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Assessment of climate change impacts on one of the rarest apes on Earth, the Cao Vit Gibbon *Nomascus nasutus*[a]

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Abstract

The Cao Vit Gibbon (*Nomascus nasutus)* is a critically endangered species of gibbon that was historically wide-ranging but is now known to occupy only one forest patch that straddles the China-Vietnam border. While past and current threats to the species include poaching and habitat destruction, the potential effects of global climate change on this species and its current habitat are still poorly known. Species Distribution Modeling (SDM) is often used to predict the risk of potential species distribution shifts in response to climate change and inform conservation planning including restoration and reintroduction efforts. Here, we present optimally tuned SDMs to predict climatically suitable habitat for *N. nasutus,* projected under a range of future climate change scenarios. Our SDMs showed high predictive performance and successfully predicted the current known range, but also showed expected areas of overprediction to a much wider area that likely reflects the historical distribution of the Cao Vit Gibbon across southern China and northern Vietnam. SDMs that projected across a range of future scenarios estimated an overall loss in total area of climatically suitable habitat, with the average value of about -23,000 km^2 in 2041 – 2060 period and about -25,000 km^2 in 2061 – 2080 period, compared to the current predicted range, but they also predicted the currently occupied Trung Khanh-Jingxi Forest as suitable across all future scenarios. Thus, some of the predicted climatically suitable areas that are close to the current known range may be worth targeting for future habitat restoration and population re-establishment and recovery efforts, while balancing other threats and management concerns.

Highlights

- For species with a very small population such as the critically endangered Cao Vit Gibbon, climate change presents a potentially severe threat to its long-term conservation in synergy with other direct threats such as habitat loss and poaching.
- Planning for habitat restoration and population re-establishment efforts for critically endangered species should take into consideration future climatic suitability.
- Cross-border partnerships are essential for conservation management of critically endangered species under climate change.
- Species distribution models for the critically endangered Cao Vit Gibbon suggest its current occupied area will remain climatically suitable into the future, and while the total area of climatically suitable habitat in the future is highly likely to decrease overall, we reveal potential sites for habitat restoration and population re-establishment.

Keywords: bioclimate envelope, China, conservation planning, cross-border conservation, *Nomascus nasutus,* species distribution modeling, species reintroduction,Vietnam

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Introduction

Nomascus is the second-most species rich genus of gibbons with a total of seven species, of which six occur in Vietnam (Rawson et al. 2011). All six gibbon species in Vietnam are severely threatened by illegal hunting and habitat destruction, and are listed either as Endangered, or Critically Endangered in the IUCN Red List (Rawson et al. 2020). Among them, the Cao Vit Gibbon *Nomascus nasutus* Kunkel d'Herculais, 1884 has the lowest total population, estimated at about 107 – 136 individuals remaining (Ma et al. 2020). Historically, *N. nasutus* had a broad distribution covering southeastern China and northeastern Vietnam (Appendix S1), but the species was believed to be extinct in China since the 1950s (Tan 1985), and the last documented record in Vietnam in the 20th century was from the 1960s (Tien 1983), until a small population in Cao Bang along the northern border of Vietnam was rediscovered in 2002 (Geissmann et al. 2003). In 2006, this species was recorded in the same forest area on the Chinese side of the border (Chan et al. 2008). Consequently, Trung Khanh Cao Vit Gibbon Conservation Area was established in Vietnam in 2007, and Bangliang Nature Reserve was established in China in 2009 to conserve this population. Although there was no concrete population data for the species before the 2000s, given the scale of poaching and habitat destruction in both China and Vietnam for the last 60 years (Sterling et al. 2006, Liu et al. 2019), many presumed that the Cao Vit Gibbon populations had declined and were extirpated at most sites (Rawson et al. 2011), resulting in its listing as critically endangered in the IUCN Red List (Rawson et al. 2020). The species is now restricted to the same forest patch straddling the Chinese - Vietnamese border where it was initially rediscovered, which comprises a total of 2,500 ha of limestone forests.

The isolated forest block is surrounded by human residential and cultivation areas, and the habitat of the Cao Vit Gibbon has been degraded as a result of timber extraction, fuel-wood collection, charcoal production, selective logging, and agriculture encroachment (Geissmann et al. 2002, Fan et al. 2011, Fan et al. 2013). Hence, the main threats to the population, and also to the species, are insufficient quality habitat (Fan 2017) and the vulnerability of the small population to genetic diversity loss due to low numbers of individuals and stochastic events which might cause a sudden catastrophic loss of many individuals (Rawson et al. 2011). Since the rediscovery of the Cao Vit Gibbon, other surveys have failed to record any other surviving populations in Vietnam, although local community members have reported the existence of the gibbon before the 2000s in several sites (Rawson et al. 2011). Hence, the population in Trung Khanh and Bangliang have been monitored by frequent surveys (Geissmann et al. 2002, Hoang 2004, Hoang 2007, Dat et al. 2008, Cuong 2012, Hoang et al. 2018, Ma et al. 2020) in order to inform conservation and research. Records from surveys in Vietnam from 2007, 2012, 2016, and 2018 showed that the population has remained stable, and possibly may have increased slightly.

Simultaneous surveys by Chinese scientists and conservationists at the same time indicated that the population was approaching the habitat carrying capacity (Fan 2017). Fan et al. (2011) also reported the disappearances of two juveniles, coincident with periods of cold weather in 2008 and 2009. Such information raised serious concern on the viability of the population in its small and isolated remaining habitat, especially in the context of a changing climate, given that there were periods recently (December 2013, January 2016, and January 2021) of sudden colder weather in southern China and northern Vietnam (Kug et al. 2015, Sun et al. 2016, Liao et al. 2020, Dai et al. 2021). The potential effects of global climate change on this critically endangered species and its current habitat are poorly known. Given this and also the perhaps more pressing threats to its current habitat, the species may have a better chance of survival if other populations could be re-established at several sites while keeping the potential effects of climate change in mind. Following recommendations by Fan et al. (2013), pilot habitat restoration has begun in China and could be expanded (Ma et al. 2020).

Taxonomic studies of the Western Black-crested Gibbon (*N. concolor)* and *N. nasutus* have led many to assume these species are separated by a zoogeographic barrier formed by the Red River in Vietnam, with *N. concolor* inhabiting the western side of the river system (Geissmann et al. 2000, Rawson et al. 2011). However, records of *N. concolor* have been reported on the eastern side of the Red River in China, and conversely, records of supposedly *N. nasutus* have been documented on the western side of the river (Tien 1983, Tan 1985). On the other hand, those records are often undated, or incomplete, or from the period when taxonomic issues for *Nomascus* had not yet been resolved, hence the river system as a biogeographical barrier for these two species is still being debated. Further information on the biogeography of *N. nasutus* would thus be very helpful to inform potential habitat restoration and population re-establishment efforts.

Species distribution modeling (SDM) is widely used to study biogeography, biodiversity patterns, evolutionary ecology, and to inform conservation efforts including reintroduction planning and predicting species' distribution shifts in response to climate change (Urbina-Cardona et al. 2019). Overall, SDM explores and utilizes possible interactions between species occurrence records and environmental variables to calculate and produce a probability map of environmental suitability for a species in a given area. SDM can help identify the potential distribution range of an endangered species that may be included in protected area planning (Thapa et al. 2018), resolve taxonomy issues for species groups whose other traits may not be clearly distinguishable and conclusive (van Schingen et al. 2016), predict vulnerable regions for invasive species risk (Ren et al. 2016), determine areas of refugia that may be home to many rare and endemic species (Tang et al. 2018), and examine processes influencing biodiversity and evolution over a long timescale (Musher et al. 2020). The wide range of applications has pushed the development of many different SDMs approaches, among which Maximum Entropy (Maxent) is among the most commonly used (Urbina-Cardona et al. 2019). Compared to other modeling approaches, Maxent only requires presence records, and still produces robust results when only a small number of occurrences is available (Elith et al. 2006, Phillips et al. 2006, Pearson et al. 2007). Maxent also provides tools to assess and project models of species' suitable habitat under future climate scenarios to better understand the potential impact of this threat (Phillips and Dudík 2008, Phillips et al. 2017).

Here, we reviewed and compiled presence records for the Cao Vit Gibbon throughout its known distribution range. We then incorporated locality data into SDM to generate distribution maps of the species under current conditions and future climate scenarios to help advance understanding of the environmental requirements of this primate, and to inform related conservation measures. Specifically, we address the following questions:

- What areas are most climatically suitable for the Cao Vit Gibbon today? How does the currently occupied Trung Khanh-Jingxi Forest remnant habitat compare in climate suitability to overall suitable areas that may have been part of the species' historical distribution?
- How may climatically suitable areas for the Cao Vit Gibbon change in the future, and where might additional habitat restoration and population re-establishment efforts be focused to account for this issue?

Materials and Methods

Occurrence data compilation

We reviewed available records of the Cao Vit Gibbon by searching the Web of Science, Google Scholar, ResearchGate, GBIF, and iNaturalist using the following queries: "*Nomascus nasutus*", "*Nomascus concolor*", "*Nomascus leucogenys*", "*Nomascus hainanus*", "*Nomascus*", "*hainnanus*", "*nasutus*", "Cao Vit Gibbon", "Eastern Black-crested Gibbon", "Gibbon", "Crested Gibbon", and their local language equivalents such as "Vượn Cao Vit", "Vượn đen tuyền", "Vượn đen Đông Bắc" and so on. In addition, library archives, reports, and specimens from related institutions were also examined. To account for taxonomic confusion (Geissmann et al. 2000, Roos et al. 2007, Rawson et al. 2011), for all records that mentioned the other *Nomacus* species but came from within the distribution range of the *N. nasutus*, we documented the localities as the Cao Vit Gibbon. The collected records were then evaluated, checked, and filtered to avoid erroneous and fossil localities, and then the final set was used to train SDM for the Cao Vit Gibbon (Appendix S1).

Based on the extensive search, we obtained a total of 307 known records of the Cao Vit Gibbon, including bone and fossil records, from peer-reviewed papers, books, published and unpublished reports. A list and a map of all distribution records are shown in Supplementary Table S1 and Fig. S1. The final set that was used to train SDM for the Cao Vit Gibbon included 271 records (Fig. 1).

Data preprocessing and model tuning

To preclude spurious effects from spatial autocorrelation, we thinned the collected records using the spThin package (Aiello-Lammens et al. 2015) in R (R Core Team 2020) to within a 5 km distance (Pearson et al. 2007, Radosavljevic and Anderson 2014), resulting in the final set of 27 localities. We constructed the SDM for the current climate using 19 bioclimatic variables at 2.5-minute resolution available at WorldClim 2.1 database (Fick and Hijmans 2017); we chose to build our models at this resolution because it was the highest resolution available for future climates, and we wanted to allow spatial comparisons between current and future climate conditions. We restricted the model background training extent by using a two degree buffer around the occurrences with 10,000 background points (Anderson and Raza 2010). We ran all analyses in Maxent version 3.4.4 (Phillips et al. 2017). However, as the default settings in Maxent has the tendency to produce overfit and overly complex models (Merow et al. 2013), which are especially important to avoid when models are to be projected under future climate scenarios, we undertook the following set of additional tuning steps to minimize overfitting and maximize discriminatory ability.

We performed a model tuning process that varied the number and types of feature classes included in the model (linear, linear and quadratic, linear and quadratic and hinge, and hinge features), and tested the models with a range of regularization multipliers ranging from 1.0 to 10.0 by increments of 0.5. Other model parameters, e.g., convergence threshold and feature selection, followed recommendations from the developers (Phillips et al. 2006). We then used the jackknife method for model evaluation as recommended for species with a small number of input records (Pearson et al. 2007, Muscarella et al. 2014).

Model selection and future projections

To assess model performance and select the most suitable one, we used the 10% omission rate threshold to select models that showed the least overfitting. Of this subset, we then chose the model with the highest AUC values. Final models were then compared using the Akaike information criterion (AIC), which balances complexity with model fitness (Warren and Seifert 2011). For the final model, we used the 10% training presence threshold to classify between suitable and unsuitable areas for the Cao Vit Gibbon.

The best model was then projected to two future periods, the 2050s (2041 – 2060) and the 2070s (2061 – 2080), using data for two global climate models, BCC-

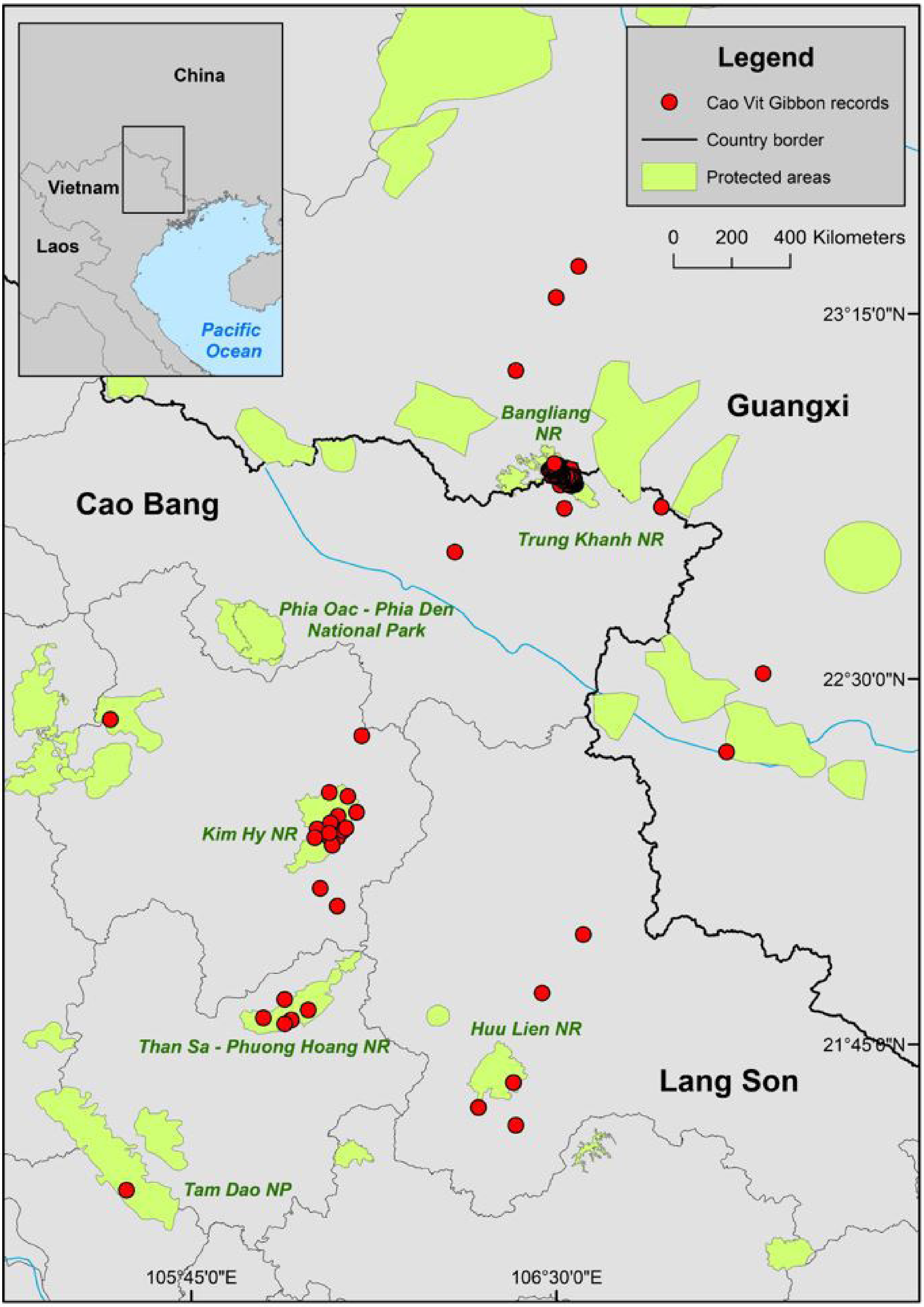

Figure 1. Occurrence records for the Cao Vit Gibbon, obtained through a literature and database review.

CSM2-MR (Wu et al. 2019) and MIROC6 (Tatebe et al. 2019). We chose these two models because they were most appropriate for our region of interest. All four socio-economic pathway scenarios were used for each model, ranging from SSP1-2.6, which assumes there will be an increasing shift toward sustainable practices in global economy, to SSP5-8.5, which assumes the world will adjust towards an energy-intensive, fossil fuel-based economy (Riahi et al. 2017). Individual binary maps for each scenario of the same model and the same duration were then stacked and combined in an ensemble approach to generate presence probability maps for the species (Araujo and New 2007).

Results

For the SDM, Maxent models showed reasonable predictive power, and the optimal model for the current potential distribution of the Cao Vit Gibbon had a regularization multiplier of 3.5 and included the hinge feature class (average test omission rate at the 10% training presence threshold = 0.148, average evaluation AUC = 0.892, Fig. S2). Spatially, the final model successfully predicts the known range of *N. nasutus* but also overpredicts beyond the current known range likely into the historic range (Fig. 2). The bioclimatic variables with non-zero lambda values in the final model are mean diurnal range, iso-thermality, temperature annual range, mean temperature of wettest quarter, mean temperature of driest quarter, mean temperature of coldest quarter, precipitation seasonality, precipitation of driest quarter, and precipitation of coldest quarter.

Combining the model results with the occurrence record review, we found that several protected areas located within current predicted climatically suitable habitat for the Cao Vit Gibbon also have or are near historical records of *N. nasutus*. They include: Tam Dao National Park (Vinh Phuc – Thai Nguyen), Than Sa – Phuong Hoang Nature Reserve (Thai Nguyen), Huu Lien Nature Reserve (Lang Son), Cham Chu Nature Reserve and Na Hang Nature Reserve (Tuyen Quang), Nam Xuan Lac Nature Reserve, Ba Be National Park and Kim Hy Nature Reserve (Bac Kan), Bac Me Nature Reserve and Du Gia National Park (Ha Giang), Phia Oac – Phia Den National Park and Cao Vit Species Conservation Reserve (Cao Bang). In China, the following areas, all in Guangxi Province, are within the distribution range of the Cao Vit Gibbon and also have or are near historical recorded presences: Xialeishuiyuanlin Nature Reserve, Gulongshanshuiyuanlin Nature Reserve, Bangliang Nature Reserve, Dizhoushuiyuanlin Nature Reserve, Nongxinshuiyuanlin Nature

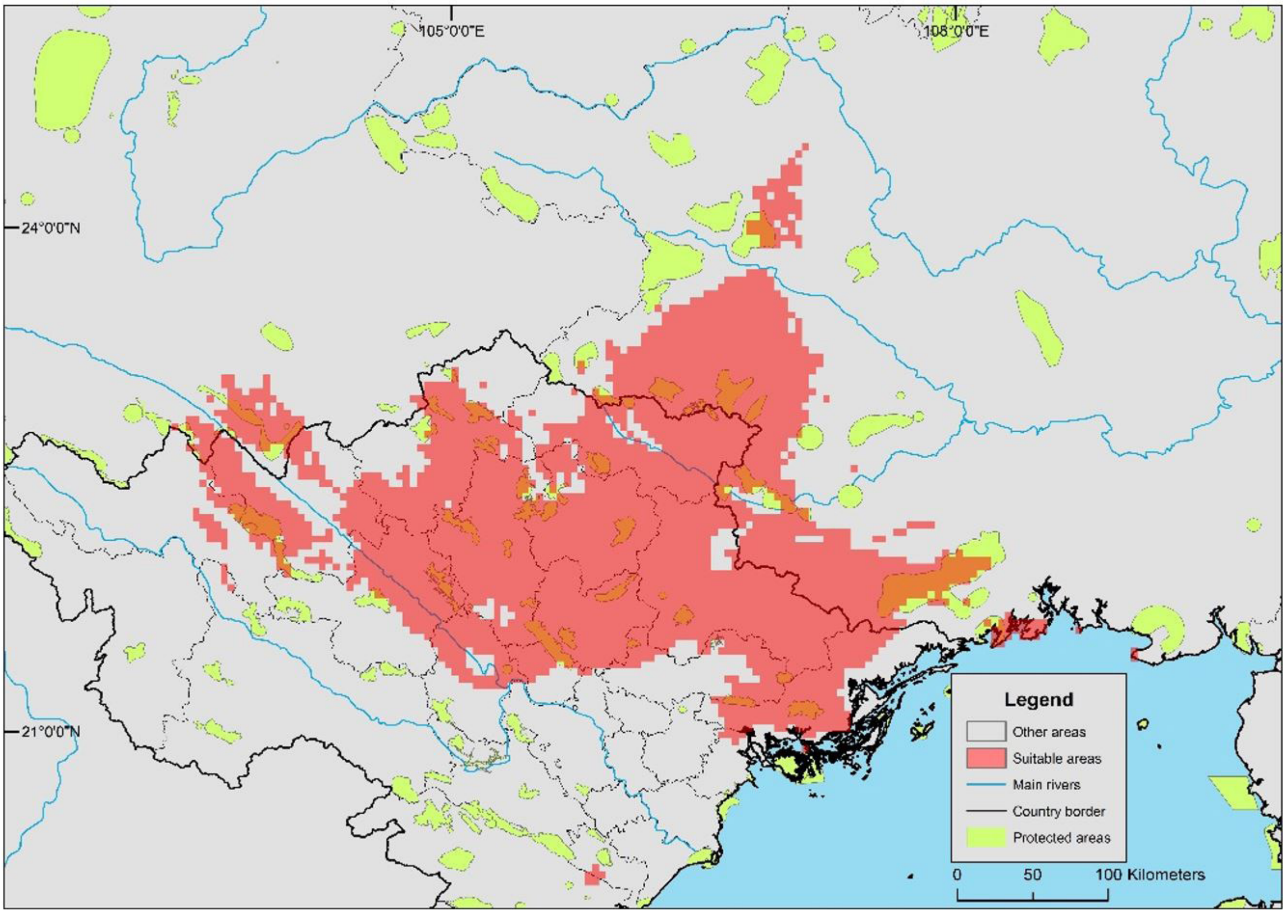

Figure 2. Potential current distribution of the Cao Vit Gibbon

Reserve, Huanglianshanshuiyuanlin Nature Reserve, Dawanglingshuiyuanlin Nature Reserve, Nonggang Nature Reserve, Qinglongshanshuiyuanlin Nature Reserve, Shiwandashanshuiyuanlian Nature Reserve, and Chunxiushuiyuanlin Nature Reserve.

Future SDM projections demonstrate potential shifts in the Cao Vit Gibbon's distribution under a range of climate change scenarios (Table 1). Changes in the distribution are illustrated in Fig. 3, which are probability density maps that were ranked in a graduated color scale following an ensemble approach to show the likelihood of gibbon presence. Each ensemble is a combination of model results of all four scenarios for one particular timeframe from one global circulation model. The highest value (100%) means that the area was estimated to be suitable for the gibbons in all scenarios. Although model predictions differ slightly on the overall directions of shift, most projections showed that the distribution is likely to shrink significantly, with the average value of

Table 1. Total projected suitable habitat changes in different future scenarios (km^2)

Time-frame	BCC-CSM2-MR models	MIROC6 models
2041 - 2060	-28,000 (-37,000 to -17,000)	-18,000 (-23,000 to -11,000)
2061 - 2080	-19,000 (-35,000 to 16,000)	-30,000 (-46,000 to -23,000)

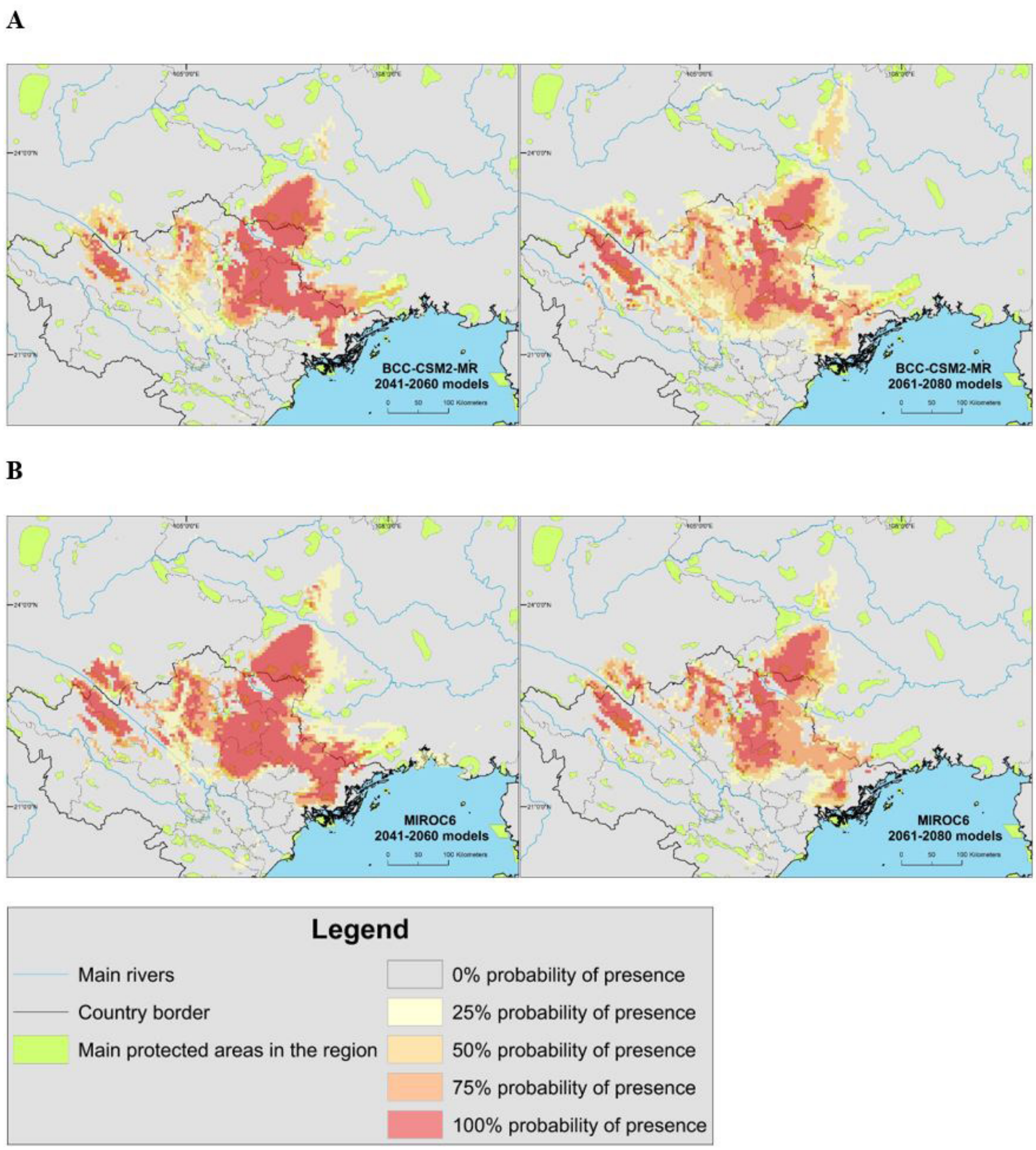

Figure 3. Predicted distribution of climatically suitable habitat for the Cao Vit Gibbon under a range of different future climate change scenarios. A. BCC-CSM2-MR models. B. MIROC6 models.

about -23,000 km^2 in 2041 – 2060 period, and about -25,000 km^2 in 2061 – 2080 period, compared to the current predicted range, and concentrated in areas around northeastern Vietnam and southwestern Guangxi. The currently occupied Trung Khanh-Jingxi Forest is predicted as suitable across all future scenarios. Other sites which are estimated to be climatically stable over time include Phia Oac – Phia Den National Park, Kim Hy Nature Reserve, and Than Sa – Phuong Hoang Nature Reserve.

Discussion

SDMs built for *N. nasutus* showed high predictive performance and the predicted range successfully included the current known range as a subset, but also showed expected areas of overprediction to a much wider area that likely reflects the historical distribution of the Cao Vit gibbon across southern China and northern Vietnam (Appendix S1). Such overprediction is expected when building SDMs from only climate data, and is also useful for the research questions of this study, as discussed further below. The variables that contributed to the optimal SDM were largely related to temperature, with temperature-related variables comprising six out of the nine variables with important contributions to model training (Supplementary Table S2). Seasonal climate with the presence of cold weather has been documented to affect the gibbons' daily activity patterns as well as food choices through behavioral responses (Fan et al. 2012, Guan et al. 2018). SDMs projected across a range of future scenarios estimated an overall decrease in total area of climatically suitable habitat but predicted the currently occupied Trung Khanh-Jingxi Forest as suitable across all future scenarios (Fig. 3). Given ongoing threats to the survival of the Cao Vit Gibbon at the site and the logistic constraints of potential population re-establishment efforts, some of the predicted climatically suitable areas that are close to the current occupied area may be worth targeting for further feasibility assessments to establish a second population of the Cao Vit Gibbon.

While cross-border cooperative agreements have been established for the Cao Vit Gibbon conservation, as described further below, it is probable that gibbon translocation within a province or country is more feasible than translocations to other provinces or countries in terms of administration permission, time, finance and logistics. Fauna & Flora International (FFI) and partners have been conducting habitat suitability assessments in the proposed western extension of Trung Khanh Nature Reserve, with two potential sites identified and they are connected to Trung Khanh through a narrow strip of forest, which may form a biological corridor for the gibbon movements (Fan et al. 2013). In addition, Phia Oac-Phia Den National Park, which is also situated within the jurisdiction of Cao Bang Province and was likely to be within the historical range of the gibbons (Geissmann et al. 2000), falls within the climatically suitable range predicted for current conditions and future scenarios. This National Park, currently having a management board and protection staff, constitutes a good potential candidate site for the establishment of a second population, although further assessments of the site are needed.

Our results are also highly informative in terms of inferring the biogeographic histories of *Nomascus* gibbons. Bioclimatically speaking, *N. nasutus* can readily inhabit both sides of the Red River, but on the western side of the river, the range of the gibbons stops around the Hoang Lien Mountain Range. Even with a more relaxed threshold, minimum training presence, the optimal distribution of the Cao Vit Gibbon is still restricted almost entirely to the eastern side of the Mountain Range. Therefore, the zoogeographic barrier between *N. concolor* and *N. nasutus* may be formed by the Red River or the combination of both the Red River and the Hoang Lien Range. Given that the Western Black-crested Gibbon is genetically more closely related to *N. leucogenys* and *N. siki*, which live in the more southern areas of both the Red and Black river systems, than the Cao Vit Gibbon (Thinh et al. 2010), and that the historical localities of *N. nasutus* are near the headwaters of the Red River itself (Fig. S1), one possible explanation for the current biogeographic distribution of these species is that the shared common ancestor of the genus once distributed in the North of the Red River and/or the Hoang Lien Mountain Range, and then migrated to the south. Such a hypothesis has also been proposed for other vertebrates including species in *Odorrana* and *Microhyla* taxa (Bain and Hurley 2011). Further studies such as ours for a number of species or even scaling up to the biological communities of this region are needed to resolve this issue.

In this paper, we decided not to incorporate model training variables related to more recent human pressures such as forest cover or human footprint because of the wide temporal range of occurrence input data we included. Thus, the future projections we report do not take into account other factors such as changes in human land use. Also, while natural dispersal for this species is highly unlikely, our future projections do not consider potential dispersal limitations and thus might overestimate potential shifts in climatically suitable habitats. This makes the predicted decrease in climatically suitable habitat for the Cao Vit Gibbon all more concerning in terms of informing potential population re-establishment efforts. Further, other factors such as forest cover, socio-economic situations, and political will, are more likely to affect any specific, site-based decisions about re-establishment efforts. While our work specifically focuses on general estimates of risk and potential climate change vulnerability, additional studies that do incorporate the effects of human land use changes and dispersal limitations on SDM predictions could further inform site-based follow-up efforts. For example, forest structure has been shown to affect the density of other gibbon species and may be important to consider at the site level (Hankinson et al. 2021). Also, future studies that include models of other key interacting species in the community, such as fruit trees or macaques, would further inform conservation efforts along the Sino-Vietnamese border.

The process to achieve the 2017 formal cross-border cooperative agreement between China's Guangxi Province and the Vietnam Forestry Administration for Cao Vit Gibbon conservation (Ma et al. 2020) can serve as a model to begin similar processes in other areas towards forward-thinking cross-border conservation of other threatened species. Agreements may take years to establish but signal high willingness and likelihood for future cooperation to tackle complex challenges such as climate change. For example, pilot habitat restoration has begun in China and could be expanded (Ma et al. 2020). As described above, organizations in Vietnam are also tentatively considering plans for relocations or releases into some unoccupied patches (Trinh-Dinh, pers. comm.), knowing that cross-border relocations would be prohibitively complicated, but that parallel efforts in each country could be coordinated (and in fact are already conducted, e.g., the simultaneous population survey efforts; Ma et al. 2020). For other critically endangered species that are either transboundary already or may become transboundary species under future climate change, cross-border cooperation efforts should follow the example of the Cao Vit Gibbon and start to build relationships and agreements now to prepare for the future.

Author Contributions

NTA led study design and writing of the manuscript as well as model training, tuning, and projections, TDH co-led study design, provided input data and contributed to model tuning decisions and writing the manuscript, LXK provided input data and contributed to study design and writing the manuscript, and MDL, MEB, CTHN contributed to study design and writing the manuscript.

Data Accessibility

The R script file of modelling procedures is available for free online at GitHub repository: https://github.com/kuznetsov186/VN_Biodiversity.

Environmental input data used in this study are available for free online at WorldClim.org (bioclim layers; Fick and Hijmans 2017).

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Supplementary Material

The following materials are available as part of the online article at https://escholarship.org/uc/fb

Appendix S1. Comprises the following elements:

Table S1: Occurrence records collected for N. nasutus from the scientific literature

Table S2: Predictor variables used by the optimally tuned model

Figure S1: All records, including historical records, of the Cao Vit Gibbon

Figure S2: The receiver operating characteristic (ROC) curve for the optimal model

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