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Planning priority conservation areas under climate change for six plant species with extremely small populations in China

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Abstract

The concept of Plant Species with Extremely Small Populations (PSESP) has been employed to guide conservation of threatened plant species in China. Climate change has a high potential to threaten PSESP. As a result, it is necessary to integrate climate change effects on PSESP into conservation planning in China. Here, ecological niche modelling is used to project current and future habitat distributions of six PSESP in China under climate change scenarios and conservation planning software is applied to identify priority conservation areas (PCAs) for these PSESP based on habitat distributions. These results were used to provide proposals for in-situ and ex-situ conservation measures directed at PSESP. It was found that annual precipitation was important for habitat distributions for all six PSESP (with the percentage contribution to habitat distributions ranging from 18.1 % to 74.9 %) and non-climatic variables including soil and altitude have a large effect on habitat suitability of PSESP. Large quantities of PCAs occurred within some provincial regions for these six PSESP (e.g. Sichuan and Jilin for the PSESP *Cathaya argyrophylla*, *Taxus cuspidata*, *Annamocarya sinensis* and *Madhuca pasquieri*), indicating that these are likely to be appropriate areas for in-situ and ex-situ conservation measures directed at these PSESP. Those nature reserves with large quantities of PCAs were identified as promising sites for in-situ conservation measures of PSESP; such reserves include Yangzie and Dongdongtinghu for *C. argyrophylla*, Songhuajiangsanhu and Changbaishan for *T. cuspidata* and Shiwandashanshuiyuanlian for *Tsoongiodendron odorum*. These results suggest that existing seed banks and botanical gardens occurring within identified PCAs should allocate more resources and space to ex-situ conservation of PSESP. In addition, there should be additional botanical gardens established for ex-situ conservation of PSESP in PCAs outside existing nature reserves. To address the risk of negative effects of climate change on PSESP, it is necessary to integrate in-situ and ex-situ conservation as well as climate change monitoring in PSESP conservation planning.

Keywords
PSESP, climatic change, systematic conservation planning, China, in-situ and ex-situ conservation measures

Introduction

Climate change has a large potential to threaten plant diversity from species to biomes, as well as hinder endangered species protection (Thuiller et al. 2005, Bellard et al. 2012, Diez et al. 2012, Grimm et al. 2013, Watson et al. 2013). Climate change may result in the migration, vulnerability or extinction of plant species by causing species distributions to shift, habitat fragmentation to increase, population sizes to decrease and genetic diversity to decline (Thuiller et al. 2005, Heller and Zavaleta 2009, Bellard et al. 2012, Diez et al. 2012, Grimm et al. 2013, Watson et al. 2013). Furthermore, other human impacts are likely to cause additional habitat loss and threaten plant species (Tilman and Lehman 2001, Kier et al. 2005, Vásquez et al. 2015). In particular, threatened plants with narrow niche width and small population sizes may fail to adapt to novel climatic conditions and thus become endangered or even extinct (Bellard et al. 2012, Botts et al. 2013, Slatyer et al. 2013). Future climate may change rapidly and enhance loss of threatened plant species stemming from vulnerability to climate change, which is influenced by species' sensitivity and adaptive capacity, as well as the degree of exposure (Thuiller et al. 2005, Bellard et al. 2012, Diez et al. 2012, Watson et al. 2013). Plant conservation faces great uncertainty as a result of climate change; decreasing this uncertainty is a challenge for conservation biologists and government managers (Lavergne et al. 2004, Heller and Zavaleta 2009). There is a need to integrate climate change into conservation planning for threatened plants.

As many of its species are currently threatened or on the brink of extinction, China is one of the highest priorities for biodiversity conservation globally (López-Pujol et al. 2006, Wang et al. 2015, Zhang et al. 2015, Feng et al. 2017). It is urgent for China to take effective measures to conserve threatened plant species. A list of 120 wild plant species was recently identified as the first set of species in the nation to receive urgent protection (Ren et al. 2012, Volis 2016). These 120 species are labelled Plant Species with Extremely Small Populations (PSESP) due to: 1) the limited number of mature individuals in the wild; 2) restricted distribution ranges; 3) recognition as national or regional endemic species in China; and 4) economic development or scientific value (Ma et al. 2013, Chen et al. 2014, Wade et al. 2016, Volis 2016, Wang et al. 2017). To conserve the 120 PSESP, several national and regional conservation strategies have been implemented and such strategies will be expanded across China (Ren et al. 2012, Ma et al. 2013). In-situ and ex-situ conservation methods have been widely employed for PSESP (Ren et al. 2012, Ma et al. 2013, Wade et al. 2016, Volis 2016). These approaches have the advantage of being cost-efficient, flexible and capable of supplementing other conservation measures (Wade et al. 2016, Volis 2016). However, due to the vulnerability of PSESP to rapid climate change, the effectiveness of in-situ and ex-situ PSESP conservation actions may be decreased by climate change (Chen et al. 2014, Wang et al. 2017). Planning long-term in-situ and ex-situ conservation strategies for the protection of PSESP under scenarios of climate change can be challenging (Wang et al. 2017).

Identifying priority conservation areas (PCAs) is a useful step in making climate change adaptation strategies for the conservation of PSESP. Recently, many conservation biologists and ecologists have used ecological niche modelling (ENM) in combination with conservation planning software to identify PCAs for endemic, threatened and endangered plant species under climate change conditions (Pérez and Font 2012, Wan et al. 2014, 2015, Adams-Hosking et al. 2015, Wang et al. 2015). ENMs, which are based on occurrence records and climatic variables, are widely used to predict spatial distribution patterns of species diversity (Merow et al. 2013, Adams-Hosking et al. 2015, Wang et al. 2015). Such models are used to generate proposals for biological conservation actions and to examine their probable feasibility (Adams-Hosking et al. 2015, Wang et al. 2015, Abrahms et al. 2017, Reside et al. 2017). For example, ENMs may enable conservation practitioners to predict previously unknown locations of species (Pearson et al. 2007). Conservation planning software is commonly used to generate a spatial conservation framework that can be used to prioritise large-scale conservation projects that involve numerous species or to identify the most effective conservation areas that will capture target species, as predicted by the results of ENMs (Moilanen 2007, Di Minin and Moilanen 2012, Lehtomäki and Moilanen 2013, Wan et al. 2014, Abrahms et al. 2017). The ability of existing or proposed nature reserves to protect threatened plants can be evaluated using ENMs and conservation planning software and new conservation areas could be designated in order to respond to climate change effects (Wan et al. 2014, 2015, 2017, Wang et al. 2016). In this way, the plant conservation effectiveness of a network of nature reserves can be maximised under climate change conditions (Wan et al. 2015, Wang et al. 2016, Abrahms et al. 2017). For example, Wang et al. (2015) used ENM coupled with conservation planning software to identify PCAs for threatened plants in China under climate change. The habitat distributions of PSESP are related to the climatic variables temperature and precipitation and therefore may be affected negatively by future climate change (Wang et al. 2017). Hence, there is a need to identify PCAs for PSESP in China under climate change conditions and to provide a simple protection assessment system for either in-situ or ex-situ conservation measures.

PSESP as a designation is not only important for conservation prioritisation in China, but also may be a useful framework in conservation efforts for threatened plants around the world (Wang et al. 2017). As a consequence of climate change, species will respond by shifting their distributional ranges and some populations may shrink to the point of extinction (Thuiller et al. 2005, Mawdsley et al. 2009, Bellard et al. 2012, Grimm et al. 2013, Watson et al. 2013). Hence, it is important for conservation biologists and governmental managers to integrate the impacts of climate change on habitat distributions of plants into conservation planning for PSESP (Mawdsley et al. 2009, Bellard et al. 2012). Here, PCAs are delineated and potential sites identified for conservation of PSESP in China under climate change conditions (Chen et al. 2014, Wade et al. 2016, Volis 2016, Wang et al. 2017). Conservation of PSESP in China requires an integrated approach, encompassing both in-situ and ex-situ conservation measures and their methodologies, as well as establishing effective evaluation systems for PSESP (Wade et al. 2016, Volis 2016, Wang et al. 2017). In-situ conservation measures, which may occur within nature reserves and other types of scenic locations, can be used to maintain the evolutionary and biological reproductive potential of the ecological system (Wade et al. 2016, Volis 2016). Ex-situ conservation measures, in which parts of the population are placed in a new location, can be used to identify suitable living environments for species for the future and to retain existing populations (Wade et al. 2016, Volis 2016). By definition, PSESP have a limited number of individuals and small population sizes in China (Wade et al. 2016, Volis 2016). Natural regeneration of PSESP is poor and some species have no chance of survival (Ren et al. 2012, Ma et al. 2013). There is a need for increased research on reproduction, wild endangered population dynamics, conditions conducive to growth and seed bank establishment to facilitate ex-situ conservation of PSESP (Wade et al. 2016, Volis 2016).

The primary objective of this study is to identify PCAs for PSESP in China under climate change conditions. To achieve this objective, six PSESP were selected as study species and ENM used to model the habitat distributions of these PSESP under current and future climate scenarios and the environmental variables that contribute significantly to the habitat distributions of the focal PSESP were explored. Then, conservation planning software was used to identify PCAs for PSESP in China under projected climate change conditions based on the species' habitat requirements. Finally, the regions were identified with high potential to serve as effective conservation sites for the focal PSESP based on identified PCAs and suggestions were developed for in-situ and ex-situ conservation measures of PSESP.

Materials and methods

Study species and occurrence records

The State Forestry Administration of China has been concentrating on management of PSESP through its "Conservation Programme for Wild Plants with Extremely Small Populations in China (from 2011 to 2015)" (http://www.forestry.gov.cn/portal/main/s/72/content-540092.html). This plan identifies PSESP as species comprising fewer than 5,000 individuals and restricted to known localities (Ren et al. 2012, Ma et al. 2013). *Cathaya argyrophylla*, *Taxus cuspidata*, *Annamocarya sinensis*, *Ulmus elongata*, *Tsoongiodendron odorum* and *Madhuca pasquieri* were selected as the study species for the present analysis. Occurrence records were obtained from the State Forestry Administration of China and were also obtained from a number of reference resources (e.g. China's State Forestry Administration and the Institute of Botany, Chinese Academy of Sciences, 2013; Flora of China (http://foc.eflora.cn/), Fang et al. 2009, Ren et al. 2012, Wang et al. 2017). Occurrence points were recorded in 10 arc-minute grid cells to avoid errors in georeferencing, obvious misidentifications and duplicate species records in each grid cell (Wang et al. 2016). The number of occurrence records used as inputs into the ENMs ranged from 10 to 49 per species (Pearson et al. 2007, Merow et al. 2013, Table 1).

Environmental variables

Spatial data were obtained for 14 environmental variables at a 10-arc-min resolution including eight soil, one topographic, one natural state and four climate variables (Suppl. material 1: Table S1; Wang et al. 2016). Multi-collinearity was tested amongst variables using Pearson correlation coefficients and variables were excluded with a cross-correlation coefficient absolute value exceeding 0.85. These 14 environmental variables may influence the current distribution and physiological performance of threatened plant species and can therefore be used in ENMs to infer the current climate suitability of PSESP (Wang et al. 2017).

To model the future habitat distributions of PSESP in the 2080s (i.e. 2070–2099), the average projection maps generated under four global climate models were used (i.e. bcc_csm1_1, csiro_mk3_6_0, gfdl_cm3 and mohc_hadgem2_es) and two greenhouse gas concentration scenarios as representative concentration pathways (RCPs) of 4.5 (mean, 780 ppm; range, 595 to 1005 by 2100) and 8.5 (mean, 1685 ppm; range, 1415 to 1910 by 2100), representing low and high gas concentration scenarios, respectively (http://www.ccafs-climate.org/).

Modelling the distributions of PSESP

Using Maxent (a commonly-used ENM software) and the 14 environmental variables, the current and future species distributions for the six focal PSESP were modelled with maximum entropy (Phillips et al. 2006, 2017, Merow et al. 2013). Then, RCPs 4.5 and 8.5 were used to project distributions of PSESP under low and high greenhouse gas concentration scenarios. These projections kept the non-climatic variables constant into the future, with only the climate variables changing in accordance with these scenarios (Wang et al. 2016). Maxent is appropriate for this type of modelling for a variety of reasons: (1) it can be used with small sample sizes, which drastically impact both the performance and the adjustment of ENM (Pearson et al. 2007, Merow et al. 2013, Fourcade et al. 2014, Proosdij et al. 2016); (2) It is insensitive to multicollinearity amongst predictors, which can impede the analysis of species-environment relationships

Table 1. Characteristics of the six focal PSESP and Maxent performance test results.

Name	Form	Altitude (m)	Individual	Record	Training AUC	Test AUC	Training Omission	Ecoregion
Cathaya argyrophylla	Tree	900–1900	4484	10	0.983	0.980	0.00±0.00	TBMF
Taxus cuspidata	Tree	500–1000	42700	24	0.997	0.996	0.03±0.04	TBMF
Annamocarya sinensis	Tree	500–2500	472	19	0.993	0.987	0.04±0.02	TBMF
Ulmus elongata	Tree	500–900	1430	11	0.995	0.993	0.03±0.04	TSMBF
Tsoongiodendron odorum	Tree	500–1000	6548	49	0.989	0.985	0.04±0.04	TSMBF
Madhuca pasquieri	Tree	0–1100	6429	23	0.992	0.990	0.05±0.04	TBMF

Individual: the number of saved individuals; Record: the number of occurrence records as an input of Maxent; TBMF: Temperate Broadleaf & Mixed Forests; TSMBF: Tropical & Subtropical Moist Broadleaf Forests.

in multiple regression settings; finally, (3) it provides the relative contribution of each variable as an output (Pearson et al. 2007, Merow et al. 2013, Phillips et al. 2017). All grid cells were assumed to be possible distribution space with maximum entropy (Phillips et al. 2006, Merow et al. 2013). Maxent predicted habitat suitability across maps wherein pixel values of 1 indicated the highest scores of habitat suitability and values of 0 indicated the lowest habitat suitability (Phillips et al. 2006).

For modelling the distributions of PSESP, the Maxent sets were as follows: 1) the regularisation multiplier (beta) was set to two to produce a smooth and general response that could be modelled in a biologically realistic manner (Radosavljevic and Anderson 2014); 2) a 10-fold cross-validation approach was used to remove bias from recorded occurrence points (Oke and Thompson 2015); 3) the maximum number of background points was set to 10,000 (Phillips et al. 2006); 4) the jackknife method was used to determine the response curves of environmental variables to habitat suitability (Merow et al. 2013); 5) The cloglog was used as the output of modelling, giving it a stronger theoretical justification than the logistic transformation (which it replaces by default) (Phillips et al. 2017); and 6) other settings were identical to those described in Phillips et al. (2006). The variable jackknife was used to evaluate the percentage contribution (PC) of environmental variables to distribution modelling for each species (Merow et al. 2013). The threshold PC of habitat suitability was set at 15%; environmental variables exceeding this level of PC were considered important for each species (Oke and Thompson 2015).

The analysis produced a receiver operating characteristic (ROC) curve, which established each value of the prediction results as a possible judging threshold; the corresponding sensitivity and specificity of the predicted results were obtained (Phillips et al. 2006). The performance of the model was evaluated by calculating the area under the ROC curve (AUC). Models were graded as poor (AUC<0.7), fair (0.7<AUC<0.8), good (0.8<AUC<0.9) or very good (0.9<AUC<1.0) (Swets 1988). However, AUC alone is not sufficient to evaluate the model performance (Lobo et al. 2008). The training omission rate is the proportion of the training occurrence localities that fall in pixels of predicted absence based on binomial probabilities (Phillips et al. 2006, Anderson and Gonzalez 2011). These are 1-sided tests of the null hypothesis that test points are no better predicted than random (Phillips et al. 2006, Anderson and Gonzalez 2011).

Binomial probabilities were based on three thresholds: Fixed cumulative value 10, 10th percentile training presence and Equal training sensitivity and specificity, used by default by Maxent (Phillips et al. 2006). An average training omission rate of less than 17% is considered good for the model (Anderson and Gonzalez 2011).

Prioritising conservation areas for PSESP

The Zonation conservation planning software (http://cbig.it.helsinki.fi/software/) was used to prioritise conservation areas for PSESP under conditions of climate change (Lehtomäki and Moilanen 2013; Wan et al. 2017). Zonation is usually used as a spatial conservation prioritisation framework for large-scale conservation planning directed at multiple biodiversity features (e.g. species; Lehtomäki and Moilanen 2013). The highest priorities for conservation, namely protection of hot-spot areas, were confirmed by identifying the top-ranking cells after computation in Zonation (Moilanen 2007, Di Minin and Moilanen 2012). To decrease conservation uncertainty due to climate change, the geographic distance between the current and future distributions of each PSESP was minimised and the influence of climate change on species distributions was considered when selecting potential sites in Zonation for reserves (Lehtomäki and Moilanen 2013, Wang et al. 2015).

The distributions of each species under current, low and high gas concentration scenarios, as assessed by the Maxent value of each grid cell, were used as input feature maps for the Zonation software (Wang et al. 2015). The present distributions of the target species were weighted as 1 and future distributions were weighted as 0.5 when input into Zonation (Adams-Hosking et al. 2015). The core-area Zonation solutions were used to optimally capture the areas of the distribution of PSESP at each removal step (Lehtomäki and Moilanen 2013; Wan et al. 2017). The 'warp factor' was set to 1 (i.e. the single worst pixel was removed at each iteration) to maintain the reliability of the output. Default settings were used for 'edge removal' (i.e. pixels were removed preferentially from the edges of distributions; Lehtomäki and Moilanen 2013).

As limited resources rarely allow all potential habitats to be conserved, the top 10% of grid cells of distributions were extracted (referred to as the grid cells ranking in the top 10% in the following), based on PCAs for each PSESP according to realised ecoregional ranges of species as presented in Wang et al. (2017), Olson et al. (2001) and Xu et al. (2017). *Ulmus elongata* and *T. odorum* belong to the Tropical & Subtropical Moist Broadleaf Forests ecoregion and *C. argyrophylla*, *T. cuspidata*, *A. sinensis* and *M. pasquieri* belong to the Temperate Broadleaf & Mixed Forests ecoregion (Olson et al. 2001, Wang et al. 2017).

Identifying potential regions for conservation of PSESP

First, grid cells of PCAs were downscaled from 10 arc-minutes to 2.5 arc-minutes and the number of grid cells was used to quantify the size of PCAs in order to improve the precision of the assessment (Araújo et al. 2011). Then, the grid cells were identified where PCAs occurred in each provincial region and those occurring within existing nature reserves belonging to each provincial region (Araújo et al. 2011). 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). This allowed the identification of potential regions (including nature reserves) with high potential to conserve PSESP (Wang et al. 2015). The map of ecoregions used for this purpose was downloaded from http://www.worldwildlife.org/ and the map of nature reserves was obtained from the World Database on Protected Areas (WDPA; http://www.wdpa.org/; Fig. 1). Finally, proposals were developed for in-situ and ex-situ conservation of PSESP based on this process of delineation of PCAs.

Results

All ENMs had AUC values greater than 0.7 for both the training and test data sets and the training omission rates were less than 17 %, indicating a high level of accuracy for each model (Table 1). Annual precipitation was important for the distributions of all six PSESP (with PCs ranging from 18.1 % to 74.9 %; Table 2). The annual precipitation response curves of distributions of *T. cuspidata*, *A. sinensis* and *T. odorum* were single peak in shape (Fig. 2b, c, e). Response curves indicated that with increasing annual precipitation, habitat suitability of *C. argyrophylla*, *U. elongata* and *M. pasquieri* is likely to increase and then remain stable (Fig. 2a, d and f). Temperature seasonality contributes substantially to the distribution of *T. cuspidata* and precipitation seasonality was the most important variable influencing distributions of *C. argyrophylla* and *U. elongata* (Table 2). Soil variables, such as bulk density, cation exchange capacity and sand as a fraction of soil texture, exert a large effect on distributions of *C. argyrophylla*, *T. cuspidata* and *U. elongata*. Habitat suitability of *A. sinensis* was affected by altitude (PC = 18.4%; Table 2).

Out of all provinces, the greatest total area of PCAs for the studied PSESP occurred in Sichuan and Jilin; PCAs in these provinces included those of *C. argyrophylla*, *A. sinensis* and *M. pasquieri* and *T. cuspidata* (Fig. 3). Overall, PCAs of *C. argyrophylla* occurred in Anhui, Henan, Hubei, Hunan, Jiangsu and Jiangxi (Fig. 3). For *T. cuspidata*, PCAs occurred in Heilongjiang, Jilin and Liaoning; PCAs for *A. sinensis* occurred in Sichuan, Hubei, Shaanxi and Tibet; PCAs for *U. elongata* occurred in Jiangxi, Fujian and Hunan; PCAs of *T. odorum* occurred in Guangdong and Guangxi; and PCAs for *M. pasquieri* occurred in Sichuan, Tibet and Jiangxi (Fig. 3).

The nature reserves with largest capacity to conserve the focal PSESP included Yangzie, Songhuajiangsanhu, Changbaishan, Dongdongtinghu and Shiwandashanshuiyuanlian (Figs 1, 3; Suppl. material 1: Table S2). Specifically, PCAs indicate that Yangzie and Dongdongtinghu are highly suitable for *C. argyrophylla* and Songhuajiangsanhu and Changbaishan demonstrate high PCA occurrence for *T. cuspidata* (Figs 1, 3; Suppl. material 1: Table S2). There is high overlap between PCAs of *A. sinensis* and the

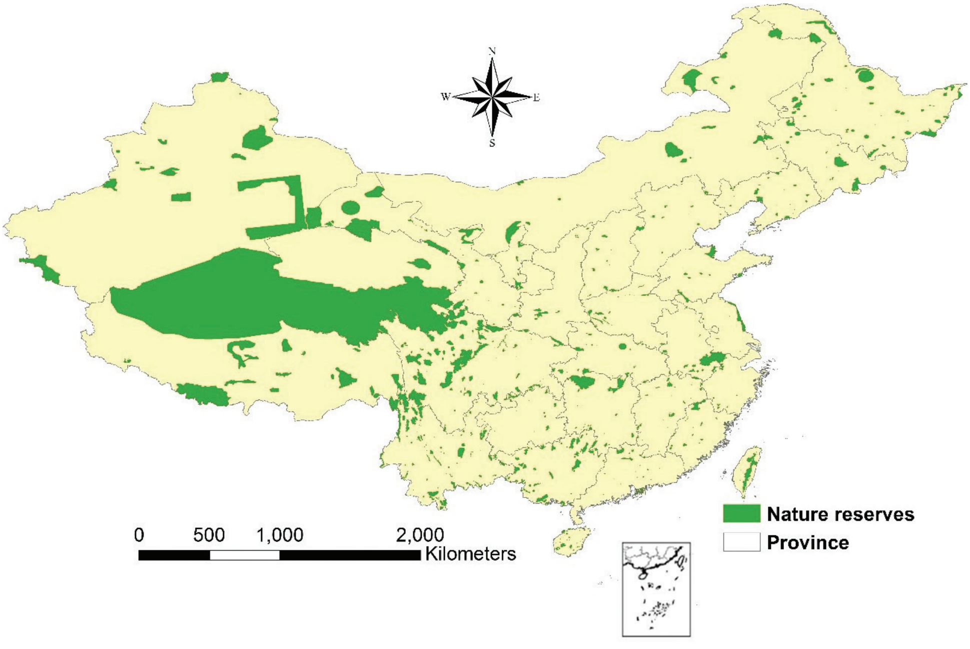

Figure 1. Nature reserves in China.

existing nature reserves Baishuijiang and Cuiyunlanggubai, between PCAs of *U. elongata* and the reserves Jiangxiwuyishan and Mountwuyi, between PCAs of *T. odorum* and the reserves Shiwandashanshuiyuanlian and Xishuangbanna and between PCAs of *M. pasquieri* and the reserves Cuiyunlanggubai and Jinyunshan (Figs 1, 3; Suppl. material 1: Table S2).

Discussion

These results indicate that some provincial regions (e.g. Sichuan and Jilin) contain large areas of habitat as identified by the PCAs for the six PSESP. As such, the outputs serve as tools to identify potential areas for the conservation of PSESP. Figure 3 may be regarded as an important reference for determining promising locations for in-situ and ex-situ conservation efforts directed at PSESP. In-situ and ex-situ conservation are effective approaches for protecting PSESP (Wade et al. 2016, Volis 2016, Wang et al. 2017). Via in-situ conservation, protection in each region is increased, establishing local protected zones for PSESP that conserve the natural environment. In China, many nature reserves have been established for conservation of threatened plant species (Wade et al. 2016, Volis 2016). For example, the aim of the nature reserves in Muling was to protect *T. cuspidata*. Based on these results, it is suggested that the Songhuajiangsanhu and Changbaishan nature reserves also have high potential to be effectively used for conservation actions for *T. cuspidata*. Furthermore, Yangzie and Shiwandashanshuiyu-

Table 2. Percentage contribution of environmental variables to predicted distributions of PSESP.

Name	Alt	Bio1	Bio4	Bio12	Bio15	BLD	CEC	CLYPPT	CRFVOL	OCSTHA	PHIHOX	SLTPPT	SNDPPT	HF
Cathaya argyrophylla	2.36	1.5	1.06	20.88	16.39	52.72	0.26	0.23	0.13	0	4.47	0	0	0
Taxus cuspidata	6.41	1.84	33.6	18.12	0.13	19.91	0.63	0	0.91	0.44	1.3	0.28	16.28	0.14
Annamocarya sinensis	18.65	0.16	3.4	63	0	4.31%	0.3	0.57%	5.13%	2.16%	0.6	0.72	0.92	0.09
Ulmus elongata	2.54	0	1.72	22.11	21.81	23.06	22.53	1.18	0.52	0.02	4.21	0.31	0	0
Tsoongiodendron odorum	7.58	5.13	1.39	74.91	0.28	1.08	1.17	0.15	5.91	0.01	0.33	1.67	0.16	0.23
Madhuca pasquieri	6.91	3.83	9.72	61.74	0.01	2.32	12.62	1.01	1.46	0.07	0.02	0.25	0	0.05

The code was the same as in Suppl. material 1: Table S1.

Table 3. Priority conservation areas of PSESP across the provinces.

Province	*Cathaya argyrophylla*	*Taxus cuspidata*	*Annamocarya sinensis*	*Ulmus elongata*	*Tsoongiodendron odorum*	*Madhuca pasquieri*	Total
Anhui	98999	0	7122	0	0	4946	111067
Fujian	0	0	0	44356	9013	0	53369
Gansu	0	0	14403	0	0	0	14403
Guangdong	0	0	0	7970	77130	0	85100
Guangxi	0	0	0	4303	74487	0	78790
Hainan	0	0	0	0	19843	0	19843
Hebei	0	800	0	0	0	0	800
Heilongjiang	0	112413	0	0	0	0	112413
Henan	72	0	4828	0	0	0	4900
Hubei	60968	0	37233	159	0	16691	115051
Hunan	50584	0	3484	38545	0	14745	107358
Inner Mongolia	0	2400	0	0	0	0	2400
Jiangsu	22032	0	0	0	0	6798	28830
Jiangxi	55232	0	9043	54250	839	70620	189984
Jilin	0	168579	0	0	0	0	168579
Liaoning	0	62161	0	0	0	0	62161
Shaanxi	0	0	38544	0	0	0	38544
Shandong	0	0	0	0	0	205	205
Shanxi	0	0	215	0	0	0	215
Sichuan	7032	0	189237	0	0	177506	373775
Taiwan	0	0	0	7350	12078	0	19428
Tibet	0	0	36198	0	919	31169	68286
Yunnan	0	0	494	0	7465	494	8453
Zhejiang	51113	0	6197	45862	0	22938	126110

The values represent the number of grid cells containing priority conservation areas.

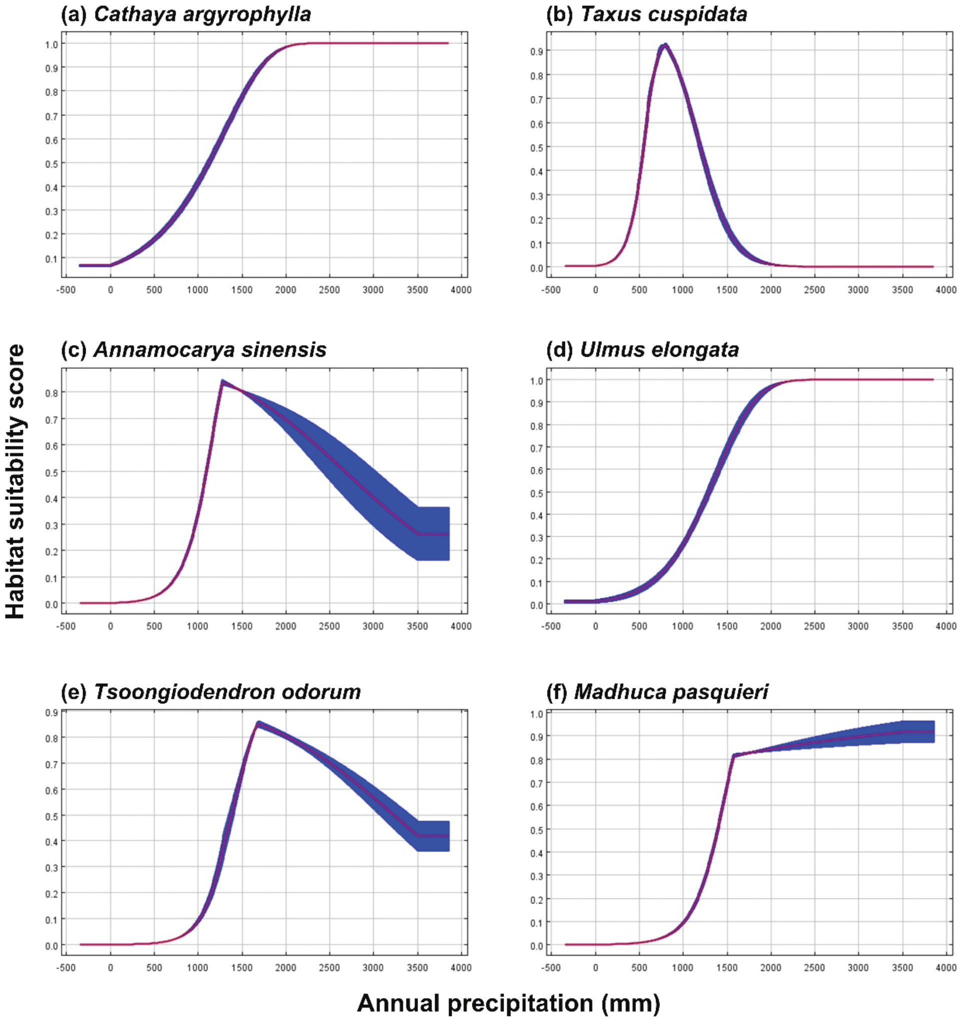

Figure 2. Response curves of annual precipitation to habitat suitability for six PSESP.

anlian have the potential to play an important role in the protection of *C. argyrophylla*. This study identifies key existing nature reserves for in-situ conservation of *C. argyrophylla*, *T. cuspidata*, *A. sinensis*, *U. elongata*, *T. odorum* and *M. pasquieri*. Within these reserves, the construction of small nature reserves, eco-orchards and forest eco-stations for in-situ conservation should be bolstered (Wade et al. 2016, Volis 2016). However, climate factors, including temperature and precipitation, should be regarded as important monitoring indicators for in-situ conservation of PSESP because future climate change may alter suitable sites for PSESP (Suppl. material 1: Figure S1). Just as existing habitats are predicted to be disrupted by climate change, in some cases forcing the use of ex-situ conservation, newly established conservation sites may be impacted in the future (Wang et al. 2017).

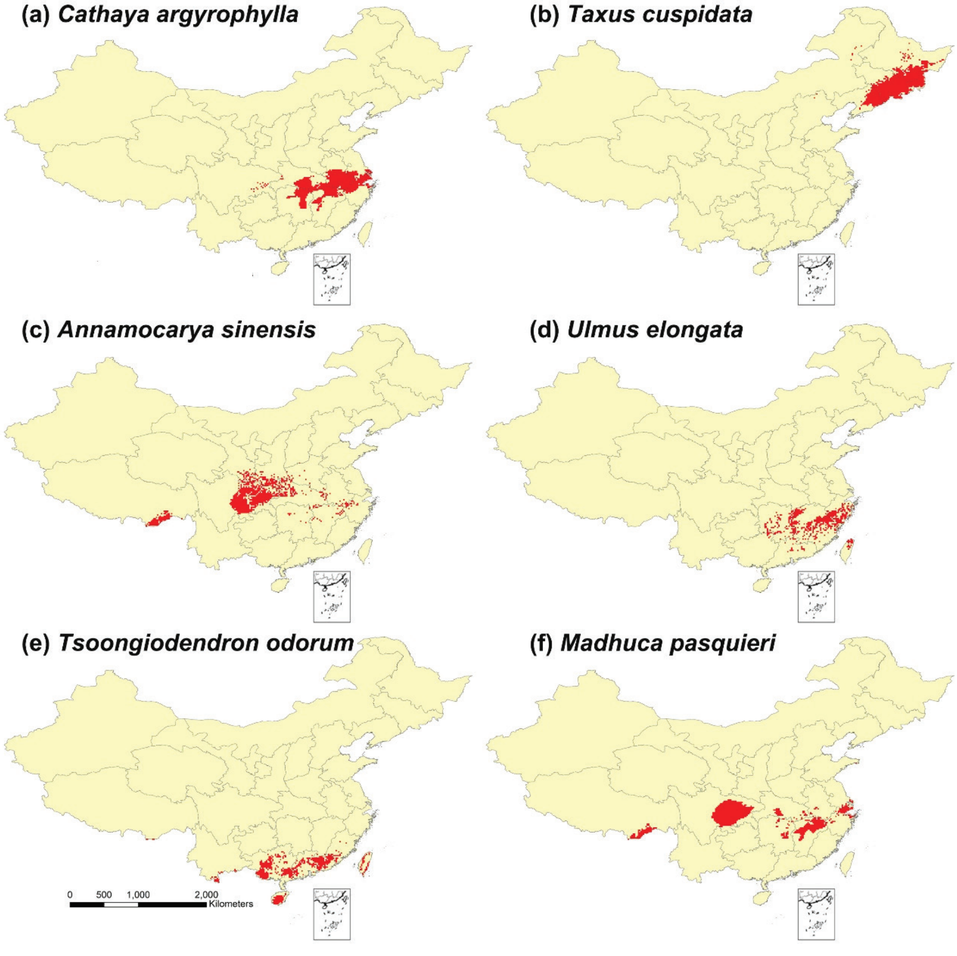

Figure 3. Priority conservation areas for six PSESP in China under climate change.

In an attempt to take into account these future scenarios, current and future suitable distributions were integrated into PCA predictions in order to consider where and how ex-situ conservation could be used in PCAs for PSESP (Wang et al. 2015). Vulnerability of PSESP to climate change must be adopted as the most important indicator that the species is really endangered due to climate change effects. As shown in Fig. 3, PCAs often included areas outside the network of established nature reserves, indicating that ex-situ conservation or the establishment of new protected areas with less vulnerability to predicted climate change may be appropriate for species currently reliant on nature reserves (Wang et al. 2016; Wan et al. 2018). For instance, Cuiyunlanggubai and Jinyunshan appear to be suitable experimental areas for future research on *M. pasquieri* and Baishuijiang and Cuiyunlanggubai are likely to be key nature reserves for ex-situ conservation for *A. sinensis*. The construction of conservation areas for PSESP should be increased in PCAs outside existing nature reserves (Wade et al.

2016, Volis 2016). For example, few seedlings have been observed in natural populations of *A. sinensis* and climate change has a large potential to decrease the distribution probability; thus, both range and population sizes are projected to decline for *A. sinensis* (Wade et al. 2016, Volis 2016). To conserve *A. sinensis*, it is necessary to mitigate the impacts of climate change by establishing areas of ex-situ conservation with the ability to adapt to future climate change for *A. sinensis* (Wade et al. 2016, Volis 2016). Existing seed banks and botanical gardens occurring within PCAs should allocate more resources and space to PSESP. Usage of integrated ex-situ/in-situ approaches must become the norm for PSESP.

It was found that climatic variables and, particularly annual precipitation, were important for distributions of the six focal PSESP in China (Table 2), indicating that there is a need to consider climate change when planning PSESP conservation efforts via in-situ and ex-situ measures. PSESP with a high protection value, such as plants with high scientific research values and ornamental plants, are threatened by over-exploitation and utilisation, habitat fragmentation and the small sizes of their wild populations in broad-leaved forests and bush fallows (Wang et al. 2017). For example, for *T. odorum* and *M. pasquieri*, habitat fragmentation is very severe in China (Wang et al. 2017). Population persistence and growth are at high risk for *T. odorum* and *M. pasquieri*. As discussed for *A. sinensis*, above, populations of PSESP that are already this vulnerable may be further impacted by rapid climate change (Bellard et al. 2012, Wang et al. 2016, 2017). Future climate change has a large potential to impact populations, individuals and habitats of PSESP in China. Wang et al. (2017) has shown that high temperatures and low temperature seasonality could influence the occurrence of suitable habitats for the PSESP in China. For example, these results demonstrate that temperature seasonality could affect distributions for *T. cuspidata* (Table 2). However, these models found different distribution responses to climatic variables for different PSESP, suggesting that different conservation strategies will be necessary for the different PSESP. The importance of each climatic factor may vary depending on the PSESP of interest (Fig. 2). There is a need to monitor the patterns of responses of habitat suitability to environmental variation for these six PSESP. However, it is also important for protection efforts to consider non-climatic factors, such as soil, vegetation types, slope, aspect and elevation etc., so that protection areas can be chosen appropriately (Parmesan et al. 2005, Schwartz et al. 2006, Austin and Van Niel 2011, Oke and Thompson 2015). Altitude and soil variables, including bulk density, cation exchange capacity and fraction of sand as a component of soil texture, have a large contribution to distributions of PSESP (Table 2).

To address the negative effects of climate change on PSESP, there is a need to integrate in-situ and ex-situ conservation measures and climate change monitoring into conservation planning for the six focal PSESP. The delineation of PCAs may be used for providing in-situ and ex-situ conservation measures for PSESP populations and habitats. Monitoring of environmental variation is essential for successful in-situ and ex-situ conservation management of PSESP (Wade et al. 2016, Volis 2016; Wan et al. 2018). However, limits to this study include a need for more detailed empirical data collection. Future studies must take future land use and land cover into account in conservation planning and consider conservation management needs of more PSESP under future global change. Furthermore, PSESP as a designation is likely to be globally useful and it is recommended that global assessments of species be selected based on PSESP criteria.

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Supplementary material 1

Table S1, S2; Figure S1, S2

Authors: Hong Qu, Chun-Jing Wang, Zhi-Xiang Zhang

Data type: (measurement/occurence/multimedia/etc.)

Explanation note:

Table S1. Environmental variables used in this study.

Table S2. Potential nature reserves overlapped with priority conservation areas for PSESP.

Figure S1. Distribution probabilities of PSESP under current, low and high greenhouse gas concentration scenarios. The colour from yellow to blue represents increasing distribution probability for PSESP.

Figure S2. Priority conservation rank of PSESP. The colour from yellow to blue represents increasing priority conservation rank for PSESP.

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