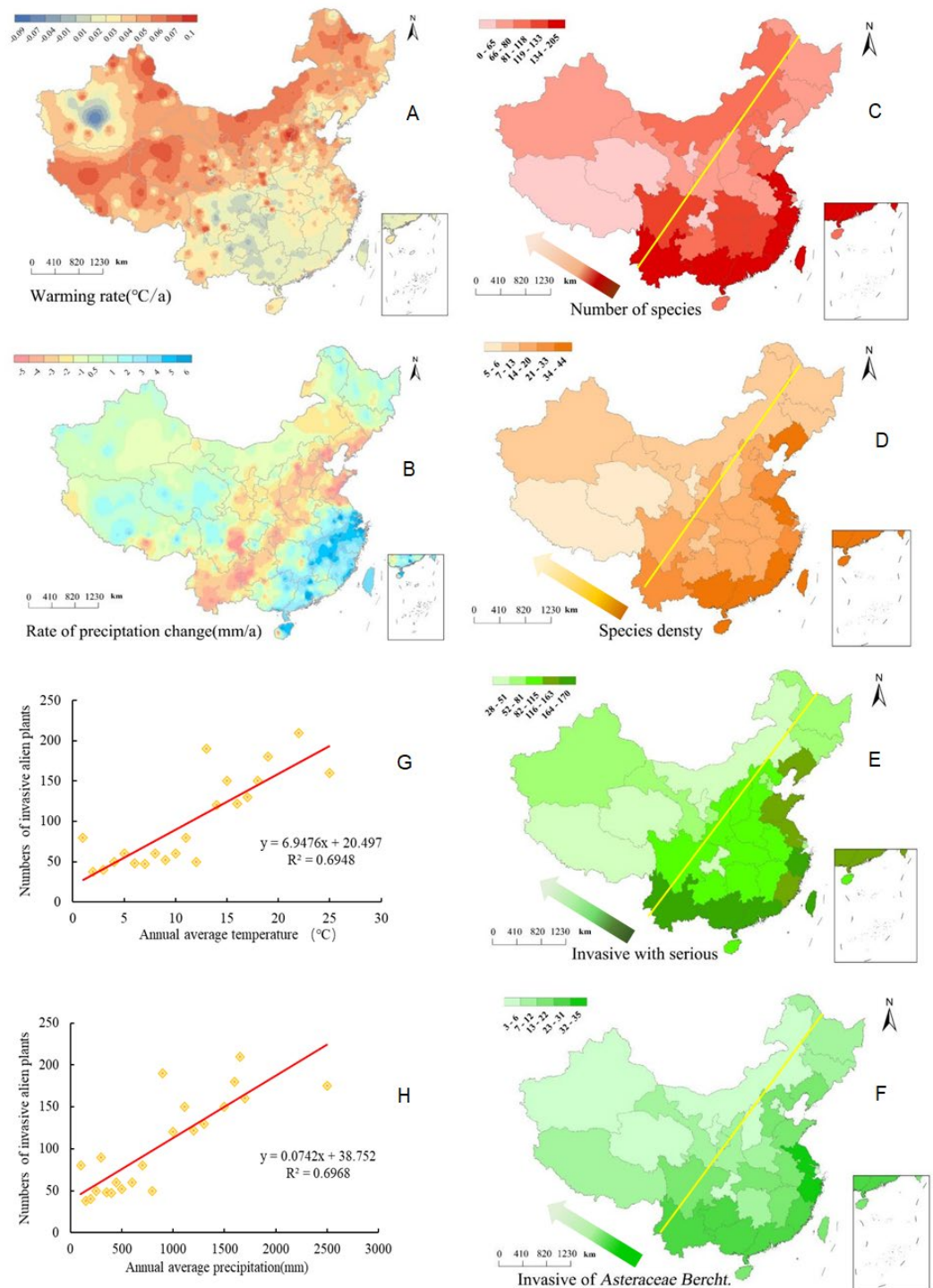

Figure 3. Effects of climate change on the distribution of invasive alien species in China, the surface warming rate in China from 1960 to 2019 (**A**), the rate of precipitation changes in China from 1960 to 2019 (**B**), the distribution pattern of invasive species in China (number of species) (**C**), the distribution pattern of invasive species in China (species density) (**D**), the distribution pattern of invasive with serious ecological hazard in China (**E**), the distribution pattern of invasive *Asteraceae Bercht.* in China (**F**), Annual average precipitation and the annual average temperature had a linear relationship with

invasive alien plant species (**G**,**H**). Data: Sourced from the China Meteorological Administration Meteorological Data Center (https://data.cma.cn/ (accessed on 4 June 2020)) and the Database of Invasive Alien Species in Chia (http://www.chinaias.cn/ (accessed on 4 June 2020)). The yellow line in the figure roughly represents the dividing line between temperature and precipitation rate.

3.3.2. Increasing Threat of Extreme Events

According to the Intergovernmental Panel on Climate Change (IPCC), climate change leads to the frequency, intensity, spatial scope, and duration of extreme climate events and may cause unprecedented impacts on terrestrial ecosystems [3]. Global warming is expected to further increase the frequency and intensity of extreme climate events (drought, rainstorms, heat waves, etc.) in the middle and late 21st century [45,46], which makes the impact of future climate change on terrestrial ecosystems more uncertain [47].

According to the Ministry of Emergency Management of the People's Republic of China in 2019, affected by the El-Niño phenomenon, some parts of China suffered the worst drought in 50 years. Extreme weather such as high temperatures, strong winds, thunderstorms, and other extreme weather increased significantly. The negative impact of extreme climate on natural ecosystem and agriculture has been widely reported. For example, the extreme drought in 2000 [48] led to a sharp decline in crop yield in North China and Northeast China [49,50]. In Southwest and Southern China, the heatwave and drought in the past 50 years has reduced annual total primary productivity by 4% [51,52]. In Central and Southern China, a large number of vegetation deaths were caused by freezing disasters in 2008 [53]. In Southwest China, extreme drought events between 2009 and 2013 significantly reduced lake diatom diversity [54]. In 2018, temperature and precipitation anomalies led to changes in NDVI (Normalized Difference Vegetation Index) in the Yangtze River Basin [55].

In general, the frequency and intensity of extreme climate events (drought, rainstorm, freezing, heatwave, etc.) are increasing in China. North China, Northeast China, and Southwest China will become a hot area of the drought threat, while Southern China will be the main threat area for rainstorms and floods. In addition, the extreme drought events will also aggravate the frequency of forest fires in most areas of Southwest China [56]. Therefore, for government decision-makers, it is necessary to understand which areas are most vulnerable to extreme events and why, which will improve the effectiveness and scientific of formulating response strategies.

3.3.3. The Prediction of Potential Impact

Combined with the previous studies, we further found that the warming rate in the vast areas of China was accelerated according to the meteorological data analysis in recent decades (1970–2019). The temperature in Northwest, Northeast, and Qinghai–Tibet Plateau increased significantly, and the warming rate was accelerated. The precipitation changes had regional differences, and the average annual precipitation shows an increasing trend. Among them, the precipitation in Northwest, Northeast, and Qinghai–Tibet Plateau areas have significantly increased, and the precipitation change rate has accelerated (Figure 4). We found that the sensitive regions of climate change in China are similar to the forest ecosystem, grassland ecosystem, farmland ecosystem, glacier wetland ecosystem, sandy bare land ecosystem, and urban ecosystem in geographic spatial distribution (Figure 4). According to the previous studies, climate change will have a "double-sided effect" on China's ecosystem, especially in fragile ecological environment areas. For example, climate warming will aggravate the humidification of western China to a certain extent, but it will also accelerate the invasion of alien species.

Warming and humidification in Northwest China are conducive to the development of forest and grassland ecosystems [57], and will effectively slow down the development of sand and bare land ecosystems. However, for Southwest China, warming will increase the frequency of forest fires [58,59]. For Northeast China, warming will threaten the survival of Alpine coniferous forests [23]. At the same time, climate change will increase the instability

of the agricultural ecosystem, leading to changes in the layout and structure of production. It will also further threaten the glacier and wetland ecosystems in the Qinghai Tibet Plateau and Northwest China [59]. Therefore, according to this trend, future research and natural resource conservation and management should pay more attention to the ecosystem in such areas so as to minimize the negative effects of climate change on human well-being.
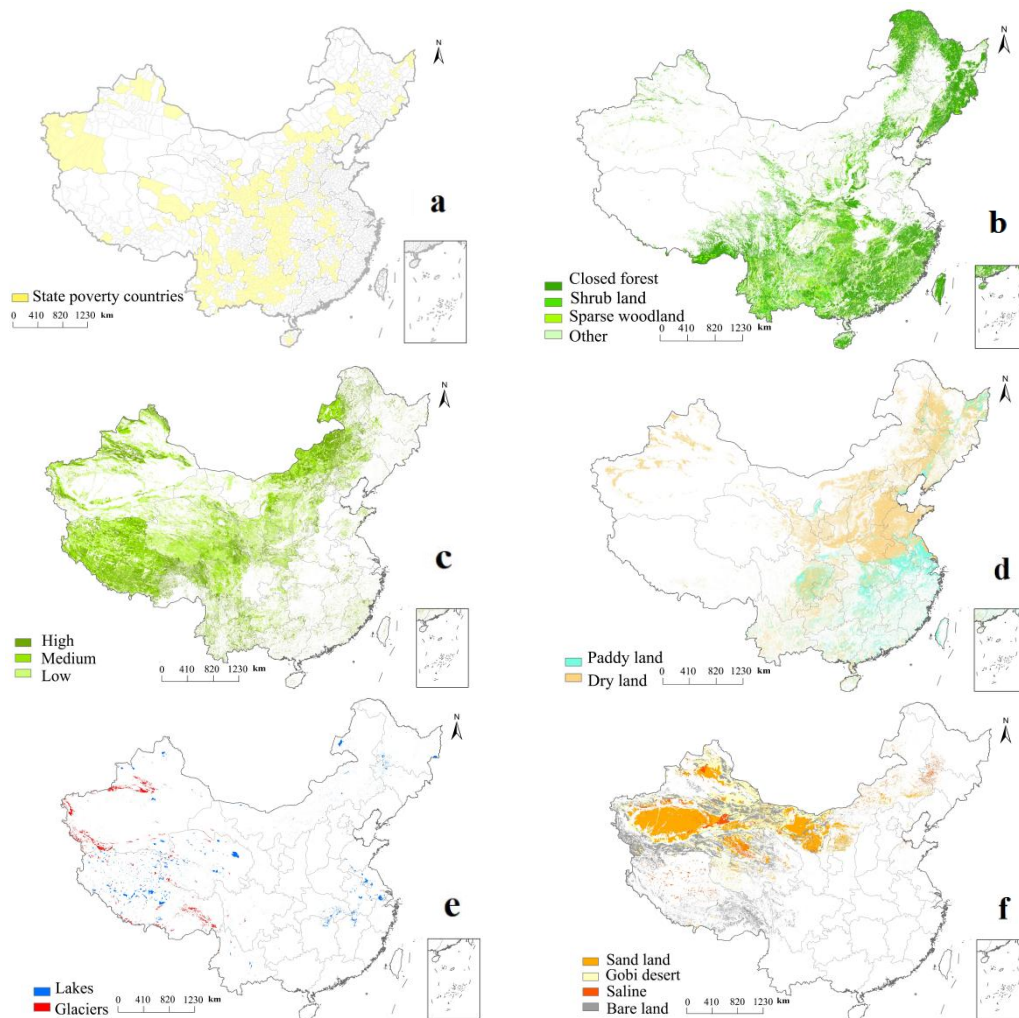

Figure 4. The distribution of state poverty counties in China (2012) (**a**); the distribution of forest ecosystems in China (**b**); the distribution of grassland ecosystems in China (**c**); the distribution of farmland ecosystems in China (**d**); the distribution of glacial and lake ecosystems in China (**e**); the distribution of sand and bare land ecosystems in China (**f**). Land use and land cover data: Sourced from the Resource and Environmental Science Data Center of the Chinese Academy of Sciences (http://www.resdc.cn/ (accessed on 6 June 2020)); China's state poverty counties data: From the official website of the Leading Group Office of Poverty Alleviation and Development (of the State Council) (http://www.cpad.gov.cn/ (accessed on 6 June 2020)).

3.4. Ecosystem Services

Ecosystems provide a wide range of direct and indirect services, including provision, regulation, support, and cultural services, which are vital to human well-being [2,60]. Therefore, the impacts of climate change on species, populations, and ecosystems will profoundly affect ecosystem services. We found that the geographical distribution of climate change-sensitive areas is similar to the distribution of state poverty counties in China (Figure 4), which indicates that climate change will affect China's ecosystem services to a large extent, thereby threatening human well-being.

3.4.1. Provisioning Service

Provisioning services refer to the material products that people get from the ecosystem, such as food, freshwater, biofuels, and so on. Climate-induced changes in the provision of services may have a profound impact on the human economy and well-being [61]. For example, from 1980 to 2008, climate change has reduced China's wheat and corn yields by 1.27% and 1.73%, respectively. Meanwhile, the cost of drought resistance in China is expected to reach 500 billion yuan from 2010 to 2030.

The reduction of supply will have a negative impact on regional economic development. In terrestrial ecosystems, plantation construction has brought huge ecological benefits to regional development [62], but climate change is changing the water supply of the basin [63,64], such as the Loess Plateau [65]. In the Shiyang River Basin in the arid region of Northwest China, the decrease of precipitation in the past 50 years has reduced the average annual flow by 64%, aggravating the shortage of surface water resources [66], further affecting agricultural production and reducing the yield and quality of crops [67]. In addition, in Yunnan–Guizhou Plateau, frequent rainstorms caused by climate change bring more soil and fertilizer into rivers and lakes, which aggravated the accumulation of pollutants, caused agricultural non-point source water pollution [68], and increased the cost of sewage treatment.

In the marine ecosystem, the global marine capture fisheries supply the world with approximately 80 million tons of protein and micronutrient-rich food for human consumption per year [69,70]. In addition, these fisheries support global economies with an estimated annual gross revenue of $80–85 billion [70]. However, the observations, experiments, and simulation models show that climate change would result in changes in primary productivity, shifts in distribution, and changes in the potential yield of exploited marine species, resulting in impacts on the economics of fisheries worldwide [70]. China's ocean is one of the marine ecosystems with the fastest warming rate in the world. Between 2003 and 2018, the surface temperature in the East China Sea increased by 0.04–1.2 °C [71], threatening the marine habitat of fish and affecting the stability of the marine ecosystem, This is closely related to global warming [72].

3.4.2. Regulating Services

Biodiversity and ecosystems provide important regulating services, such as climate regulation, carbon storage, natural disaster control, and disease transmission control. Regulation services can maintain the smooth operation of various biological processes in nature. For example, forests provide a wide range of ecosystem services, including carbon storage, local climate regulation, etc. [73]. However, climate change is profoundly impacting the regulation services of ecosystems, because of the increase of temperature, water stress and disturbance, and the increase of fire frequency, carbon storage may be reduced in forests [56], and the ability to regulate services will be weakened. For China, forestry carbon sequestration is an important way to increase carbon sink at present and in the future. It is estimated that by 2030, the carbon dioxide emission reduction potential of the energy supply sector will reach about 4.5 billion tons, and that of afforestation and forest management will be about 492–811 million tons.

Ecosystems also regulate the distribution, abundance, and life cycle services of disease-carrying organisms [74]. For example, affected by climate change, the invasive Aedes mosquitoes, which spread diseases such as dengue fever, increases the risk of disease transmission. In China, climate factors and the East Asian summer monsoon have positive impacts on dengue fever outbreaks, while Guangdong, Guangxi, Fujian, and Yunnan are more susceptible to dengue fever [75].

The regulating services of China's marine ecosystem are also strongly affected by climate change. In the last 30 years, the sea level in China's coastal areas has generally fluctuated and risen. From 1980 to 2019, the rising rate was 3.4 mm/year, which was higher than the global average in the same period. In 2019, the sea level was 72 mm higher than that of the normal year [76]. In a word, seawater intrusion, soil salinization and coastal

erosion will damage coastal wetland, mangrove and coral reef ecosystems, and reduce the service function and biodiversity of coastal ecosystem [77]. Therefore, the public and government must pay attention to the impact of climate change on coastal ecosystem and actively put forward relevant adaptive strategies.

3.4.3. Supporting Services

Supporting ecosystem services refers to the basic process of maintaining ecosystem structure and function, includes ecosystem primary production, biogeochemical cycle, etc. For terrestrial ecosystems, the temperature sensitivity of decomposition of the enormous global stocks of soil organic matter (SOM) has recently received considerable interest [78]. Research shows climate warming is expected to increase soil carbon loss and change carbon and nitrogen balance in permafrost and most peatlands in high latitude areas [78]. It has been shown that large amounts of soil organic carbon (SOC) are stored in the permafrost regions of Qinghai Tibet Plateau (QTP), and the carbon pools there might play an important role in regional or global climate changes [79]. But in global climate change scenarios, SOC in permafrost regions becomes accessible to microbial degradation as permafrost degradation progresses [80]. Global warming has also had a serious impact on water ecosystems. Taking Taihu Lake of China as an example, when the temperature increased by 1.0 °C, the algae biomass increased by 0.145 times [81]. The higher the degree of eutrophication, the greater the impact of temperature on algal growth, which has negative effects on aquaculture, recreation and other activities [81]. The capacity of forests in sequestering carbon dioxide and releasing oxygen is closely related to photosynthetic and respiration rate [82]. In recent years, climate change has posed a great threat to China's forest supporting services because the continued rise in temperature will destroy this relationship [83]. This will make more big cities in China face the test of high temperature. In short, climate change is continuously affecting the supporting services of China's frozen soil, lakes, forests and other ecosystems, so scientists need to pay continuous attention.

3.4.4. Cultural Services

Cultural ecosystem services can be defined as the intangible benefits of human beings, biodiversity and ecosystems, includes spiritual, aesthetic, educational and recreational values [84]. Although cultural services are important for human well-being, it is still underestimated compared with other ecosystem services [85].

More and more studies have shown that ecosystem diversity and species richness are positively correlated with physical and mental health [86,87]. On the contrary, indirect economic losses caused by extreme events can have adverse social and psychological effects [88]. For example, in order to reduce the disaster risk caused by climate change, restore important ecosystem services and improve human well-being, China has implemented an ecosystem services protection and human development policy (the relocation and resettlement plan of Southern Shaanxi Province) [89]. For a household participating in the resettlement program, the upfront cost of relocation is much higher than the one-time subsidy payment from the government. Therefore, moving might not bring any net benefit to the households in the short term, on the contrary, it may cause adverse social psychological effects [89]. But in the long run, easy access to roads, transportation, education, communications, and markets would make households economically better off [89]. Therefore, it will bring positive social psychological impact.

In addition, natural landscape tourism, such as glacier viewing, has been carried out in many parts of China. However, with the continuous rise of temperature, the melting of glaciers in Western China has accelerated [24,57]. This change has not only brought losses to the ecosystem, but also brought huge losses to the cultural value of natural landscape.

4. Discussion

4.1. Improve Ecosystem Resilience and Reduce the Loss of Ecosystem Services

To create effective adaptation strategies, managers need to understand which regions and ecosystems are most at risk and why. We will discuss it from the following aspects.

To maintain biodiversity in ecologically vulnerable areas and minimize the loss of ecosystem services. For China, the impact of climate change on ecologically fragile areas (arid and semi-arid areas in the North, Hilly areas in the South, mountainous areas in the Southwest, Qinghai Tibet Plateau and land-water interface zones in the Eastern coastal areas) is particularly obvious. Since 1978, a number of major ecological restoration policies have been implemented in northern China, including the Three Norths Shelter Forest Program (TNSFP), Combating of Desertification Program (CDP), Natural Forest Protection Project (NFPP) [90]. However, the study found that the deep-rooted trees consume a large amount of soil moisture during growth, which may reduce groundwater level, causing a low survival rate for the planted trees and degradation of the original grassland vegetation, with negative consequences for biodiversity and ecosystem services. Thereby we need to strength the emphasis on natural restoration, pay attention to the tree structure configuration and improve the resistance to pests and diseases [91], to minimize losses in valuable ecosystem services [92].

Limiting invasive species spread can help maintain biodiversity, ecosystem function, and resilience [93]. The geographical distribution and density of alien species in China tended to decrease from the south and the east to the north and the west [40]. The simulation of the range change of invasive species in different climate scenarios and found that invasive alien plants may further expand into Northern China [42], Therefore, it will pose a great threat to climate sensitive terrestrial ecosystem (Agro-pastoral Ecotone in Northern China) [44]. We believe that understanding the geographic distribution and development trends of various invasive alien species is very important for Chinese decision makers, which can effectively improve the initiative to formulate relevant policies to minimize potential negative impacts. In addition, dialogue between scientists and policymakers also can help ensure that climate change mitigation does not exacerbate invasive species spread [94].

Expand and protect climate change shelters, retain valuable natural resources and improve ecosystem resilience. China has stepped up efforts to promote the construction of national parks. By 2020, China has approved the construction of 10 pilot national parks (Northeast Tiger and Leopard National Park, Giant Panda National Park, Qilian Mountain National Park, Three-River-Source National Park, Hainan Tropical Rainforest National Park, Wuyishan National Park, Shennongjia National Park, Pudacuo National Park, Qianjiangyuan National Park and Nanshan National Park), which covering more than 220,000 square kilometers. Integrate nature reserves into the scope of national parks, and unified management, overall protection and systematic restoration are implemented to promote the integration of habitat patches and enhance the integrity and authenticity protection of natural ecosystems, and enhance the ability to addressing climate change [95].

4.2. Update Technology and Artificial Intervention to Improve Adaptability

Human beings may need to adapt to climate change by updating technology and artificial intervention, and improve the adaptability to minimize the negative impact of climate change. In glacial ecosystems, in order to reduce the melting of the Muz Taw Glacier, the artificial snowfall experiment was conducted and found that artificial snow reduced the mass loss of the glacier by 40% [96].

In order to alleviate the drought and water shortage in the Qilian Mountains, in 2017, the Northwest Regional Weather Modification Project-Qilian Mountain Topographic Cloud Artificial Precipitation (Snow) Technology Research Project was launched and achieved positive benefits. The vegetation coverage of Qilian Mountain was the highest since 2000. In recent ten years, the water storage of major lakes has increased, and the total snow area has increased compared with the same period in previous years [97].

In coastal ecosystems, natural infrastructure is used more to increase the resilience of coastal communities. For example, the implementation of the Shenzhen Bay Land Reclamation Project (SZBLRP) resulted in significant deposition in the SZIB, which accelerated the spread of mangroves and counterbalanced the negative effect of sea level rise [98], therefore, it is beneficial to enhance the barrier function of mangroves to protect the coastline from erosion [99,100]. In comparison to traditional grey (e.g., seawall) approaches, SZBLRP can be cheaper and survive extreme events better than traditional infrastructure.

In the farmland ecosystem, Chinese farmers have been adapting to climate change in the past few decades. With future climate warming, the farmers have a wider sowing window in spring and can select cultivars with long growing season duration and frost-tolerance to mitigate detrimental effects of a future warmer climate [101].

4.3. Strengthen Government Intervention and Management

National agencies that manage natural resources are increasingly considering climate change impacts in their management plans (Table 1). In 2008, the Ministry of Ecology and Environment of China incorporated climate change into the national sustainable development strategy and strengthened international cooperation in the fields of agriculture and animal husbandry, forestry, natural ecosystem, water resources, etc. In 2014, in order to protect important ecological function areas, sensitive and vulnerable areas of land and marine ecological environments in China, the Red Line of Ecological Protection was written into the environmental protection law of the people's Republic of China for the first time. In 2015, in response to the impact of climate change on the habitat of species, Qinghai Three River Source Ecological Protection Project was launched [102]. In 2020, the Ministry of Natural Resources of China proposed to carry out the protection and restoration of mangroves on the "World Ocean Day and National Ocean Day" to tackling the impact of climate change on China's coastal ecosystems [103]. Despite progress, institutional barriers such as a focus on near-term planning, fixed policies and protocols, jurisdictional restrictions, and an established practice of management based on historical conditions remain a challenge [104].

Table 1. Examples of China's response to climate change.

Government Department	Government Documents	Time
Office of the National Climate Change Coordination Group	National Communication on Climate Change of the People's Republic of China (I)	2004
Ministry of Science and Technology, China Meteorological Administration, Chinese Academy of Sciences, etc.	China's National Assessment Report on Climate Change (I)	2007
Ministry of Science and Technology, National Development and Reform Commission, etc.	China's Special Science and Technology Action on Climate Change	2007
National Development and Reform Commission, Ministry of Science and Technology, etc.	China's National Climate Change Program	2008
Office of the National Climate Change Coordination Group	National Communication on Climate Change of the People's Republic of China (II)	2012
Ministry of Science and Technology, China Meteorological Administration, Chinese Academy of Sciences, etc.	China's National Assessment Report on Climate Change (II)	2011
Ministry of Science and Technology, Chinese Academy of Sciences, Chinese Academy of Engineering, etc.	China's National Assessment Report on Climate Change (III)	2014
Ministry of Science and Technology, Chinese Academy of Sciences, Chinese Academy of Engineering, etc.	China's National Assessment Report on Climate Change (IV)	2020
Office of the National Climate Change Coordination Group	National Communication on Climate Change of the People's Republic of China (III)	2018
China Meteorological Administration	Blue Book on Climate Change in China	2020

Based on this, China put forward the idea that mountains, rivers, forests, fields, lakes, and grasses constitute a community of life. With the help of advanced technologies such as spatial information, artificial intelligence, and big data, we need to build an efficient

natural resources supervision system. On the basis of national main function areas and ecological function division, strengthen natural resources system evaluation and early warning, and build a bridge from nature to society, from science to decision-making. The scientific management of natural resources will effectively improve the country's ability to respond to the threat of future climate change while minimizing the long-term negative impact of climate change.

5. Conclusions and Future Prospects

In general, climate change has a profound impact on China's ecosystem in many aspects, and also has an impact on China's biodiversity, ecosystem services, and human well-being. Therefore, it will bring severe challenges to the management of China's natural resources. Our main conclusions and future prospects are as follows:

(1) Ecosystem: We found that the temperature has risen significantly in the vast area of China, and the average annual precipitation also showed an increasing trend, which would have an impact on the ecosystem. In recent years, the frequency of extreme events (droughts, rainstorms, fires, etc.) has increased in China. We found that extreme events may bring more significant impacts on the ecosystem in the short term, especially in natural ecosystems and agricultural ecosystems. Therefore, we need to pay more attention to the impact of extreme events on China's sensitive and fragile terrestrial ecosystems in the future. At the same time, we predict that climate change may aggravate biological invasion to the North and Northwest. Therefore, we still need to learn from the international biological invasion database and strengthen international cooperation, build and improve China's biological invasion database, and speed up the legislation of biosafety laws.

(2) Biodiversity: A large number of studies have proven that plant phenology has shown an obvious advance trend in recent decades in most of China's land, and the growing season is continuously extending, which has brought great challenges to the management of agricultural resources. Therefore, the farmers have a wider sowing window in spring and can select cultivars with long growing season duration and frost tolerance to mitigate the detrimental effects of a future warmer climate.

(3) Ecosystem services: Our analysis suggests that the impact of climate change on most types of services in China is mainly negative. The favorable aspects involve the expansion of some crops, which can provide more products for human beings, while the unfavorable aspects may affect the yield and quality of food, water resources, human settlements, and other aspects. Therefore, it is necessary to vigorously improve the ecosystem service functions of remote areas to ensure the livelihood and well-being of local people in the future.

(4) Natural resource management: Climate change challenges and opportunities co-exist, and it is yet to be realized to integrate climate change into natural resource management. Climate change can have a significant impact on the effectiveness of management decisions targeted at sustaining ecosystem service provision, but implementing actions on the ground can be difficult due to lack of funding and time, negative public perceptions, and difficulty transferring science between researchers and policymakers. Meanwhile, pose challenges to natural resource management in government departments. Moving forward, it is necessary to evaluate and research the effectiveness of typical demonstration cases and guide climate-smart management.

(5) Positive impacts and actions of climate change: We are facing due to climate change about ecosystems challenges (negative impacts). Meanwhile, there are following positive impacts on the ecosystem due to climate change: For example, the regional "warming and wetting" caused by climate change in recent years has accelerated the restoration of ecosystems such as forests, grasslands and deserts; Climate change is a global issue that requires joint governance by multiple jurisdictions and countries. Therefore, climate change can promote international cooperation and strengthen links among countries and build a community of common destiny for all mankind; It can

improve human resistance to climate change and promote the progress of science and technology. At the same time, it will also accelerate the rise of scientific research such as ecosystem services and ecosystem management.

(6) What specific topics should scientists particularly put more efforts into? We believe that in the context of climate change, scientists from various countries need to further strengthen communication and exchange, and constantly expand new research fields, research methods, and ideas. According to our research summary, future scientists should pay special attention to topics such as climate change and food security, climate change and biodiversity, climate change and global diseases, ecosystem change and human well-being, ecosystem services and management, and pay attention to the combination of multiple disciplines.

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