Nature Conservation 51: 167–188 (2023)
doi: 10.3897/natureconservation.51.90373
https://natureconservation.pensoft.net

RESEARCH ARTICLE

A peer-reviewed open-access journal
Nature Conservation
Launched to accelerate biodiversity conservation

Changes in suitable habitat for the critically endangered Northern white-cheeked gibbon (*Nomascus leucogenys*) in the Western Nghe An Biosphere Reserve, Vietnam: Implication for conservation

Khoa Van Phung[1], Dung Van Tran[2], Hai Thanh Dong[2], Vinh Quang Luu[2], Van Bac Bui[3], Thinh Tien Vu[2]

1 *Department of Environmental Management, Faculty of Forest Resources and Environmental Management, Vietnam National University of Forestry, Xuan Mai, Chuong My, Ha Noi, Vietnam* **2** *Department of Wildlife, Faculty of Forest Resources and Environmental Management, Vietnam National University of Forestry, Xuan Mai, Chuong My, Ha Noi, Vietnam* **3** *Department of Plant Protection, Faculty of Forest Resources and Environmental Management, Vietnam National University of Forestry, Xuan Mai, Chuong My, Ha Noi, Vietnam*

Corresponding author: Dung Van Tran (trandungfuv@gmail.com)

Academic editor: C. Knogge | Received 14 July 2022 | Accepted 31 January 2023 | Published 21 February 2023

https://zoobank.org/4778ABCC-2A21-45E0-8D8C-DAD53FB86D3A

Citation: Van Phung K, Van Tran D, Thanh Dong H, Quang Luu V, Bac Bui V, Tien Vu T (2023) Changes in suitable habitat for the critically endangered Northern white-cheeked gibbon (*Nomascus leucogenys*) in the Western Nghe An Biosphere Reserve, Vietnam: Implication for conservation. Nature Conservation 51: 167–188. https://doi.org/10.3897/natureconservation.51.90373

Abstract

Several recent studies have highlighted that change in land use and land cover (LULC) is the main threat causing the decline and extinction of certain species. Gibbons (Hylobatidae) could be excellent examples, on account of their potential for extinction in the near future under the effects of LULC changes due to their particular ecological traits. This study aims to model the current suitable habitat of the Northern white-cheeked gibbon (*Nomascus leucogenys* (Ogilby, 1840)) in the Western Nghe An Biosphere Reserve (BR), Vietnam and assess the changes in its suitable habitat following the changes in LULC from 1990 to 2020. The maximum entropy approach (MaxEnt) was used to predict the suitable habitat of the gibbon using its occurrence localities and environmental predictors. The model analysis showed that the "Distance to Agriculture" variable had the strongest impact on the gibbons' suitable habitat. Our results predicted the present suitable habitat of the gibbon species at approximately 4,022.42 km^2 (30.95% of the overall BR area) in three spatially separated areas inside the Western Nghe An BR. Furthermore, the suitable habitat areas of the gibbon in 1990, 2000, and 2010 were projected at roughly 4,347.68 km^2, 4,324.97 km^2, and 2,750.21 km^2, respectively, following a decreasing trend from 1990 to 2010, but a gradual increase between 2010 and 2020. The suitable habitat of the gibbon inside three core protected areas (Pu Mat National Park, Pu Huong, and Pu Hoat Nature Reserves) showed a continually increasing trend from 1990 to 2020. Our results highlighted the influence of LULC changes and the role of the protected area network in gibbon conservation. The information from the study provides a quantitative baseline for the future conservation of the critically endangered gibbon in the Western Nghe An BR.

Keywords

Gibbon, land use & land cover, MaxEnt, *Nomascus*, species distribution modeling, suitable distribution

Introduction

Southeast Asia contains approximately 15% of the world's tropical forests and is home to at least four globally important biodiversity hotspots (Myers et al. 2000). However, the region is also assessed as a deforestation hotspot. From 2005 to 2015, around 80 million ha (28%) of natural forests were lost in Southeast Asia (Estoque et al. 2019). Researchers also predicted that the forest in Southeast Asia would experience a significant change, either shrinking by 5.2 million ha or growing by 19.6 million ha, depending on the choice of the pathway (Estoque et al. 2019). Several recent studies have highlighted that the change in land use and land cover (LULC) is the main threat driving the decline and extinction of species, with loss in the habitat sustainability of wildlife species (Jetz et al. 2007; Díaz et al. 2019; Su et al. 2021), especially for large-bodied species. Gibbons could be excellent examples revealing the impacts of the extreme effects of LULC changes due to their particular ecological traits. The species are strictly arboreal and highly frugivorous, preferring closed-canopy broadleaved evergreen forests (Geissmann et al. 2000; Ruppell 2013). Territoriality and monogamy are observed in almost all gibbon species (Mitani 1987; Brockelman et al. 2014). Gibbons also respond sensitively to habitat degradation and fragmentation, as well as anthropogenic activities (Geissmann et al. 2000; Rawson et al. 2011; Tran and Vu 2020; Sarma et al. 2021).

The northern white-cheeked gibbon (NWCG) (*Nomascus leucogenys*) is classified as a Critically Endangered species on the International Union for Conservation of Nature (IUCN) Red List (Rawson et al. 2020). The species is native to northwestern Vietnam, northern Lao PDR, and southwestern China (Rawson et al. 2011; Rawson et al. 2020). The gibbon is believed to be extinct or functionally extinct in China (Fan et al. 2014), while the largest remaining population probably persists in Lao PDR, although its current status is still unclear (Rawson et al. 2011; Rawson et al. 2020). In Vietnam, the distribution of NWCG is restricted in the north by the Black River (Geissmann et al. 2000; Rawson et al. 2011) and limited in the south by the Rao Nay river (Thinh et al. 2010). The species' total population was estimated to be only around 300 groups remaining in Vietnam, most of them persisting in a few isolated forest blocks close to the Lao PDR border (Rawson et al. 2011).

The largest population of NWCG was found in Pu Mat National Park (NP), with 22 confirmed groups; the site was also considered as the highest priority area for conserving the species (Rawson et al. 2011). The occurrence of the species was also confirmed in several other protected areas, although their population is likely low or very low, for example, in Muong Nhe Nature Reserve (NR), Sop Cop NR, Xuan Lien NR, Vu Quang NP, and Pu Huong NR (Rawson et al. 2011). It should also be noted that the species seems to have been extirpated from many other protected areas, including Hang Kia – Pa Co NR, Ngoc Son – Ngo Luong NR, and Pu Luong NR (Rawson et al. 2011). Hunting and habitat loss are currently considered as the major threats to NWCG, especially with the high rate of forest fragmentation and degradation pushing the species into a few isolated forest areas (Rawson et al. 2011; Rawson et al. 2020). To date, studies on gibbons in Vietnam have mainly focused on population size assessments (Luu and Rawson 2009, 2010, 2011; Hoang et al. 2010; Ha et al. 2011; Tran and Vu 2020). Gibbons require high-quality habitat with high food abundance and a dense canopy (Geissmann et al. 2000; Sarma et al. 2021). However, limited efforts have been made to monitor gibbon habitat, and no current studies report the changes in suitable habitat for gibbons in Indochina.

In this study, we aimed to predict the suitable habitat of NWCG in the Western Nghe An BR by using species distribution modeling (MaxEnt) based on identified presence localities of the species and environmental predictors. We also attempted to project suitable habitat fluctuation in relation to the changes in LULC from 1990 to 2020. Based on the results, we discussed the impact of LULC changes and the role of the protected area network in gibbon conservation in Vietnam. Our results are a baseline for researchers, conservationists, and wildlife and habitat managers to aid decision-making and plan future conservation strategies for NWCG in the Western Nghe An BR, Vietnam.

Methods

Study area

The Western Nghe An Biosphere Reserve (BR) was recognized by UNESCO as the 6th Biosphere Reserve of Vietnam in 2007. The Western Nghe An BR (18°34'43"–19°59'44"N, 103°52'28"–105°30'07"E) is located in the western part of Nghe An province, central Vietnam, covering an area of 12,997.95 km^2 with three functional zones: the core zone (1,683.01 km^2), buffer zone (6,085.47 km^2), and transition zone (5,229.47 km^2). The Biosphere Reserve is expected to create a green corridor between the three protected areas: Pu Mat NP, Pu Huong NR, and Pu Hoat NR. The forest cover of the Western Nghe An BR is approximately 66.4% of the total area. The area is home to more than 3,000 vascular plants and more than 940 vertebrate animals, with several species listed as threatened, rare, and endemic. More than 900,000 people in five indigenous minority groups currently reside within Western Nghe An BR (Western Nghe An Biosphere Reserve 2017). Most wild groups of NWCG in the Western Nghe An BR were detected in the three protected areas, including Pu Mat NP, Pu Huong and Pu Hoat NR. Pu Mat NP is one of the largest remaining natural forests in

Vietnam and is believed to be home to the largest population of the NWCG with an estimated 455 gibbons in 130 different groups (Luu and Rawson 2011). However, the forests in Pu Huong and Pu Hoat NR are isolated and probably not effectively linked ecologically to the Pu Mat NP. More than a decade ago, researchers confirmed at least seven groups of the gibbon remaining in the Pu Hoat NR (Luu and Rawson 2009). However, the last field survey in Pu Hoat NR and adjunction areas detected at least 40 gibbon groups (Pu Hoat NR 2021).

Occurrence data

To predict the suitable habitat of NWCG in the Western Nghe An BR, we collected the occurrence of the endangered species through our field surveys in Pu Mat NP, Pu Huong NR, and Pu Hoat NR from March–May 2021 (Phung and Dong 2021), and another published document (Pu Hoat NR 2020). The localities of gibbons in Pu Mat NP, Pu Huong, and Pu Hoat NR were used as presence data for the MaxEnt model in 2020. For presence data on the species for the 2010 model, we gathered data from published documents (Luu and Rawson 2009, 2010, 2011). Initially, we collected 36 presence localities for the 2010 model, and 98 localities for the 2020 model. To avoid spatial autocorrelation among localities that could cause an overestimation, we used the "spThin" package (Aiello-Lammens et al. 2015) in R version 4.1.2 to thin out the locations of gibbons within one km radius by randomly selecting one location and removing the others, similar to the models for the Southern white-cheeked gibbon (*N. siki*) in Tran et al (2023). One km was used as a criterion for thinning because gibbons in the genus *Nomascus* have a relatively small home range, around 0.45 km^2 for the Southern yellow-cheeked gibbon (*N. gabriellae*; Hai et al. 2020). Consequently, we used 25 and 40 occurrence localities of NWCG for the 2010, and 2020 models, respectively (Fig. 1).

Environmental predictors

To predict the suitable habitat of NWCG in the Western Nghe An BR, we obtained variables on climate, topography, and LULC. The variables were selected based on our knowledge of the habitat of the gibbon and consulting the available research sources. For the climatic variables, we downloaded 19 predictors with the highest available resolution (30 arcseconds) from the World Clim database (http://www.worldclim.com/; Fick and Hijmans 2017). The variables include 11 and eight layers of temperature and precipitation, respectively, which were derived from the monthly temperature and rainfall values in order to generate more biologically meaningful variables. According to Tran and Vu (2020), elevation might also highly contribute to the species distribution modeling of gibbons. Therefore, we used the Digital Elevation Model with a resolution of 30 × 30 m (available from https://earthexplorer.usgs.gov) as elevation variables. Then, we calculated the Slope and Aspect variables based on the Digital Elevation Model in ArcMap version 10.2 (ESRI). To assess the change of habitat suitability of the threatened gibbon, we extracted the LULC of the Western Nghe An BR from the LULC of Vietnam in 1990, 2000, 2010, and 2020 at 30 × 30 m resolution (Fig. 2)

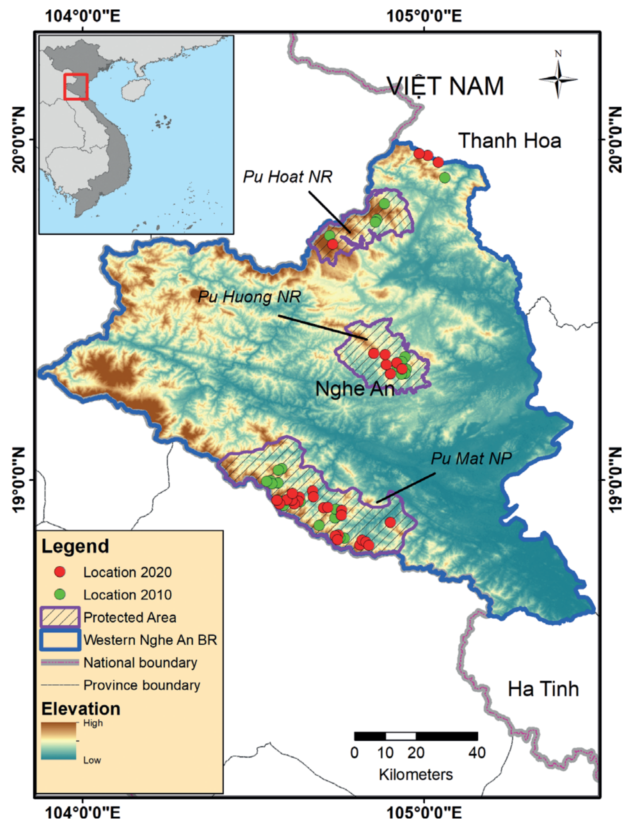

Figure 1. The occurrence localities in 2020 (red) and 2010 (green) of NWCG in the Western Nghe An BR were used for predicting the suitable habitat by the MaxEnt model.

available at https://www.eorc.jaxa.jp/ALOS/en/dataset/lulc/lulc_vnm_v2109_e.htm (Phan et al. 2021). The distance to the settlement plays an important role in modeling suitable habitat for gibbons (Tran and Vu 2020). Here, we extracted the settlement area from the LULC layer (Phan et al. 2021). The agricultural land was also selected from the LULC layer (Phan et al. 2021), including rice paddies, woody crops, other croplands, and in-house crops' categories. To assess the effect of settlement and agricultural land on the suitable habitat of the gibbon, we calculated the distance to settlement and agricultural land by the Euclidean Distance tool in ArcMap version 10.2 to create two variables: Distance to Settlement, and Distance to Agriculture in 1990, 2000, 2010 and 2020. Due to the difference in the resolution of variables, we resampled all variables to a resolution of 30 × 30 m using the Resample tool in ArcMap version 10.2. The collinearity among environmental predictors might cause the overestimation of species distribution modeling. Thus, we calculated Pearson's correlation index (*r*) using ENMTools version 1.4.4 (Warren et al. 2010). With the highly correlated predictor pair ($|r| > 0.80$), we eliminated one variable and kept the remaining variables for final analysis (Nazeri et al. 2012). To select or remove variables, we considered our understanding of the ecology of gibbons, and other publications on predicting habitat

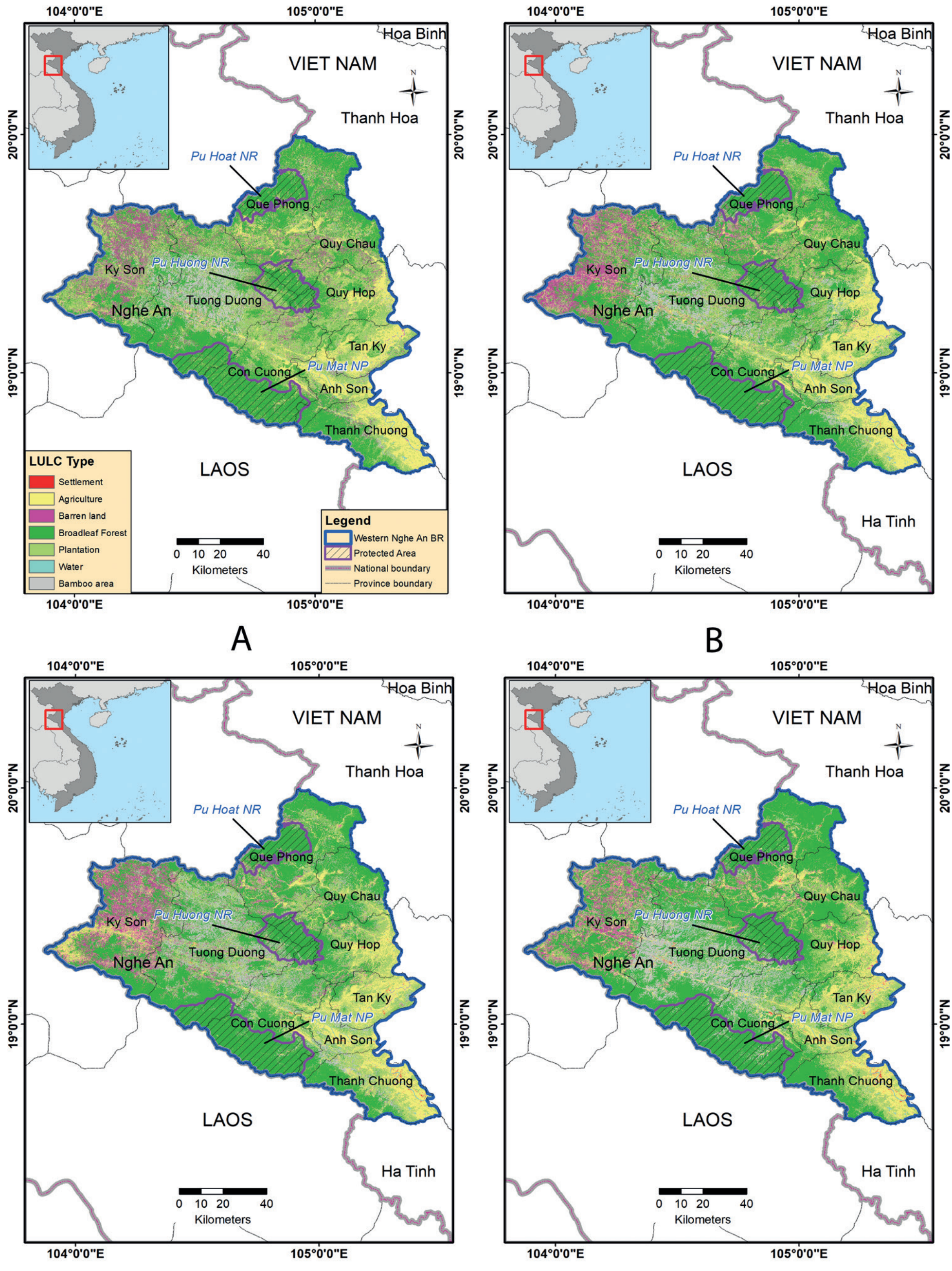

Figure 2. The LULC in the Western Nghe An BR in **A** 1990 **B** 2000 **C** 2010, and **D** 2020 extracted from Phan et al. (2021).

suitability, including Sarma et al. (2015, 2021); Tran and Vu (2020). Additionally, we also ran a model with all the variables and then considered the contribution of each variable. Finally, we used 13 predictors for the final models (Table 1).

Table 1. The predictor variables used for generating the habitat suitability of NWCG in the Western Nghe An BR.

No.	Name	Sources	Description
1	Bio01	WorldClim	Annual Mean Temperature
2	Bio03		Isothermality (BIO2/BIO7) (×100)
3	Bio07		Temperature Annual Range (BIO5-BIO6)
4	Bio12		Annual Precipitation
5	Bio13		Precipitation of Wettest Month
6	Bio15		Precipitation Seasonality (Coefficient of Variation)
7	Bio16		Precipitation of Wettest Quarter
8	Elevation	Earthexplorer.usgs.gov	Height above sea level
9	Slope		Degree of rise/run
10	Aspect		Direction a slope face
11	LULC	ALOS Research and Application Project	Land Use and Land Cover
12	Distance to settlement		Distance to residential land
13	Distance to Agriculture		Distance to agricultural land

Ecological niche modeling processing

To generate the suitable habitat model for NWCG in the Western Nghe An BR, we applied the Maximum Entropy approach (MaxEnt) version 3.4.4 available from https://biodiversityinformatics.amnh.org/open_source/maxent/. The MaxEnt model predicts the habitat suitability of species based on the probable occurrence of species in distinct localities finding the maximum entropy distribution of environmental predictors (Phillips et al. 2006). The model was assessed as one of the most accurate species distribution models and has been broadly applied to predict suitable habitats for species, especially for the small sample size of presence data (Elith et al. 2006; Phillips et al. 2006; Raxworthy et al. 2007). Here, we applied the default setting for the MaxEnt models as suggested by the model developer (Phillips et al. 2006). The area under the receiving operator curve (AUC) has been widely used to evaluate the accuracy of the model performance (Elith 2000; Phillips et al. 2006; Nazeri et al. 2012). The higher AUC values indicate better model performance: inability to predict model (AUC < 0.5), poor performance (AUC = 0.5–0.7), moderate performance (AUC = 0.7–0.9), excellent performance (AUC = 0.9–1) (Peterson et al. 2011).

To assess the changes in the suitable habitat of NWCG from 1990 to 2020, we ran separately two models for 2010 and 2020 based on the presence localities and environmental data set of each year. For the model of 2020, we ran the model using 10-folds cross-validation to evaluate the model, while we applied the jackknife method due to the small sample size for the model 2010 (Pearson et al. 2007). Due to the lack of occurrence data of the gibbons before 2000, we applied the projection function of the MaxEnt model to project the suitable habitat into the past (2000 and 1990) based on the presence localities in 2010, 2020 and the available environmental data set in 2000 and 1990. Because 2010 was closer to 2000 and 1990 than 2020, we assumed that the suitable habitat models in 2000, and 1990 that were projected using presence localities in 2010, would be more accurate than the models projected using localities in 2020. Therefore, we used the models projected from localities in 2010 to analyze the gibbon's suitable habitat in 2000 and 1990 instead of the projected models from localities in 2020. However, the results of models in 1990, and 2000 projected from localities in 2020, were also presented in the Suppl. material 1: SI–III, and IV. For the environmental variables, we kept topographic variables as unchanged while LULC, Distance to Settlement, and Distance to Agriculture variables were changed following the time. We also assumed that the climate did not change much during this time by keeping the climatic variables as unchanged due to the lack of climate data in the study area for each study period.

The relationship between the predicted suitable habitat of species and environmental variables in the MaxEnt model was shown by response curves. We presented the response curves of the most contributing variables to identify the main impact of the variables on the change of suitable habitat of NWCG in the Western Nghe An BR.

The result of the MaxEnt model is presented in a logistic format ranging from 0 to 1, in which the higher values mean higher suitability. The threshold selection should be determined according to the objectives of the study (Merow et al. 2013; Vale et al. 2014). To maximize the area for conservation purposes, we applied the threshold "Minimum training presence logistic threshold" to determine the suitable/unsuitable categories. To clearly show the changes in suitable habitat, we also categorized suitable areas into three sub-levels by dividing equally suitability values: High, Moderate, and Low suitability (Tran et al. 2020; Sarma et al. 2021).

Results

Performance of models and importance of variables

The MaxEnt model predicted the habitat suitability of NWCG based on the available presence localities and predictor data set of LULC, climate, and topography with mean test AUC at 0.896 ± 0.043 and 0.936 ± 0.084 for the model of 2020 and 2010, respectively (Fig. 3). The AUC values showed the high discrimination capacity of the model to predict the suitable habitat of NWCG in the Western Nghe An BR.

For the contribution of each environmental variable in the model of suitable habitat in 2020, the top three variables were "Distance to Agriculture" (39.2%), "Temperature Annual Range – Bio7" (25.3%), and "Precipitation of Wettest Quarter – Bio16" (23.3%). For the model of 2010, the highest contribution variables were "Distance to Agriculture" with 55.4%, followed by "Distance to Settlement" and "Elevation" with 29.3% and 6.6%, respectively (Table SI-II). The response curves in the MaxEnt model show the changes in habitat suitability in response to the changes in the predictors used in the model. The response curve of the highest contribution variables of both models (2020 and 2010) was mainly identical when the habitat suitability of NWCG increased significantly for the distance to agricultural land below around one km, and rose gradually for the distance above about one km (Fig. 4).

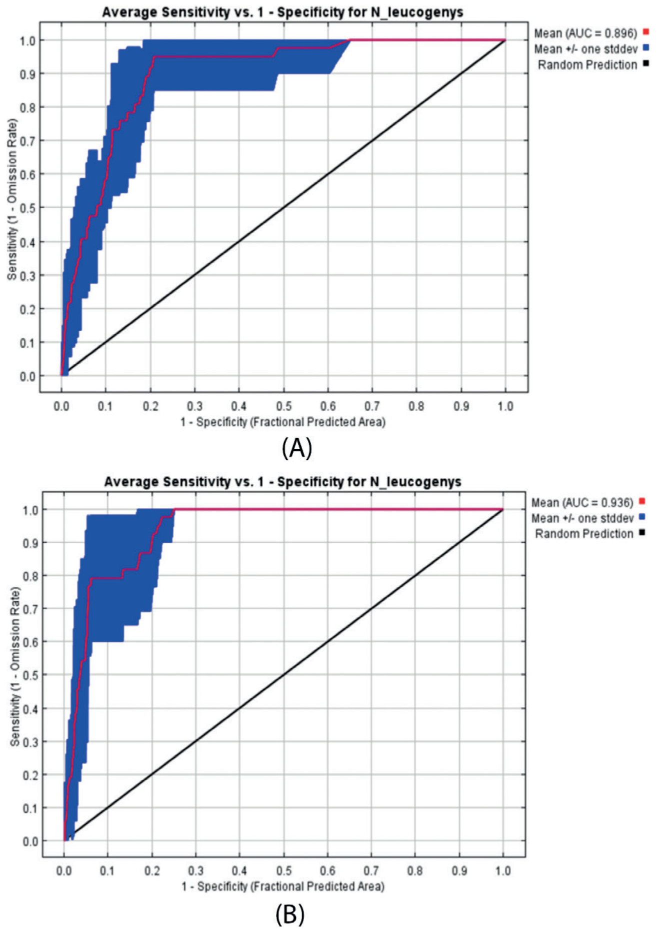

Figure 3. The results of AUC curves in developing the suitable habitat model of NWCG in **A** 2020, and **B** 2010. The red line showed the mean of AUC, and the blue area showed the standard deviation.

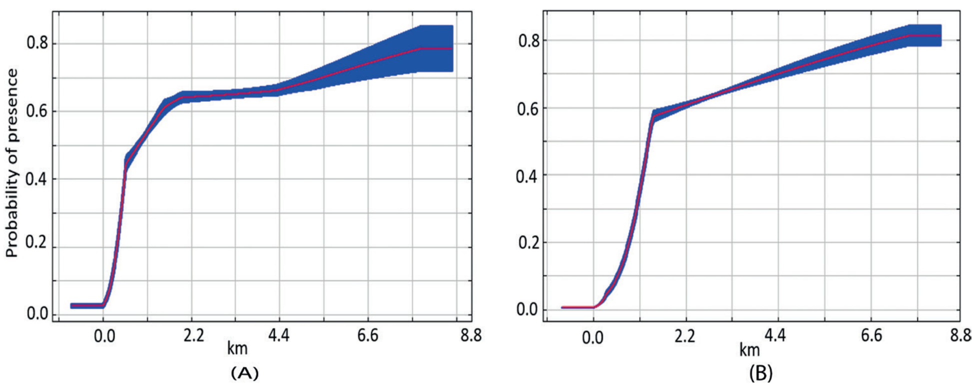

Figure 4. The response curve of Distance-to-Agriculture, the most contribution variables to predicting the suitable habitat of NWCG by the MaxEnt model in **A** 2020, and **B** 2010.

The suitable habitat of NWCG in the Western Nghe An Biosphere Reserve in 2020

The total suitable habitat of NWCG in Nghe An BR under the current land cover condition was estimated at around 4,022.42 km^2 (30.95% of the overall BR area; Table 2) and mainly concentrated in three areas including the (i) the northern part of Que Phong and Quy Chau district – close to Thanh Hoa province, (ii) Pu Huong NR, and (iii) in the southern Tuong Duong, Con Cuong district – within Pu Mat NP. However, the high habitat suitability with around 380.64 km^2 only occurred in the northern part (adjacent to Thanh Hoa province) and the southern part of Nghe An BR (within Pu Mat NP; Fig. 5).

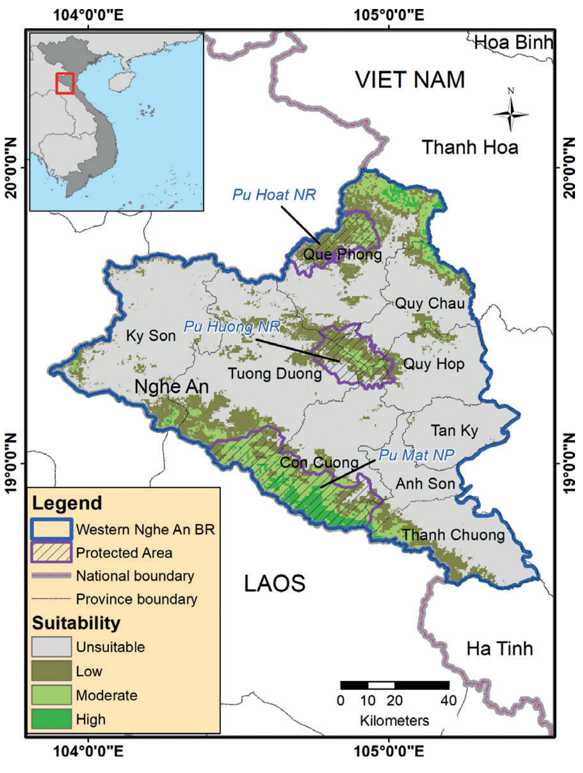

Figure 5. The suitable habitat of NWCG under present landcover condition (2020) predicted by the MaxEnt model.

Table 2. Area of suitable habitat of NWCG projected by the MaxEnt model in 1990, 2000, 2010, 2020 (unit: km^2).

Habitat suitability	Year			
	1990	2000	2010	2020
Low	3,091.51	3,221.81	1,719.21	2,488.18
Moderate	871.28	793.30	708.17	1,173.40
High	384.89	309.86	322.83	360.84
Total	**4,347.68**	**4,324.97**	**2,750.21**	**4,022.42**

Habitat suitability changes of NWCG in the Western Nghe An Biosphere Reserve from 1990 to 2020

Using the MaxEnt model, we projected the suitable habitat of NWCG in 1990 and 2010 (Fig. 6A–C). The predicted suitable habitat of NWCG in the Western Nghe An BR under the changes in LUCL showed a fluctuating trend from 1990 to

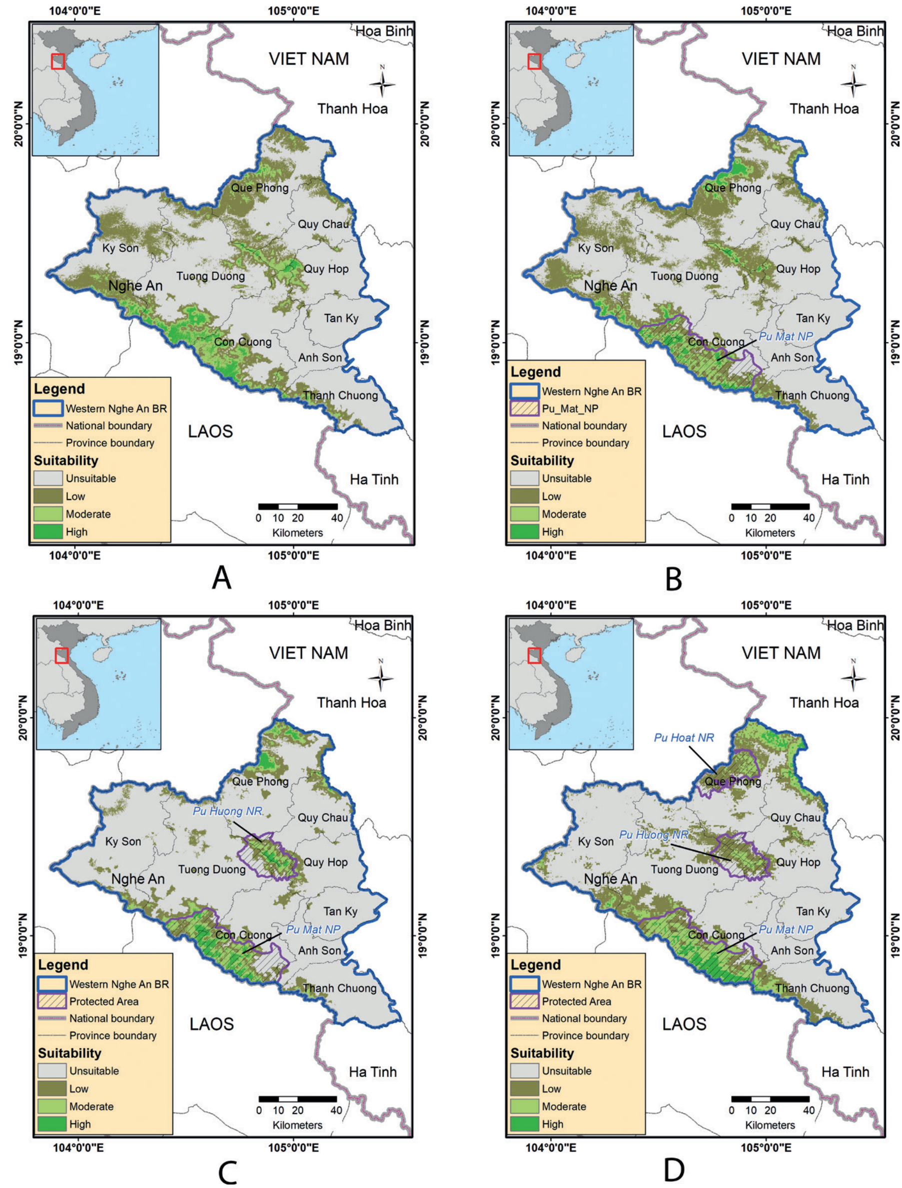

Figure 6. The suitable habitat of NWCG in the Western Nghe An BR in **A** 1990 **B** 2000 **C** 2010, and **D** 2020 (Pu Mat NR was established in 1995, and upgraded to be national park in 2001; Pu Huong, and Pu Hoat NRs were established 2003, and 2013, respectively).

2020. In particular, the total suitable habitat gradually declined by around 22.72 km² from 1990 to 2000. The moderately and highly suitable habitat shrank by around 77.98 km² (8.95%) and 75.04 km² (19.49%), respectively. Between 2000 and 2010, there was around 1,574.76 km² contraction of suitable habitat for the gibbons in the Western Nghe An BR. The majority of habitat lost lay within the low to moderate suitable habitat types. The predicted suitable habitat of NWCG increased significantly from 2750.21 km² to 4,022.42 km² between 2010 and 2020. All suitable categories of habitat showed an expanding trend in the period. The high, moderate, and low habitat suitability categories were estimated to increase by around 38.01 km² (11.77%), 456.23 km² (65.69%), and 768.97 km² (44.73%), respectively (Table 2).

The extracted LULC in the Western Nghe An BR from 1990 to 2020 constituted seven main types, including Settlement, Agriculture, Barren land, Broadleaf forest, Plantation, Water, and Bamboo forest (Table 3). The Broadleaf Forest type occupied the largest area and showed different trends between 1990 and 2020: 6,366.36 km² (46.01%), 7,145.05 km² (51.64%), 6902.46 km² (49.89%), and 7695.72 km² (55.62%) in 1990, 2000, 2010, and 2020, respectively (Table 3). On the other hand, the Settlement area was the smallest category but presented an increase from around 0.56 km² (0.004%) in 1990 to 34.75 km² (0.25%) in 2020 (Table 3).

Table 3. Area and change of the LULC categories in the Western Nghe An BR from 1990 to 2020 extracted from Phan et al. (2021) (unit=km²).

No	LULC categories	Year				Change		
		1990	2000	2010	2020	1990–2000	2000–2010	2010–2020
1	Settlement	0.56	1.86	13.79	34.75	1.30	11.93	20.97
2	Agriculture	1,789.05	2,008.77	1,835.63	1,707.34	219.72	-173.14	-128.29
3	Barren land	791.70	869.97	899.11	549.95	78.27	29.13	-349.16
4	Broadleaf Forest	6,366.36	7,145.05	6,902.46	7,695.72	778.69	-242.59	793.26
5	Plantation	3,930.07	2,681.34	2,733.05	2,275.61	-1,248.73	51.71	-457.43
6	Water	68.27	83.86	69.91	125.89	15.59	-13.94	55.96
7	Bamboo forest	889.56	1,044.72	1,381.62	1,446.31	155.16	336.90	64.68

Table 4. Area of suitable habitat inside and outside borders of protected areas (Pu Mat NP, Pu Huong NR, and Pu Hoat NR*) of NWCG projected by the MaxEnt model in 1990, 2000, 2010, 2020.

Suitability	1990		2000		2010		2020	
	Inside	Outside	Inside	Outside	Inside	Outside	Inside	Outside
Low	0	3,091.51	382.32	2,839.49	437.10	1,282.11	723.43	1,764.75
Moderate	0	871.28	348.16	445.15	444.19	263.99	613.29	560.11
High	0	384.89	137.57	172.28	228.84	93.99	236.99	123.85
Total	0	4,347.68	868.05	3456.91	1,110.13	1,640.08	1,573.71	2,448.70

*: Pu Mat NR was established in 1995, and upgraded to national park in 2001; Pu Huong, and Pu Hoat NR were established 2003, and 2013 respectively.

Habitat suitability changes of NWCG within existing protected areas inside the Western Nghe An BR.

The overlay between the existing protected areas within the Western Nghe An BR, including Pu Mat NP, Pu Huong, and Pu Hoat NRs, and the suitable habitat of NWCG predicted by the MaxEnt model was only approximately 868.05 km^2 (25.11%) of suitable habitat lies within protected areas (PAs) in 2000. In 1990, three protected areas in the core zone of the BR were not yet established. In 2010, the areas of suitable habitat inside PAs increased to 1,110.13 km^2. Then, the predicted suitable habitat rose to approximately 1,573.71 km^2 in 2020 (Table 4).

Discussion

The AUC value of both models in 2010 and 2020 shows a high capacity to predict the suitable habitat of NWCG with a good performance. The MaxEnt model has been broadly employed to predict the potential distribution of primates (Sarma et al. 2015, 2021; Tran and Vu 2020; Widyastuti et al. 2020; Yang et al. 2021), and also to assess the changes in the suitable habitats of several species under changes in land cover or climate (Tran et al. 2020; Vu et al. 2020; Sarma et al. 2021; Trinh et al. 2021; Blair et al. 2022; Ngo et al. 2022). The predicted suitable habitat of the 2020 model of NWCG in the Western Nghe An BR covered all of the known presence points within Pu Hoat, Pu Huong NR, and Pu Mat NP and adjacent areas (Fig. 5). The predicted suitable habitat of the 2010 model also fitted with the known occurrence of the species in Luu and Rawson (2009, 2010, 2011), and Rawson et al. (2011). Our result indicates that the model could reliably predict the change of suitable habitat over the years 1990–2020 of NWCG in the Western Nghe An BR.

In the present study, we tried to predict the suitable habitat changes of NWCG in the Western Nghe An BR. Modeling a partial distribution could not provide a complete species range because a part of the environmental conditions and presence records of species outside of the target area of the model are not included (Carretero and Sillero 2016; Sillero et al. 2021). Models for the entire distribution of a species can provide a better result than models of partial distribution (Barbet-Massin et al. 2010; Carretero and Sillero 2016). However, it also should be noted that a model on a partial range of a species can forecast other distribution constraints on this species, which may fluctuate in distinctive parts in the whole range (Martínez-Freiría et al. 2008; Vale et al. 2015; Sillero et al. 2021). Our study focused on a small part of the species' overall distribution range that spans Vietnam, northern Lao and southern China (Rawson et al. 2011). Thus, the results could reveal the distinctiveness of environmental variables in the Western Nghe An BR, resulting in changes in suitable habitat of the Western Nghe An BR under changes in LULC between 1990 and 2020. The results also provided valuable insights that could assist in predicting changes in habitat suitability in the entire distribution range of the species.

Our models indicated that the "Distance to Agriculture" was the most significant variable for both predicted models 2020, and 2010 of NWCG, with the highest contributions to the models. The habitat suitability was likely to increase when the distance to agricultural land value was high (Fig. 3), which was also shown in a model of the Northern yellow-cheeked gibbon by Tran and Vu (2020). Gibbons are very sensitive to human disturbances (Geissmann et al. 2000) and habitats near agricultural land can be more easily accessed. Therefore, these areas are considerably impacted by anthropogenic activities such as illegal logging or hunting. Previous studies also emphasized that habitat loss is an important issue and has caused a dramatic reduction of gibbon populations throughout their distribution (Rawson et al. 2011; Rawson et al. 2020).

The suitable habitat generated by species distribution modeling could be very useful in suggesting areas to find new populations, especially for rare and threatened species (Pearson et al. 2007; Thorn et al. 2009; van Schingen et al. 2016; Ngo et al. 2019, 2022). Our model for the present suitable habitat of NWCG in the Western Nghe An BR showed a concentration in three distinctive areas, including the northern part of Que Phong and Quy Chau districts, Pu Huong NR, and the southern Tuong Duong, Con Cuong districts – within Pu Mat NP (Fig. 4). Our result also revealed that the predicted suitable habitat area lies outside the existing protected areas at around 2,448.70 km^2. This area is primarily located in the northern region of Pu Hoat NR, near Thanh Hoa province, and in the northwest and southeast areas of Pu Mat NP, Nghe An province (Fig. 5). Rawson et al. (2011) indicated that the majority of NWCG populations in Vietnam were detected within existing protected areas, while a large forest area outside the established protected area system has not been surveyed. Recently, researchers also found at least 40 groups of NWCG, mainly inhabiting an area to the north of Pu Hoat NR, outside the current protected systems (Pu Hoat NR 2021). Thus, we believe that a large population of NWCG outside protected areas probably have not been detected yet. We recommend that more survey efforts on gibbons should be spent on the higher suitable habitat areas outside protected areas that were predicted by our model, besides the priority for gibbon surveys within Pu Hoat NR, Pu Huong NR, and Pu Mat NP. Our suitable habitat results given by the MaxEnt model can allow managers, conservationists, and researchers to easily plan field surveys for exploring the unrecorded population of NWCG in the Western Nghe An BR with greater confidence.

Our current study indicates that LULC changes may significantly impact the distribution of gibbons in the Western Nghe An BR, central Vietnam, as projected from 1990 to 2020. Knowledge of habitat transformation plays a crucial role in making decisions regarding biodiversity conservation (Fletcher et al. 2018; Su et al. 2021). Additionally, monitoring gibbons and their habitat is extremely important for conservation due to their shrinking populations globally (Sarma et al. 2021). The Western Nghe An BR was assessed as the most important site for the conservation of NWCG (Rawson et al. 2011), while Pu Mat NP might hold the largest population of the species, with an estimated population of 130 groups through gibbon surveys in 2010 (Luu and Rawson 2011). Our models showed that the habitat suitability for NWCG slightly declined from 1990 to 2000, and greatly decreased between 2000 and 2010. On the other hand, from 2010 to 2020, the predicted suitable habitat increased by around 1272.20 km^2. It showed that the suitable habitat area of the NWCG strongly depended on the change of LULC. The main LULC types of the Western Nghe An BR constituted Agriculture land, Broadleaf forest, and Plantation, while changes in LULC in the area showed complex trends consistent with a case study in the highland area of Nghe An Province (Leisz 2009).

The Distance to Settlement variable was the second most important variable for the habitat suitability model of NWCG, although the Settlement was the smallest area among seven main LULC types in the Western Nghe An BR, probably indicating the high impact of human residence settlement areas to habitat suitability of NWCG. The settlement area in the transition zone of the Western Nghe An BR continually increased from 1990 to 2020, probably due to urbanization and population expansion. Between 1990 and 2000, the agricultural land area increased, leading to a slight decrease in the suitable habitat of NWCG. The broadleaf forest areas significantly decreased between 2000 and 2010, reflecting the ineffective activities for habitat conservation in the area. In contrast, there was an increase in the broadleaf forest from 2010 to 2020 that was probably facilitated by government policies, notably the closing of natural forest policy in the late 2010s, and the National Action Programme on REDD+ in the period 2011–2020 (Government of Vietnam 2012). Gibbons are known to be sensitive to human disturbance and to prefer pristine broadleaf forests. Based on our model results on habitat suitability, we strongly recommend protecting the suitable habitat for NWCG and increasing the broadleaf forest areas.

Although the Western Nghe An BR has been established since 2007 with only three core protected areas, including Pu Mat NP, Pu Huong, and Pu Hoat NR, most areas of the Biosphere Reserve have remained currently intact even with the increasing settlement, agricultural land, and the fluctuation of broadleaf forest areas. As a positive human policy, establishing protected areas for protecting all environmental components, including populations, habitats of wild species and natural ecosystems, is crucial because of its mitigations of negative impacts on biodiversity at a local scale (Margules and Pressey 2000; Estrada and Real 2018). Through the efforts of the Vietnamese government, Pu Mat NR was established in 1995 and upgraded to the national park level in 2001; Pu Huong and Pu Hoat NR were established in 2003 and 2013, respectively. The establishment is probably the major reason for the increase of suitable habitats for NWCG inside protected areas. In the general planning for biodiversity conservation of the country to 2020, orientation to 2030 in Degree 45/QĐ-TTg/2014 (Government of Vietnam 2014), the government also proposed three biodiversity corridors inside the Western Nghe An BR to support the movement of wildlife species under the impact of climate change. However, connectivity habitat for gibbons among the three core protected areas (Pu Mat NP, Pu Luong, and Pu Hoat NR) is very poor when the suitable habitat within these protected areas seems to be isolated. We suggest that areas for connecting three core protected areas inside the Western Nghe An BR also should receive high priority in habitat monitoring of the gibbon.

In this study, land-use change has a strong relationship with the suitable habitat of NWCG, which resulted in the contraction of the suitable habitat of the endangered gibbon from 2000 to 2010. Interestingly, an expansion of suitable habitat of NWCG was revealed in the period 2010 – 2020, which provides a positive sign for habitat conservation in the study areas. Additionally, a limitation of the study is the lack of information on specific habitat parameters that might be critical for defining the selection habitat of gibbons, such as the height of tree canopy, food preference, and availability. We recommended that more intensive surveys should be focused on the suitable habitat areas suggested by our model to reveal the forest quality of these areas.

Vietnam is located in the Mekong region, which was assessed as one of the 11 areas experiencing the largest forest loss. The average rate of deforestation in the Mekong region was approximately 0.4% per year (Leinenkugel et al. 2015). Researchers also predicted that the Mekong area will have lost about 15–30 million hectares of natural forest by 2030 if there are no effective urgent measures from governments (WWF 2018). In the best scenario, countries have strong reforms toward green and clean development, and the natural forest of countries in Southeast Asian countries can increase by around 19.6 million hectares (Estoque et al. 2019). However, we have not yet had any fine-scale forecasts on forest status scenarios for the region in the future. With an increasing trend in forest areas, and the efforts and commitments of the Vietnamese government in recent times (De Jong et al. 2006; Government of Vietnam 2017), we predict that the natural forest area in the Western Nghe An BR will continually show a slight increasing trend in the next few decades, leading to an increase in the suitable habitat of gibbons in the study area. But it also should be noted that the increased forest area comes mainly in the form of young forests, which cannot meet the habitat needs of gibbons. Gibbons are specialized in arboreal life and require good-quality forests with a high canopy closure and large trees for their survival (Geissmann et al. 2000; Nadler and Brockman 2014). Therefore, we strongly recommend that activities to enrich young forests are also necessary for the conservation activities of NWCG and its habitats in the Western Nghe An BR.

Finally, we highly recommend the implementation of the following actions for protecting existing populations of NWCG and its habitat in the Western Nghe An BR: 1) implement population surveys, monitoring and conservation awareness programmes not only in three core protected areas (Pu Mat NP, Pu Hoat, and Pu Huong NR) but also in other highly suitable habitats that are predicted by our model, especially for the northern Pu Hoat NR, northern and southern Pu Mat NP; 2) upgrade the Pu Hoat watershed protection forest, the highly suitable habitat in the north of Pu Hoat NR, to be a Nature Reserve (Fig. 4). 3) improve green corridors connecting three core protected areas inside the Western Nghe An BR and other highly suitable habitats; 4) predict the suitable habitat of the NWCG in its whole distribution range, including northern Vietnam, Laos, and southern China, then, propose transboundary conservation programs, especially between Vietnam and Laos; 5) conduct surveys to obtain specific habitat parameters at the suitable habitat area and confirmed the presence of gibbon, then implement the enrichment activities in young forest areas that do not meet the requirements of gibbons for living.

Conclusion

There is currently a lack of research on the changes in suitable habitats for gibbons, leading to limited efforts to protect and conserve their habitats. Here, we applied the species distribution modeling to predict the suitable habitat of NWCG in the Western

Nghe An BR, and assessed the impact of changes in land use and land cover from 1990 to 2020 on the suitable habitat of this species. The current suitable habitat for the gibbon in the Western Nghe An BR was estimated at approximately 4,022.42 km^2, mainly concentrated in three distinctive areas (Pu Mat NP, Pu Huong, and Pu Hoat NR), while the predicted suitable habitat area lies outside the existing protected areas at around 2,448.70 km^2. Our result also indicated that due to the changes in LULC, the predicted suitable habitat of the gibbon decreased from 1990 to 2010 but gradually increased from 2010 to 2020. Based on our findings, we suggested that more survey efforts should be focused on areas of predicted suitable habitat regions outside existing protected areas, in addition to continuing efforts for suitable habitat areas within protected areas. We also highly recommend enriching young forests and protecting the preferred habitat for the gibbon, specifically broadleaf forests. Finally, we proposed several actions to safeguard NWCG and its habitat in the Western Nghe An BR.

Acknowledgements

We would like to thank the "Mainstreaming Natural resource management and Biodiversity conservation objectives into socio-economic development planning and management of biosphere reserve in Viet Nam" project (BR project) for their supports. We are grateful to Dr. Greg Nagle for proofreading this manuscript. We wish to thank Management Broad of Western Nghe An BR, Pu Mat NP, Pu Hoat, and Pu Huong NR, and our field assistants for their support during our field surveys. Many thanks to anonymous reviewers for improving a previous version of the manuscript.

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Supplementary material 1

Supporting information

Authors: Khoa Van Phung, Dung Van Tran, Hai Thanh Dong, Vinh Quang Luu, Van Bac Bui, Thinh Tien Vu

Data type: figures and tables

Explanation note: SI–I. Map of each variable that was used for the final model. SI–II. The percent contribution of environmental variables. SI–III. The suitable habitat of *N. leucogenys* were predicted from occurrence localities in 2020. SI–IV. Area of suitable habitat of *N. leucogenys* projected by MaxEnt model in 1990, 2000, 2010, 2020 from the model of 2020 (unit: km2).

Link: https://doi.org/10.3897/natureconservation.51.90373.suppl1