Biological Conservation xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Biological Conservation

journal homepage: www.elsevier.com/locate/bioc

Historical anthropogenic footprints in the distribution of threatened plants in China

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ARTICLE INFO

Article history:
Received 18 November 2015
Received in revised form 17 May 2016
Accepted 26 May 2016
Available online xxxx

Keywords:
Biodiversity conservation
Extinction debt
Human impacts
Land-use change
Plant diversity
Rare plants

ABSTRACT

A large proportion of Earth's plant species diversity is threatened with extinction. Unprecedented anthropogenic activities are the main drivers, with habitat loss due to land transformation and unsustainable use being the most important factors. These anthropogenic activities are not just a contemporary phenomenon, but also have a long history, and their historical dynamics may shape distributions of threatened plants. However, the relative roles of historical and current changes in anthropogenic activities in determining the distribution of threatened plant species across large geographic regions have hitherto been rarely studied. In this study, for the first time, we linked the distribution of threatened species across China to current and historical changes in human population densities, cropland area, and pasture area since 1700 (at a 100 km × 100 km resolution). We find that variables describing historical changes in human impacts were consistently more strongly associated with proportions of threatened plants than variables describing current changes in human impacts. Notably, threatened plant species in China tend to be concentrated where historical anthropogenic impacts were relatively small, but anthropogenic activities have intensified relatively strongly since 1700. Hence, threatened species are likely to be concentrated in areas that have only recently come under anthropogenic pressure.

1. Introduction

Intensifying human activities may already have caused half of the world's flora to be threatened with extinction, a trend that is likely to continue across the 21st century (Pitman and Jørgensen, 2002; Pereira et al., 2010). Therefore, to inform conservation planning it is important to gain a better understanding of the generality and geography of these dynamics of plant diversity loss and the underlying mechanisms. Anthropogenic activities have been widely found to strongly correlate with species and population declines, with climate change also beginning to play a role (Lewison et al., 2004; Scharlemann et al., 2005; Davies et al., 2006; Linares et al., 2009). However, few studies have considered the historical legacies of human activities on the distributions of threatened species, especially across broad scales.

Environmental changes driven by anthropogenic activities may not only have immediate effects on species ranges and abundances, but could also cause delayed extinction debts (Diamond, 1972; Tilman et al., 1994; Kuussaari et al., 2009). Notably, long-lived species may persist for a long time after anthropogenic disturbance has created unsuitable environmental conditions or reduced habitat area too much for their equilibrium persistence (Kuussaari et al., 2009; Svenning and Sandel, 2013). Sizes and connectivity among patches will also affect species responses to land-use changes, with larger area and better connection may have stronger extinction debt (Gonzalez, 2000; Ferraz et al., 2003).

A recent study across Europe at the country scale reports a delayed effect of anthropogenic activities on numbers of threatened species (Dullinger et al., 2013). Several studies in Europe also have found that forest and grassland biodiversity is related to past anthropogenic activities dating back to hundreds years ago, at local or regional scales (Vellend et al., 2006; Dambrine et al., 2007; Pärtel et al., 2007). Nevertheless, to what extent these relations can be generalized to other spatial scales and regions remains to be seen. Further, the main existing broad-scale study (Dullinger et al., 2013) focuses on legacies of socio-economic pressures across the last century, while anthropogenic activities have shaped many areas for much longer periods (Ge et al., 2008; Goldewijk et al., 2011).

China has a long history of dense human populations and agriculture and thus also a long history of deforestation and other anthropogenic land cover transformations (Ge et al., 2008; Goldewijk et al., 2011). China also has a highly diverse flora, composed of 35,112 native high plant species (López-Pujol et al., 2006; Wang et al., 2015). A recent

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http://dx.doi.org/10.1016/j.biocon.2016.05.038
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evaluation of the conservation status of 34,450 Chinese higher plants following to the IUCN Red List Categories and Criteria (Version 3.1) lists 3819 species as vulnerable or more threatened, 2723 species as near-threatened, and 3612 species as data deficient (Chinese Academy of Sciences and Ministry of Environmental Protection of the People's Republic of China, 2013).

Here, for the first time, we assessed the relative roles of historical and recent anthropogenic activities (cropland area, pasture area and human population density) in determining the geographic distribution of threatened plants across China, considering pre-1700 anthropogenic activities and changes in anthropogenic activities between 1700 and 1950 and between 1950 and 2000. We hypothesize that proportions of threatened plant species may have higher positive associations with historical human land use than with current and recent human land use, reflecting extinction debts or cumulative losses effect in areas with high historical human impacts (Dullinger et al., 2013).

2. Methods

2.1. Threatened species

Recently, a red list for higher plants in China following the IUCN Red List Categories and Criteria (Version 3.1) has been published (Chinese Academy of Sciences and Ministry of Environmental Protection of the People's Republic of China, 2013), based on contributions from 294 experts on plant taxonomy. After the evaluation of 34,450 higher plants, 27 species were found to be extinct, 10 extinct in the wild, 15 regionally extinct, 583 critically endangered, 1297 endangered, 1887 vulnerable, 2723 near-threatened, 24,296 least concern, and 3612 data deficient (Qin and Zhao, 2014).

In this study, we only considered species that are threatened (critically endangered, endangered and vulnerable) or near-threatened. To check if these levels of threatened species have different response to anthropogenic activities, we analyzed the two groups separately. Distributions of proportions of these species were mapped on a 100 km × 100 km grid, using the Chinese Vascular Plant Distribution Database (CVPDD), which includes plant occurrence records at county level, mainly compiled from *Flora Reipublicae Popularis Sinicae*, provincial and regional floras in China, and some spatial distribution data of specimen. The proportion of threatened/near-threatened species was computed as the number of threatened/near-threatened species in a given grid cell divided by all seed plant species number in that grid cell.

2.2. Anthropogenic activities

Areas of cropland and pasture, as well as population density were extracted from the History Database of the Global Environment (HYDE 3.1; Goldewijk et al., 2011). Because there were strong increases in population and cropland after year 1700 and especially after the establishment of People's Republic of China in 1949 (Peng, 2011; He et al., 2013), we focused on anthropogenic activities pre 1700, change in anthropogenic activities between 1700 and 1950 (values in 1950 minus values in 1700), and between 1950 and 2000 (values in 2000 minus values in 1950) (Fig. 1).

2.3. Statistics

Random Forests is a non-linear method for classification and regression of high-dimensional data based on ensembles of regression trees (Breiman, 2001). The Random Forests algorithm bootstraps both cases and predictors to build different regression trees, the accuracy and error rate of which are evaluated using an out-of-bag sample (cases not used to calibrate the trees). The predicted value of a given case is computed as the statistical mode of the results for that case over all the trees of the Random Forests (500 by default). We have selected Random Forests because it overcomes known limitations of more traditional methods like GLMs, which less easily capture interactions and non-linear relationships and require the data to follow stricter assumptions, e.g., normality in errors and homoscedasticity. Random Forests does not require any assumptions in the data and it is well suited to accommodate non-linear relationships and considers interaction among variables automatically.

We used Random Forests to model the relationship between the proportions of threatened and near-threatened plant species and the variables representing the changes in anthropogenic activities between different periods, repeating each model 1000 times on random splits of the data (50% training data and 50% evaluation data) and averaging the Pearson correlation between the predicted and the observed values (proportion of threatened and nearly threatened species) across all models.

Single-predictor simultaneous autoregressive (SAR) modelling was used in supplement to assess the association between the proportion of threatened and near-threatened plant species (square-root transformed to get a normalized distributed residual error) and each single predictor, while controlling for spatial autocorrelation in the response residuals. All variables were standardized before analyses to get standardized coefficients.

To further assess the relation between proportions of threatened/near-threatened species and the anthropogenic predictors, we divided the 100 km × 100 km grid cells into five groups according their proportions of threatened/near-threatened species, and then multiple comparisons (Tukey HSD) were conducted to compare the predictors among these groups. Random Forests, SAR modelling and multiple comparisons were performed in R (version 3.1.1, R Development Core Team, 2009).

3. Results

Both near-threatened and threatened species were non-randomly distributed across China and mainly concentrated in southwestern China (Yunnan, Guangxi, Hainan, Xizang, Sichuan and Guizhou provinces), which have relatively low historical, but high current anthropogenic activities (Fig. 1).

Although the correlations between the observed and predicted proportions of threatened and near-threatened plant species by Random Forests were not very high, the results still showed clear patterns of the relative importance of variables from different time periods in predicting proportions of near-threatened and threatened species. Pre-1700 anthropogenic activities contributed more to the overall fit of the model than changes between 1700 and 1950, which was again more important than changes between 1950 and 2000 (Fig. 2).

Single-predictor simultaneous autoregressive modelling showed that the two variables most associated with proportions of both threatened and near-threatened species all represented changes in cropland area (Table S1, Fig. 3). Importantly, the proportion of threatened and near-threatened species were negatively related to human activities prior to 1950, but positively related to more recent human activity increases (Table S1).

The group of grid cells with the highest proportions of threatened/near-threatened species tended to have the highest level of recent human activities, but relatively low levels of historical human activities (Fig. 4).

4. Discussion

Our results show that near-threatened and threatened plants are mainly concentrated in southwestern China, and that this concentration can be at least partly attributed to the relatively recent expansion of human populations and cropland in this region. Notably, we found that anthropogenic activities pre-1950 and in particular before 1700 consistently had stronger associations with proportions of near-threatened and threatened plants species than anthropogenic activity

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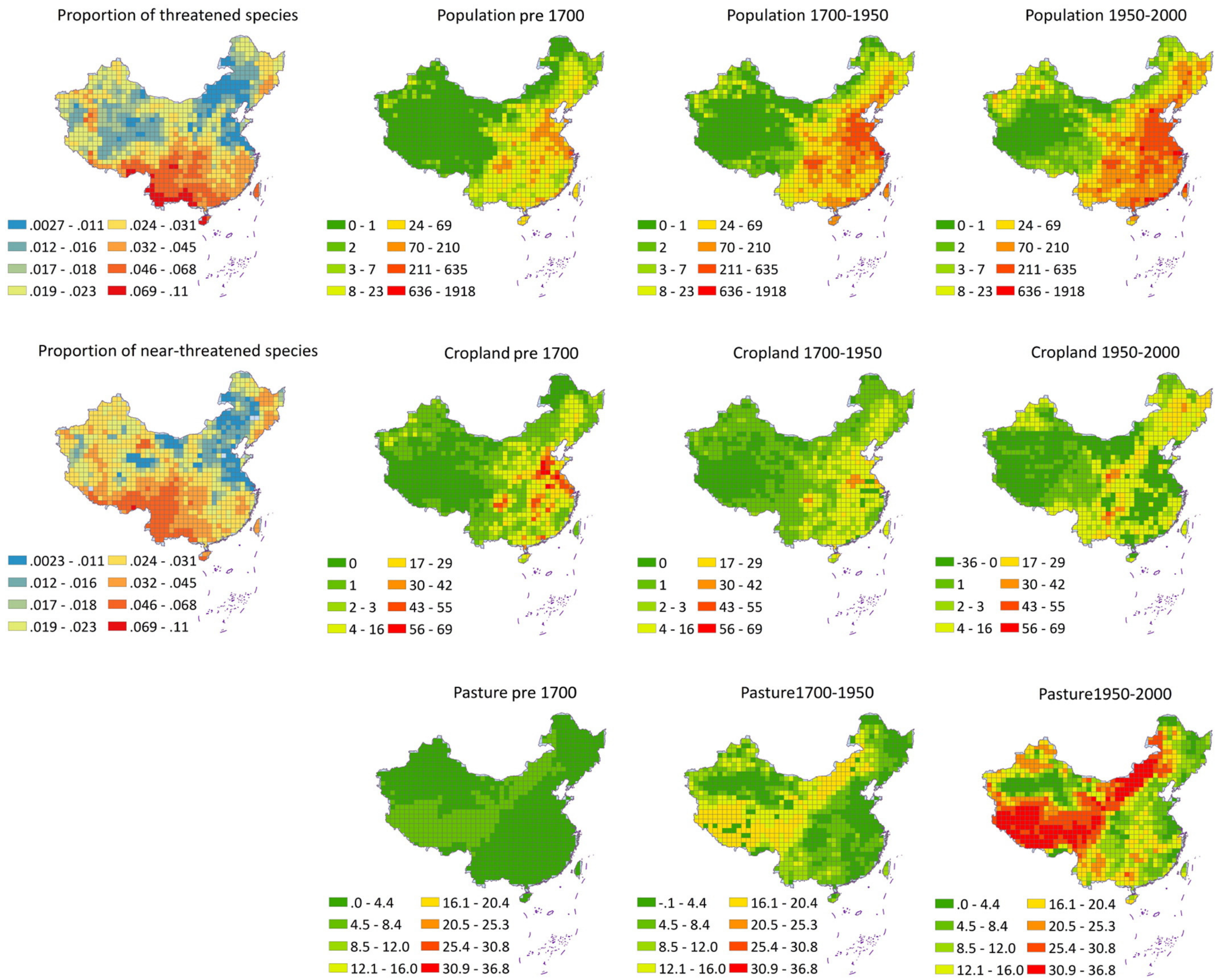

Fig. 1. Distributions of proportion of threatened plant species, proportion of near-threatened plant species, anthropogenic activities (human population density, cropland area and pasture area) pre-1700, between 1700 and 1950, and between 1950 and 2000. Units: cropland and pasture area, km^2 per 5′ × 5′ grid cell; population density, inhabitants/km^2 per grid cell.

increases occurring between 1950 and 2000, with former having negative relations and the latter positive relations. These patterns show that near-threatened and threatened plant species in China tend to be concentrated where historical anthropogenic activity levels were relatively low and current anthropogenic activities are relatively intense (Figs. 1, 3 and 4).

4.1. Distribution of threatened plants in China

The recently updated red list indicates that threatened and near-threatened plants are mainly clustered in southwestern China, i.e. in Yunnan, Guangxi, Hainan, Xizang, Sichuan and Guizhou provinces, consistent with previous studies using older and less complete threatened plant species lists (covering only 388 or 302 plant species; Tang et al., 2006; Zhang and Ma, 2008). This pattern is also consistent with the distribution of all plants and endemic plants in China (López-Pujol et al., 2006; Huang et al., 2012; Feng et al., 2016), indicating the critical role of these regions for China's biodiversity conservation framework.

4.2. Historical vs. current anthropogenic activities

Studies on the broad-scale distribution of threatened species often focus on current land use and current environmental factors as well as the potential effects of future climate change (Lewison et al., 2004; Scharlemann et al., 2005; Davies et al., 2006; Linares et al., 2009). In contrast, few studies have considered the role of historical human activities

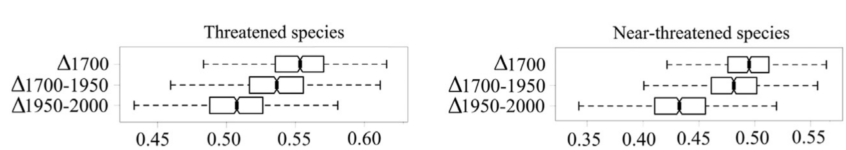

Fig. 2. Pearson correlations between the observed and predicted proportions of threatened and near-threatened plant species by Random Forests for three sets of explanatory variables: anthropogenic activities pre 1700 (Δ1700), changes between 1700 and 1950 (Δ1700–1950), and between 1950 and 2000 (Δ1950–2000).

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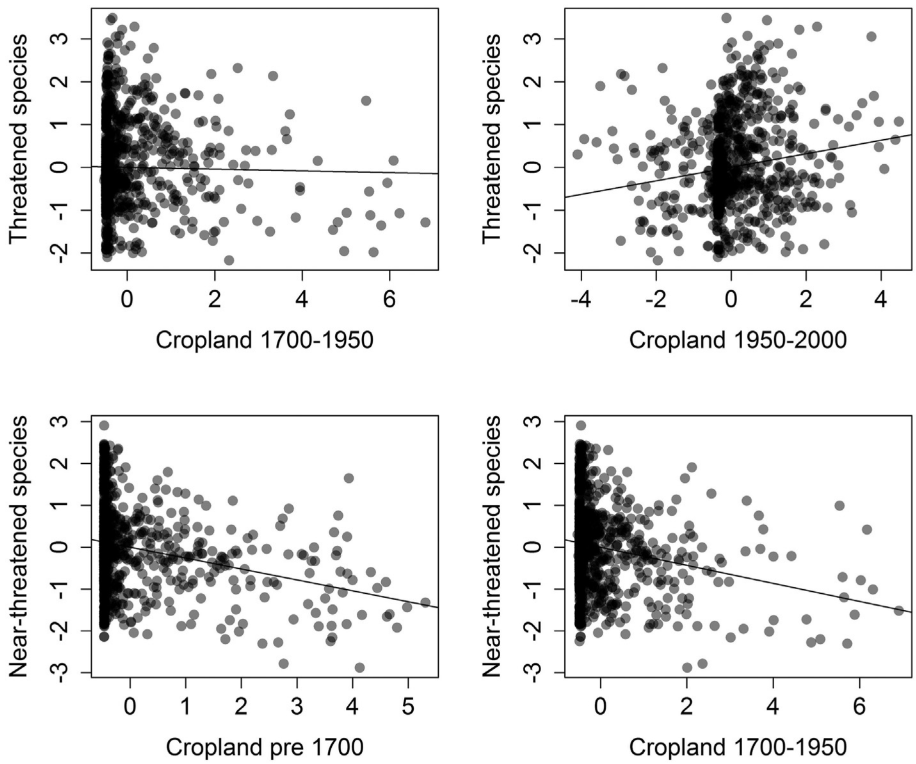

Fig. 3. Relations between proportions of threatened and near-threatened plant species (square-root transformed) and their two best single predictors, namely cropland area before 1700, between 1700 and 1950, and between 1950 and 2000.

in shaping the distribution of threatened species, although lagged effects in biotic responses to anthropogenic environmental changes has been reported in several previous large-scale studies (Bertrand et al., 2011; Essl et al., 2011). For example, Essl et al. (2011) found that historical socioeconomic activities are more closely related with current numbers of alien species than recent socioeconomic activities in Europe. Another recent study on European threatened species also reported delayed effect of historical socioeconomic pressures (Dullinger et al.,

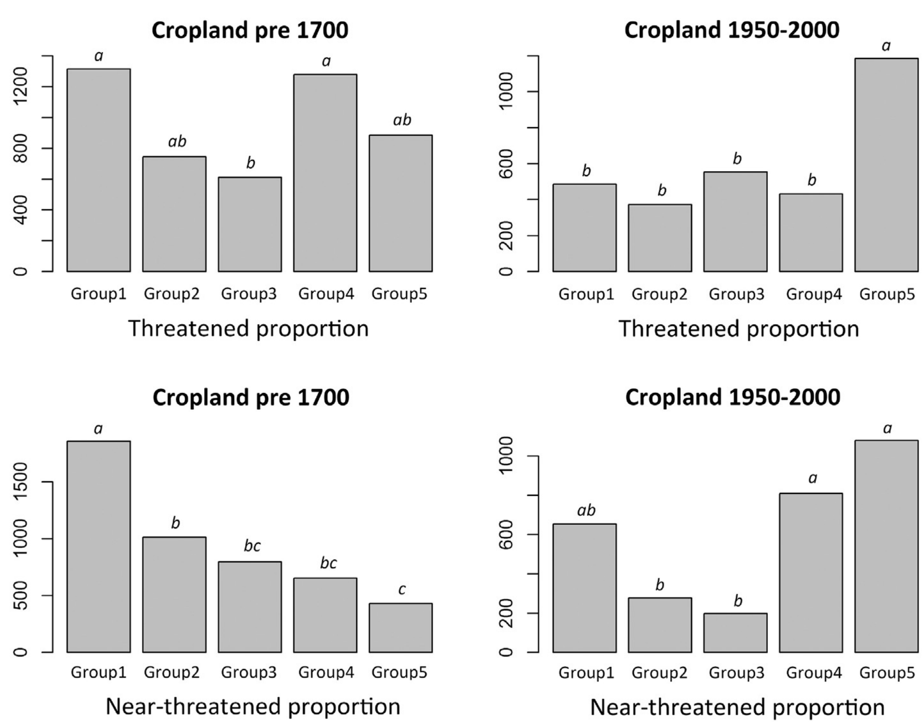

Fig. 4. Cropland area of different groups of grid cells according to the proportion of threatened/near-threatened species. Group 5 has the 180 cells with the highest proportions, while Group 1 has the 180 cells with the lowest proportions. Letters above bars indicate significant differences in cropland area among different groups ($p < 0.05$).

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2013). Both studies focus on the most recent history, only considering historical impacts dating back to the beginning of the 20th century (Essl et al., 2011; Dullinger et al., 2013).

China's long history of dense human populations and associated agriculture provides a chance to study the effects of deeper-time anthropogenic activities on species distribution and diversity patterns (Goldewijk et al., 2011). In this study, we indeed found that anthropogenic activities before 1700 were better at predicting proportions of threatened and near-threatened plant species than later land use changes. This result is in line with the European studies, in which historical socioeconomic conditions are better predictors than current conditions (Essl et al., 2011; Dullinger et al., 2013).

We found that proportions of threatened and near-threatened species were negatively correlated with changes in anthropogenic activities pre-1950 and especially before 1700, but positively correlated with later 1950–2000 changes, indicating that China's threatened plants are likely to be concentrated in areas with low historical, but high current human disturbance. This result is different from the European studies, in which they found positive relations for both historical and current human impacts (Essl et al., 2011; Dullinger et al., 2013). Our results imply that intense historical anthropogenic activities may have already caused many extinctions of plant species in parts of China, where they were already densely occupied and subject to strong conversion of natural land cover to cropland before 1700, as reflected in the low proportions of threatened and near-threatened plant species in these regions. Exemplifying this, fir trees (*Abies* spp.) declined in the Liupan Mountains in western China 2200 yr BP and went extinct there 530 yr BP (Sun et al., 2011). In contrast, in areas where anthropogenic disturbance is new, many species may still persist in the small natural habitat remnants, as stable, but small populations or as slowly declining remnant populations (i.e., reflecting an extinction debt; Yang and Xu, 2003).

4.3. Other drivers of threatened species

In this study, anthropogenic activities are indicated by cropland area, human population and pasture area, which may not fully represent the actual intensity of anthropogenic activities and could contribute to the relatively low correlations between the observed and predicted proportions of threatened and near-threatened plant species. Other kinds of anthropogenic activities may also affect the distribution of threatened species. For instance, expansions of urban and industrial land in China have been rapid and massive over the past decades, which could further impact cultivated land changes by leading loss of cultivated land (Deng et al., 2015; Kuang et al., 2016). Forest fragmentation and isolation as well as an increase of secondary forest, especially in southwest China, may also affect the distribution of threatened species (Brandt et al., 2012; Ahrends et al., 2015).

4.4. Applications for biodiversity conservation

Our findings point to the need to provide special conservation attention to areas that have relatively recently come under intense agricultural use, as this is where threatened species are particularly concentrated, i.e. in China towards its southwestern region. Here, habitat conservation and restoration should be a high priority to prevent their many threatened plant species from going extinct. Notably, further human expansion into natural areas in these regions should be avoided. These goals will not be easy to achieve, as China's population further increased 5.4% from 2000 to 2010, and will continue to increase for at least one more decade (Peng, 2011). Moreover, the expansion of urban population will have a much faster rate (Peng, 2011). However, it is paramount for preserving China's rich flora that effective protection and restoration of its many threatened plant species can be achieved.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.biocon.2016.05.038.

Acknowledgments

We thank the Chinese Scholarship Council (file no. 201204910187, to GF) for the financial support for GF. GF was also funded by the Starting Funding for Scientific Research from Inner Mongolia University (21400-5165111). JCS was funded by the European Research Council (ERC-2012-StG-310886-HISTFUNC) and the Danish Council for Independent Research Natural Sciences (12-125079). NGS was funded by the National Science Foundation (DBI-1262475).

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