

PREDICTING THE POTENTIAL DISTRIBUTION OF *Pinus cernua* L.K. PHAN EX AVER., K.S. NGUYEN AND T.H. NGUYEN, A CRITICALLY ENDANGERED CONIFER SPECIES

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Received: 4 August 2023, Revised: 19 March 2024, Accepted: 14 October 2024

PREDICTING THE POTENTIAL DISTRIBUTION OF *Pinus cernua* L.K. PHAN EX AVER., K.S. NGUYEN AND T.H. NGUYEN, A CRITICALLY ENDANGERED CONIFER SPECIES. *Pinus cernua* L.K. Phan ex Aver., K.S. Nguyen and T.H. Nguyen (Pinaceae) is a critically endangered species restricted to the Laos - Vietnam border. The population of this species has been declining due to habitat loss and forest fire. Predicting the potential distribution of the species is an important priority for conservation plans and strategies. In this study, a MaxEnt model was used for predicting the potential distribution of *P. cernua* using 21 occurrence data and 13 environmental variables. Precipitation of driest month (with 32.3% of contribution), annual mean diurnal range (23.4%), elevation (18.4%), and aspect (12.3%) are crucial factors for predicting the species' potential distribution in the MaxEnt model, while remaining factors are less important factors. The suitable distribution was predicted in the north-western region of Vietnam and the adjacent regions of Son La and Thanh Hoa provinces (Vietnam) and Houaphan province (Laos) with 1,544 km² in total. The high, medium, and low suitability areas are 159 km² (10%), 475 km² (31%), and 910 km² (59%), respectively. The current protected areas do not contain many of the possible habitats for this species. Priority should be given to conservation efforts for species in these potentially suitable locations both in- and outside of current protected areas, particularly in the surrounding area of Vietnam and Laos.

Keywords: Conservation, conifer, critically endangered species, ecological niche model, geographic distribution

MEMPREDIKSI DISTRIBUSI POTENSIAL *Pinus cernua* L.K. PHAN EX AVER., K.S. NGUYEN DAN T.H. NGUYEN, SPESIES KONIFER YANG TERANCAM PUNAH SECARA KRITIS. *Pinus cernua* L.K. Phan ex Aver., K.S. Nguyen dan T.H. Nguyen (Pinaceae) adalah spesies yang terancam punah secara kritis dan terbatas di perbatasan Laos - Vietnam. Populasi spesies ini telah menurun akibat hilangnya habitat dan kebakaran hutan. Memprediksi distribusi potensial spesies ini adalah prioritas penting untuk rencana dan strategi konservasi. Dalam penelitian ini, model MaxEnt digunakan untuk memprediksi distribusi potensial *P. cernua* menggunakan 21 data kemunculan dan 13 variabel lingkungan. Curah hujan pada bulan terkering (dengan kontribusi 32,3%), rata-rata tahunan kisaran diurnal (23,4%), elevasi (18,4%), dan aspek (12,3%) adalah faktor penting untuk memprediksi distribusi potensial spesies dalam model MaxEnt, sedangkan faktor lainnya kurang penting. Distribusi yang cocok diprediksi di wilayah barat laut Vietnam dan daerah sekitar provinsi Son La dan Thanh Hoa (Vietnam) dan provinsi Houaphan (Laos) dengan total 1.544 km². Daerah dengan kesesuaian tinggi, sedang, dan rendah masing-masing adalah 159 km² (10%), 475 km² (31%), dan 910 km² (59%). Area yang dilindungi saat ini tidak mencakup banyak habitat yang mungkin untuk spesies ini. Prioritas harus diberikan kepada upaya konservasi untuk spesies di lokasi yang berpotensi sesuai ini baik di dalam maupun di luar area yang dilindungi saat ini, khususnya di daerah sekitar Vietnam dan Laos.

Kata kunci: Konservasi, konifer, spesies yang terancam punah secara kritis, model relung ekologi, distribusi geografis

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I. INTRODUCTION

Globally, a large number of species (approximately 20 percent) are on the verge of extinction (Brummitt & Bachman, 2010; Brummitt et al., 2012) due to habitat degradation and fragmentation, alien species invasion, overexploitation, increasing human population, and climate change (Barnosky et al., 2011; Haddad et al., 2015; Nogu   et al., 2009). The rare, endemic species distributed in fragmented and narrow (and single) geographical areas (I  ik, 2011; Jump & Penuelas, 2005; Primack, 2006) are prone to environmental changes. Gymnosperms (i.e., conifers, cycads) are the most threatened group (Brummitt & Bachman, 2010; Brummitt et al., 2012), with about 40 percent of the conifer species at risk of extinction, especially in the Asia region (Forest et al., 2018; IUCN, 2023a; Magri et al., 2020; Rosenblad et al., 2019). Therefore, endemic species (i.e., conifers) are important targets for conservation and management (Myers et al., 2000; Rosenblad et al., 2019).

To conserve endemic and threatened species, detailed knowledge on the range of their potential distribution is necessary. However, incomplete information on the distribution of endemic and threatened species has caused many difficulties in conservation and management activities (Gogol-Prokurat, 2011; Mousikos et al., 2021). Species distribution modeling (or ecological niche modeling) has been an effective approach to determine the current potential distribution areas and identify the environmental requirements of species (Guisan et al., 2002; Giriraj et al., 2008; Gogol-Prokurat, 2011), project the species distribution in the past, and assess the influence of climate change on species distribution (Dai et al., 2022; Qin et al., 2017), which may help managers and conservationists save time and budget to inform conservation planning and decisions. Among species distribution models, Maximum Entropy (MaxEnt) is considered to be a popular model for estimating the potential distribution areas

of species, especially endemic and threatened species, because it has some advantages: 1) It requires only species occurrence (even small size) data and environmental information as input data; 2) Both continuous and categorical data are simultaneously handled; and 3) It tests model robustness using cross-validation, bootstrapping, and repeated subsampling in replicated runs. (Phillips, Anderson, & Schapire, 2006; Phillips & Dud  k, 2008; Elith et al., 2011; Garcia et al., 2013; Wang et al., 2015). *Pinus cernua* L.K. Phan ex Aver., K.S. Nguyen and T.H. Nguyen has been listed as Critically Endangered (CR) in the International Union for Conservation of Nature Red List (IUCN, 2023b), distributed on very steep slopes and cliffs at approximately 900 – 1,800 m a.s.l., on the transboundary range between Son La (Vietnam) and Houaphan (Laos) provinces (Averyanov et al., 2014; Averyanov et al., 2015; Averyanov et al., 2017; Loc et al., 2017). The population of the species is small, with more than 250 mature individuals, but the population has declined significantly due to deforestation and loss of habitat related to wildfire and human activities (i.e. illegal logging) (Averyanov et al., 2015; Averyanov et al., 2017; IUCN, 2023b).

In recent years, studies have focused on seed germination, seedling cultivation, and biological characteristics of *P. cernua* (Averyanov et al., 2015; Hoa et al., 2016; Loc et al., 2017). However, the information may not be adequate to build a scientific conservation plan for the species. Thus, a comprehensive study on the potential distribution and environmental requirements of *P. cernua* is essential for conservation aspects.

In this study, we predicted the possible habitat range of *P. cernua* using data of its presence in northern Vietnam and Laos, and utilized Maxent modeling to identify the important environmental factors affecting *P. cernua* distribution. The results of this investigation could help with planning for the species' conservation.

II. MATERIALS AND METHODS

A. Species occurrence data

Twenty-one location points of *P. cernua* were obtained from previous published literatures, including Averyanov et al. (2014), Averyanov et al. (2015), Hoa et al. (2016), and Loc et al. (2017), used in this study. (Figure 1).

B. Environmental variables

Twenty-four variables were selected and used as predictors in models (Table 1). In particular, 19 bioclimatic variables from 1970 to 2000 were

obtained from the WorldClim website <http://www.worldclim.org/> (Fick & Hijmans, 2017) at 1 km resolution. The elevation variable with the resolution of approx. 90m was extracted from the Global Digital Elevation Map (GDEM) generated from the CGIAR Consortium for Spatial Information (<https://srtm.csi.cgiar.org>) (Jarvis, Reuter, Nelson, & Guevara, 2008). Slope and aspect layers were extracted from the elevation layer using the Surface Analysis tool in ArcGIS version 10.1 (ESRI, 2015).

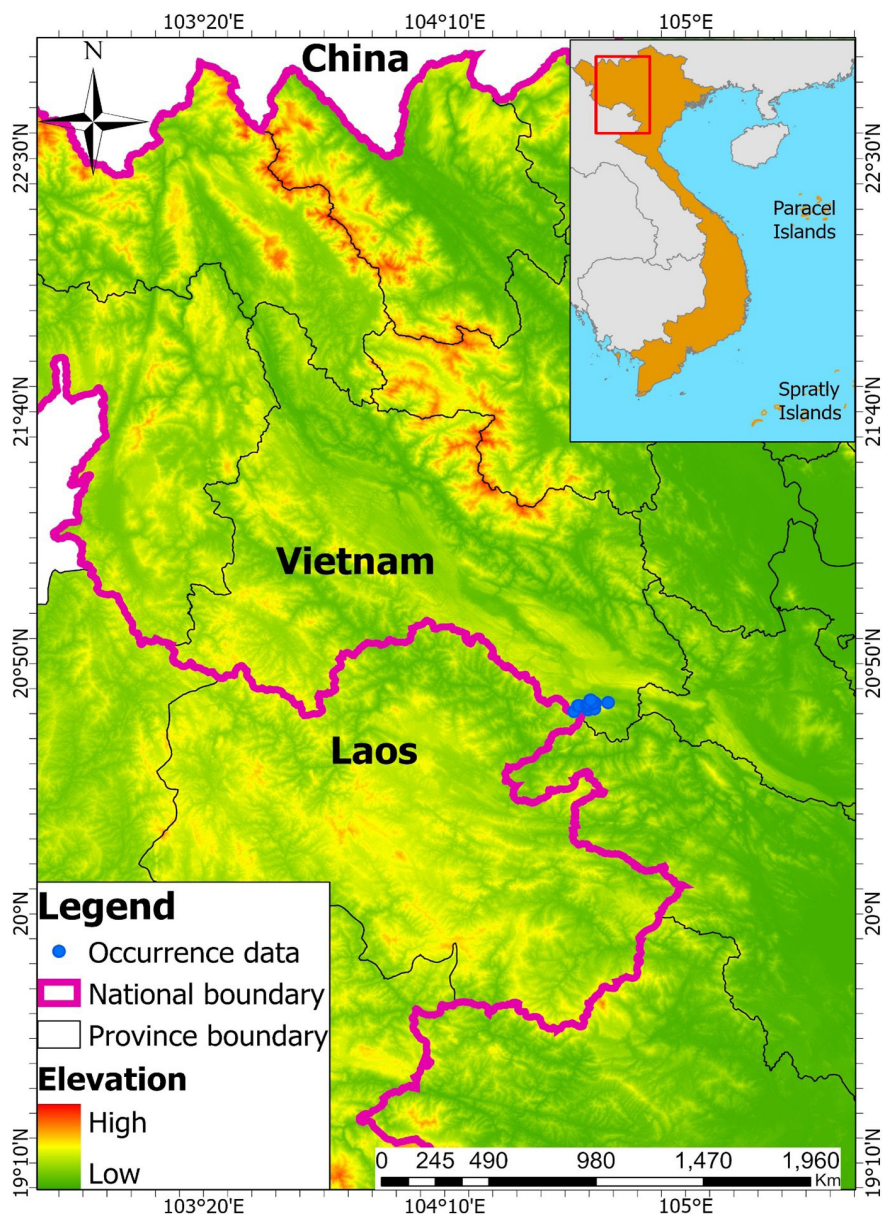


Figure 1. The research site

Table 1. Environmental variables used in this study

Variable	Unit	Code
Annual mean temperature	°C	bio_01
Annual mean diurnal range (Mean of monthly =max temp - min temp)	°C	bio_02*
Isothermality (BIO2/BIO7) (* 100)	-	bio_03
Temperature seasonality (standard deviation *100)	C of V	bio_04*
Max temperature of warmest month	°C	bio_05
Min temperature of coldest month	°C	bio_06*
Annual temperature range (BIO5-BIO6)	°C	bio_07*
Mean temperature of wettest quarter	°C	bio_08
Mean temperature of driest quarter	°C	bio_09
Mean temperature of warmest Quarter	°C	bio_10
Mean temperature of coldest quarter	°C	bio_11
Annual precipitation	mm	bio_12*
Precipitation of Wettest month	mm	bio_13
Precipitation of driest month	mm	bio_14*
Precipitation seasonality (Coefficient of variation)	mm	bio_15*
Precipitation of wettest quarter	mm	bio_16
Precipitation of driest quarter	mm	bio_17
Precipitation of warmest quarter	mm	bio_18*
Precipitation of coldest quarter	mm	bio_19
Land cover	type	lulc*
Soil organic carbon (0-30cm in depth)	t/ha	soc*
Elevation	m	elevation*
Slope	degree	slope*
Aspect	degree	aspect*

Note: * indicated that these variables were used in modeling.

Soil organic carbon (SOC) with a spatial resolution of 1 km was obtained from the Global Soil Organic Carbon Map (GSOCmap, version 1.5). The index is available and provided by FAO and ITPS (2018). Land cover layers at 10 m resolution in 2020 were collected from the website https://env1.arcgis.com/arcgis/rest/services/Sentinel2_10m_LandCover/ImageServer (Karra, 2023).

All the spatial layers of variables used in MaxEnt models were resampled to 90 m using the Resample tool in ArcGIS 10.1 (ESRI, 2015). In order to avoid the influence of multicollinearity, we used ENMTools (version 1.4.4, Warren et al. (2010)) to determine the correlation among variables. We did not include variables with a high correlation ($>|0.8|$) in the same model (Table A1). As a result, 13 variables were eventually chosen to model the distribution of *P. cernua* (Table 1).

C. Species distribution modeling

The Maximum Entropy Model (MaxEnt) (version 3.4.4; Phillips et al., 2023) was used for predicting the potential distribution of *P. cernua*. The ENMval package in R (version 3.6.3, Muscarella et al. (2014)) was used to choose the best model to predict species' potential distribution based on the AICc value. The minimum AICc value indicates the best model (Muscarella et al., 2014). Ultimately, the model with the feature class H (hinge) and a regularization value of 3 was selected; thus, the setting was chosen for the final models. The species occurrence datasets in Section 2.1 were repeated for 21 replicates (Pearson et al., 2007). Maximum iterations were 5,000.

The area under the curve (AUC) was used to determine the accuracy of the model. The AUC value ranges from 0 (low accuracy) to 1 (high accuracy) (Fielding & Bell, 1997; Phillips et al.,

2006). The Jackknife method was used to assess the importance of variables for predicting the potential distribution of *P. cernua* in the MaxEnt model.

The response curves from MaxEnt's result show the relationship between species' potential distribution and environmental factors.

Finally, a map layer was generated by the MaxEnt model, representing suitability levels (from 0 (not suitable) to 1 (highly suitable)). The "10th percentile training presence logistic threshold" was used as a threshold to identify the suitable for the species, according to the suggestion of Liu et al. (2005). Four levels were categorized, including: unsuitable habitat (<0.736), low suitable habitat (0.736-0.816), medium suitable habitat (0.816-0.896), and high suitable habitat (>0.896).

III. RESULTS AND DISCUSSION

A. Result

The MaxEnt model (AUC = 0.99) has better performance than the random model (AUC = 0.5) (Figure 2). Our model indicated that climate group was identified as the main factor contributing to the potential distribution of this species with 61.7% of cumulative contribution, especially precipitation of the

driest month (32.3%) and mean diurnal range (23.4%), followed by topography (e.g., elevation (18.4%), aspect (12.3%) (30.7%). Soil organic carbon (soc) and land cover (lulc) were less contributing with 6.8% and 0.8%, respectively (Table 2).

The response curves of four main variables and others to *P. cernua* habitat suitability are shown in Figure 3. According to the obtained response curves of the species, *P. cernua* prefers habitats at 1,000 – 1,500 m elevation and in the North and North-east areas with precipitation of driest month less than 8 mm and an annual mean diurnal range around 7.5°. Additionally, the response curves of nine remaining environmental variables, shown in Figure A1, indicated that the potential distribution of this species occurred in the areas where temperature seasonality ranged 3.5 – 4°C, the minimum temperature of the coldest month was around 8°C, and the annual temperature range was less than 18°C. The suitable annual precipitation, precipitation seasonality, and precipitation of the warmest quarter were approximately 1,400 mm, 91 mm, and 700 mm, respectively. In terms of land cover, this species preferred clustering of tall dense vegetation with a closed canopy. Suitable soil organic carbon less than 50 tones/ha.

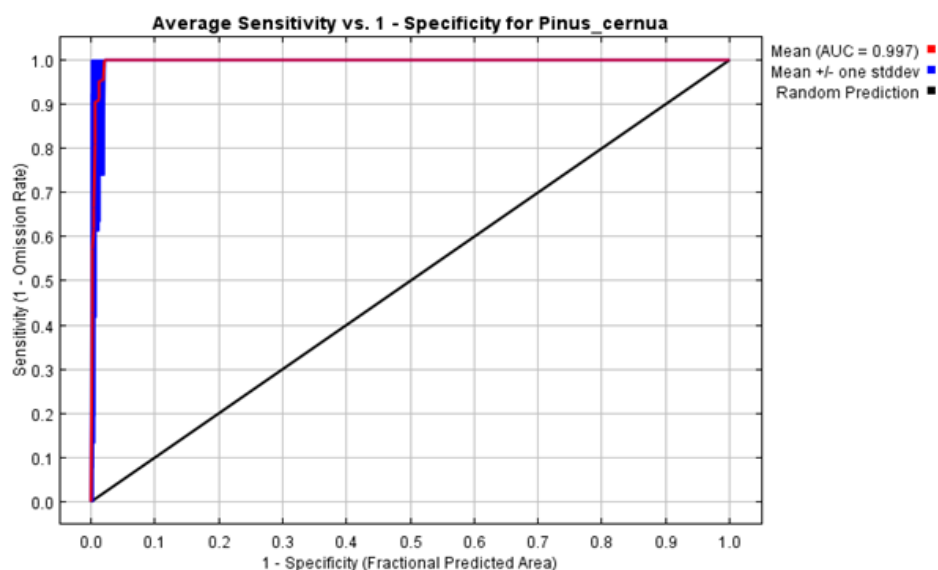
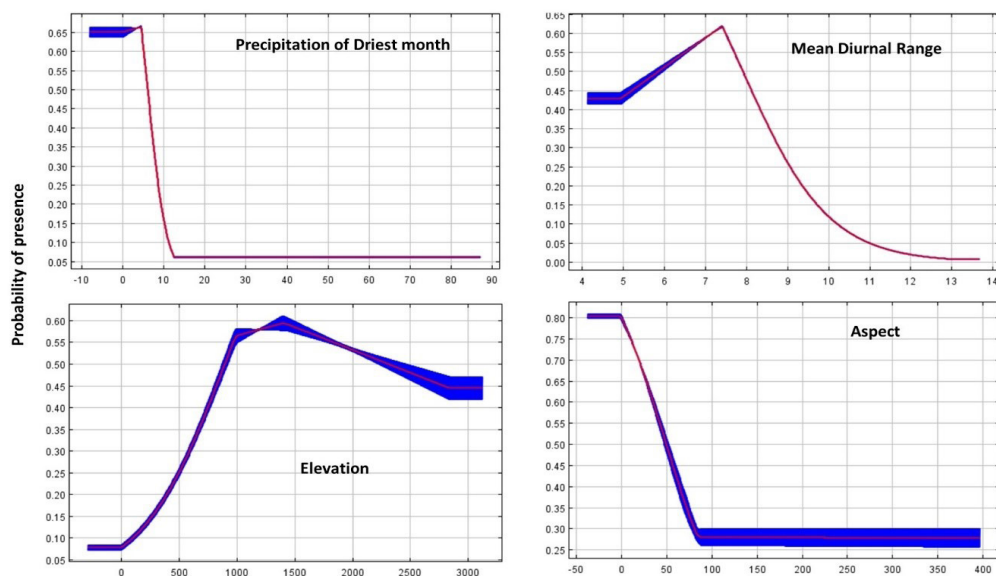


Figure 2. The AUC value and ROC curve of the Maxent model for *P. cernua*

Table 2. The percentage contribution of environmental variables used in the MaxEnt model for predicting the potential distribution of *P. cernua*

Variable	Code	Percent contribution
Precipitation of driest month	bio_14	32.3
Annual mean diurnal range (Mean of monthly =max temp - min temp)	bio_02	23.4
Elevation	elevation	18.4
Aspect	aspect	12.3
Soil organic carbon	soc	6.8
Temperature seasonality (standard deviation *100)	bio_04	5.0
Land cover	lulc	0.8
Annual temperature range (BIO5-BIO6)	bio_07	0.8
Annual precipitation	bio_12	0.2
Min temperature of coldest month	bio_06	0
Precipitation of warmest quarter	bio_18	0
Slope	slope	0
Precipitation seasonality (Coefficient of Variation)	bio_15	0

Figure 3. *P. cernua* response curves in relation to the four most important environmental variables

Jackknife test results showed that climatic variables demonstrated the highest gain in AUC, indicating their crucial contribution to the distribution of *P. cernua*, followed by topography (i.e., elevation and aspect) and soil organic carbon. Whereas land cover and slope had the

lowest gain in AUC, showing a minimal effect on prediction of species distribution (Figure 4). The results of the Maxent indicated that the effect of climatic factors on the distribution of *P. cernua* is greater than that of other factors.

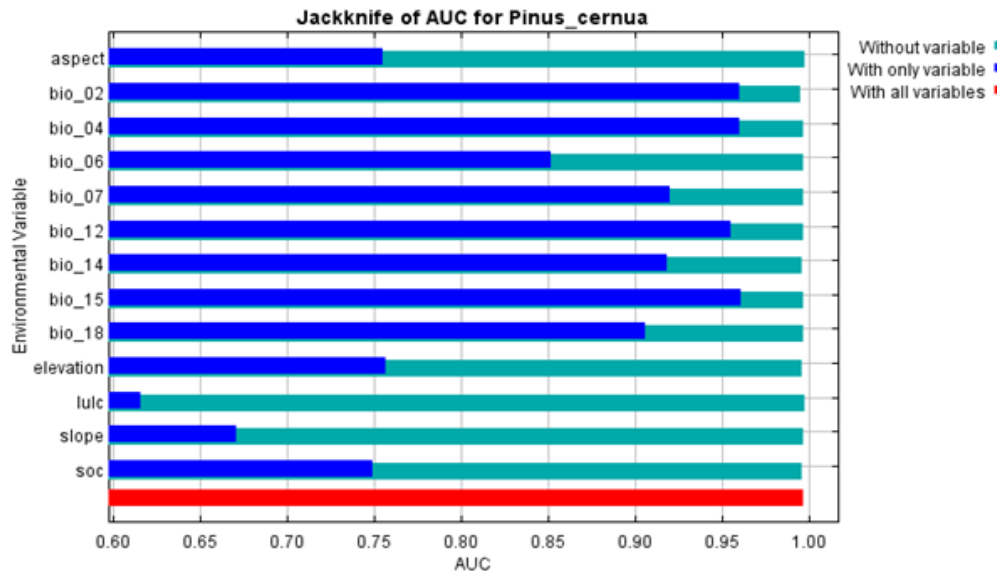


Figure 4. The relative importance of environmental variables based on the jackknife test of area under the curve (AUC). The abbreviations of variables were detailed in Table 1

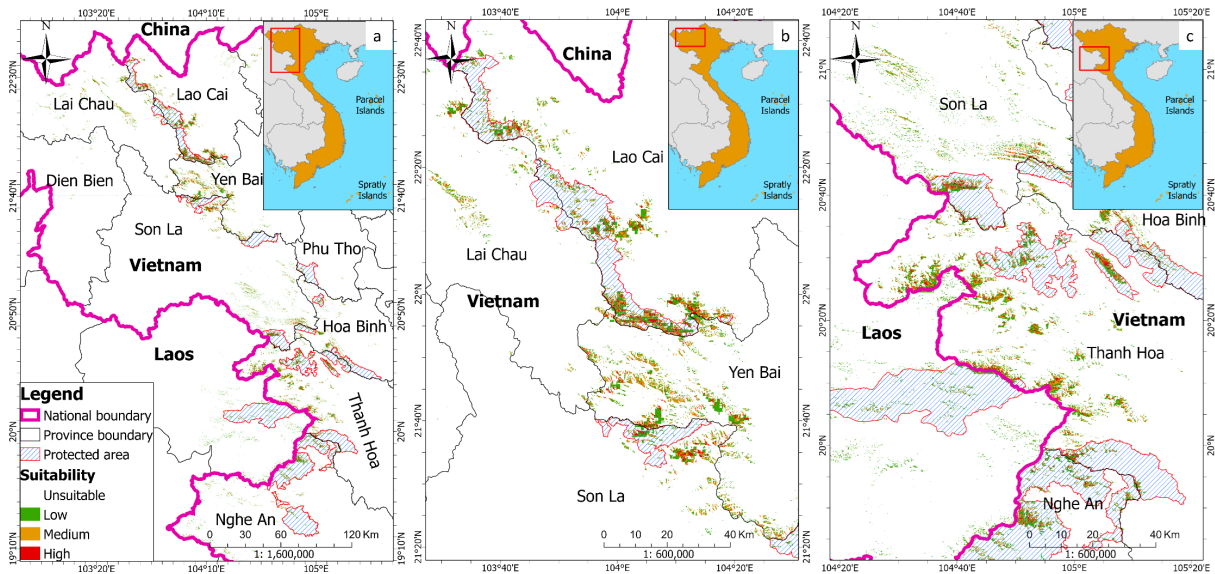


Figure 5. Current potential suitable habitat of *P. cernua* in Northern, Vietnam

Notes:(a: the whole studied area; b: the north of the studied area; c: the south of the studied area). The protected areas were downloaded from <http://www.protectedplanet.vn/en>.

Figures 5 and 6 show the potential distribution map of *P. cernua*. The total predicted suitable habitat area of the species was approximately 1,544 km², ranges c. 19°N – 23°N and 103°E – 106°30'E, mainly distributed in north-western and north-central Vietnam (Son La, Hoa Binh, Lao Cai, Lai Chau, Phu Tho, Yen Bai, Thanh Hoa, and Nghe An

provinces) and Houaphan province (Laos). The high, medium, and low suitable habitat areas are 159 km² (10%), 475 km² (31%), and 910 km² (59%), respectively. In the high suitable areas, Thanh Hoa, Lao Cai, Son La, and Yen Bai provinces (Vietnam) occupy the largest areas at 46 km², 44 km², 24 km², and 22 km², respectively, followed by smaller areas in Nghe

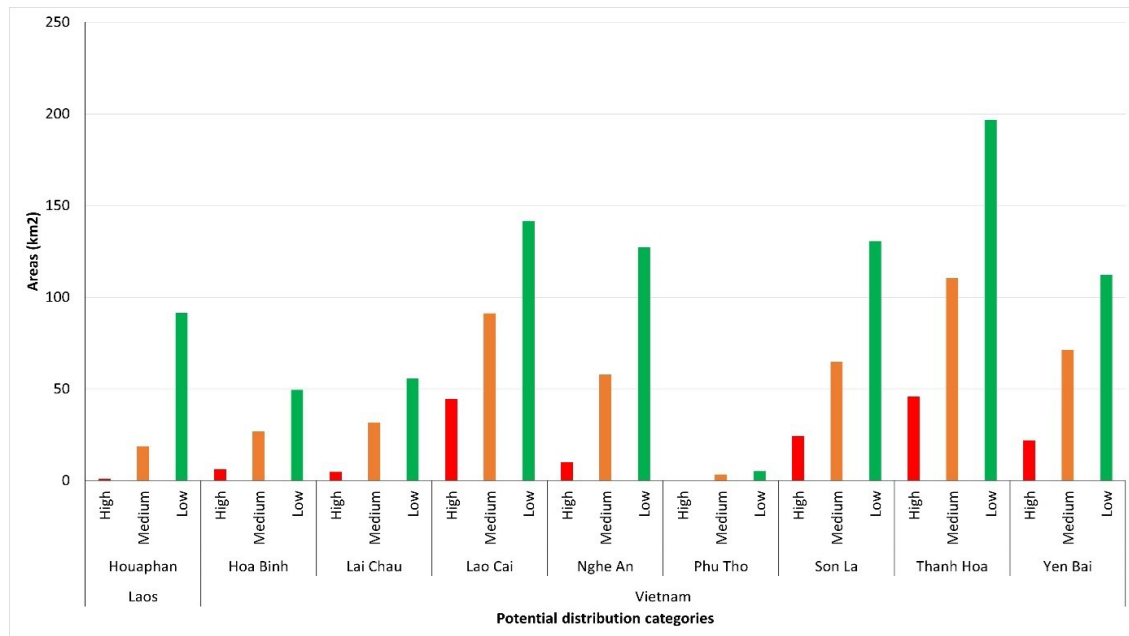


Figure 6. Areas for the low, medium, and high potential distribution of *P. cernua* in Houaphan (Laos), Yen Bai, Thanh Hoa, Nghe An, Hoa Binh, Lai Chau, Lao Cai, Phu Tho, and Son La, (Vietnam) provinces

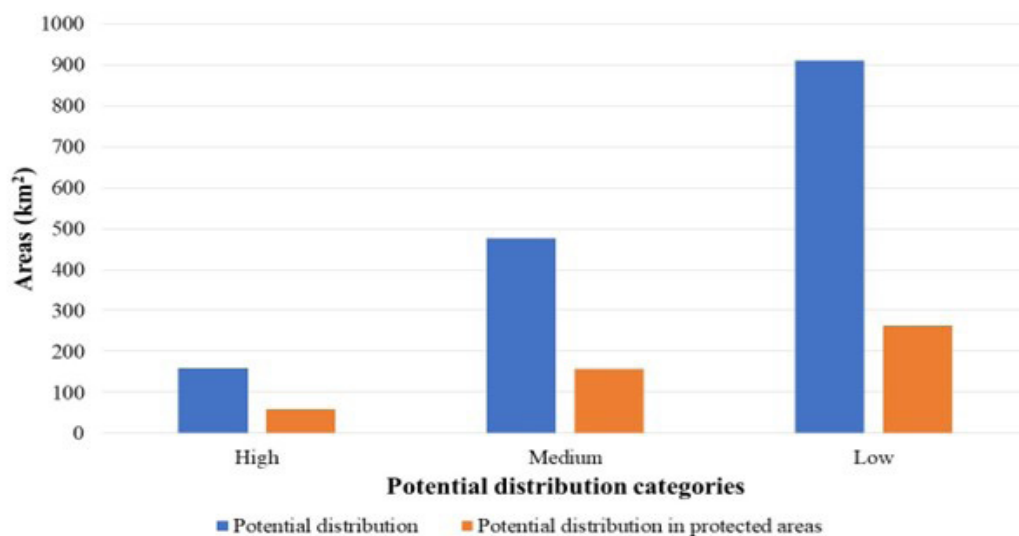


Figure 7. Areas for the low, medium, and high potential distribution of *P. cernua* in total and in protected areas

An, Hoa Binh, Lai Chau, Phu Tho (Vietnam), and Houaphan (Laos) provinces. Total of predicted suitable habitat of this species within protected areas is 479 km² (~ 31% of the total predicting potential suitable areas from model) (Figure 7).

B. Discussion

Spatial distribution of species is linked to environmental conditions due to long term species – environment interactions (Jiang et al., 2014; Kaeslin et al., 2012; Wisz et al., 2013). Temperature and precipitation are important

factors influencing the growth and spread of plant species (Cornett et al., 2000; García et al., 2000; Ruan et al., 2012; Wiens et al., 2010; Xie et al., 2022). The MaxEnt model shows that climatic factors are the most important for predicting the potential distribution of *P. cernua* in the studied area. From the results of the MaxEnt model, the suitable annual mean diurnal range was around 7.5°C, precipitation of the driest month was less than 8 mm, and annual precipitation ranged 1,000 – 1,500 mm (Figure 3 and A1), which is in accordance with these climatic characteristics in the study area obtained from the local meteorological station (Quynh, 2024), including the annual mean diurnal range (7.8°C), precipitation of the driest month (10 mm) and annual precipitation (1,500 mm). Also, the results agree with Averyanov et al. (2017) who reported that *P. cernua* occupies areas with an average annual precipitation above 1,000 mm. Therefore, the suitable habitats of *P. cernua* may prefer humid areas at high elevation with low temperatures that strongly affect buds for mountainous gymnosperms (Pan et al., 2022). The effect of climatic factors on *P. cernua* distribution range is consistent with factors influencing the suitable habitats of some high mountain coniferous species such as *Cephalotaxus oliveri* (Xie et al., 2022) and *Thuja sutchuenensis* (Qin et al., 2017), indicating that climatic factors were the key drivers in these species' distribution. In Vietnam, Tuyet and Tra (2021) showed that climatic factors had crucial effects on the spatial distribution of *Cupressus torulosa*. The importance of climatic factors in the Maxent model for predicting the species' potential distribution may indicate that climate change will affect its distribution in the future. Moreover, topography in mountain areas in northern Vietnam is complex (Averyanov et al., 2003), which is considered a major factor influencing local climate (Meehl, 1992; Ogwang et al., 2014) and results in strong microclimate heterogeneity (Opedal et al., 2015). Thus, in further in-depth studies on *P. cernua* conservation, attention should be given to microclimate at a fine scale and the effect of

climate change on this species distribution.

Topography (i.e., elevation, aspect) is also an important variable for species distribution. Topography is considered an influencing factor of climate and soil condition, which contribute to species distribution (Barry, 2008; Bunyan et al., 2015; Grzyl et al., 2014; Jiao et al., 2009; Youcefi et al., 2020). The results of the MaxEnt model indicate that the suitable distribution areas (especially high suitability) are concentrated on the north, north-west, and north-east aspects at high elevations (1,000 – 1,500 m) in tropical forests in the north-western region of Vietnam and the eastern areas of Houaphan provinces (Laos), which have many peaks higher than 1000 m, such as Hoang Lien Son (3,143 m), Pa Phanh (1,400 m), Pha Luong (1,500 m), and Ta Sua (2,400 m), indicating this species might respond sensitively to temperature and precipitation as noted above. The result is in accordance with the known distribution range recorded by Averyanov et al. (2014), Averyanov et al. (2017), and Loc et al. (2017), who reported that this species occurred on the north, north-west, and north-east at 900 – 1,800 m elevation, which receive lower solar radiation, heavy rainfall, and have higher tree cover compared to other aspects.

Unlike the above factors, land cover is less important for the model. The result of the model shows that *P. cernua* tends to distribute in areas characterized by tall, dense vegetation (Figure A1). The result agrees with Averyanov et al. (2017), who reported that *P. cernua* mainly occurred in primary evergreen coniferous tropical submontane forest and primary evergreen mixed tropical submontane forest, which are main land cover types at elevations above 1,000 m a.s.l. in the studied area. However, a part of these land cover types is replaced by secondary forest, pastures, and agricultural fields.

The areas of potential distribution for the *P. cernua* from MaxEnt modeling are consistent with the known distribution reported in many previous studies (Averyanov et al., 2015; Averyanov et al., 2017; Hoa et al., 2016; Loc et

al., 2017; Thomas, 2022), and suggest that the distribution areas of this species represent its optimum climate in wet, cool, and/or cold sites at high elevation. Additionally, the potential suitable habitats for the *P. cernua* species occupy not only in the forest areas with a high elevation and characterized by the montane climate in Son La (Vietnam) and Houaphan (Laos) provinces (reported by Averyanov et al. (2017)), but also in other forest places with similar elevation and climate conditions in the north-western region of Vietnam (e.g. Lai Chau, Lao Cai, Phu Tho, Yen Bai, Thanh Hoa, and Hoa Binh provinces) and the adjacent areas of Son La and Thanh Hoa provinces (Vietnam) and Houaphan province (Laos) (mainly in Pha Luong and Pa Phanh mountain ranges), where the species has not been recorded so far. These results agree with previous studies (Kumar & Stohlgren, 2009; Pearson, 2007; Yang et al., 2013) that found that the Maxent model using only presence data often overestimates the potential distribution areas compared to the observed niche of species.

From the results of models, most suitable areas lie outside of existing protected areas, which may cause adverse influences on the species population in the future by human activities (i.e., illegal logging, fire). It is important that new protected areas should be established for conservation of this species and its habitat, but the establishment of protected areas must depend on the overall and long-term national planning. Thus, conservation outside the protected areas is crucial for this species, as noted below. The potential distribution areas of this species lie in the adjacent areas between Son La, Thanh Hoa (Vietnam), and Houaphan (Laos) provinces. Thus, effective cross-border conservation partnerships should be a key component to successful management of this transboundary critically endangered species. For instance, managers should disseminate local people about the species conservation practices. In addition, inventories should be conducted to explore the new locations,

especially high-suitable areas where *P. cernua* may already exist, as well as protect and maintain its habitat and mature individuals. In terms of ex-situ conservation, seeding and cutting propagation should be used to provide seedlings for conservation planting and reintroduction programs in (highly) suitable areas because natural regeneration of *P. cernua* is poor (Averyanov et al., 2017). Indeed, seeding and cutting propagation and an experimental model for the species ex-situ conservation were conducted by managers and scientists and have been successful in Son La province (Averyanov et al., 2015; Hoa et al., 2016). The successful model may be applied in other suitable areas to conserve this species and avoid extinction in the future.

V. CONCLUSION

The MaxEnt model results indicate that the suitable areas for *P. cernua* are approximately 1,544 km² in the north-western of Vietnam and on the Laos-Vietnamese border between Son La, Thanh Hoa (Vietnam), and Houaphan (Laos) provinces. The contribution of precipitation of the driest month in the MaxEnt model to predict the species' potential distribution is highest, followed by annual mean diurnal range and elevation. Most suitable habitats of *P. cernua* are not found within existing protected areas. This study may provide a better understanding of environmental factors influencing the species' potential distribution in northern Vietnam and provide recommendations for evidence-based transboundary conservation management in the distribution ranges of the endemic and threatened tree species.

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