

Article

What Will Remain? Predicting the Representation in Protected Areas of Suitable Habitat for Endangered Tropical Avifauna in Borneo under a Combined Climate- and Land-Use Change Scenario

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Abstract: The responses of threatened tropical avian species to projected climate change and land-use change are important for evaluating the ability of the existing protected areas to provide habitat to these species under future scenarios in biodiversity hotspots. This study uses Maxent, a species distribution model that employs a maximum entropy machine learning approach to map the spatial distributions of habitats suitable for the International Union for Conservation of Nature threatened birds under present and future climate and land-use change in Borneo. We find that the existing protected areas provide very low coverage of the threatened bird species' suitable habitat areas (95%CI = 9.3–15.4%). Analysis of habitat suitability projections for 18 species of threatened birds suggests that in 2050, under Special Report on Emissions Scenarios A1B and B1, avian species with currently little suitable habitat may gain area but lose in the proportion of this that is protected. Large-ranged species are likely to lose habitat area and this will inflate the proportion of this remaining in protected areas. The present availability of suitable habitat was the most important determinant of future habitat availability under both the scenarios. Threat level, as measured by the International Union for Conservation of Nature and the habitat preferences considered here, Lowland or Lowland–Montane, are poor predictors of the amount of habitat contraction or expansion undergone by the species.

Keywords: biodiversity; climate change; conservation of nature; Maxent; entropy machine learning



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1. Introduction

Climate change and anthropogenic forest loss are the greatest threats facing tropical biodiversity [1]. Many biodiversity hotspots, such as the Indo-Malayan region, which is home to many threatened and endemic species, are vulnerable to both these drivers of biodiversity decline [2,3]. The island of Borneo in the heart of this region that has seen high levels of deforestation, from 76% forest-cover (560,000 km²) in 1973 to approximately 53% in 2010 [4,5]. The land-use changes driving forest loss, such as agricultural expansion and poorly-regulated timber extraction, will increasingly interact with climate change, and these interactions are likely to combine to have a substantial negative impact on tropical biodiversity [6]. In the face of rapid landcover and climate changes, it is vital to evaluate the impact of these on biodiversity, including the persistence of biodiversity of tropical regions such as Borneo under future scenarios.

Birds are frequently used as umbrella species and bioindicators in conservation efforts; they are wide-spread and, unusually for tropical taxa, have relatively well-studied ecologies and life-histories [7]. Climate change and land cover change dynamics act synergistically to have a negative impact on avian persistence. Ignoring the interaction between these can undermine the robust identification of future suitable habitats [8]. They are also highly sensitive to changes in their environment, making them excellent bellwethers for global

change research [8–10] Quantifying the potential impacts of predicted climate and land-use change scenarios on the “suitable habitat” size of threatened montane and lowland avian species will help us to predict patterns of future vulnerability at species-scale. Birds classified by the International Union for the Conservation of Nature (IUCN) as “threatened” are already vulnerable as they face considerable risk of extinction. Estimating the response of these species to potential future scenarios will be important in predicting whether these species are set to undergo further range size declines as a result of climate or land-use change and thus may require additional conservation efforts. Other studies have investigated the response of avian assemblages to these drivers in both temperate [11] and boreal zones [12,13], but Borneo, with its particular vulnerabilities, remains unexplored in this way. Further, a meta-analysis of the literature discovered future biodiversity related projections mostly consider the impact of climate change and leave out land cover. Given Borneo’s rapid land cover change, it is vital to quantify the impact of both climate and landcover change on habitat suitability [14]. In addition to predicting the changes in suitable habitat available to threatened avian species, understanding this in the context of the island’s protected area (PA) network under present and future scenarios will be important for informing conservation strategy both locally and across the Asian tropics.

Protected Areas are the cornerstone of conservation actions designed to ensure the long-term viability of biodiversity [15]. Tropical biodiversity-rich regions are, however, often at risk of failing to enforce the requirements of PAs, with their effectiveness limited by rapid population growth and development and additionally challenged by the triumvirate of weak institutional capacity, poverty, and corruption [16]. Threatened species do not exist exclusively within PAs, and many only find a proportion of their range protected in this way. Gap analyses can be used to quantify representation, the proportion of a species range, or of their potentially suitable habitat that lies within PAs. Biodiversity representation within the Indo-Burma hotspot PA network is already limited [17], and climate change-driven range shifts may cause the suitable habitats of vulnerable species to shift outside these [18].

The main aim of this research is to model the suitable habitat availability for the IUCN-listed threatened Bornean avian species in the island’s PA network under present and future climate and land cover scenarios. To this end, the main objectives of the research are to: (a) estimate whether the suitable habitat area of these species is likely to change substantially under specific scenarios; (b) identify whether habitat availability is differentially affected by characteristics such as their habitat preference or their IUCN threat level; and, (c) evaluate the “representation” of each species’ suitable habitat lying within the protected area network with the view of assessing the effectiveness of Borneo’s PAs for threatened bird species, both currently and under future scenarios. This is expected to provide measure of the conservation value of IUCN PA categories (Ia–VI), to assist in identifying which protected area category is most widely valuable in terms of representation of predicted suitable habitat for the different species and identify the species at the greatest risk of losing habitats.

2. Materials and Methods

2.1. Study Site

The equatorial island of Borneo in Southeast Asia spans approximately 4° S to 7° N and 108° to 118° E. At 743,330 km², it is Asia’s largest, and the world’s third-largest, island. This study focusses on the IUCN listed threatened avian species of Borneo’s lowland and montane forests (see Figure 1). Avian species of both lowland and montane rainforests are vulnerable to anthropogenic disturbances [19].

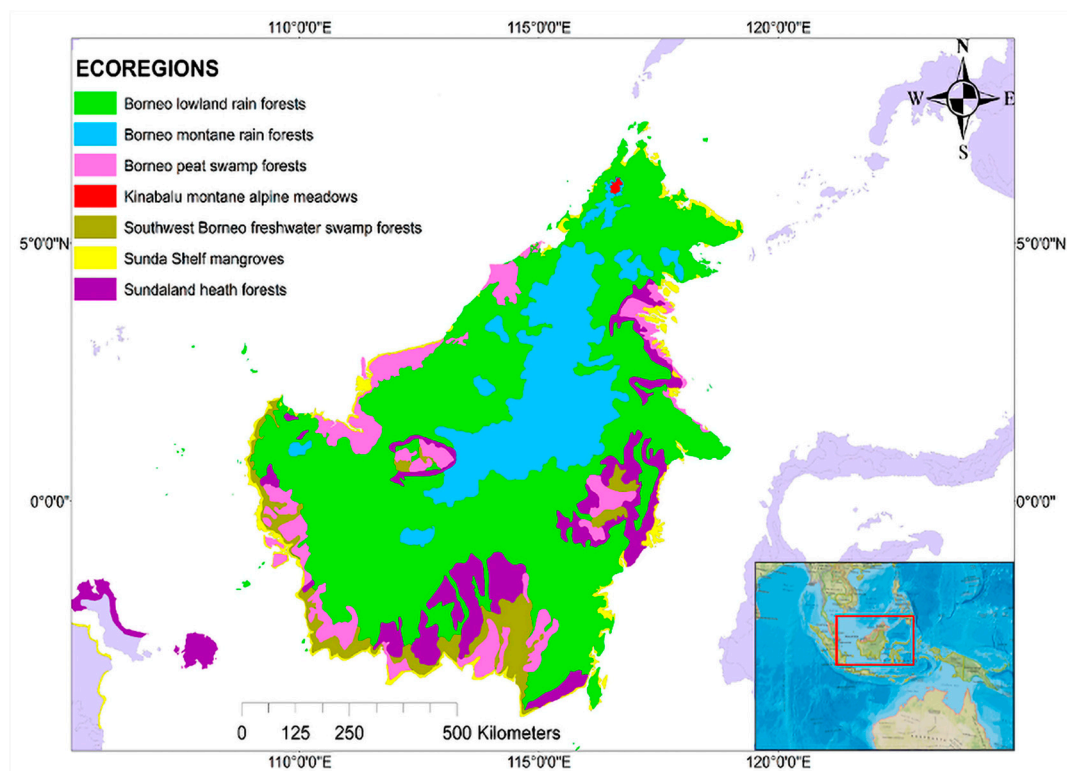


Figure 1. The seven terrestrial ecoregions of Borneo (as defined by the World-Wide Fund for Nature (WWF) with data from Dinerstein et al. [19].

2.2. Focal Species Selection

Bird species were selected from the IUCN Red List (IUCN, 2019), which identifies threatened species through many criteria that include population size, size of geographic range, and rate of decline. Borneo-resident species were identified then filtered to retain those occurring in Subtropical/Tropical Moist Lowland and Subtropical/Tropical Moist Montane Forests [20]. The search results were then further filtered to retain those classified as Critically Endangered, Endangered, or Vulnerable.

Point locality data for the species records were extracted from the Global Biodiversity Information Facility (GBIF) portal (GBIF.org, 2019) and filtered to a dataset of 20 species with 4766 geolocation records (Table 1). Habitat preference data, including details such as the elevational range limits of the species, were assembled from both the Handbook of the Birds of the World and the IUCN RedList species records [21]. The WWF delimits montane forests starting at around 1000 m above sea level [22]. Species with an upper range limit above 1000 m were classified as “lowland/montane”, those with an upper range limit below 1000 m were classified as being “lowland” residents (Table 1).

2.3. Environmental Data

2.3.1. Present Climate Data

Environmental data, consisting of 19 bioclimatic variables at a spatial resolution of 30 arc seconds (approximately 1 km at the equator) and representing aggregated climate data from 1970 to 2000, were downloaded in raster format from WorldClim 2.0 [23]. These variables are obtained through a thin-plate spline smoothing algorithm that interpolates data from a large number of weather stations across the globe. The 19 variables represent climate factors of varying temporal scales, from annual and seasonal trends to extreme monthly and quarterly variables that may prove to be limiting factors to flora and fauna [24]. After a preliminary model assessment, nine of the 19 WorldClim variables were retained (Table 2); the ten variables which consistently contributed little or nothing to the model

explanatory power were excluded. The elimination of these redundant variables also reduced multicollinearity between variables and potential model overfitting [21].

Table 1. The bird species included in this dataset along with their International Union for the Conservation of Nature (IUCN) classification and habitat preferences.

Species (Latin)	Species (Common)	IUCN Category	Habitat Preference
<i>Aceros corrugatus</i>	Wrinkled Hornbill	EN	Lowland evergreen forest extends into the selectively logged forest (Kemp, A.C, Boesman, P and Sharpe, 2019)
<i>Anthracoceros malayanus</i>	Black hornbill	VU	Lowland primary forest, mostly <200 m, very occasionally up to 600 m (Kemp, Boesman and Sharpe, 2019)
<i>Berenicornis comatus</i>	White-crowned hornbill	EN	Primary lowland and sometimes montane forest up to 1675 m (A. C. Kemp and Boesman, 2019b)
<i>Buceros rhinoceros</i>	Rhinoceros hornbill	VU	Primary lowland forest, extending into the secondary forest up to 1400 m (A. C. Kemp and Boesman, 2019a)
<i>Caprimulgus concretus</i>	Bonaparte's Nightjar	VU	Lowland dipterocarp forest and secondary growth, sea level to <500 m (Cleere and Sharpe, 2019)
<i>Centropus rectunguis</i>	Centropus rectunguis	VU	The undergrowth of lowland forest (Payne and de Juana, 2019)
<i>Chloropsis sonnerati</i>	Greater green leafbird	VU	Lowland evergreen forest, extending up to 1100 m (Wells and Sharpe, 2019)
<i>Ciconia stormi</i>	Storm's stork	EN	Undisturbed lowland forest
<i>Cyornis caerulatus</i>	Sunda Blue Flycatcher	VU	Lowland dipterocarp forest, sea-level to <500 m (Clement, 2019)
<i>Hydrornis baudii</i>	blue-headed pitta	VU	Lowland primary forest extends up to 600 m (Erritzoe, 2019)
<i>Leptoptilos javanicus</i>	Lesser adjutant	VU	Mangroves, coastland wetlands adjacent to lowland forest
<i>Mulleripicus pulverulentus</i>	Great slaty woodpecker	VU	Semi-open tropical lowland forests, extending up to 2000 m (Winkler, Christie and Kirwan, 2019)
<i>Nisaetus nanus</i>	Wallace's hawk-eagle	VU	Lowland forest, rarely up to 1000 m (Clark and Kirwan, 2019)
<i>Psittacula longicauda</i>	Long-tailed parakeet	VU	Extreme lowland, <300 m (Collar and Sharpe, 2019)
<i>Ptilocichla leucogrammica</i>	Bornean wren-babbler	VU	Lowland dipterocarp forest extends into the montane forest (Collar and Robson, 2019)
<i>Rhinoplax vigil</i>	Helmeted hornbill	CR	Extends up to 1500 m (Kemp, Sharpe and Boesman, 2019)
<i>Rhyticeros undulatus</i>	Wreathed hornbill	VU	Occasionally lowland forest extends up to 2560 m (A. Kemp and Boesman, 2019)
<i>Setornis criniger</i>	hook-billed bulbul	VU	Lowland forest, extending up to 1000 m (Myers, 2016b)
<i>Spilornis kinabaluensis</i>	Mountain serpent eagle	VU	Montane and sub-montane forests, preferably ridgetops, 750–2900 m (Clark, Kirwan and Christie, 2019)
<i>Treron capellei</i>	large green pigeon	VU	Lowland forest, preferably primary forest (Baptista et al., 2019)

Table 2. The area of suitable habitat available to each bird species under the modelled current (2010) scenario and the percent of this suitable habitat that currently lies within a protected area (PA).

Available Range Size	IUCN Status	Species	Habitat Type	Suitable Available Habitat (km ²)	Habitat within a PA (%)
Large	VU	<i>Buceros rhinoceros</i>	Lowland/Montane	36,400	11.1
	VU	<i>Ptilocichla leucogrammica</i>	Lowland/Montane	44,616	6.16
	CR	<i>Rhinoplax vigil</i>	Lowland	50,166	5.9
	VU	<i>Rhyticeros undulatus</i>	Lowland/Montane	41,200	18.2
	VU	<i>Anthracoceros malayanus</i>	Lowland	25,554	9.6
	EN	<i>Berenicornis comatus</i>	Lowland/Montane	12,721	13.4
Medium	VU	<i>Caprimulgus concretus</i>	Lowland	10,431	20.5
	VU	<i>Centropus rectunguis</i>	Lowland	15,404	14.2
	VU	<i>Cyornis caerulatus</i>	Lowland	21,760	15.5
	VU	<i>Hydrornis baudii</i>	Lowland	25,542	14.9
	VU	<i>Mulleripicus pulverulentus</i>	Lowland/Montane	22,292	8.6
	VU	<i>Psittacula longicauda</i>	Lowland	21,394	6.7
	VU	<i>Treron capellei</i>	Lowland	15,702	3.4
	VU	<i>Aceros corrugatus</i>	Lowland	8844	8.2
	EN	<i>Ciconia stormi</i>	Lowland	3950	11.5
	VU	<i>Leptoptilos javanicus</i>	Lowland	5957	6.5
Small	VU	<i>Nisaetus nanus</i>	Lowland	9639	16.4
	VU	<i>Spilornis kinabaluensis</i>	Lowland/Montane	7881	30.2

2.3.2. Future Climate Data

Tiles of spatially downscaled climate model data for all 19 bioclimatic variables were downloaded from the CCAFS-Climate data portal (<http://www.ccafs-climate.org>) (1 March

2021)) at the same resolution. Future climate change scenarios for the time interval 2046–2065 (mean = 2050) were considered. Future climate projections were derived from CSIRO Mk3.5, a General Circulation Model (GCM) used in the Coupled Model Intercomparison Project 3 (CMIP3). Simulations from the Mk3 family of models have contributed towards the IPCC AR4 Assessment and have been used in modelling bat and bird distributions in Southeast Asia and South America [22,25]. For this period, the climate parameters of two IPCC Special Report on Emissions Scenarios (SRES), A1B, and B1, both representing medium–high and lower emissions scenarios, respectively, were used. Thus, two future climate scenarios were modelled and considered in this study: A1B 2050 and B1 2050.

2.3.3. Topographic Data

Digital elevation data from the Shuttle Radar Topography Mission (STRM) was downloaded in $5 \times 5^\circ$ tiles from the CGIAR Consortium for Spatial Information at a resolution of 90 m. It was assumed that topographic data would remain stable in this time frame. An additional topographic variable raster, slope, was also generated from the SRTM elevation raster.

2.3.4. Land-Use Data

A Future Land-Use Simulation (FLUS) system modelling land-use and land cover change at a fine resolution of 1 km was downloaded for the years 2010, A1B, and B1 2050 from [26]. As with the climate change scenarios, the land-use scenarios arrived-at reflect predicted demographic, economic, climate change, and energy requirement drivers for the years stated, with the land-cover scenarios derived using a combination of “top-down” agro-economic allocation and “bottom-up” spatial modelling [26].

2.3.5. Layer Preparation

The modelling of suitable habitat for all 20 species across all periods and SRES scenarios is implemented with the Maxent model of 12 variables (Table S1: The twelve (12) bioclimatic, topographic and land-use variables used as input variables in the MaxEnt modelling).

2.3.6. Protected Area Data

The Bornean PA network shapefile data was supplied by the World Database on Protected Areas (WDPA), ProtectedPlanet.net. The WDPA provided a comprehensive and global database of terrestrial and marine protected areas and was set up by the UN Environment Programme and the IUCN [27]. The IUCN categories PAs according to several guidelines and management approaches [28]. Strictly protected areas, in which it is recommended that extractive and mining activities are prohibited, constitute categories I–IV, while categories V–VI permit localized extractive activities [28]. Only categories Ia–VI from the downloaded dataset were considered; any PA listed as “Not Reported” or “Not Applicable” by the IUCN was excluded. A total of 213 protected areas were included in the analysis (Figure 2).

2.3.7. Habitat Suitability Modelling

For each species, one current (2010) distribution and two SRES scenario future distributions were modelled (total = 60) using the maximum entropy modelling software Maxent [29]. The default settings were used; the regularization parameter (used to reduce overfitting) was fixed at 1, and the maximum number of background points was set at 10,000 [28,30]. The replicated run type was set to “cross-validate”, and the number of iterations to 500. These auto-features have been previously validated and tuned [31,32]. Estimates of the independent contribution of each variable to the model outcome were calculated. However, these are heuristically defined and path-dependent. Jackknife tests were additionally used to estimate the importance of each variable [33].

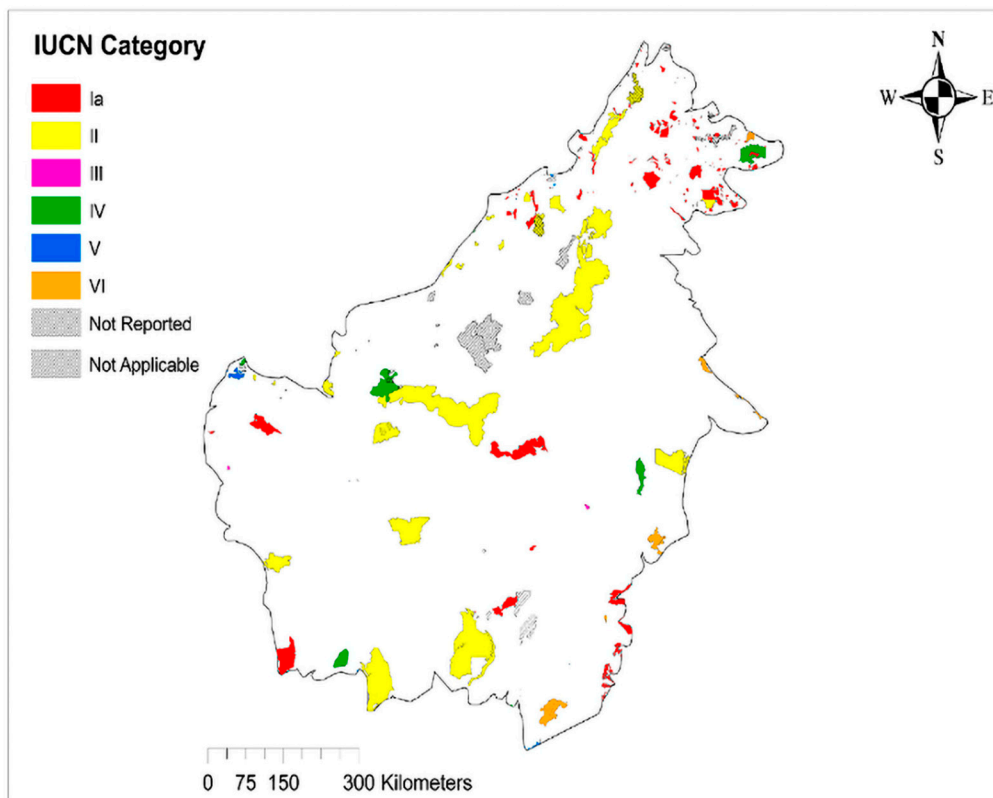


Figure 2. Protected Area Network Protected areas of Borneo, classified according to their IUCN category. Mapped in ArcMap using data taken from UNEP-WCMC (UN Environment Programme World Conservation Monitoring Centre) and Protected Planet (2019).

In the absence of independent data for model validation, the dataset was randomly partitioned into test (25%) and training (75%) data (as used in [27,29,34]). Model quality was assessed using the area under the receiver operating characteristic (ROC) curve (AUC), a threshold-independent metric and true skill statistics (TSS) [34]. The ROC value is obtained by plotting sensitivity (proportion of known presence predicted present (=1-false negative rate)) against 1-specificity (proportion of known absences predicted present (=false positive rate)) [35]. The resulting test area under the curve (AUC) value ranges from 0 to 1, with 1 indicating a model with perfect discrimination and an AUC of 0.5, indicating that model performance is equivalent to that of random prediction [36]. TSS scores are classified as moderate performance (≥ 0.5), fair performance (≥ 0.3), and poor performance (< 0.3) [37]. Two species with test AUC values < 0.75 (*Chloropsis sonnerati*, *Setornis criniger*) were then excluded as this threshold indicates reasonable discriminatory power [27,32]. All the remaining species had a TSS > 0.6 .

The Maxent logistic output format produces continuously scaled distribution maps of habitat suitability on a scale from 0 to 1, where cells assigned a value of 1 to contain theoretically high habitat suitability, and cells with a value of 0 are considered highly unsuitable. These maps were converted into binary presence/absence maps by setting a probability of occurrence threshold of 0.6, as recommended by Nazeri et al. [38]. This conservative approach is often preferred in conservation contexts, where a more liberal interpretation of a probability of habitat suitability could result in the misdirection of resources [39].

2.3.8. Habitat Suitability and Protected Area Coverage Calculation and Analysis

Binary maps were used to calculate the absolute area of the habitat suitability for each of the species in 2010 and in 2050 under the two future scenarios modelled (A1B/B1). The suitable habitat available was classified into three levels, Small ($< 10,000 \text{ km}^2$), Medium

(10,000–30,000 km²) and Large (>30,000 km²). The overlap of the habitat suitability maps and the protected areas was calculated using Zonal Statistics [40].

We used an analysis of covariance (ANCOVA) to investigate whether the current IUCN categorization, the 2010 suitable habitat area, and the habitat type preference varied systematically with predicted changes in habitat area and in the portion of suitable habitat predicted to lie within protected areas in 2050. The IUCN categories CR and EN were collapsed to a single level, “EN+”, in the analysis as there was a single species in the CR category. Generalized linear models were fit independently to the species predictions arising from modelling of the two future scenarios and the influence of each factor/variable was assessed by sequential deletion testing until the minimally adequate model was identified. Only main effects and no interactions were fit as the data set was small. All analyses were performed in R version 3.6.3 [41].

3. Results

All the current and future habitat suitability maps retained in this analysis performed well, with mean testing and training AUC values of 0.892 (± 0.051) and 0.936 (± 0.036), respectively. Isothermality (Bio3) was the most important predictor of species distribution for the present time period and was the highest contributing variable in 52.6% of cases with an average explanatory contribution of 41%. In all four future scenarios, precipitation of the driest quarter (bio17) was the most important predictor, ranking as the highest contributor in the model 31.7% of the time and contributing, on average, 32.9%. A jackknife test of variable importance confirmed bio17 to be the highest contributing variable of 32.3% of the time.

One species, *Caprimulgus concretus*, was predicted to make such habitat gains (>200%) that it was an outlier in both future models and was excluded from the statistical analyses of habitat area change as it obscured the generality of interpretation. Modelling was, however, performed with, and without, this species to confirm general patterns. These did not vary, but model fit was much improved with the outlier removed.

3.1. Current (2010) Habitat Suitability Modelling and Estimated Portion Protected

The available habitat predicted to be suitable for each species varied substantially. *Buceros rhinoceros*, a large-bodied hornbill has over 50,000 km² available whereas *Ciconia stormi*, the rarest of all storks, has less than 3000 km² of suitable undisturbed forest remaining on Borneo. The percentage of the available habitat lying within protected areas was low (95%CI = 9.3–15.4 %) but also varied substantially from *Spilornis kinabaluensis*, the Mountain Serpent Eagle, which prefers high ridges and has >30% within PAs to *Treron capellei*, a large, green pigeon, with only 3.4% of its range protected (Table 2). The large-ranged, critically-endangered *Rhinoplax vigil* had only 5.9% of its suitable habitat within the protected areas.

3.2. Future Habitat Suitability Modelling and Estimated Portion Protected

The details of predictions for each species varied slightly between the two modelled scenarios, but their general behavior was largely similar (Table 3). All species with current large areas of habitat available are predicted to lose under both future climate scenarios. The picture is more mixed in the species with less habitat currently available to them. In the medium category (10,000–30,000 km²), five of the nine are predicted to have more habitat available in future with *Caprimulgus concretus*, Bonaparte’s nightjar, being predicted to gain substantially (Table 3). In the species with small areas of suitable habitat currently available, only one, *Spilornis kinabaluensis*, the Mountain Serpent Eagle, was predicted by both models to lose over a fifth of its currently suitable area; the others are predicted to make habitat gain.

Table 3. Predicted changes (%) in suitable habitat availability on the island of Borneo and the change in portion (%) of a species' range that lies within a protected area between 2010 and 2050. Two future scenarios were modelled independently, A1-B (Medium–high emissions) and B1 (Low emissions).

Available Range Size	IUCN Status	Species	Predicted Change in Range Size over the 2010–2050 Window (%)		Predicted Change in the Portion of the Range Found within a PA over the 2010–2050 Window (%)	
			Scenario A1-B	Scenario B1	Scenario A1-B	Scenario B1
Large	VU	<i>Buceros rhinoceros</i>	−10.41	−7.10	0.67	−2.53
	VU	<i>Ptilocichla leucogrammica</i>	−71.22	−66.20	6.16	4.14
	CR	<i>Rhinoplax vigil</i>	−32.15	−37.45	2.01	0.79
	VU	<i>Rhyticeros undulatus</i>	−12.12	−3.91	1.10	−2.82
	VU	<i>Anthracoceros malayanus</i>	19.21	37.74	−3.59	−4.11
Medium	EN	<i>Berenicornis comatus</i>	22.26	51.09	−3.80	−6.50
	VU	<i>Caprimulgus concretus</i>	292.22	207.51	−11.90	−13.86
	VU	<i>Centropus rectunguis</i>	13.49	26.09	−7.44	−8.44
	VU	<i>Cyornis caerulatus</i>	−5.58	−25.75	−0.27	0.88
	VU	<i>Hydrornis baudii</i>	−31.47	−30.46	2.39	1.09
	VU	<i>Mulleripicus pulverulentus</i>	−6.57	2.08	−2.96	−4.41
	VU	<i>Psittacula longicauda</i>	9.32	27.34	−2.97	−3.88
	VU	<i>Treron capellei</i>	−16.57	−2.01	1.90	0.93
	VU	<i>Aceros corrugatus</i>	67.31	39.15	−2.52	−3.99
	EN	<i>Ciconia stormi</i>	16.63	19.18	−4.64	−5.14
Small	VU	<i>Leptoptilos javanicus</i>	19.25	21.67	−2.38	−3.63
	VU	<i>Nisaetus nanus</i>	79.49	84.81	−10.12	−10.65
	VU	<i>Spilornis kinabaluensis</i>	−20.94	−24.49	−6.73	−5.01

Protected area coverage (%) of suitable habitat is projected to decline for all bird species with small available ranges by 2050. For the four species with more than 30,000 km² available currently, the percent coverage is mostly projected to increase, though this is largely an artefact of substantial range loss outside PAs (Table 3).

Although the details of predictions for each species varied slightly between the two modelled emissions scenarios, their general behavior was largely similar (Table 3). Although each scenario was analyzed independently, the statistical summaries reflect this similarity and are largely concordant, though the effects of the higher emissions scenario A1-B are more marked (Table 4).

Table 4. Statistical summary of the deletion tests of the variables assessed as potentially associated with the change in range size, and the percentage of range protected for eighteen Bornean bird species between 2010 and 2050. The calculated F-ratio (F), the degrees of freedom (d.f.) associated with the comparison and its probability (p) are presented.

	Scenario B1 Predictions (Low Emissions)				Scenario A1B Predictions (Medium–High Emissions)				
	F	d.f.	p	effect	F	d.f.	p	Effect	
Predicted Change in Suitable Habitat between 2010 and 2050									
IUCN Category	0.09	1,13	0.77	none detected	0.00	1,13	0.97	none detected	
Habitat	0.28	1,14	0.60	none detected	1.10	1,14	0.31	none detected	
Current (2010) area available	9.35	1,15	0.008	Greater loss for large ranged-species	11.24	1,15	0.004	Greater loss for large ranged-species	
Predicted change in the proportion of the suitable habitat within a currently protected area between 2010 and 2050									
IUCN Category	0.08	1,13	0.78	None detected	0.08	1,13	0.77	None detected	
Habitat	0.11	1,14	0.77	None detected	1.04	1,14	0.33	None detected	
Current (2010) coverage in PAs	2.45	1,15	0.14	None detected	4.39	1,15	0.05	None detected	
Current (2010) area available	8.93	1,16	0.008	Most loss at higher initial coverage	13.24	1,16	0.002	Most loss at higher initial coverage	

The predicted change in range was not detected to vary between the IUCN categories nor with whether the species preferred a Lowland or Lowland/Montane habitat. The suitable habitat available in 2010 was an effective predictor and greater habitat loss was observed in larger ranges. The portion of the range that lay within a protected area had

a similar pattern with systematic variation identified with the area of habitat available in 2010. For this the pattern was a greater loss of habitat protection in small-ranged species than in large-ranged ones (Figure 3a). The portion of range within PAs in 2010 displays a clear visual pattern, but its importance is not statistically convincing in this small data set and may be obscured by the influence of the 2010 area available (Figure 3b and Table 4). This tentatively suggests that species with higher 2010 levels of habitat coverage within protected areas were also predicted to lose most protection under future scenarios.

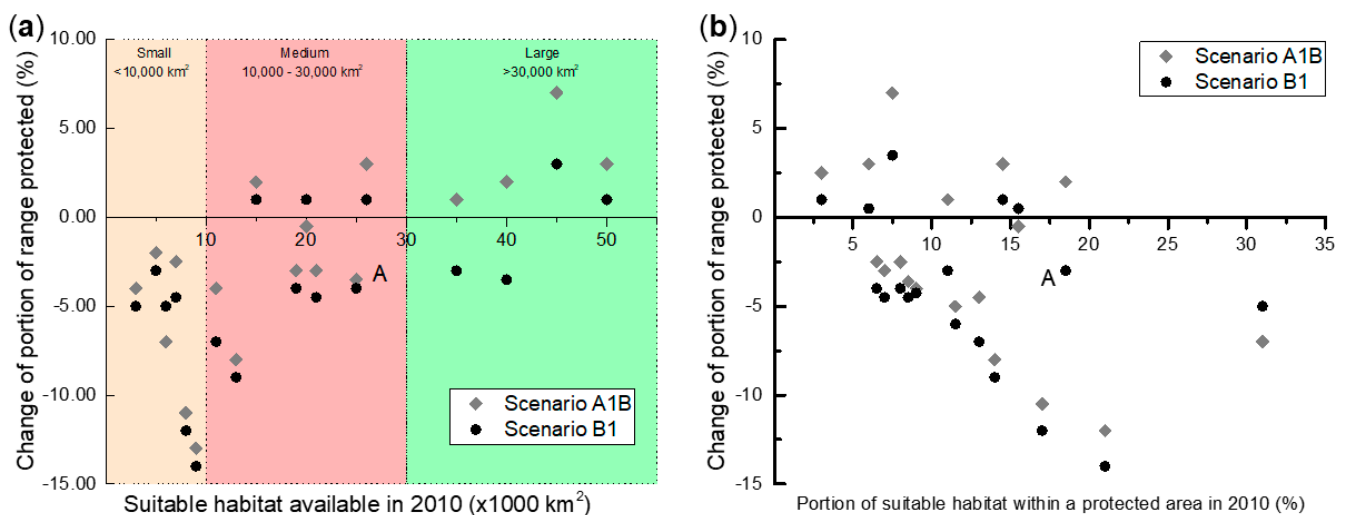


Figure 3. Change in percentage of suitable habitat lying within a Protected Area (PA) by (a) estimated area of suitable habitat in 2010 and (b) The portion of this that lay within a PA in 2010. Two future scenarios were modelled independently: A1-B (Medium–high emissions) and B1 (Low emissions).

4. Discussion

4.1. Changes in the Area of Suitable Habitat

In our research we have used a combination of climate change and land cover variables to predict the changes in bird habitat suitability under different future scenarios. Incorporating land cover change dynamics is important for generating robust habitat suitability forecasts. Ignoring the interaction between these can undermine the robust identification of future suitable habitats [8]. Previous research indicates that land-use change is likely to interact with climate change and that these climates–land-use change interactions are likely to have a significant impact on tropical biodiversity [6]. Climate change and vegetation changes are expected to act in conjunction to cause a decline in the species richness of bats of SE Asia circa 2050–2080 under a high emissions scenario [6]. Previous SE Asia wide research has indicated that future forest loss will decrease suitable habitats for threatened birds within PAs [42]. While incorporating landcover change dynamics is important for habitat suitability modelling, the uncertainties in land cover interpretation need to be accounted for [43]. In case of Borneo, it is important to develop regional scale future land cover scenarios such as these [44] which also account for the spread of infrastructure [45] and oil palm plantations.

Both climate and land cover change have been seen to, and, are expected to have future impact on tropical bird biodiversity and the interaction between these factors is projected to increase the impact on bird species by altering the spatial distribution of threats [46]. Looking beyond the frame of our work, projected climate change for the period 2061–2080 is expected to severely inhibit the ability of Borneo’s protected areas to conserve avian species and biodiversity in general; these are expected to have different climatic conditions relative to today [42,47]. Our research examined a subset of Borneo’s threatened avian species and identified “winners” and “losers” under different future scenarios. Further,

we identified some of the attributes that potentially make different avian species more vulnerable to losing suitable habitat.

By showing that restricted-range birds are estimated to lose the greatest proportion of suitable habitat we support existing observational and experimental studies that have reported the looming threat of range contractions for smaller-ranged avian species (e.g., in Peruvian and New Guinean birds [48,49], and in a global dataset [50]. Simple temperature change-based modelling predicts that 53% of lowland species face lowland biotic attrition [51], here we did not detect a habitat association and may have been constrained by the particular avian subset used. Our findings do coincide with studies such as those by Freeman et al. [40] and Ramiles-Villegas et al. [52]; in the first, Peruvian lowland birds were seen to expand their ranges, while in the latter birds in the tropical Andes were predicted to be either unaffected or even favored by the warming climatic conditions in 2050, with 45% of birds estimated to undergo expansions in their climate niche in the range of 100% or more. These suggest that lowland bird species can expand their range size as a consequence of the leading edges of their distribution shifting upslope as climate conditions at higher elevations become more agreeable [48]. Climate change can, therefore, result in the promotion of range expansion under some circumstances, for instance when lowland birds prefer drier/warmer conditions that could be provided under future climate change [53]. We find no discernible difference in the predicted change in size of suitable habitat between EN+ and VU categories. This agrees with previous studies of birds in finding that IUCN threat status is not only associated with range size and predictions of range size alteration under future scenarios [54].

4.2. Representation of Threatened Avifauna in the BORNEAN PA Network

The variation in the portion of suitable habitat represented in PAs is substantial among the species used here. Rodrigues et al. proposed a scale of “appropriate representation” relating the habitat available or potential range of a bird species to the proportion of this range that should be protected [55]. For the suitable habitat extents modelled here, these species should achieve 76.9–100% representation of suitable habitat within the PA network. The highest we identify is just over 30% in *S. kinabaluensis* and this is also the species predicted to fall to around a 10% representation within PAs over the window modelled. Although more than 16% of Borneo is protected, the representation afforded by the PA network suggested by this study—both now and under future scenarios—remains woefully below the levels of adequacy recommended. Although this study does not identify any species with no suitable habitat within PAs, or “gap species”, all species as modelled here classify as “partial gap” species according to the definition of [55] and none are afforded adequate protection. The small-ranged avian species modelled here are highly likely to undergo a greater decline in suitable protected habitat availability and have been identified elsewhere as vulnerable to suitable habitat decline under future climate scenarios [9] and to loss of habitat for such species are rapidly affected by high levels of land cover change [54]. A similar study of range-restricted species in the Andes also suggested a habitat decline in protected areas under different future climate scenarios [25].

4.3. Conservation Implications and Recommendations

There are already very-low to low levels of representation of threatened birds within Bornean PAs, and with land-use change predicted to increase outside of PAs, efforts must be focused towards preserving what little is still protected. This should include efforts to monitor populations of birds in PAs that have been flagged as being potentially at higher risk of habitat decline (e.g., small-ranged and specialist birds). Protected areas do have a positive effect on maintaining the diversity of range-restricted species [56–58] and inclusion of existing nature reserves into the formal PA network system was recommended as a way of conserving the habitats of small-ranged birds [59]. Further, protected areas can mitigate the climate change impacts and are an effective tool for conservation in a changing climatic world [60]. However static reserve networks are likely to struggle to

account for future climate change scenarios. This message, that areas under protection will have to shift or expand under climate change scenarios is likely universal. Analyses of the habitat dynamics of all vertebrate classes, including identifying refugia and habitat areas that are suitable for species both under present and future climate change scenarios has been recommended [61]. Future conservation in this region could benefit substantially by expanding the protected areas to ensure that their configuration in terms of size and connectivity account for future scenarios [62].

The climate change related variables we identify as the strongest drivers of change in suitable habitat under the future scenarios, precipitation in the driest quarter and isothermality, have been noted in other studies. A global scale analysis revealed that these aspects of climate change remain drivers of species habitat availability, and, in many tropical ecosystems, surpass the importance of land cover change [63]. Borneo, however, faces rapid forest loss with oil palm plantation cultivation driving deforestation and population expansion driving other agriculture. Future oil palm expansion is projected to have a damaging impact on ecosystems worldwide [64,65]. However, no specific Bornean projections exist of the future temporal-spatial distributions of these agricultural plantations and this makes it difficult to quantify habitat availability in the face of future climate change and oil palm expansion. The climate and land use change scenarios modelled here are thus not necessarily representative of real-life trajectories; scenario B1, for example, represents full mitigation of emissions and a decrease in farmland. In reality, we have passed the point of such complete mitigation. Given the current political and economic climate, a business-as-usual scenario predicts that we will reach much higher emissions scenarios than those used by this study. Similarly, decreasing cropland, as predicted in B1, is a scenario that is improbable, given the current population growth trajectory and land conversion rates [26]. Consequently, the effects of some of the patterns reported in this study (e.g., decrease in range size for small-ranged) would almost certainly be magnified under a more realistic scenario. In addition, the omission of certain species-specific factors such as those pertaining to physiology from our model may have resulted in an overestimate of the suitable habitat size of species under future scenarios.

5. Conclusions

Threatened bird species can act as an indicator group for patterns of predicted biodiversity change. Employing climatic, topographic, and land-use variables in maximum-entropy modelling, we find that overall, the threatened avian species found in the lowland and montane regions of Borneo are not predicted to experience vast range size contractions in the next century in either an A1B or a B1 world. Some assemblages, however, may be “losers” (e.g., large-ranged birds) under future scenarios, while others may be “winners” as they are predicted to expand their suitable habitat (e.g., birds with small areas of habitat currently available to them). The majority of modelled suitable habitat, both now and in the future, was found to lie outside of current PA boundaries, with no species approaching the recommended representation targets. This work reinforces conservation messages from other taxa and biogeographic regions. Suggested conservation actions include both localized (e.g., increasing the area and ensuring the persistence of individual upland PAs) and regional-scale (e.g., managing wider landscapes, for example, through retaining selectively logged forests as a complement to PAs) approaches.

Borneo, although undergoing some of the most extensive changes globally in terms of forest conversion and habitat degradation, is not unique in the situation it faces. Southeast Asia generally is not only a biodiversity hotspot, but also a hotspot of threats, and as such, the conservation recommendations we make apply widely.

Supplementary Materials: The following are available online at <https://www.mdpi.com/2071-1050/13/5/2792/s1>, Table S1: The twelve (12) bioclimatic, topographic and land-use variables used as input variables in the MaxEnt modelling.

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