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Predicting climate change impacts on the threatened *Quercus arbutifolia* in montane cloud forests in southern China and Vietnam: Conservation implications

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A B S T R A C T

Trees of montane cloud forests (MCFs) often have small and isolated populations and face numerous threats. Due to limited conservation resources, management decisions are often based on scarce biological information. This study investigated the current status of populations of the critically endangered oak species *Quercus arbutifolia* in southern China, including its distribution, threats, population structure, and area of occupancy (AOO). Additionally, by using ensembles of small models (ESMs), the present and future (2050) distributions of climatically suitable habitats were predicted throughout south China and Vietnam. The present distribution of *Q. arbutifolia* is extremely fragmented, with only eight confirmed populations and a very small number of individuals (ca. 1200 in total). The results presented here show that *Q. arbutifolia* populations suffer from habitat destruction and fragmentation, small population size, unbalanced population structure, and pressure from strong competitor species, even though all known occurrences of *Q. arbutifolia* are in already established nature reserves. Based on the utilized models, the current potential distribution is limited to MCFs, and 17 new areas were predicted to have complete habitats suitability for *Q. arbutifolia*. However, only a small area in Fujian province will remain suitable for *Q. arbutifolia* in the future. The current AOO of *Q. arbutifolia* is very small (8.49 km^2), with one-third of all populations predicted to be extinct by 2050, even under the minimum emission assumption. Finally, various actions and conservation measures, such as search for new unknown populations as well as *ex situ* and *in situ* conservation, are introduced and discussed in this paper.

1. Introduction

Global climate change significantly impacts on species distribution, causing reductions in population size, and even extinction or extirpation of range-restricted or isolated species and populations (Feeley et al., 2013; Mawdsley et al., 2009; Pounds et al., 1999; Prieto-Torres et al., 2016; Root et al., 2003). Additionally, habitat destruction, fragmentation, and over-exploitation, can easily lead to the extinction of endangered species (Lomba et al., 2010; Ma et al., 2013; Ren et al., 2012). This poses severe challenges for the conservation and management of endangered species. Furthermore, a substantial gap exists between conservation science and the practical application of conservation measures by policy makers (Levin et al., 2013). On the one hand, species distribution models (SDMs) can predict the current and future suitable habitats; on the other hand, corresponding research with the aim to better incorporate a range of threatening processes, both ecological and evolutionary, is needed to provide viable conservation plans for endangered species (Joseph et al., 2009; Levin et al., 2013).

Species distribution models map the relationships between species distribution and environmental conditions (Booth et al., 2014), and can be used to project the spatial distribution of species in regions without biodiversity observations (Guisan and Thuiller, 2005; Tulloch et al.,

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2016). Thus, SDMs have become a powerful tool in both ecology and applied conservation biology (Ferrer-Sanchez and Rodriguez-Estrella, 2016; Rodriguez et al., 2007; Royzar et al., 2016; Tang et al., 2017). However, the modeling of endangered or rare species remains difficult, due to a combination of few occurrences and many predictor variables, which could easily leads to model overfitting (Breiner et al., 2015). Ensembles of small models (ESMs) is a novel strategy for species distribution models that enables the analyses of a small number of observations, and has been shown to be superior to standard models in terms of model performance and transferability (Breiner et al., 2015, 2018; Lomba et al., 2010). The ESMs can provide accurate forecasts of range dynamics under climate change scenarios, and identify suitable habitats for recolonization patterns of threatened species with restricted distribution.

Montane cloud forests (MCFs), which occur between 1000 and 3000 m a.s.l., are located in tropical and subtropical regions of the world, and are frequently enveloped by trade wind-derived orographic clouds and mist. Due to their dependency on the local climate, they are strongly affected by global climate change (Chu et al., 2014; Foster, 2001; Still et al., 1999). MCFs are renowned for their high biodiversity and their exceptional concentration of endemic species (Toledo-Aceves et al., 2011; Foster, 2001). However, suitable habitats for species that are endemic to MCFs are limited and often highly fragmented, resembling sky islands. Under pressures of anthropogenic disturbances and global climate change, MCFs have been recognized as one of the most threatened terrestrial ecosystems and are rapidly disappearing (Feeley and Rehm, 2015; Morueta-Holme et al., 2015; Rehm, 2014; Ulrey et al., 2016; Williams-Linera, 2002). Both the conservation and restoration of endangered species in MCFs are top priorities for the maintenance of biodiversity. The novel approach of ESMs provides a method for the precise prediction of potentially suitable habitats for endemic species in MCFs.

Quercus arbutifolia is a critically endangered species in southern China and Vietnam that is restricted to highly fragmented MCFs between 1000 and 2000 m a.s.l. (Fig. 1A) (Deng et al., 2011a; Huang et al., 1999; Oldfield and Eastwood, 2007). A previous population genetic study based on five known populations of *Q. arbutifolia* in China indicated both high genetic differentiation among populations and genetic diversity within populations (Xu et al., 2016).

Recent studies assessed the impact of present and future global climate change on species' ranges; however, the potentially confounding effect exerted by current population threats on their future existence has not been evaluated to date. The aim of this study was to use *Q. arbutifolia* as a model taxon, and to explore the threats of the current distribution and population status of this representative endangered woody species in MCFs in response to global climate change. More specifically, the following questions were addressed: (1) What is the present global geographical distribution and current conservation status of *Q. arbutifolia*? (2) What are the threats observed in the *Q. arbutifolia* populations of southern China? (3) What is the accurate current potential distribution of *Q. arbutifolia*, as indicated by using the ESMs approach? (4) Where will the last suitable habitats be under the future climate conditions of 2050? (5) What will be the change in area of occupancy (AOO) and the upslope distribution shift in all known populations of southern China? Finally, based on the results of this study and of previously obtained relevant data (Xu et al., 2016), the consequences of climate change on threatened and extremely rare woody species in MCFs are discussed, with the ultimate goal to provide systematic conservation and management guidelines for the long-term conservation of *Q. arbutifolia*.

2. Materials and methods

2.1. Data collection and field survey

Occurrence data with geographical coordinates of *Q. arbutifolia* were compiled from the Chinese Virtual Herbarium (CVH, 2016), the Global Biodiversity Information Facility (GBIF, 2016), and all publications related to *Q. arbutifolia*. In total, 10 *Q. arbutifolia* sites were identified in China and Vietnam after synthesis of all available information (Table 1), eight of which could be confirmed during field surveys. Additionally, between 2011 and 2016, an intensive field survey was conducted and an additional 31 sites were visited with similar habitat to *Q. arbutifolia* in south China and north Vietnam (Fig. S1). However, these surveys did not discover any new populations.

All eight *Q. arbutifolia* populations in south China were investigated in detail using the methodology of Kozlowski et al. (2014), adapted for *Q. arbutifolia*. In each of the investigated populations, the lower and upper elevation (m a.s.l.) and the slope exposition were measured, and the boundaries of extant population were drawn on a map. In small populations (1–100 individuals), the entire area covered with *Q. arbutifolia* was investigated. In large populations (> 100 individuals), the lower and upper boundaries were investigated in detail, while the central part of the population was explored using transect along the road, followed by extrapolation for the whole area. Additionally, the survey of the big population in the Luo-Keng Nature Reserve used literature data (Wang et al., 2008) and personal communication of the local nature reserve staff.

In each population, the number of individuals was counted and the population age structure was elucidated by categorizing each counted and measured individual: adult (trunk above 3 m), intermediate (between 1 and 3 m), and plantlets (between 0.1 and 1 m). Additionally, the fruit yield was estimated, based on long-term observations of the staff in all investigated protected areas. During the field survey, three main threats have been investigated: (1) soil erosion, (2) habitat destruction caused by agricultural expansion and touristic development, and (3) the *Q. arbutifolia* habitat invasion by fast-growing species (e.g. bamboo and grasses) from the upper or lower elevations.

2.2. Species distribution modeling with ESMs

All occurrence data of *Q. arbutifolia* were used for the analyses, including re-evaluated populations in southern China and historical records from Vietnam. To run the model, a random sample of 10,000 pseudo-absence points was generated within the studied area (Fig. 2A). Defining the study required the delineation of an ecological unit, which is accessible for species (Barve et al., 2011). The study area was defined as the bio-regions covered by the species occurrences (Olson et al., 2001). A set of 19 bioclimatic variables at a 30 arc sec resolution that covers the distribution range of *Q. arbutifolia* under the current conditions was downloaded from the WorldClim website (Hijmans et al., 2005). Additionally, the aridity index (Trabucco and Zomer, 2009) and topographical index (computed in QGIS, indicating concavity/convexity) were included. The background data used in these analyses are the ecoregions (south China-Vietnam subtropical evergreen forests) covered by *Q. arbutifolia*.

Based on a Spearman correlation, the 21 variables were clustered into six groups, showing a correlation below 0.7 on average. Then, a univariate permutation *t-test* was performed along each variable and the variables that better discriminate the presences from the background data were retained. Finally, the correlated variables were removed and the six uncorrelated variables provided by the evaluation were retained (see subsection 3.2).

The ESMs approach was employed as modeling algorithm, since *Q. arbutifolia* is a rare species with very restricted occurrence data. ESMs generate models with all bivariate combinations among the selected variables and only retain good bivariate models, then combining all possible bivariate models into an ensemble (Lomba et al., 2010). In this study, three different modeling techniques were explored: maximum entropy (Maxent), generalized boosted models (GBM), and generalized additive models (GAM). Each bivariate model was evaluated using a split sample approach: 80% of the data were used to calibrate the model

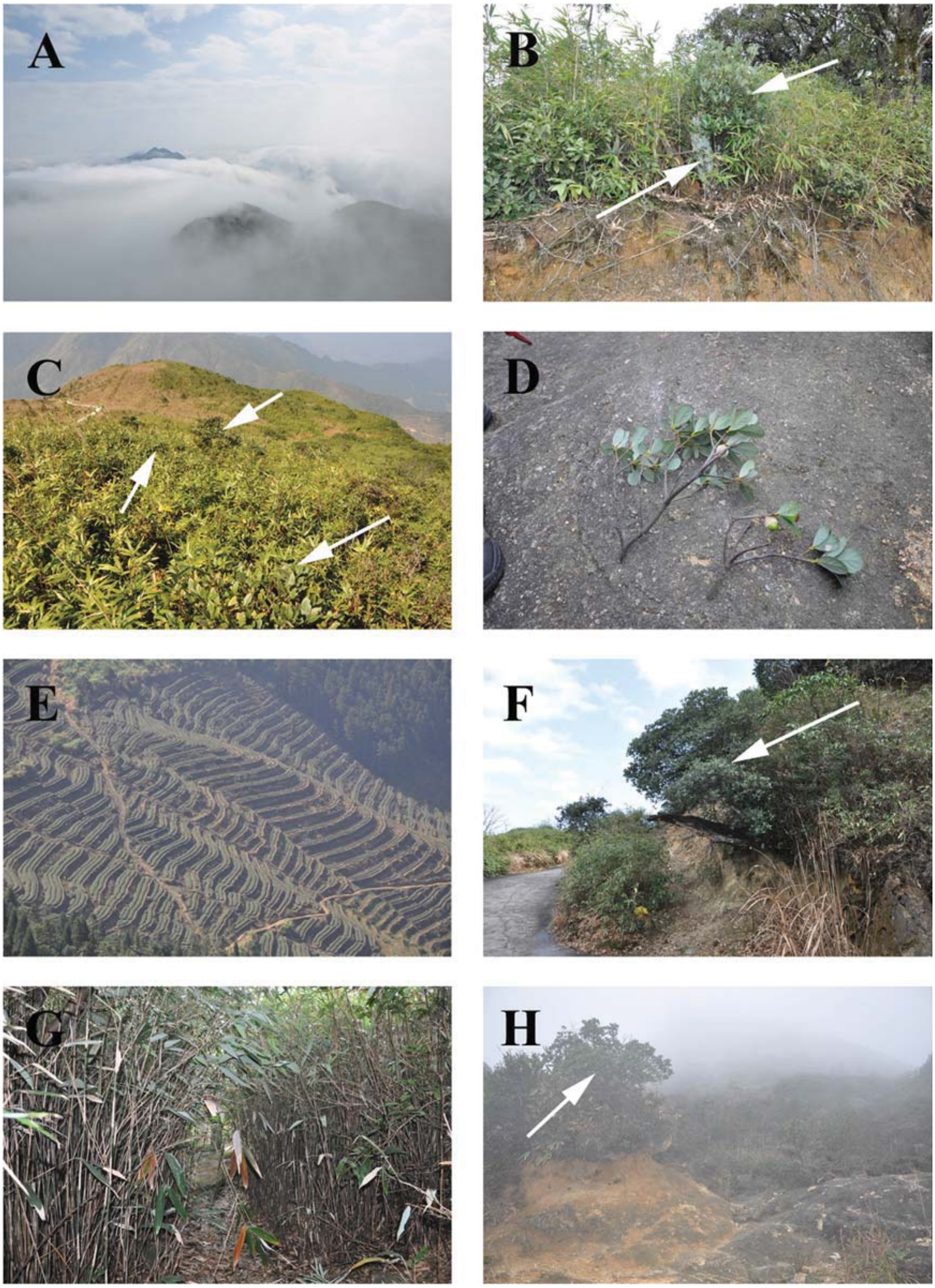

Fig. 1. Habitats and threats of Quercus arbutifolia. (A) Montane cloud forests in NL; (B) Q. arbutifolia re-sprouted from old stumps and surrounded by bamboo in NL; (C) scattered Q. arbutifolia individuals in bamboo thicket in DQ; (D) scarce fruit production; (E) habitat degradation: establishment of tee plantation in the vicinity of DQ; (F) forest exploitation and road construction leading to mortality of old trees in NL; (G) domination of competitor species (bamboo) in GY; (H) soil erosion in GY. White arrows indicate Q. arbutifolia individuals. For abbreviations of populations see Table 1.

and 20% of the data were used to evaluate the model; this process was repeated 10 times. The area under the receiver operating characteristics curve (AUC) was used (Hanley and McNeil, 1982) as evaluation index and only models were retained with an AUC ≥ 0.7 in the ensemble of models. The remaining models were weighted following their AUC in the final ensemble model:

$$w = (2 \cdot AUC) - 1$$

The distribution models for *Q. arbutifolia* under current and future climate change conditions (climate scenarios in 2050) were projected in

Table 1
Geographical information of all *Quercus arbutifolia* sites investigated in this study.

Population	Province, Country	Latitude (°N)	Longitude (°E)	Lower-upper (mean) elevation (m a.s.l.)	Major peak (m a.s.l.)	Slope exposition
MH (Mei-Hua Mountain National Nature Reserve)	Fujian, China	25.35	116.83	1450–1700 (1575)	1811	E/SE
YZ (Yun-Zhong Mountain Nature Reserve)	Fujian, China	25.32	117.68	1450–1550 (1500)	1600	S
NL (Nan-Ling National Nature Reserve)	Guangdong, China	24.92	112.98	1500–1900 (1700)	1902	S
LK (Luo-Keng Nature Reserve)	Guangdong, China	24.48	113.25	1000–1500 (1250)	1587	N/NE
DQ (Da-Qin Mountain Nature Reserve)	Fujian, China	24.21	117.11	1200–1500 (1350)	1545	N
TG (Tong-Gu-Zhang Nature Reserve)	Guangdong, China	24.18	116.35	1250–1500 (1375)	1560	N/NE
GY (Guan-Yin Mountain Nature Reserve)	Guangdong, China	23.96	113.53	1000–1100 (1050)	1288	E
DM (Da-Ming Mountain National Nature Reserve)	Guangxi, China	23.48	108.44	1400–1500 (1450)	1785	S/SE
QT (Tiger Mountain)	Quang Tri, Vietnam	16.76	106.73	na	na	na
NT (Annam)	Nha Trang, Vietnam	12.22	108.72	na	na	na

this study. To predict potential shifts in the geographic distribution that might be the result of global climate change, three different general circulation models (GCMs) were used: HadGem ES, MIROC-EMS, and BCC-CSM, since these achieve the best consensus among the various available GCMs. These three models were run in two of the four representative concentration pathways (RCPs) that were used in the Fifth Assessment IPCC report: RCP 4.5 and RCP 8.5. RCP 4.5 represents the middle extreme scenario, while RCP 8.5 represents the most extreme scenario. Model predictions were imported into a geographic information system (GIS), and maps were generated using QGIS 3.0 (QGIS Development Team, 2018). Five arbitrary categories of habitat suitability for *Q. arbutifolia* were defined according to no suitability (0), low suitability (250), medium suitability (500), high suitability (750), and complete suitability (1000) based on predicted habitat suitability scores.

Predicted species distribution in climates that are not part of the calibration data should be carefully interpreted, because species distribution models are not evaluated in such novel climates (Mesgaran et al., 2014). Here, an existing approach was used and implemented in the ecospat R library (Di Cola et al., 2017), which emphasizes that future climates that do not exist during current conditions.

2.3. *Calculation of the current and future area of occupancy (AOO)*

Based on the utilized survey data, the boundaries were drawn on the map for all eight populations in China, and the current AOO was measured using Google Earth Pro (download from: https://www.google.com/earth/download/gep/agree.html). Additionally, the future AOO (2050) was also measured under two different simulations:

Simulation 1 (AOO-S1): Upslope distributional shifts of montane species were assumed in response to global climate warming based on Dullinger et al. (2004), Morueta-Holme et al. (2015), and Feeley et al. (2013). The underlying assumption is that the lower elevational limits of *Q. arbutifolia* will upslope under global warming. Temperature decreases by an average of 0.6 °C for each 100 m increase in elevation (Berry, 2008). Climate data (BIO1 to BIO19) were obtained from WorldClim (Version 1.4) with a spatial resolution of 30 arc sec. Climate projections for BC-RPC26 (RCP 2.6: assumes that the global annual greenhouse gas peak between 2010 and 2020) of 2050 under the general circulation models (GCMs) were used for this analysis. In this simulation, the AOO in 2050 (AOO-S1) was calculated under the smallest climate change.

Simulation 2 (AOO-S2): Based on the studies of on the southeastern slope of the Chimborazo volcano in Ecuador, Morueta-Holme et al. (2015) and Feeley and Rehm (2015) assumed that montane grasslands can prevent woody species in MCFs from shifting their leading edges upslope. Thus, in this simulation, the underlying assumption of simulation 1 is that the upper distributional limits of *Q. arbutifolia* would be stable, while the lower elevational limits of *Q. arbutifolia* would still upslope in response to global warming. Then, using the same methods of simulation 1, the AOO of *Q. arbutifolia* populations in 2050 was evaluated under this assumption (AOO-S2).

3. Results

3.1. *Distribution and conservation status of Q. Arbutifolia*

According to this survey, globally, only two population records exist for *Q. arbutifolia* from 90 years ago in Vietnam, as well as eight recently confirmed populations in southern China. The abbreviations of each population are listed in Table 1. *Q. arbutifolia* is an extremely rare species, with a very scattered distribution of approximately 12–25°N and 106–117°E in southern China and Vietnam, encompassing both subtropical and tropical MCFs (Table 1).

The species occurs exclusively in MCFs with elevations between 1000 and 1900 m a.s.l. The elevational span of *Q. arbutifolia* in each population is very narrow (less than 500 m), and three populations occur within only 100 m spans (YZ, GY, and DM). Moreover, the upper limits of each population are located near or on top of mountains. *Quercus arbutifolia* preferentially grows on sunny slopes or sunny positions along ridgelines (Table 1).

A total of less than 1200 individuals of *Q. arbutifolia* have been found, and the populations are extremely small, with 50 individuals per population or less in half of the surveyed populations (DQ, TG, GY, and DM). The largest population was found in NL, with 500 individuals or less (Table 2).

All populations showed an asymmetric population structure, where most of the individuals are old or have re-sprouted from old stumps (Fig. 1B), indicating low seedling establishment (Table 2). It was difficult to find seedlings in MH, YZ, DQ, TG, GY, and DM populations, and all young trees in these populations look as if they were older than several decades (Table 2, Fig. S2A–C). Furthermore, most individuals were scrubby (2.5–5 m), and only few individuals at lower elevations grew to a height of 10 m, showing a tree-like form. Individuals with a tree form were only found in MH, NL, and LK populations, and all individuals in other populations were scrubby (Figs. 1C, S2D–F).

Although all populations produce acorns, in the majority of populations, only few individuals produce a small number of fruits per year (e.g. YZ, DQ, TG, GY, and DM). Moreover, based on the conducted surveys and personal communication of the nature reserve staff, only one or two masting years have occurred over the last six years. Thus, even the big populations of MH and NL had an abundance of acorns only during the masting years (Table 2, Fig. 1D).

The obtained data show that even though all investigated populations of *Q. arbutifolia* were located in established nature reserves (Table 1), the trees still suffered from habitat destruction and fragmentation, as well as from pressure of strong competitor species (Table 2).

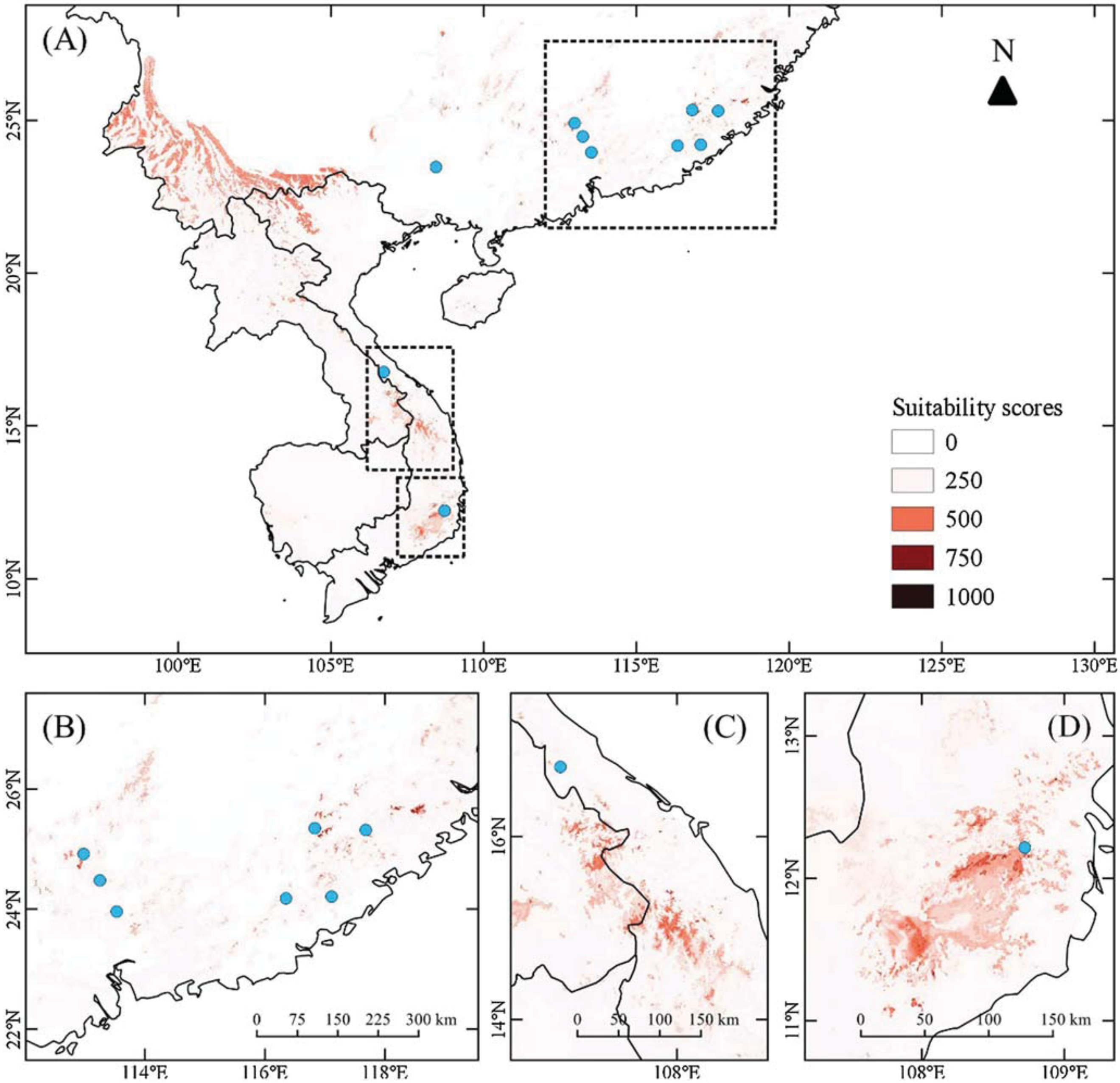

Fig. 2. Present and potential distribution of *Quercus arbutifolia* under the current climate. Blue dots: known occurrences of *Q. arbutifolia* investigated in this study. (A) The whole study area; (B) Fujian and eastern Guangdong in China, (C) the central highlands of Vietnam, and (D) the south-central coast of Vietnam. Explanation of pixels shaded in different colors: white (0), no suitability; pink (250), low suitability; orange-yellow (500), medium suitability; red (750), high suitability; and black (1000), complete suitability. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Characterization of all populations of *Quercus arbutifolia* investigated in this study. Population age structure (adult individuals: intermediate individuals: plantlets); AOO: area of occupancy (km^2), AOO-S1: area of occupancy in 2050 (km^2) under simulation 1. AOO-S2: area of occupancy in 2050 (km^2) under simulation 2. Threat intensity: ****: extreme, ***: strong, **: relatively low, *: negligible. For abbreviations of populations see Table 1.

	MH	YZ	NL	LK	DQ	TG	GY	DM
Number of individuals	90	100	500	300	40	50	40	50
Population structure (%)	25:75:0	65:35:0	65:30:5	40:55:5	0:100:0	45:50:5	55:45:0	15:85:0
Fruit yield	abundant	scarce	abundant	abundant	scarce	scarce	scarce	scarce
Competitor species (bamboo)	**	**	***	**	****	***	***	***
Habitat destruction	**	**	***	**	****	***	**	***
Soil erosion	***	**	**	**	**	*	****	***
Current AOO	0.99	0.40	1.98	3.51	0.51	0.68	0.10	0.32
Future AOO-S1	0.17	0.00	0.56	1.18	0.64	0.32	0.00	0.00
Future AOO-S2	0.17	0.00	0.42	0.90	0.12	0.13	0.00	0.00

The most dramatic habitat destruction due to agriculture was observed in the forests of the DQ population (Table 2, Fig. 1E). Additionally, in the DM, TG, and NL populations, the *Q. arbutifolia* habitat was heavily affected by touristic development (Table 2, Figs. 1B and F, S2G–H). Furthermore, most of the populations, are rapidly becoming dominated by fast-growing vegetation (Table 2, Fig. 1G). In general, the most threatening fast-growing species that compete for habitat with *Q. arbutifolia* is bamboo. For example, in the DQ population, *Q. arbutifolia* individuals are scattered among bamboo thickets (Fig. 1C); and in the GY population, large areas next to *Q. arbutifolia* have been completely occupied by bamboo (Fig. 1G). In other locations, *Q. arbutifolia* forests were often surrounded by bamboo thickets and grasslands at the upper and lower boundaries, starting to invade the oak stands (Fig. S2I–L). Finally, soil erosion forms a significant threat to *Q. arbutifolia* in the GY and MH populations (Table 2, Fig. 1H).

3.2. Model performance and prediction of current potential distribution

Six variables were selected for use in the ESMs: topography, maximum temperature of the warmest month, annual precipitation, precipitation of the driest quarter, annual temperature range, and mean temperature of the warmest quarter. Among the 45 ‘small’ bivariate models, 13 had an AUC below 0.7 and were therefore not included in the final ensemble models. The remaining 32 models had an average AUC of 0.86 $\pm$ 0.1.

According to the obtained results, three regions with suitable habitats for *Q. arbutifolia* were detected: Fujian and the eastern part of Guangdong provinces in China, the central highlands in Vietnam, and the south-central coastal region of Vietnam. By analyzing detailed maps, a further 17 mountainous areas were defined as perimeters with complete habitat suitability (Fig. 2, Table S1).

3.3. Potential distribution under future climate conditions (2050)

Under both investigated climatic scenarios (RCP 4.5 and RCP 8.5), the total number of potentially suitable *Q. arbutifolia* habitats will be considerably reduced by 2050 (Figs. 2–4). Only three mountain chains will remain highly suitable for this species under the RCP 4.5 scenario and two mountains under the RCP 8.5 scenario. These habitats are all exclusively located in the Fujian province (Figs. 3 and 4). In other areas (Guangdong in China, and central and south highlands of Vietnam), habitats with medium and high suitability will completely disappear or will be strongly decreased compared to the current situation (Figs. 2–4). Non-analog climate mostly affects lowland areas, which is not covered by actual or potential species distributions (Fig. S3). Thus, regardless of which scenario is applied, the utilized models predict that the current *Q. arbutifolia* habitats will experience a dramatic reduction. As a consequence, climatically suitable habitats in the regions will be decreased from the current 25 mountain regions to only two regions by 2050, located in the Dai-Yun and Shi-Niu Mountains of Fujian province (Figs. 3 and 4, Table S1).

3.4. Current and future area of occurrence (AOO)

The total current AOO of all mapped *Q. arbutifolia* populations in southern China is 8.49 km^2. Only two populations (NL and LK) have distribution areas exceeding 1 km^2. The smallest population (GY) has a distribution area of 0.10 km^2. Under simulation 1, only five populations will survive under the climatic changes (62.5%), leaving a total of 2.87 km^2 in 2050 (33.8% of the current area), of which the largest population is LK with 1.18 km^2 (Table 2, Fig. S4). Under simulation 2, the total AOO of *Q. arbutifolia* will be reduced to 1.74 km^2 (20.5% of the current area), and all populations will be smaller than 1 km^2 (Table 2, Fig. S4).

4. Discussion

Climate is one of the primary factors that limit species distribution at the geographic scale (Loidi et al., 2010; Pearson and Dawson, 2003). SDMs are powerful research tools and have been widely applied to aid conservation decision-making (Fois et al., 2015; Tulloch et al., 2016). In SDM climate change analyses of tree species, climatic requirements should not only be estimated using data from natural distributions, but also from trial plantings outside of their natural range (Booth, 2017). Since no *ex situ* data were available for *Q. arbutifolia* (BGCI, 2019), this study adopted the equilibrium assumption that analysis of the natural distribution only provides a reliable estimate of the climatic requirements of this species.

At landscape scales, species distribution is more likely governed by local conditions (Hansen et al., 2001; Qian et al., 2016). MCFs, with their strong dependency on local climatic conditions, will be particularly affected by global climate change (Chu et al., 2014; Still et al., 1999). Both SDMs and the monitoring of local populations are very important for the management and conservation of endangered species (Menges and Gordon, 1996; Qian et al., 2016).

4.1. Current status of Q. arbutifolia populations

Species in the MCFs face threats of habitat loss, fragmentation, and degradation, with the added natural vulnerability of narrow elevational ranges (Ocampo-Penuela and Pimm, 2015). Endemic species with narrow elevational ranges are particularly susceptible to such decreases of range size, since these might significantly reduce the population size (Hermes et al., 2018). The typical MCFs that are characteristic for *Q. arbutifolia*, with their fragmented habitat and very narrow elevational span in each population, indicate the high conservation value of this species.

It is generally accepted, that population size is a major determinant of extinction risk: the smaller the population, the more susceptible it is to extinction due to various causes, such as environmental stochasticity, natural catastrophes, and habitat loss (Brook et al., 2006; Shaffer, 1981; Traill et al., 2007). Additionally, the environmental fluctuations and life history characteristics of the species can cause recruitment failures (Qian et al., 2016; Reed et al., 2003). The results of this study show that each of the investigated *Q. arbutifolia* population has a very small population size. Any deliberate or accidental detrimental event could ultimately cause extinction of an entire population. Thus, its small population size is one of the main threats of this species. The individuals of the two big populations (NL and LK) were estimated and require further investigations. Unfortunately, according to the obtained results, *Q. arbutifolia* also faces a severe survival threat due to its asymmetric population structure, severe habitat destruction, and strong competition of fast-growing plants.

4.2. ESMs: Important tool for the discovery of new populations of threatened trees

Since the completion of the Flora of China two decades ago (Huang et al., 1999), surveys of regional Chinese flora remain limited. Still, three new populations (DM, TG, and YZ) of *Q. arbutifolia* were discovered during the last ten years (Deng et al., 2011b; Qian, 2009; Zeng, 2010). One of the main difficulties for this identification of new populations is the specific characteristic and inaccessibility of *Q. arbutifolia* habitats. It was recently demonstrated, that ESMs offer useful methods that have increasingly been used to predict species distributions and to detect previously unknown populations of endangered species (de Siqueira et al., 2009; Fois et al., 2015; Jimenez-Valverde et al., 2008; Williams et al., 2009). This study predicted 17 new areas with complete habitat suitability for *Q. arbutifolia*, which are mainly distributed in the provinces of Fujian and Guangdong (Table S1). This work narrowed target areas for future field surveys, and thus greatly

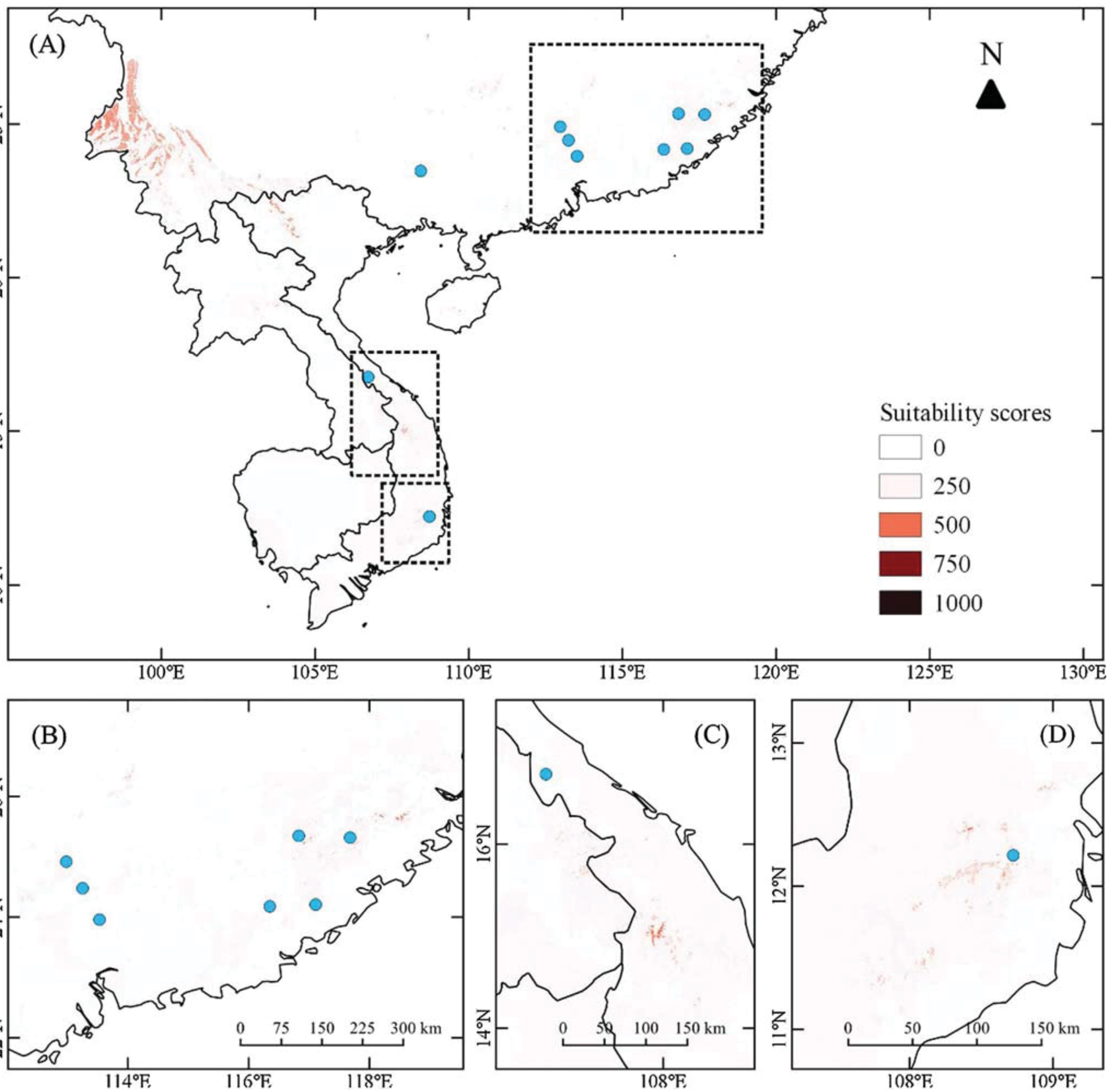

Fig. 3. Suitability of habitats for *Quercus arbutifolia* under future climatic scenario RCP 4.5 in 2050. Capital letters represent the same projected areas as shown in Fig. 2. The explanation of the shaded pixels is identical to that in Fig. 2.

improved the time and cost efficiency of the related conservation practices. This is particularly the case for Vietnam, where no recent records are available and where it is very likely that these stands no longer exist (FIPI, 1996; Nghia, 2000). Thus, new field surveys in search for *Q. arbutifolia* are urgently required in the central highlands and the south-central coastal area of Vietnam.

4.3. *Quercus arbutifolia: A MCFs tree at the brink of extinction*

Quercus arbutifolia grows near the top of the mountains in MCFs. This spatial limitation might cause a rapid loss of suitable habitats. The ESMs also predict a dramatic reduction of suitable habitats until 2050. Species that are sensitive to global warming may shift their species ranges to cooler locations at higher elevations or latitudes (Feeley et al., 2013; Molina-Martibez et al., 2016; Tang et al., 2017). However, since acorns possess a very limited dispersal ability and low seedling establishment rate (Valkonen, 2008; Xu et al., 2016), rapid increases in temperature could easily wipe out species and lead to regional or even global extinction. Additionally, their general rarity and long distances among MCFs habitats make establishment of new populations at different latitudes very unlikely.

According to the conducted simulations, the AOO of eight known populations in China will significantly decrease (indicating that one-third of the populations might be extinct by 2050), even under a minimum emission scenario of future climate warming. This study demonstrates that the upper limits of distribution of most *Q. arbutifolia* populations are located near the top or on the top of mountains. Additionally, the dense bamboo thickets on the upper limits of *Q. arbutifolia* populations will prevent any establishment of woody species and make their upward shift impossible. Thus, this study provided strong support for the assumption that the upper limit of the tree line in MCFs can hardly change or will even show a downward shift (Morueta-

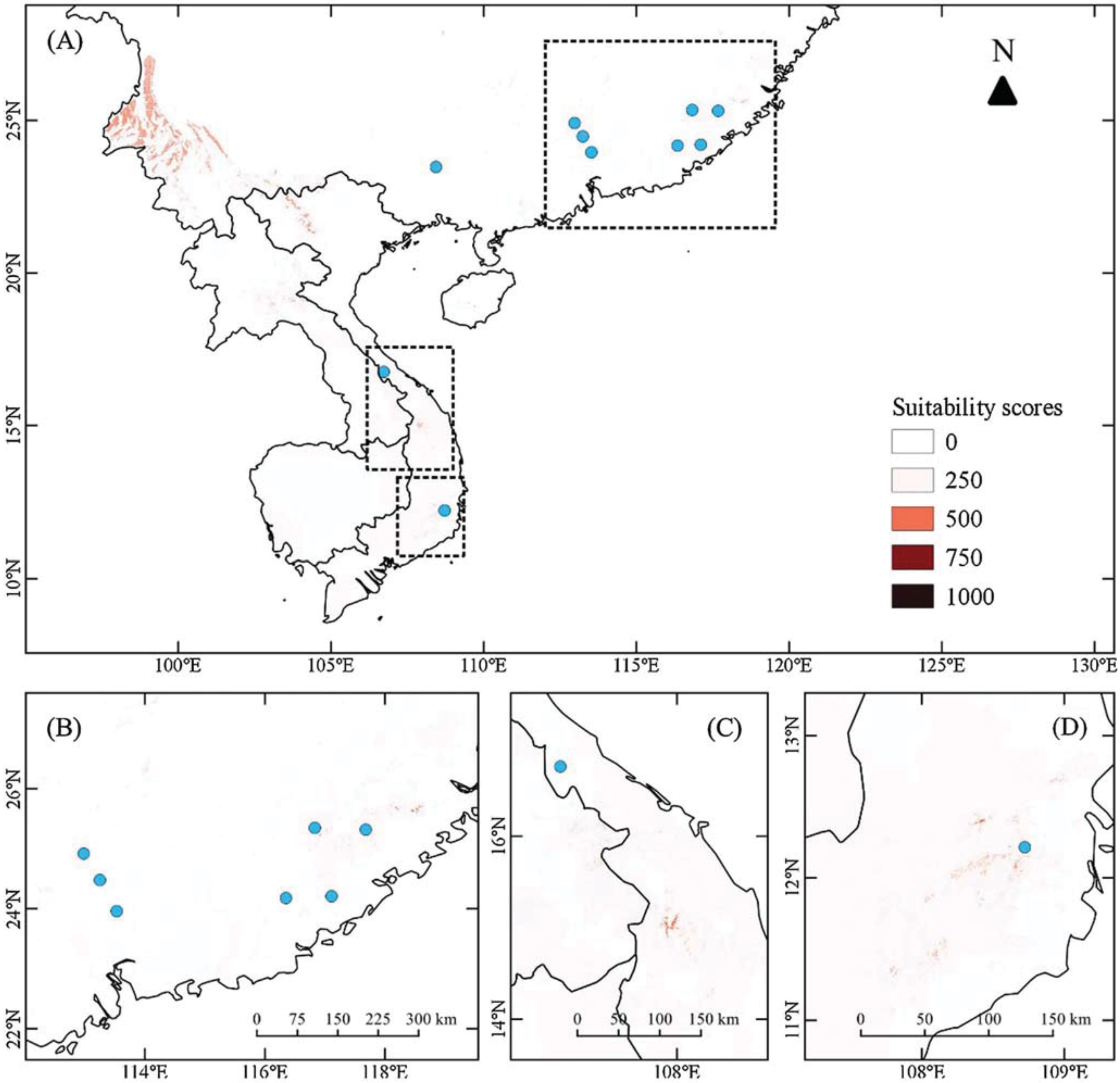

Fig. 4. Suitability of habitats for *Quercus arbutifolia* under future climatic scenario RCP 8.5 in 2050. Capital letters represent the same projected areas as shown in Fig. 2. The explanation of shaded pixels is identical to that in Fig. 2.

Holme et al., 2015).

Many plants are considered as ecological conservatives, which cannot sufficiently adapt to changing climatic conditions (Tang et al., 2017). *Quercus arbutifolia* is a habitat specialist of MCFs, defined by its narrow elevational ranges and small population size. Thus, niche evolution might be impossible for this taxon. Climate change appears to be the main driver of distributional changes, and the populations are under more immediate threats by habitat destruction due to land use changes and competitive species. Therefore, according to the conducted models, *Q. arbutifolia* requires long-term conservation practices as described in the following section.

5. Conservation implications and management recommendations

To assure long-term conservation of the threatened *Q. arbutifolia* and its populations, the following research, conservation, and management actions must commence.

5.1. Search for new populations

Intensive field surveys in all 17 localities with complete suitability habitat of *Q. arbutifolia* presence as elucidated by the models utilized in this study (see Table S1) should be undertaken. Any new discovery of an additional population would significantly improve the knowledge of this species, and improve the conservation of MCFs in the ecoregions of south China-Vietnam subtropical evergreen forests.

5.2. In situ conservation and management

In situ conservation measures should be applied to all known populations of *Q. arbutifolia*. Canopy thinning of broad-leaved trees that share the same habitat, could improve understory light conditions and promote the growth and success of seedling establishment of *Q. arbutifolia*. Additionally, according to the conducted analysis, fast growing competitors cause a compression of the available habitat, both from the lower and upper boundaries. Notably, severe invasion by dense bamboos and grasslands occur in the core area and in the upper boundaries of all populations, especially in the DQ and GY populations. Removal of bamboos along with their root systems could significantly improve seedling establishment and the survival of *Q. arbutifolia* in general.

According to the current population conditions, *in situ* population restoration needs to be implemented in populations of DQ, TG, GY, and DM. Through assisted propagation, seedlings could be established and recruited in each of the natural populations. To maintain genetic diversity and to rejuvenate the population structure, it is recommended to cultivate seedlings from seeds that have been collected from each population.

5.3. Ex situ conservation

Ex situ cultures of all known *Q. arbutifolia* populations should be established, followed by transplantations and reinforcement of the threatened populations. Thus, a major coordinated effort is required to establish viable, representative, and well-documented collections at botanical gardens, arboreta, and/or in local nurseries of the protected areas. Since *Q. arbutifolia* exhibits an unexpectedly high level of genetic diversity, and high genetic uniqueness of the populations (Xu et al., 2016), all known populations should be secured with *ex situ* collections. Particular focus should be directed on populations that face significant habitat loss in current habitats (DQ and TG) and predicted habitats for 2050 (YZ, GY, and DM). Additionally, germplasm resources of *Q. arbutifolia* need to be collected and stored by relevant departments and institutions. *Ex situ* conservation of long-term suitable areas that have been predicted by the ESMs is also urgently required for *Q. arbutifolia*. Recently, a successful case of a climate change mitigation strategy of cloud forest trees with narrow distributions was reported, using so-called assisted migration (García-Hernández et al., 2019). Thus, it would be very important to consider such assisted migration of this species to areas with suitable climatic conditions.

5.4. Legal protection

The development of tourism and road constructions in MCFs with *Q. arbutifolia* should be strictly regularized by the local governmental administration. Construction of scenic areas already exerts significant negative effects on the *Q. arbutifolia* populations, e.g., road constructions that caused the death of big trees of *Q. arbutifolia* trees in NL. Any new activities that allow the access and destruction of the MCFs should be prohibited. With regard to *Q. arbutifolia*, each of the isolated and small populations is at risk of loss as a result of any deliberate or accidental events (e.g. fire).

5.5. Public awareness and outreach

Local administration and the staff of protected areas should develop public awareness and outreach programs in regions with *Q. arbutifolia* presence. As with all successful conservation activities, the involvement of local communities and organizations is critical for the long-term conservation of threatened species, and should be encouraged and supported from the earliest stages of conservation.

We believe that the conservation and management measures described above will contribute to the efficient conservation of *Q. arbutifolia*, and will be applicable more generally for other characteristic MCFs species throughout eastern and southeastern Asia.

Declaration of interest

We declare there are no conflicts of interest in this paper.

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Appendix A. Supplementary material

Supplementary data to this article can be found online

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