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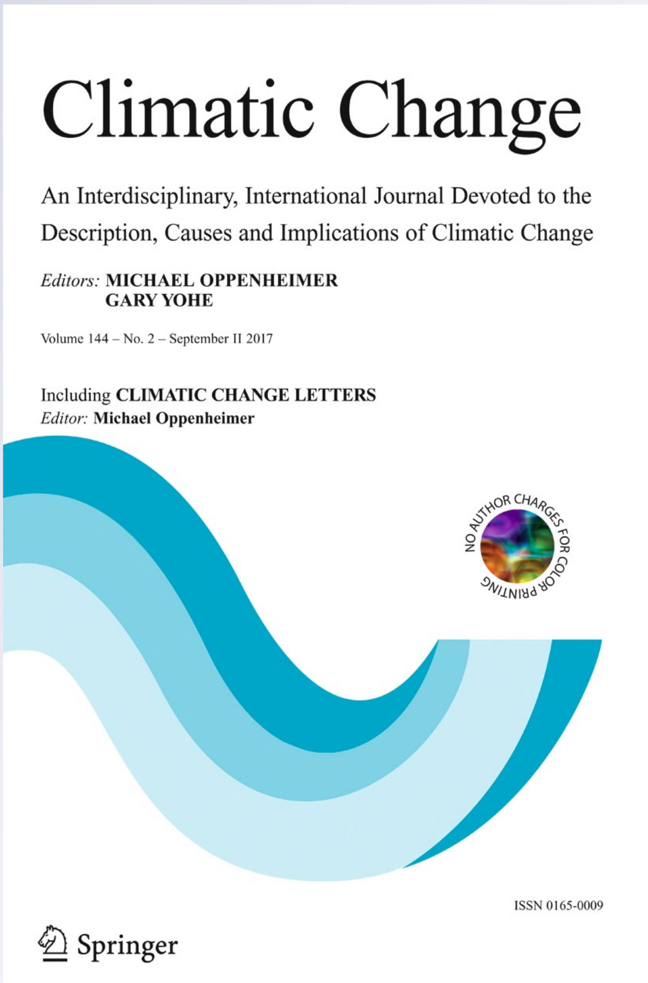
Climatic Change
An Interdisciplinary, International Journal Devoted to the Description, Causes and Implications of Climatic Change

ISSN 0165-0009
Volume 144
Number 2

Climatic Change (2017) 144:303-316
DOI 10.1007/s10584-017-2044-7



Springer

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Spatial conservation prioritization for dominant tree species of Chinese forest communities under climate change

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Received: 5 April 2016 / Accepted: 30 July 2017 / Published online: 12 August 2017

Abstract Climate change is likely to threaten forests in future. Because dominant tree species (DTS) play central roles in stabilizing forest ecosystems, to effectively protect forests, we need to pay more attention to the protection of DTS. Furthermore, we need to integrate potential impacts of climate change into conservation efforts of DTS for improving forest protection. We utilized species distribution modeling, coupled with conservation planning, to establish climate-informed conservation prioritization for 136 taxa of DTS in three forest types (broad-leaved forests, mixed broadleaf-conifer forests, and coniferous forests) in China. We considered both current and future distributions and assessed the ability of existing nature reserves in China to protect forests based on these DTS. Regions with the highest climate-informed conservation prioritization were distributed in the southern, southwestern, and northeastern regions of China. There was a small gap between existing nature reserves and predicted conservation prioritization areas for conserving forests: the proportions of overlap between existing reserves and areas prioritized under climate change scenarios were 87.8, 95.7, and 80.4% for broad-leaved forests, mixed broadleaf-conifer forests, and coniferous forests, respectively. Even so, we need to increase the number and/or area of nature reserves to protect coniferous forests in Tibet, Sichuan, and Yunnan, and broad-leaved forests in Guizhou, Guangxi, Hu'nan, Yunnan, and Sichuan. Our results demonstrate the importance of conservation planning under climate change, taking both current and future distributions of plant species into consideration. Nature reserves should develop different management strategies for different forest types.

Electronic supplementary material The online version of this article (doi:10.1007/s10584-017-2044-7) contains supplementary material, which is available to authorized users.

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1 Introduction

The ongoing, global climate change may greatly affect the structure and function of forests globally (Dale et al. 2001). It may weaken the stability of forest ecosystems and thus increase the vulnerability of forest biodiversity (Fang 2000; Willis et al. 2008; Bernazzani et al. 2012; Hanewinkel et al. 2013). In China, due to the large population and the fast economic development, forest resources are increasingly limited and a great effort has been spent to protect forests (Hou 2001). To effectively conserve these valuable forest resources in China, we need to plan management strategies taking potential impacts of climate change into consideration (Margules and Pressey 2000; Pressey et al. 2007; Li et al. 2016). So far, however, such management strategies are still lacking.

Across the globe, protected areas covered about 12.7% of the world's terrestrial and inland water areas (http://www.wdpa.org/). In China, 2740 nature reserves have been established by 2016 (www.datacenter.mep.gov.cn). Although the number of Chinese nature reserves rise persistently, the total area of nature reserves increases only slowly (Guo and Cui 2015). Furthermore, when nature reserves were established, impacts of climate change were rarely considered. Previous studies have suggested that climate change may decrease the ability of nature reserves to protect species and communities of forests (Araújo et al. 2011; Yu et al. 2014). For instance, climate change may threaten the conservation of plant species diversity in forests of the European nature reserves (Araújo et al. 2011; Proctor et al. 2011; Bernazzani et al. 2012) and weaken the ability of Chinese nature reserves to protect endangered tree species (Yu et al. 2014). Thus, the current number and area of nature reserves may be insufficient to support forest conservation (Yu et al. 2014; Wan et al. 2016). We need to propose effective methods to protect forests and to increase efficacy of nature reserves for forest conservation.

To effectively protect forests, we need to pay more attention to the protection of dominant tree species (DTS), i.e., species with a large number and a high coverage, which are sometimes also the constructive species of forest communities (Hou 2001; Pitman et al. 2001; Barbier et al. 2008). This is because DTS play a key role in the stabilization of forests and the conservation of DTS supports the conservation of also all other species in the forests (Whittaker 1965; Hou 2001). However, an overexploitation of DTS in natural forests is still a common phenomenon in many regions of the world, which may reduce the stability of natural forests and thus threaten forest species diversity (Canadell and Raupach 2008; Prieto-Torres et al. 2015). Climate change may also negatively affect DTS (Parmesan and Yohe 2003; Gebrekirstos et al. 2008), reduce forest stability, and accelerate the loss of plant species diversity in forests (Prieto-Torres et al. 2015). Thus, the conservation of DTS is of central importance for maintaining forest stability under climate change (Canadell and Raupach 2008), and integrating impacts of climate change into conservation planning is urgently needed for protecting forests (Bernazzani et al. 2012). So far, however, conservation planning rarely accounts for forests based on DTS under climate change.

We assessed potential impacts of climate change on the spatial distribution patterns of DTS in China and integrated such impacts into the conservation prioritization for forests. Specifically, we addressed two questions: (1) Where are the regions of conservation prioritization for forests under climate change? (2) Are the current nature reserves in China sufficient for the conservation of forests under climate change? To address these questions, we utilized species distribution modeling (SDM) coupled with conservation planning to establish climate-informed conservation prioritization for 136 taxa in three forest types (broad-leaved forests, mixed broadleaf-conifer forests, and coniferous forests) in China. We considered the distributions of DTS in the current as well as in four future greenhouse gas concentration scenarios (RCPs 2.6, 4.5, 6.0, and 8.5). Furthermore, we assessed the ability of existing nature reserves to protect the forests based on these DTS and proposed management suggestions for the effective conservation of forests.

2 Materials and methods

2.1 Study area

The study area comprised all parts of China, characterized by a higher altitude in western regions than in eastern regions, a continental monsoonal climate and considerable climatic variation (Hou 2001). The total area of national forests is 2.08×10^6 km^2, covering 21.63% of the area of mainland China (Fig. S1; Hou 2001). China consists of 34 provincial regions (for simplicity, Hong Kong was also considered a provincial region in this study). Data for the cities Beijing and Tianjin and data for Hebei Province were combined, as were data for Shanghai with Zhejiang Province, Chongqing with Sichuan Province, and both Hong Kong and Macau with Guangdong Province (Axmacher and Sang 2013). The forest types include broad-leaved forests, coniferous forests and mixed broadleaf-conifer forests (Hou 2001).

The area and point maps of nature reserves in China were obtained from the World Database on Protected Areas (WDPA; http://www.wdpa.org/; the detailed information in Fig. S2; Li et al. 2015). We collected the WDPA data of November 2016, representing the complete nature reserves of China. This data includes 2155 nature reserves (the total area 1,598,470.5 km^2), covering 17.1% of the land area of China (Fig. S2; http://www.wdpa.org/). Based on the list issued by the Chinese Ministry of Environmental Protection in November 2016, the current number of nature reserves is 2740 (http://www.zhb.gov.cn/stbh/zrbhq/qgzrbhqml/). The numbers of national nature reserves protecting forest ecosystems, wild plants, and animal species are 215, 17, and 121, respectively. The largest nature reserve is Sanjiangyuan, and its role is to protect the forests, meadows, wetlands, and animals. The discrepancy between the number of total nature reserves obtained from the WDPA and the list issued by the Chinese Ministry of Environmental Protection in November 2016 was 585.

2.2 Environmental data

We collected 29 environmental variables at the 10-arc-min resolution, including altitude (http://www.worldclim.org/), human footprint (http://sedac.ciesin.columbia.edu/wildareas/), eight soil variables (http://soilgrids.org/) and 19 climate variables (http://www.worldclim.org/). Data for the eight soil variables at the 0.5-arc-minute resolution were downloaded from SoilGrids1km (http://soilgrids.org/). Data for human footprint at the 0.5-arc-minute resolution were obtained from the Global Human Footprint Dataset of the Last of the Wild Project, Version 2, 2005 (LWP-2; HFD). This dataset was created from nine global data layers covering human population pressure (population density), land use and infrastructure (developed areas and land use/land cover), and human access (coastlines, roads, railroads and navigable rivers). Resampled analyses in ArcGIS 10.2 (Esri; Redlands, CA, USA) were used to translate the 0.5-arc-minute into the 10.0-arc-minute resolution for human footprint and soil variables, as summarized in Table S1. Environmental variables with Pearson's correlation coefficients and other variables between −0.8 and 0.8 were selected to eliminate the negative effect of multicollinearity on the adjustment of the SDM (Merow et al. 2013). These variables were closely related to the distribution and physiological performance of plants. Finally, we used 17 variables (one human footprint, eight climate, and eight soil variables) to model the potential distributions of the 136 taxa of DTS (Table S1; Hijmans et al. 2005).

Values of these eight climatic variables under future climate conditions were obtained via average values of the analogue datasets (for 2070–2099 and the 2080s) of three climate models (mohc_hadgem2, csiro_mk3_6_0, and gfdl_cm3), downloaded from the website of the International Centre for Tropical Agriculture (http://ccafs-climate.org). These three climate models include bio-geochemical components that account for the important fluxes of carbon among ocean, atmosphere, and terrestrial biosphere carbon reservoirs. In addition, these models are related to dynamical vegetation components (Lee and Wang 2014). RCPs 2.6 (mean, 270 ppm; range, 140–410 by 2100), 4.5 (mean 780 ppm; range 595 to 1005 by 2100), 6.0 (mean 1060 ppm; range 840 to 1250 by 2100), and 8.5 (mean 1685 ppm; range 1365 to 1910 by 2100) were selected to represent the scenarios from low to high greenhouse gas concentrations (http://www.ipcc.ch/report/ar5/). To emphasize the impact of climate change, our projections retained non-climatic variables unchanged, with only the climate variables changing. Otherwise, the modeling exercise would be complicated by interactions of biotic and abiotic factors (Belgacem and Louhaichi 2013).

2.3 Study species and occurrence data

DTS of forests in China were identified based on Hou (2001). Forest communities in China were named and mapped based on DTS in *The Vegetation Atlas of China* that was generated from data of robust field investigation and includes accurate and detailed information on the distribution of DTS. Based on Hou (2001), we checked detailed location and habitat descriptions of the DTS, extracted vegetation distribution information, and compiled a 0.5-arc-minute pixel map of China. Occurrence localities within 0.5-arc-minute pixels obtained from *The Vegetation Atlas of China* were integrated with the locations of species within 10-arc-minute grid cells (16 km at the equator), and duplicate occurrence records were removed to avoid georeferencing errors and overestimation of predictive power of models due to spatial correlations (Boria et al. 2014). The coordinates of occurrence locations and data regarding the distribution of viable species populations in their communities were obtained from Hou (2001).

DTS exhibited long-term, stable climatic niches. To remove apparent errors, all occurrence locations were checked using ArcGlobe 10.2 and ArcGIS 10.2 (Esri; Redlands, CA, USA) to determine whether they were distributed in forests and in regions with reasonable elevation ranges (Hurlbert and White 2005). Furthermore, the data of occurrence locations was consistent with the regional description of *The Chinese Virtual Herbarium* (CVH; www.cvh.org.cn) and *The Atlas of Woody Plants in China* (Fang et al. 2011). Finally, the DTS should have at least 50 occurrence locations after verification and should also be native to China. Thus, we selected 136 taxa of DTS (http://frps.eflora.cn/; Table S2). These 136 taxa were classified into three groups based on forest types, i.e., broad-leaved forests, mixed broadleaf-conifer forests, and coniferous forests, as inferred from Hou (2001) (Table S2). Occurrence locations of the DTS were used as geographic input for SDM.

2.4 Modeling potential species distributions

Maxent ver. 3.3.3k was used to model spatial distributions of the 136 taxa of DTS in the present day and the four future greenhouse gas concentration scenarios (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5; Phillips et al. 2006). The distribution probability ranged from 0 (the lowest probability) to 1 (the highest probability; Phillips et al. 2006). Maxent offers powerful tools to model the distributions of tree species under climate change based on occurrence locations of species and associated environmental variables (Phillips et al. 2006). It has revealed robust performance at small sample sizes (e.g., 50 records in this study; Merow et al. 2013).

The main sets of parameters for Maxent were as follows: (1) the regularization multiplier (beta) was set to 1.5 to produce a smooth, general response that could be modeled in a biologically realistic manner (Merow et al. 2013); (2) the maximum number of background points was set to 10,000 (Renner and Warton 2013), and the background points were selected from the areas of the occurrence location intensity in China (Phillips et al. 2009); (3) a 10-fold cross-validation approach was used to remove bias with respect to recorded occurrence points (Merow et al. 2013). Models were run ten times in total (Merow et al. 2013). In each run, 90% of all records were randomly selected and used for model training, while the remaining 10% were used for model testing. The contribution of bioclimatic variables to the distribution of DTS was tested using the jackknife method included in the Maxent software (Merow et al. 2013). Variables were considered highly important if the percentage contribution accounted for at least 15% of the observed variance in the species distribution model (Oke and Thompson 2015). We generated hotspots of DTS distributions under the current and the four future greenhouse gas concentration scenarios by stacking the potential species distribution maps based on all taxa, as well as the DTS of each of the three forest types (broad-leaved forests, mixed broadleaf-conifer forests, and coniferous forests).

We used the following methods to test the predictive power of the utilized models. First, the predictive performance of Maxent models was evaluated via the area under a receiver operator characteristic curve (AUC), and only models with an AUC value above 0.7 were used (Phillips et al. 2006). Second, the test of predictive power was performed with spatially segregated datasets of occurrence locations to avoid confounding effects of data autocorrelation (Bahn and McGill 2013). We first detected the 25th, 50th, and 75th percentile longitude of all occupied locations, and then divided the dataset into four parts along these lines, i.e., numbered 1–4 from the west to the east for all 136 taxa. Parts 1 and 3 were combined as training data to run the models, and parts 2 and 4 were combined as test data to assess them. Then, we switched the roles of these four parts and finally averaged over the two sets of model results (Bahn and McGill 2013). We used Somer's D, derived from the average AUC of models from the two segregated datasets as $D = 2 \times (\text{AUC} - 0.5)$, to represent a simple standardization of AUC for each taxon (Bahn and McGill 2013). We utilized linear regression analysis to calculate the relationship between the results of models based on the whole datasets of occurrence locations and based on spatially segregated datasets. The models based on the whole datasets of occurrence locations were useful if R^2 values were large (Bahn and McGill 2013). Third, we used a binomial test based on the training omission rate to evaluate the predictive power of Maxent modeling (Phillips et al. 2006). The training omission rate is the proportion of the training occurrence locations laid in pixels of predicted absence (Phillips et al. 2006). The binomial probabilities were based on 10 common thresholds except for minimum training presence defaulted by Maxent, and we calculated the average training omission rates based on 10 common thresholds per taxon (Phillips et al. 2006). Although the training omission rate may also be insufficient, a low omission rate below 17% per taxon is a necessary precondition for a good model (Phillips et al. 2006).

2.5 Spatial prioritization of conservation

The software Zonation (http://cbig.it.helsinki.fi/software/) was used to develop plans to conserve species richness as well as specific target species, incorporating the impact of climate change (Proctor et al. 2011). Zonation is commonly used to generate a spatial conservation framework to prioritize large-scale conservation projects that involve numerous species or to capture the most meaningful areas to conserve specific target species based on feature maps (Lehtomäki and Moilanen 2013). These feature maps included species distributions, species richness, and suitable habitats (Lehtomäki and Moilanen 2013). In this study, we used the reverse heuristic algorithm in Zonation to establish priority conservation areas for DTS. The highest priorities for conservation within the DTS distributions were confirmed by identifying the top-ranked pixels subsequent to computation.

The geographic distance between current and future distributions of each DTS was minimized, and the influence of climate change on species distributions was considered when selecting potential sites for reserves (Carroll et al. 2010). The input maps of the Zonation software were the current and future distributions of each species as assessed by the Maxent value of each pixel. The current distributions were used as input feature maps, and the four future distributions (RCP 2.6, RCP 4.5, RCP 6.0, and RCP 8.5 greenhouse gas concentration scenarios) were used as the input uncertainty maps for the Zonation software (Carroll et al. 2010; Wang et al. 2015). The distributions of target species in the current and in each of the four future scenarios were equally weighted as Zonation inputs (Carroll et al. 2010; Wang et al. 2015). The output was thus only one map of spatial conservation prioritization for each species (Carroll et al. 2010; Adams-Hosking et al. 2015; Wang et al. 2015).

We applied the core-area Zonation solutions (Proctor et al. 2011; Lehtomäki and Moilanen 2013) to optimally capture areas of the potential distribution of DTS at each removal step. The "warp factor" was set to 10 (i.e., the 10 worst pixels were removed at each iteration) to maximize analysis speed, while maintaining output reliability (Proctor et al. 2011). Default settings were used for "edge removal" (i.e., pixels were removed preferentially from the edges of species distributions; Proctor et al. 2011). Pixel areas with Zonation ranks exceeding 0.9 were extracted for each species (Carroll et al. 2010; Proctor et al. 2011). Thus, a pixel map of climate-informed conservation prioritization was obtained for each species. Then, the maps of species were stacked into a single map of climate-informed conservation prioritization based on DTS of each of the three forest types (broad-leaved forests, mixed broadleaf-conifer forests, and coniferous forests), and pixel values from the map were used as an index to evaluate conservation prioritization of these species.

Based on Target 4 of the Global Strategy for Plant Conservation (http://www.cbd.int/gspc/), it is necessary to protect at least 15% of each targeted ecological region, via effective management and/or restoration. As shown by the map of Olson et al. (2001) (http://www.worldwildlife.org/biomes), the Chinese ecoregions can be combined into three main forest ecological regions: tropical and subtropical moist broadleaf forests, temperate broadleaf and mixed forests, and temperate conifer forests (Olson et al. 2001). Consequently, we evaluated the conservation prioritization areas for DTS of broad-leaved forests based on tropical and subtropical moist broadleaf forests, for DTS of mixed broadleaf-conifer forests based on temperate broadleaf and mixed forests, and for DTS of coniferous forests based on temperate conifer forests (Olson et al. 2001). We used 15% of each of the three forest ecological regions (i.e., the target protection proportion for species with high priority) as the conservation prioritization areas without artificial surfaces and associated areas (urban areas >50%) based on the GlobCover land cover map (Arino et al. 2012). Thus, we obtained a Chinese map of the conservation prioritization areas for all 136 taxa based on the three forest types.

We assessed the proportion of conservation prioritization areas that overlapped with areas of existing nature reserves in China for DTS of each of the three forest types. Conservation prioritization areas for DTS were assessed based on pixel number. At provincial scale, we summarized the pixels of conservation prioritization areas in each provincial region and those of existing nature reserves that belonged to each provincial region. We used ArcGIS 10.2 and ArcGlobe 10.2 (Esri; Redlands, CA, USA) to check the number of pixels of conservation prioritization areas based on the locations of nature reserve points and the possible border of nature reserves. We determined whether other nature reserves without WDPA covered the pixels of conservation prioritization areas using ArcGlobe 10.2 (Esri; Redlands, CA, USA). We further calculated the proportion of conservation prioritization areas that overlapped with existing nature reserves for each region and for each of the three forest types. Finally, we determined the key nature reserve to support the conservation of DTS under climate change based on the proportion of conservation prioritization areas that overlapped with individual nature reserves in each of the three forest types.

3 Results

All the models of potential species distribution had AUC values above 0.7 for both the training and the test data; Somer's *D* values were above 0.7 for both the training and the test data, and training omission rates was smaller than 17% (Table S2). Furthermore, the modeled distributions of DTS based on the whole dataset of occurrence locations were consistent with the distributions based on spatially segregated datasets (all $R^2 > 0.85$; Table S2). These results indicated that the models had good discriminatory power. Among the eight bioclimatic variables, annual precipitation contributed the greatest to the spatial distributions of DTS using the jackknife method included in the Maxent software (mean ± SE 29.0 ± 1.6% for all 136 taxa; 30.6 ± 2.1% for taxa of broad-leaved forests, 27.4 ± 7.1% for taxa of mixed broadleaf-conifer forests and 30.0 ± 2.4% for taxa of coniferous forests; Tables S3 and S4). Temperature seasonality explained more than 15% of the variance in the distribution of the all the DTS, and its contribution was 16.2 ± 1.2%; Tables S3 and S4). Human footprint had a large contribution to the distributions of only *Abies delavayi* var. *motuoensis* (18.5%; Table S3), and the other DTS could not be affected by human footprint (Table S3).

Considering all 136 taxa of DTS (i.e., those of all three forest types), the hotspots of climate-informed conservation prioritization were distributed in the southern, southwestern, and northeastern regions of China, mainly including Heilongjiang (pixel number 500), Jilin (400), Yunnan (253), Guizhou (222), and Guangxi (180) provinces (Figs. 1 and 2; Table S5). Of conservation prioritization areas, 90.5% overlapped with areas of existing nature reserves in China (Table S5). The provinces with the largest proportion of overlap between areas of conservation prioritization and nature reserves were Liaoning (99.1%), Jilin (97.8%), Heilongjiang (95.6%), Guizhou (93.2%), and Guangxi (91.7%; Fig. 2 and Table S5).

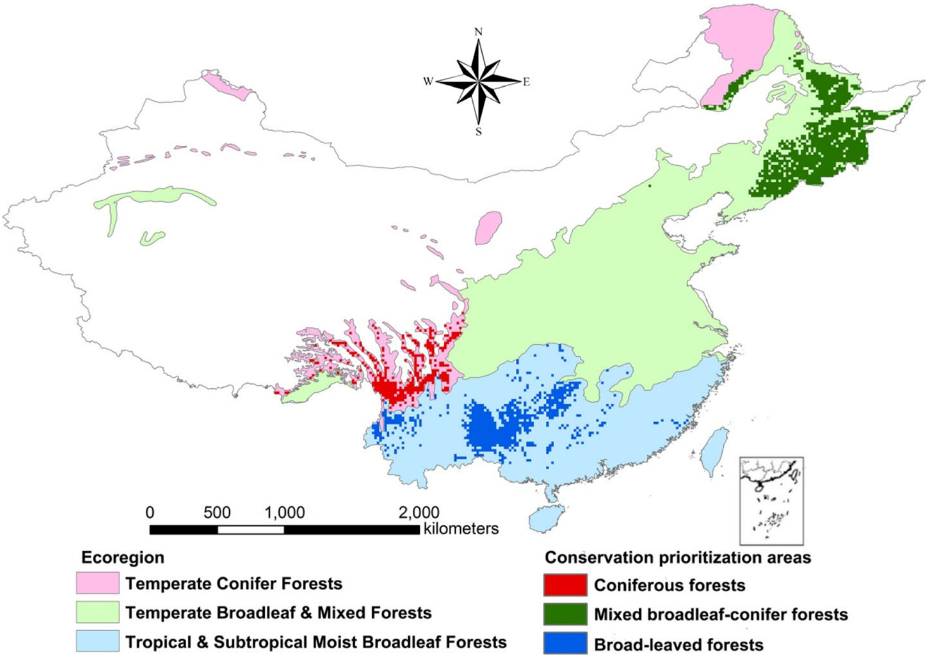

Fig. 1 Map of conservation prioritization areas for dominant tree species of broad-leaved forests, mixed broadleaf-conifer forests, and coniferous forests based on the ecoregions of China

For DTS of coniferous forests, conservation prioritization areas were located in the southwestern regions of China, including Tibet, Sichuan, and Yunnan (Figs. 1 and 2). The total proportion of overlap between areas of conservation prioritization and nature reserves in China was 80.4% (Table S5). The region with the largest proportion of overlapping area between existing nature reserves and conservation prioritization areas were Sichuan (93.0%) and Yunnan (90.9%), and the region with the lowest proportion of overlapping area was Tibet (39.5%; Fig. 2 and Table S5). Baimaxueshan (pixel number 191), Gaoligongshan (185), and Wolong (137) Nature reserves had the largest overlap areas with conservation prioritization areas.

For DTS of mixed broadleaf-conifer forests, conservation prioritization areas were distributed in northeastern China, including Heilongjiang, Liaoning, Jilin, and Inner Mongolia. The proportion of overlap between areas of conservation prioritization and nature reserves in China was 95.7% (Figs. 1 and 2). Heilongjiang, Liaoning, and Jilin had the largest proportion of overlapping area between existing nature reserves and conservation prioritization areas (Heilongjiang 95.6%; Liaoning 99.1%; Jinlin 97.8%; Fig. 2 and Table S5), while Heibei had the lowest proportion (0%; Fig. 2 and Table S5). The nature reserves with the largest conservation prioritization areas were Songhuajiangsanhu (pixel number 96), Changbaishan (79), and Ku'erbin (72).

For DTS of broad-leaved forests, conservation prioritization areas were distributed in the southern and southwestern regions of China. These provincial regions included Yunnan, Guangxi, Guizhou, and Hu'nan (Figs. 1 and 2). The proportion of overlap between areas of conservation prioritization and nature reserves in China was 87.8% (Table S5). Guangxi and Guizhou had the highest proportion of overlap in broad-leaved forests (more than 90%), while

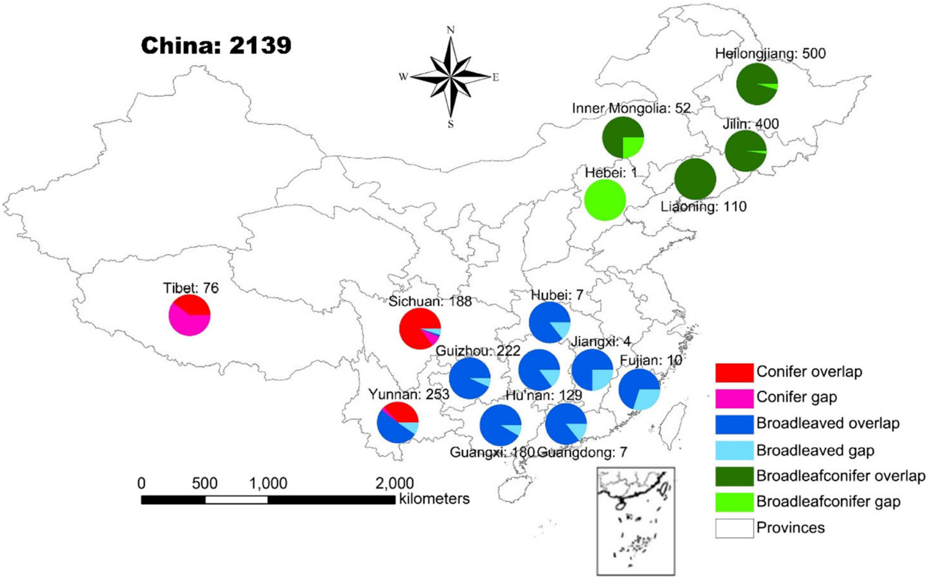

Fig. 2 Climate-informed conservation prioritization areas and proportion of overlapping areas between existing and optimized nature reserves for dominant tree species of coniferous forests, mixed broadleaf-conifer forests, broad-leaved forests, and all three forest types combined for selected provinces of China. The number accompanying the pies shows the total area including all three forest types based on pixel number; overlap is the proportion of overlapping area between existing and ideal nature reserves; the gap is the proportion of non-overlapping area between existing and optimized nature reserves. Provinces without pies did not have areas of conservation prioritization. The total area of conservation prioritization in China is 2139

Sichuan had the lowest proportion (25%; Fig. 2 and Table S5). Dayaoshanshuiyuanlin (pixel number 185), Cangshanerhai (106), and Jiuwanshanshuiyuanlin (105) were important nature reserves for climate-informed conservation prioritization of DTS in broad-leaved forests.

4 Discussion

While China has established an extensive network of nature reserves to conserve forest species diversity (Guo and Cui 2015), climate change may result in a large gap between existing nature reserves and the distribution of forests, particularly endangered forest plants (Carnaval and Moritz 2008; Carroll et al. 2010; Proctor et al. 2011; Yu et al. 2014) and inevitably challenge the effectiveness of such nature reserves (Carroll et al. 2010; Grumbine 2014). Therefore, climate change should be integrated into the conservation efforts of forests in China. Here, we developed a method to plan the conservation prioritization areas for forests based on DTS whose distribution data are sufficient and also easy to obtain from vegetation atlas of different regions (Hou 2001; Carnaval and Moritz 2008). Our study integrated impacts of climate change into conservation prioritization of forests, and such climate-informed conservation prioritization is valuable for maintaining forest stability and thus conserving forest species diversity according to the Global Strategy for Plant Conservation 2011–2020 (http://www.cbd.int/gspc/).

Considering all 136 taxa, the proportion of overlap between areas of conservation prioritization and existing nature reserves in China was 90.5%, indicating that existing nature reserves are sufficient for conserving forests. The gap of only 9.5% between existing nature reserves and conservation prioritization areas indicates that the current situations of forest protection by nature reserves in China are pretty good with regard to the impacts of future climate change. We have two suggestions for developing the reasonable network of nature reserves based on the conservation prioritization areas: (1) the establishment of botanical gardens (i.e., ex situ conservation) and scenic spots (i.e., in situ conservation) to guide forest conservation has been a good choice for the development of protected area networks (Hoegh-Guldberg et al. 2008; Grumbine 2014; Wan et al. 2016), and (2) forest type should be considered in the development of conservation strategies because climate-informed conservation prioritization differed between coniferous forests, mixed broadleaf-conifer forests, and broad-leaved forests.

4.1 Spatial conservation prioritization for coniferous forests

Conservation prioritization regions of coniferous forests were mainly distributed in southwestern China. These regions include rich plant diversity in China (Ren et al. 2013; Xu et al. 2015). In particular, the mountainous regions of southwestern China, including large areas of coniferous forests, are among the 34 biodiversity hotspots in the world (Myers et al. 2000; Hou 2001). Furthermore, these coniferous forests are important habitats for animal species throughout the world (Myers et al. 2000). Hence, such conservation prioritization areas could contribute to the conservation of both plants and animals in Chinese coniferous forests.

Special attention should be given to the Baimaxueshan Nature Reserve, which is an important conservation area for the forest resources of China and located in Tibet, i.e., a key region for the conservation of coniferous forests. Furthermore, one of the most important conservation functions of this nature reserve is to protect the populations of snub-nosed monkeys, an emblematic rare species (www.datacenter.mep.gov.cn). Hence, our climate-informed conservation prioritization can promote effective protection of endangered animals in coniferous forests. The establishment of long-term ecological monitoring of coniferous forests, associated forest succession, and habitat dynamics of animals in conservation prioritization areas is called for (Gebrekirstos et al. 2008; Bernazzani et al. 2012). The altitude factors need to be considered for the conservation planning of forests in southwestern China (Zhang et al. 2014). For example, the west mountains of Sichuan and the foothills of Tibetan mountains should be expected to create a barrier to dispersal and establishment by tree species counteracting the climatic shift (Hou 2001; Zhang et al. 2014). Considering the west edge of China, we need to establish new nature reserves in Tibet, Sichuan, and Yunnan for increasing the habitat ranges of plants and enhancing the corridor connectivity of animal habitats based on Fig. 1.

4.2 Spatial conservation prioritization for mixed broadleaf-conifer forests

Conservation prioritization regions of mixed broadleaf-conifer forests were distributed in northeastern China, including Heilongjiang, Liaoning, Jilin, and Inner Mongolia, and covered the mountainous regions of northeastern China, including the Changbai Mountains and the Xiaoxing'an Mountains. Our climate-informed conservation prioritization could help the decision-makers reach the conservation goal of mixed broadleaf-conifer forests according to the Global Strategy for Plant Conservation 2011–2020 (http://www.cbd.int/gspc/). Forest resources are rich in these mixed broadleaf-conifer forests in northeastern China (Yu et al. 2011).

Cross et al. (2012) proposed a tool to incorporate climate change into natural resource management and used this tool to establish conservation management priorities for the Greater Yellowstone Ecosystem. Similarly, considering the sufficient conservation of mixed broadleaf-conifer forests in nature reserves, we need to introduce a management program to effectively conserve and sustainably utilize DTS in mixed broadleaf-conifer forests in northeastern China. For instance, the Changbaishan Nature Reserve in Jilin plays an important role in the protection of DTS (Yu et al. 2011). It would be most beneficial to establish conservation areas for endangered DTS such as *Pinus koraiensis* and *Chosenia arbutifolia* and to take measures to ensure conservative utilization of DTS in the Changbaishan Nature Reserve (Yu et al. 2014). Although mixed broadleaf-conifer forests provide rich forest resources for sustainable economic development, we need to ensure sustainable utilization of natural resources coupled with the effective conservation of DTS in the face of climate change (Yu et al. 2011, 2014; Bernazzani et al. 2012; Hanewinkel et al. 2013). Hence, we suggest that balancing the relationship between conservation and sustainable utilization of natural resources in mixed broadleaf-conifer forests should be considered for the conservation of such forests under future climatic change.

4.3 Spatial conservation prioritization for broad-leaved forests

Conservation prioritization regions of broad-leaved forests were mainly distributed in southwestern and southern China, particularly in Yunnan, Guangxi, Guizhou, and Hu'nan. Broad-leaved forests in China are rich in plant diversity (Hou 2001; Legendre et al. 2009), and thus identifying conservation prioritization regions of broad-leaved forests is important for the conservation of plant diversity in China. Ecological niches of some DTS in Yunnan, Guangxi, and Guizhou are markedly narrow; therefore, climate change might easily and severely damage these plants in broad-leaved forests (Hou 2001). Because temperature seasonality and annual precipitation play an important role in the distributions of DTS, special attention should be focused on extreme climate events to reduce their potentially negative effects on broad-leaved forests in key nature reserves, e.g., Dayaoshanshuiyuanlin, Cangshanerhai, and Jiuwanshanshuiyuanlin (Gebrekirstos et al. 2008). Furthermore, the network of nature reserves needs to be improved in Guizhou, Guangxi, Hu'nan, Yunnan, and Sichuan to specifically account for conservation uncertainty the results from climate change (Bernazzani et al. 2012).

4.4 Limitations

It is important to note, however, that the predictive modeling of this study had limitations. First, our study did not fully consider the dispersal ability of the target species and the dynamic changes of forest ecosystems when subjected to climate change. The evolution of forest communities is complex, particularly under climate change. Hence, future studies need to integrate the assembly of also other plant species such as accompanying species. Secondly, the border data of nature reserves could not cover the current network of nature reserves in our study, and this may result in an underestimation of the protective ability of nature reserves. Future studies should take our introduced more accurate ranges of conservation prioritization areas into account. Thirdly, soil conditions, human disturbance, plant competition, and other factors also influence the presence of species in the future and probably constitute additional barriers to the distribution of the target species. However, since the climate is considered primarily responsible for future distribution changes, most modeling predictions ignored these other factors (Guisan and Theurillat 2000). Despite such limitations, species distribution modeling can well be considered a powerful tool for the conservation of plant diversity under climate change (Guisan and Theurillat 2000; Belgacem and Louhaichi 2013).

5 Conclusions

We conclude that the establishment of a nature reserve network based on species distribution modeling and conservation planning is still urgently required and will be exceptionally helpful in some regions of China. There are two main challenges for forest conservation under climate change: shifting protected area boundaries to align with anticipated future changes and increasing the total protected area just to meet existing targets. For forests in China, the establishment of protected areas and conservation actions should be based on the types of coniferous forests, mixed broadleaf-conifer forests, and broad-leaved forests, respectively. Further studies should integrate more species and regions (including other countries and continents) into climate-informed conservation prioritization for forests. We furthermore propose that biodiversity conservation planning requires analyses of not only endangered species and biodiversity hotspots but also of key species that are important for maintaining ecosystem stability.

Acknowledgements We thank three anonymous reviewers for their valuable comments on an earlier version of this manuscript. This research was supported by National Key R & D Program of China (2016YFC1201100), Fundamental Research Funds for the Central Non-profit Research Institution of CAF (CAFYBB2014ZD001) and NSFC (31570413).

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