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Identifying Important Hornbill Landscapes in Sarawak, Malaysia

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ABSTRACT

With land use change rapidly increasing in Asia, conservation prioritisation has emerged as an important tool in identifying critical landscapes for biodiversity to safeguard them from human pressures. In Peninsular Malaysia, the Malaysian Nature Society (MNS/BirdLife in Malaysia) developed a set of Criteria to identify Important Hornbill Landscapes (IHLs) – hornbill hotspots which are conservation priority sites in Malaysia and serve to inform land use planning and conservation action. Application of the Criteria has so far been restricted to Peninsular Malaysia, thus in this study, we adapt it to Sarawak, a Malaysian state in Borneo that supports 80% of the hornbill species diversity in the country. We expand on this conservation prioritisation methodology using Maximum Entropy Species Distribution Modelling (MaxEnt), to validate the Criteria's applicability and to identify potential IHLs in Sarawak. Our data sources included literature reviews, citizen science databases and interviews. Expectedly, survey effort was spatially biased. We identified eight IHLs, mostly concentrated in eastern Sarawak, across national parks, wildlife sanctuaries and forest management units. Existing published literature on the distribution of hornbill habitats in Sarawak corroborated with our MaxEnt outputs which aligned with the results of the IHL Criteria-based assessment, validating the latter and supporting its use in Sarawak. We additionally identified six potential IHLs based on MaxEnt outputs which confirmed the value of pairing MaxEnt with the Criteria-based assessment, for such a prioritisation exercise. To our knowledge, this study not only demonstrates the significance of combining MaxEnt and the Criteria for IHL identification, but it also represents the first application of the IHL Criteria outside of Peninsular Malaysia. Our findings can, therefore, serve as a case study for future applications of IHL Criteria in Borneo and potentially for other parts of Asia.

1. Introduction

Conservation prioritisation is widely used and studied as an important tool for the advancement of ecological knowledge and to inform policy and conservation action (Sinclair et al., 2018). Examples can be found from Australia, to the Middle East, and the Americas (Ortega-Huerta and Peterson, 2004; Klein et al., 2009; Karimi et al., 2023). Specific to birds, BirdLife International's Important Bird and Biodiversity Areas (IBA) programme presents a key example of a global prioritisation effort that has influenced bird

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conservation worldwide (Donald et al., 2018; Waliczky et al., 2018). In Asia, there are numerous conservation prioritisation studies (Ahmadi et al., 2017; Lehtomäki et al., 2018; Macdonald et al., 2019), but few are bird-specific (Han et al., 2018; Hu et al., 2020). Of these, only a handful are focused on hornbills despite their importance in the region (Jain et al., 2018a).

Hornbills (Family Bucerotidae) are one of the most attractive and charming birds in Asia. They are also important seed dispersers, especially of large-seeded plants due to their wide gape, large bill, and ability to fly great distances (Poonswad et al., 2013; Corlett, 2017). Their disappearance can disproportionally impact tropical forest ecosystems, and their declining populations throughout Asia is a worrying trend (Datta et al., 2020). More than half of the hornbill species in Asia are threatened (BirdLife International, 2022), and governments face a challenging task in protecting these birds in vast landscapes with limited budgets.

Researchers and expert groups such as the IUCN SSC Hornbill Specialist Group leverage their networks to support conservation activities through monitoring and capacity building. With limited resources, conservation direly needs to be targeted in the most important sites for more effective protection. Hornbill conservation in Asia will likely benefit from conservation prioritisation throughout its range countries, especially in Malaysia, which has close to a third of Asia's hornbill diversity.

The Malaysian Nature Society (MNS) launched the MNS Hornbill Conservation Project in 2004 which focuses on the Belum-Temenggor Forest Complex (BTFC) in Peninsular Malaysia. The Project has improved the extent of hornbill knowledge, engaged local communities and deepened collaborations with focal government agencies (Yeap et al., 2016). Underpinning hornbill conservation in Peninsular Malaysia is the identification of Important Hornbill Landscapes (IHL) – hornbill hotspots which are conservation priority sites for hornbills in Malaysia. IHLs are identified based on four criteria defined by Yeap and Perumal (2018) with reference to similar hornbill prioritisation exercises in India (Mudappa and Raman, 2008), Kenya (Musina, 2007) and Thailand (Trisurat et al., 2013). IHLs in Peninsular Malaysia were conceptualised because the country's national conservation agendas were previously largely centred around mammals with priority sites and ecological corridors already identified for tigers and elephants (Department of Wildlife and National Parks Peninsular Malaysia, 2008, 2013). Whereas to our knowledge, no such exercise had been conducted for hornbills in Malaysia despite the country's high hornbill diversity prior to Yeap and Perumal's (2018) study. The IHL Criteria prioritises sites which are ecologically large enough to support a high diversity of breeding populations of hornbill species. It also selects sites which align and support the implementation of existing national policies to garner political support and institutional recognition for its outputs. Since Yeap and Perumal (2018), IHLs have been used in Peninsular Malaysia by MNS to raise awareness about hornbill conservation and to highlight the importance of sensitively managing forest reserves at IHL sites such as at Temengor forest reserve where sustainable logging is allowed and practiced by the state.

Although valuable, IHL identification has not been conducted for Malaysian Borneo. This is despite Sarawak and Sabah, the two Malaysian states in Borneo, being home to large tracts of intact forests that support 8 of the 10 hornbill species found in Malaysia. Sarawak is even famously known as the 'Land of Hornbills', where indigenous cultures and beliefs are deeply tied to hornbills (Pengiran and Mohd-Azlan, 2021). Conservation is urgently needed in Sarawak as large areas of intact forests have been lost in recent decades (Gaveau et al., 2014; Jaafar et al., 2020), more are under threat by planned developments (Alamgir et al., 2020), and substantial knowledge gaps about hornbill priority areas remain (Jain et al., 2018b). Key hornbill habitat may also be lost with Sarawak's dependence on forestry (Jaafar et al., 2020), and logging still posing an issue despite the government's commitment to curb illegal logging (Pandong et al., 2019). Identifying IHLs in Sarawak is thus critical to the conservation of healthy hornbill populations that are

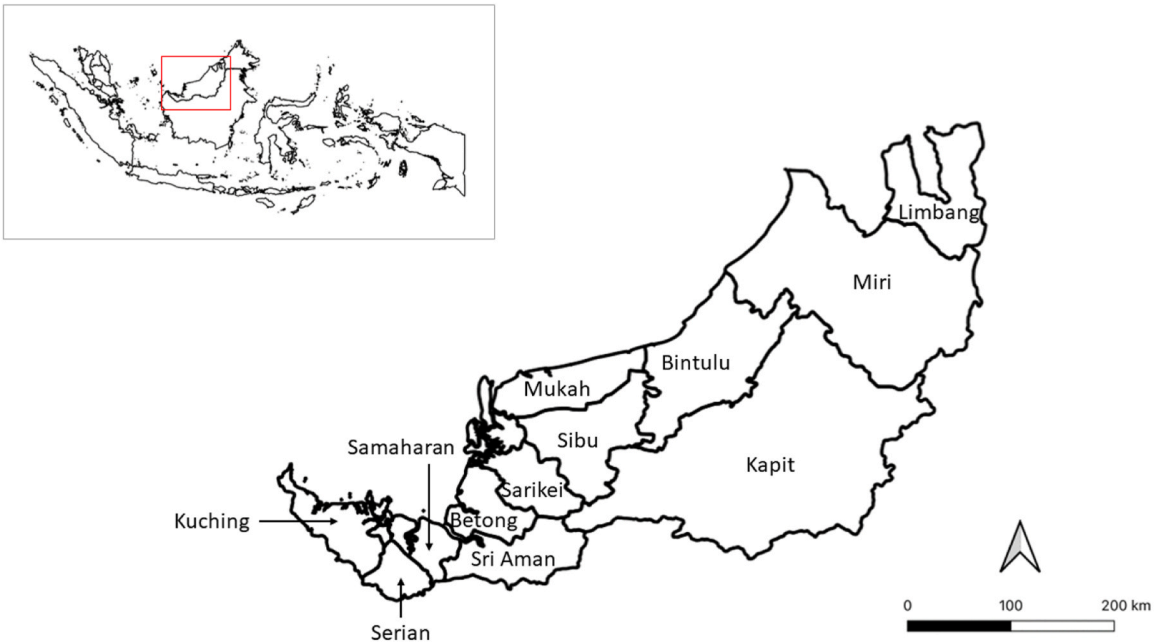

Fig. 1. Administrative divisions of Sarawak, Malaysia.

tightly linked to Sarawakians through their ecological services and cultural significance.

Our study follows Yeap and Perumal's (2018) methods, obtaining data on sites which support hornbill populations in Sarawak through literature reviews, and online citizen science birdwatching databases. We additionally conducted semi-structured interviews to derive supplementary data. Data was analysed in three ways. First, we applied the IHL Criteria established by Yeap and Perumal (2018) to assess and prioritise sites for hornbill conservation. Second, we used Kernel Density Estimation to visualise survey effort across Sarawak. Finally, we validate the efficacy of the Criteria using Maximum Entropy Species Distribution Modelling (MaxEnt) to identify predicted hotspots of hornbill occurrence.

Through this we aim to (1) identify a set of IHLs based on established criteria, and (2) use MaxEnt to validate the IHL criteria's application in Sarawak, given potential gaps in survey effort.

2. Methods

2.1. Study site

Sarawak is Malaysia's largest state and is located on Borneo (Fig. 1). It is a tropical region with an equatorial climate and experiences a wet season from November to February due to the northeast monsoon. Many types of forests are found here, including the most extensive hill mixed Dipterocarp forest (Osman et. al, 2014). Eight species of hornbills reside here, the black (*Anthracoceros malayanus*), bushy-crested (*Anorrhinus galeritus*), helmeted (*Rhinoplax vigil*), oriental pied (*Anthracoceros albirostris*), rhinoceros (*Buceros rhinoceros*), white-crowned (*Berenicornis comatus*), wreathed (*Rhyticeros undulatus*), and wrinkled hornbill (*Rhabdotorrhinus corrugatus*) (Yeap et. al, 2016). The helmeted, wrinkled and white-crowned hornbills are threatened with the former being Critically Endangered, and the latter two being Endangered (BirdLife International, 2022). The remaining forests in Sarawak are key habitats for hornbills, however, deforestation for commercial logging and land clearance for oil palm plantations has resulted in the loss of about 1.6 million ha of forests in the last two decades (Global Forest Watch, n.d.; Jaafar et al., 2020).

2.2. Data collection

We extracted data on hornbill nesting and juvenile records, and the year, sites, species, and geographical coordinates of hornbill sightings in Sarawak through three methods – a literature review, online bird-watching databases and interviews.

We compiled a list of sites where hornbills were observed based on the geographical coordinates of hornbill sightings. We obtained the size of each site from SFC (Sarawak Forestry Corporation, n.d.) and from Samling Timber Malaysia, a timber company (Samling Timber Malaysia, n.d.). To obtain data on each site's relevance to national policies, we referenced SFC's list of gazetted TPAs (Sarawak Forestry Corporation, n.d.) and the IBA list of Malaysia (BirdLife International, 2023a). We also referenced the sites covered by the Heart of Borneo (HoB) Initiative – a government-recognised initiative undertaken with other Bornean countries aimed at protecting the remaining tract of contiguous Bornean forest; this includes both protected and non-protected areas (Forest Department Sarawak, 2023).

2.2.1. Literature review

A literature review was conducted in 2021. We referenced published reports and workshop proceedings by the Sarawak Forestry Corporation (SFC) and Forest Department of Sarawak. The former is a government statutory board that oversees Totally Protected Areas (TPAs) in Sarawak, while the latter is the government department overseeing sustainable forest management. We referenced museum records from the Yale Peabody Museum of Natural History and the Sarawak Museum. We also extracted data from grey literature comprising unpublished bird lists from experienced birdwatchers known to MNS, and unpublished papers and expedition reports written by MNS. Additionally, data was extracted from published scientific articles and books resulting from a Google Scholar search using a combination of keywords: "hornbill species", "Sarawak", "Bucerotiformes", "bird survey" as well as the common and scientific names of all eight hornbills in Sarawak.

2.2.2. Online bird-watching databases

Hornbill sightings were obtained from online bird-watching databases Xeno-canto (www.xeno-canto.org), Cloudbirders (www.cloudbirders.com), and the Global Biodiversity Information Facility (GBIF) (GBIF.org, 2023a). From GBIF, only eBird records were available. We obtained permission from Sarawak's eBird reviewers to access helmeted hornbill eBird records which have otherwise been redacted from the public domain (Sullivan et al., 2009).

2.2.3. Semi-structured interviews

Interviews were conducted for data triangulation and to obtain supplementary information on Forest Management Units (FMUs) – areas which are designated for timber harvest and privately-owned by timber companies; they are not publicly accessible. A total of 22 people were interviewed, selected through purposive sampling. 13 of the 22 respondents had environment-related jobs in conservation, bird guiding, ornithology and/or biodiversity consulting. They were, therefore, familiar with a variety of sites across Sarawak and were well-positioned to provide first-hand accounts of hornbill sightings. Six respondents had jobs related to FMUs and could give insights based on non-publicly available data. Two respondents were familiar with indigenous practices and were selected because they could provide information on indigenous sites. The remaining individuals worked at the Sarawak Museum. All interviews were conducted between October 2020 and June 2021. The interviews followed a semi-structured format which was guided by a set questionnaire (see Appendix A.1). Responses were recorded by the interviewer during the interview. Through this exercise, we also obtained personal, unpublished bird lists where possible.

2.3. Data analysis

We built a profile for each site comprised of the total number of hornbill species detected, the size of the site, presence of hornbill breeding records, and the site's relevance to national policies.

2.3.1. IHL criteria

We assessed each site against the IHL Criteria (Table 1).

Ideally, a site should fulfil all four criteria, however, due to the paucity of breeding and nesting data, we made two modifications. Firstly, we considered a site an IHL if it fulfilled Criteria 1, 2 and 4. Sites that met all four criteria were classified as higher priority IHLs. Secondly, we considered Criterion 3 met in our study if at least one species was documented breeding owing to the paucity of hornbill breeding records from Sarawak. In contrast Yeap and Perumal's (2018) study, required records of all six breeding species to be met at IHL sites.

The area of 50,000 ha was selected as a cut off for IHLs based on past experience wherein sites of size 10,000 – 20,000 ha have been observed to be too small to hold long-term breeding populations of the larger hornbill species such as the Helmeted Hornbill and Great Hornbill that can fly for several tens of kilometres. Sites of at least 50,000 ha are large enough to support such movements, allow undisturbed core habitats to persist and handle localised extinctions due to stochastic events.

As museum records included historical sightings from the 1900 s, sites were re-assessed against the Criteria using only data from the most recent 20 years (2001 – 2021). Oil palm expansion accompanied by deforestation increased significantly post-1990 with more than 20% of primary humid forests lost between 2002 to 2022 (Global Forest Watch, n.d., Kamlun et al., 2012; Jaafar et al., 2020). We re-assessed sites as those which supported hornbills in the 1900 s may have been cleared or degraded.

It is important to note that several hornbill records did not provide detailed geographical coordinates. When only the name of the site surveyed was provided, we used the general geographical coordinates of the site available on Google Maps for analysis. This was especially for interview data, where interviewees would commonly respond with just the name of the sites they had visited. Additionally, a minority of museum records stated only the Sarawak administrative division as the location of sighting, for example "Bintulu", instead of the specific site surveyed. These records were not analysed as they were too generic.

2.3.2. Survey effort visualization

To visualise survey effort, a heatmap was plotted using Kernel Density Estimation on QGIS version 3.28. We combined geographical coordinates of hornbill sightings obtained through our methods (described in Section 2.2) with survey coordinates of all other birds in Sarawak which were obtained from GBIF to form this dataset (GBIF.org, 2023a). Hornbill sightings from Brunei were obtained from GBIF (GBIF.org, 2023b) and included in the analysis due to the country's proximity to Sarawak. Each unique geographical coordinate represented a sampling unit. A kernel radius of 5 km was used for two reasons. Firstly, hornbills are known to produce loud and distinctive vocalisations which can be heard over several kilometres, and therefore hornbill detections could be within a several-kilometre radius (Haimoff, 1987; Kennedy et al., 2023). Secondly, our data sources only provide a single set of coordinates for species sightings instead of transects or area covered. We accounted for these limitations using the kernel radius for more accurate visualisation of survey effort.

2.3.3. MaxEnt

MaxEnt is a species distribution modelling tool that uses presence-only data along with environmental layers to approximate the density of species occurrences across a topographical range (Merow et al., 2013). MaxEnt has been used to identify conservation priorities across tropical Asia such as for hornbills in Thailand (Trisurat et al., 2013), mammals (Clements et al., 2012) and across various taxonomic groups (Lehtomäki et al., 2018; Huang et al., 2020). The Malaysian government has even acknowledged the ecological relevance of MaxEnt in conservation planning (Rahman et al., 2019).

MaxEnt requires a set of species presence localities, and environmental layers. In our study, MaxEnt input data included hornbill survey locations obtained through various data sources (listed in Sections 2.2.1, 2.2.2 and 2.2.3). We constructed five separate models for each of the five non-threatened and most common hornbills in Sarawak – black, bushy-crested, oriental pied, rhinoceros, and wreathed – using MaxEnt version 3.4.4. We used 19 bioclimatic layers and an elevation layer from World Clim at a resolution

Table 1
The IHL Criteria originally described by Yeap and Perumal (2018) and their relevance to Sarawak.

Number	Criteria
1	The area supports at least 60% of the hornbill species found within the state/region of interest. In Sarawak, this would be five species.
2	The area should be as large as possible (at least 50,000 ha) either as a single block or made up of a cluster of nearly contiguous blocks (forest complex).
3	The hornbills in the area are known to breed either by direct (e.g., active nest tree with seal) and/or indirect evidence(s) (e.g., sighting of resident juveniles with and/or without parent birds).
4	The area identified supports and assists in the implementation of national conservation policies and/or work programmes. In Sarawak, this includes totally protected areas (which include national parks, wildlife sanctuaries, nature reserves), government backed conservation initiaves such as the Heart of Borneo (HOB). Forest Management Units (FMUs) can be included only if they are part of conservation initiatives such as HOB.

approximate to 1 km (Fick and Hijmans, 2017) and forest cover data from Global Forest Watch (2016a) at a resolution of 30 m as environmental variables. We re-sampled forest cover data to obtain a resolution approximate to 1 km before using it in the model. Cropped environmental layers included Brunei due to its proximity to Sarawak.

An underlying assumption of Maxent is that sampling within the modelled landscape is conducted randomly or representatively (Yackulic et al., 2012). Maxent is, therefore, vulnerable to sampling bias and if uncorrected, outputs can be unrepresentative of true species distributions (Phillips et al., 2009). Unequal sampling probability is a particular concern, especially with citizen science data (Geldmann et al., 2016; Sicacha-Parada et al., 2021). We expected survey effort to be uneven across Sarawak, so we addressed sampling bias by constructing a bias grid composed of geographical coordinates of all known surveyed localities for all birds in both Sarawak and Brunei. The bias grid was introduced into the background data of each model so that background points selected in the modelling process shared the same bias as the presence localities. The effectiveness of this method in reducing sampling bias is supported in several studies (Phillips et al., 2009; Kramer-Schadt et al., 2013; Syfert et al., 2013). Each MaxEnt model thus had three inputs – presence localities, environmental variables, and a bias grid.

We compared response curves available in each MaxEnt model's outputs to identify collinearities. Environmental variables which were highly correlated were identified as collinear, and we retained the variable with the highest permutation importance while eliminating the rest to remove collinearities. Afterwards, we removed all environmental variables with a permutation importance of zero. Finally, we removed any variable which had a permutation importance smaller than 1 if this resulted in improvements in the area under the Receiver Operating Characteristic curve (AUC) or caused an improvement in permutation importance for the remaining variables in the model while maintaining the AUC. This resulted in a final MaxEnt model for each species. The predicted occurrence probabilities from these final models were visualised using QGIS. Areas with an occurrence probability of 50% or more were isolated and overlaid on QGIS, yielding a distribution map of the likely (>50% probability) number of non-threatened hornbills across Sarawak.

We then identified a list of potential IHLs which are sites that did not meet Criteria 1, but met Criteria 2 and 4, and are shown on the distribution map to have at least two non-threatened hornbill species. A cut-off of two species was chosen for the maps because to qualify under Criteria 1, a site needs to support five species and there are three species – white-crowned, wrinkled, and helmeted hornbill – which were not modelled but could still be detected in these sites. Although a generous cut-off point, it allows us to identify as many potential IHLs as possible and enables a more comprehensive assessment of IHLs in Sarawak. MaxEnt models for the three threatened hornbill species were not constructed in anticipation of fewer sightings due to their threatened status and rarity in both Sarawak and Brunei compared to the five non-threatened species. The threatened species were, however, included in IHL assessments.

3. Results

We obtained 130 years' worth of hornbill records dating from 1891 to 2021, for 119 sites across Sarawak. Our data mostly came from online bird-watching databases (45.7%), and grey literature (31.0%), followed by interviews (13.2%), published studies (5.2%), and museum records (4.8%).

Online bird-watching databases were our most important source, of which eBird supplied 642 of 650 records; the remainder were obtained from CloudBirders and Xeno-canto. Data from our literature review was the second-most important, which showed that grey literature provided more information compared to published literature. In our study, grey literature comprised two expedition reports written by MNS in 2019 and 2020, and unpublished bird lists from 14 experienced birdwatchers known to MNS. Published studies comprised reports from SFC and the Forest Department, workshop proceedings from two national workshops, a report from the World Wildlife Fund Malaysia and articles from the Sarawak Museum Journal. Interviews were the third-most important source and respondents were familiar with 26 out of 119 sites across Sarawak. Besides providing data on hornbill sightings, 13 out of 22 interviewees also provided first-person accounts of nesting observations for 11 sites.

The species with the most widespread distribution was the black hornbill, with detections in 65 sites. This was followed by the rhinoceros and bushy-crested hornbill, both with sightings in 54 sites. Accordingly, these three species had the highest number of records (Table 2). Although helmeted hornbill data was used in our IHL analysis, it is redacted here due to the sensitivity of the species

Table 2
Overview of hornbill data obtained from various sources in the study.

Species	Number of sites	Administrative division	Number of sites with nesting records	Number of records
Black Hornbill	65	Betong, Bintulu, Kapit, Kuching, Limbang, Miri, Mukah, Samarahan, Serian, Sibu, Sri Aman	2	264
Rhinoceros Hornbill	54	Bintulu, Kapit, Kuching, Limbang, Miri, Sibu, Sri Aman	1	501
Bushy-crested Hornbill	54	Betong, Bintulu, Kapit, Kuching, Limbang, Miri, Mukah, Samarahan, Sarikei, Sibu, Sri Aman	3	283
Wreathed Hornbill	47	Betong, Bintulu, Kapit, Kuching, Limbang, Miri, Samarahan, Serian, Sibu, Sri Aman	1	395
Oriental Pied Hornbill	32	Betong, Bintulu, Kapit, Kuching, Limbang, Miri, Mukah, Sibu, Sri Aman	1	124
White-crowned Hornbill	29	Bintulu, Kapit, Kuching, Limbang, Miri, Sibu, Sri Aman, Serian	1	123
Wrinkled Hornbill	15	Bintulu, Kapit, Kuching, Limbang, Miri, Mukah	0	31

to poaching and trade.

In total eight IHLs were identified. Hose-Laga National Park, Lanjak Entimau Wildlife Sanctuary, Mulu National Park, Pulong Tau National Park, and Ravenscourt FMU – met all four criteria and were classified as higher priority IHLs (Table 3). Usun Apau National Park and Melatai-Para FMU did not meet Criterion 2, however, as their sizes are approximately 50,000 ha, they were deemed to qualify as an IHL. Additionally, five out of the eight IHLs, including four higher priority IHLs, are national parks or wildlife sanctuaries and are recognised as TPAs. Re-assessments of sites based on reFcent data showed that all eight IHLs identified still meet the criteria, with the same number of species qualifying under Criterion 1 for all sites.

Kernel Density Estimation showed that survey effort was unequal across Sarawak and was concentrated in the south-west, near Kuching City (Fig. 2a). Compared to protected areas, FMUs were less surveyed, although they cover a bigger proportion of Sarawak's land area. Despite the spatial bias towards Kuching city, most of the IHLs were identified in eastern Sarawak, in the relatively few sites where surveys have been conducted (Fig. 2b).

Diagnostic tests for MaxEnt models were conducted by analysing the AUC. We obtained a value of 0.723 for the black hornbill, 0.796 for the bushy-crested hornbill, 0.756 for the oriental-pied hornbill, 0.809 for the rhinoceros hornbill and 0.784 for the wreathed hornbill (see Appendix A.2–A.6 for graphical depictions of the MaxEnt results). As all values exceeded 0.7, diagnostics for all five models is considered good (Duan et al., 2014). Predictor variables which contributed the most to each model were annual precipitation (black hornbill), maximum temperature of the warmest month (bushy-crested hornbill), mean diurnal temperature range (oriental-pied hornbill), and elevation (rhinoceros and wreathed hornbills) (see Appendix A.7 for a list of variables and their contribution to each model). Overlaying areas with a detection probability of 50% or more resulted in a combined output, showing sites that support more species of non-threatened hornbills lie in eastern and north-eastern Sarawak (Fig. 3). These sites are situated in most of Sarawak's remaining hill mixed dipterocarp forests which according to Osman at al. (2014), also mainly lie in eastern Sarawak. Although this finding (Fig. 3) contrasts with survey effort (Fig. 2a), it aligns with the finding that most IHLs were identified in eastern and north-eastern Sarawak (Fig. 2b). Additionally, although there are few areas which support all five non-threatened species, most of eastern and north-eastern Sarawak supports at least two, indicating that there are potentially more IHLs yet to be identified.

Six potential IHLs (Table 4) were additionally identified using the MaxEnt output in Fig. 3. These areas had an occurrence probability of 50% or more for the non-threatened hornbills across Sarawak. Except for Baleh National Park, the remaining five potential IHLs are FMUs and are not considered TPAs.

4. Discussion

Our study is the first conservation prioritisation exercise for hornbills in Sarawak to the best of our knowledge. We hope our study's results and takeaways can inform and guide future conservation efforts. Our results indicate that critical hornbill habitats persist in Sarawak, despite historical deforestation and fragmentation. This justifies the need to protect and manage IHLs, especially in areas where sustainable logging is planned. In that sense, our methodology of identifying IHLs (congruous to Yeap and Perumal, 2018), may be applicable and pertinent to other parts of Asia where forestry remains a key industry. It is remarkable that the IHL prioritisation exercise also picked up sites that were previously deemed as knowledge gaps for hornbills such as Hose Laga (Jain et al., 2018b) and where subsequent surveys yielded the presence of a diverse hornbill fauna.

4.1. Added value of using MaxEnt estimates alongside IHL criteria for conservation prioritisation

We observed large alignment between our MaxEnt outputs and the published literature on forest cover and hornbill habitat preference. As an example, our MaxEnt outputs showed a high likelihood of occurrence for a greater number of hornbill species to be found in eastern Sarawak, particularly in hill mixed dipterocarp forests (Osman et al., 2014). These forests are prime hornbill habitat, dominated by dipterocarp trees which are the principal nesting locations for several hornbill species (Poonswad et. al, 2013; Jain et al., 2018a; BirdLife International, 2023b, BirdLife International, 2023c).

Table 3
Important Hornbill Landscapes in Sarawak. Sites in bold indicate higher priority IHLs. Sites with an asterisk (*) indicate that their sizes are approximately 50,000 ha and hence, were deemed to qualify as IHLs.

Administrative Division	Site Name	IHL Criterion 1 (Number of species)	IHL Criterion 2 (size in ha)	IHL Criterion 3 (Breeding status)	IHL Criterion 4 (Conservation status)
Miri	**Mulu National Park**	8	85,671	Confirmed	NP, IBA, WHS, HoB
Kapit	**Hose-Laga National Park**	7	51,342	Confirmed	NP, IBA
Sri Aman	**Lanjak-Entimau Wildlife Sanctuary**	7	182,983	Confirmed	WS, IBA, HoB
Limbang	**Ravenscourt Forest Management Unit**	6	117,941	Confirmed	HoB
Miri	**Pulong Tau National Park**	6	69,817	Confirmed	NP, HoB
Miri	Gerenai Forest Management Unit	7	148,305	Unknown	HoB
Miri	Usun Apau National Park	6	49,355 *	Unknown	NP
Kapit	Melatai-Para Forest Management Unit	5	49,524 *	Unknown	HoB

Abbreviations: NP = National Park / WS = Wildlife Sanctuary / IBA = Important Bird and Biodiversity Area / WHS = UNESCO World Heritage Site / HOB = Heart of Borneo

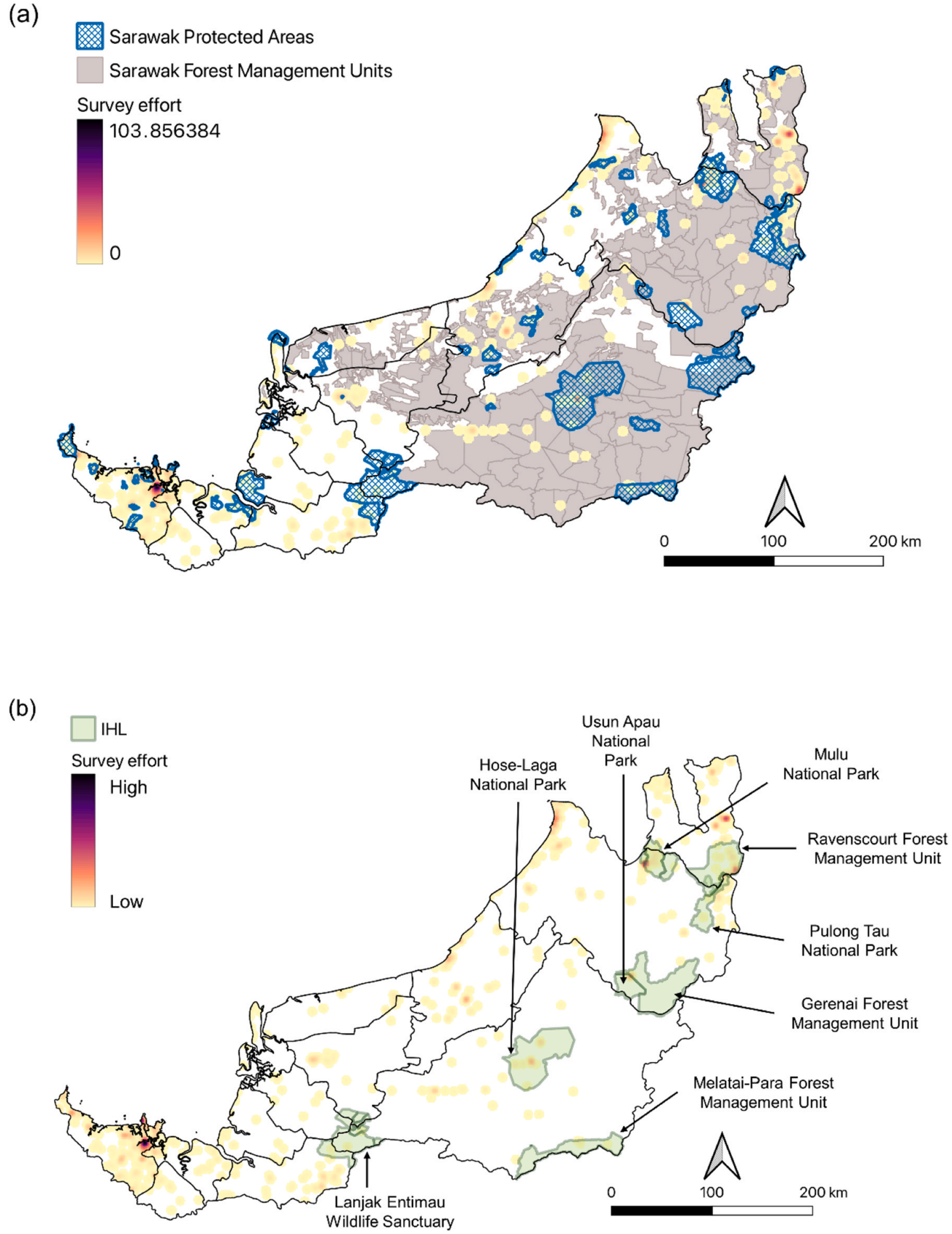

Fig. 2. (a) Kernel Density Estimation of spatial survey effort across Sarawak. Protected areas and Forest Management Units have been overlaid (Global Forest Watch, 2015; Global Forest Watch, 2016b). (b) Kernel Density Estimation of spatial survey effort overlaid with identified IHLs.

Furthermore, MaxEnt predicted that few sites can support all five non-threatened species (modelled in this study) which also agrees with published literature. These five species have different habitat preferences, particularly the oriental-pied and black hornbill. The former prefers coastal forests, mangroves and forest edges which contrasts with inland forest adapted hornbills such as the bushy-

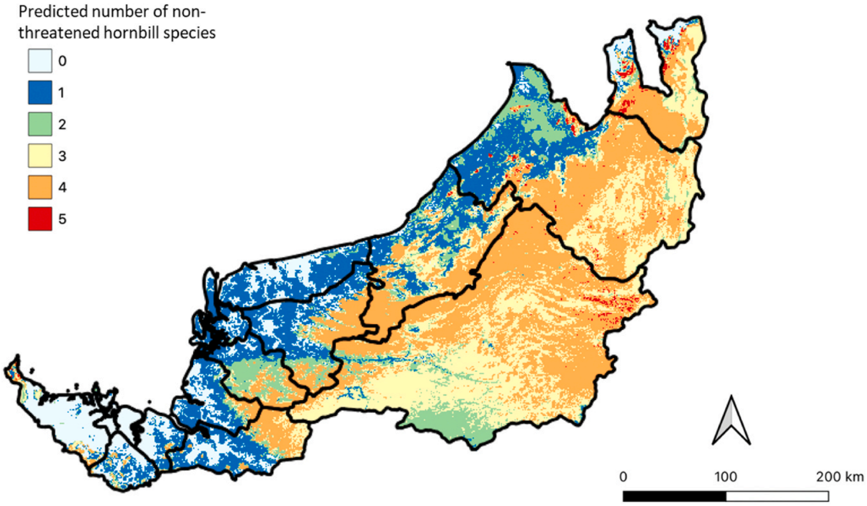

Fig. 3. Predicted distribution of the number of non-threatened hornbill species across Sarawak based on MaxEnt distributions of the black, bushy-crested, oriental pied, rhinoceros, and wreathed hornbill.

Table 4
Potential Important Hornbill Landscape (IHL) sites in Sarawak, identified using MaxEnt output with these predicted to have more than 50% occurrence probability for the non-threatened hornbills across Sarawak.

Administrative division	Site name	IHL Criterion 1 (Number of observed species)		IHL Criterion 2 (size in ha)	IHL Criterion 3 (Breeding status)	IHL Criterion 4 (Conservation status)
		N	T			
Limbang	Ulu Trusan Forest Management Unit	4		92,751	Unknown	IBA, HoB
Kapit	Baleh National Park	4		66,721	Unknown	NP, HoB
Kapit	Danum Forest Management Unit		1	200,383	Unknown	HoB
Kapit	Kapit Forest Management Unit		1	149,756	Unknown	HoB
Kapit	Pasin Forest Management Unit		1	132,151	Unknown	IBA, HoB
Kapit	Linau Forest Management Unit		1	72,685	Unknown	HoB

Abbreviations: N = Not threateaned / T = Threatened/ NP = National Park /IBA = Important Bird and Biodiversity Area / HOB = Heart of Borneo

crested hornbill's preference for closed-canopy and undisturbed habitats, so they may not occur in the same site (Anggraini et. al, 2000; Gale and Thongaree, 2006, Ng et. al, 2011; Loong et. al, 2021). Similarly, the black hornbill is observed to strongly associate with forests below an altitude of 200 m and are therefore less likely observed in hill mixed dipterocarp forests which are classified in Malaysia to exist at altitudes above 300 m (Gale and Thongaree, 2006; Saiful and Latiff, 2017; Forestry Department of Peninsular Malaysia, 2023).

The congruence between our MaxEnt results and published literature, shows that MaxEnt is a useful tool with representative outputs that can validate the applicability of the IHL Criteria and therefore, aid conservation prioritisation in Sarawak and beyond (Kaky et al., 2020; Li et al., 2022).

Sampling bias remains a concern. Survey efforts are rarely equally distributed across large landscapes, and as is the case for Sarawak, surveys (particularly those involving citizen scientists) are known to be concentrated in more accessible areas, such as near city centres and main roads (Tulloch et al., 2012; Barbosa et al., 2013; Warton et al., 2013; Mair and Ruete, 2016). IHL identification using the Criteria can be limited due to spatial bias against remote, inaccessible, and less well-known sites. MaxEnt is equally vulnerable to spatial bias. In our study, after accounting for sampling bias, we found that MaxEnt identified potentially more IHLs in eastern and north-eastern Sarawak than the Criteria identified. Intense survey efforts should be undertaken in the potential IHLs to confirm the persistence of hornbill species.

Detection bias also remains a concern. MaxEnt does not account for detection bias where a species maybe cryptic or has less probability of detection even if present at a given sampling location (Yackulic et al., 2012). Other methods tackling this exist, such as conducting repeat surveys and occupancy modelling (Mackenzie and Royle, 2005; Kéry et al., 2010). Yet, these methods imply new data collection and technical computational capacities which will limit their application in conservation prioritisation. In this study we obtained data from three sources for a more comprehensive understanding of hornbill detections. We suggest that this is more resource-effective compared to new data collection.

We also suggest that MaxEnt with sampling bias corrections is robust in visualising species distributions because it is less data hungry, easier to use and accounts for sampling bias. More computationally and data intensive methods can be considered if there is readily available capacity. Although not perfect, using MaxEnt with the IHL criteria greatly improves prioritisation by validating the Criteria's outputs, identifying potential priority areas and streamlining future ground-truthing efforts for under-surveyed landscapes like Sarawak.

4.2. Expanding survey effort & coverage of forest management units

Data is most needed for FMUs in Sarawak which comprise nearly half of Sarawak's land mass. FMUs are privately owned by timber companies and are not publicly accessible. Although the Forest Department of Sarawak conducts wildlife surveys in FMUs, the survey data is also not publicly available. This emphasises the importance of independent research and data-sharing agreements with timber companies for the collection of critical biodiversity data. The MNS Kuching Branch has brokered such agreements before and this significantly improved the dataset for Ravenscourt FMU, which we identified as a higher priority IHL. Further collaborations would be essential for hornbill conservation prioritisation in Sarawak. They would also help close a major gap towards the identification of priority sites for threatened hornbills like the helmeted hornbill (Jain et. al, 2018b).

4.3. Identification of additional higher priority IHLs relies on better nesting data

Our assessment confirms the paucity of hornbill nesting and breeding records in Sarawak. Only five sites would have qualified as an IHL if we did not modify our methods from Yeap and Perumal (2018). Knowing that anecdotal breeding records exist from other sites, we relaxed Criteria 3 but split IHLs into two categories – higher priority IHLs and IHLs – to acknowledge the importance of hornbill breeding records as an indication of healthy hornbill populations. Moving forward, for identification of additional higher priority IHLs, a concerted effort is needed to search for and formally document nesting and breeding of hornbills across Sarawak. We found a particular lack of such data in journals, books, and online resources. We obtained the majority of hornbill nesting data from interviews with SFC and FMU staff, who had collected important but unpublished nesting data as part of their work. Besides conducting targeted nest searches, future efforts should also incorporate extensive interviews with a larger number of people who may hold unpublished nesting data such as birdwatchers, TPA and FMU staff, and local community members.

4.4. Implications for hornbill conservation

While most of the IHLs identified in our study are already designated as TPAs, one of the higher priority IHLs and majority of the potential IHLs are designated as FMUs, which are not protected for wildlife. Studies have shown that bird populations can exhibit resilience in selectively logged landscapes, where hornbills can persist (Johns, 1987; Lambert, 1992; Johns, 1996). Our findings, thus, strengthens the case to incorporate hornbill conservation into FMU management. This can align with Sarawak government's move to reduce the impact of logging in FMUs by mainstreaming Sustainable Forest Management (SFM).

The Sarawak government's commitment to SFM in FMUs is positive for biodiversity. For example, the government declared that long-term Forest Timber Licences had to be certified under Forest Management Certification schemes such as the Malaysian Timber Certification Scheme (Ting et al., 2022). Additionally, the government necessitated the application of Reduced Impact Logging (RIL) in the SFM of FMUs, making it a pre-requisite to achieving Forest Management Certification (Ting et al., 2022). RIL is an approach in SFM to reduce damage caused by wholesale logging through strategic planning in all stages of the harvesting operation (Sist, 2000). Hornbill conservation threats, however, may not be adequately addressed in spite of SFM approaches. An example of a threat which may persist is the targeted removal of large trees. Being large-sized cavity nesters, the availability of trees with large girths and consequently large cavities is important in providing nesting sites to sustain hornbill populations (Kaur, 2020). Dipterocarps in particular, are known to be important nest trees. However, they are also targeted for timber harvest (Poonswad et al., 2013; Hayward et. al, 2021). The removal of these trees results in a direct loss of nesting opportunities and has indirect effects by impeding the recruitment and growth of younger Dipterocarps, limiting future nesting options (Yamada et. al, 2016; Diway et. al, 2023). Strategies such as leaving trees with hornbill nests standing and restricting logging to the non-breeding season, should be incorporated into the management strategies of FMUs (Meijaard, 2005). As a last resort, the use of artificial nest boxes can be explored to avert a significant loss of breeding sites for hornbills in identified FMU IHLs.

4.5. Limitations

We wanted to follow the IHL Criteria set out by Yeap and Perumal (2018) in Peninsular Malaysia as closely as possible. However, we recognise where it may be rather narrow in its scope. For example, IHL Criterion 4 limits prioritisation to sites that are protected or nationally recognised for wildlife and therefore, have current management plans to prioritise conservation issues. Yet, there may be sites that meet all other criteria and are, therefore, ecologically important but do not have adequate resources to prioritise conservation. This may particularly apply to community conserved areas (managed by indigenous groups) which make up about 7% of Sarawak's land area (Dayak Daily, 2023). One way to address this gap would be to loosen Criterion 4 for future studies and qualify sites as IHL if they meet Criteria 1 – 3. Sites that are currently community conserved areas, IBAs or Key Biodiversity Areas (KBAs) and may benefit from the allocation of new resources when profiled as IHLs. This may aid the identification of sites which are ecologically important for hornbills but overlooked by national policies from a wildlife perspective.

Additionally, we attempted to conduct a representative analysis of survey effort. However, it is likely that site-level location details such as exact geographical coordinates were sometimes not accurately captured in our analysis. In particular, we used generic geographical coordinates for several interviews and personal bird list records resulting in only indicative survey locations which might not fully align with the actual surveyed area per site. It is possible, that each site was surveyed more extensively than shown in our analysis. Bearing this in mind, our results should not be used for survey planning within sites. Yet, it still offers a representative overview of survey effort coverage throughout Sarawak. Despite its limitations, we feel our macro-level analysis is impactful for conservation prioritisation as it can direct future survey efforts where it is needed most across Sarawak.

5. Conclusion

In this study, we showed the applicability of IHL work in Sarawak, and demonstrated the value of MaxEnt in IHL identification. Our analysis found eight IHLs in Sarawak, of which five are of higher priority. Using MaxEnt, we validated results produced by the IHL criteria and showed their congruence with existing hornbill and forest cover knowledge, signifying the applicability of the IHL criteria in Sarawak. Furthermore, we identified six potential IHLs which can benefit from targeted surveys and data-sharing agreements with FMUs. Data gaps in breeding and nest records were also identified as liming factors for IHL identification. This inaugural IHL assessment can also inform land use and management plans, and guide hornbill conservation planning in Sarawak for the coming years.

Being similarly situated in Borneo (as Sarawak), IHL identification can also be replicated in Sabah, applying similar methods outlined in this study, to produce comparable results, and expand hornbill conservation prioritisation in Malaysia. At a regional level, applicability of the IHL criteria to other Asian contexts could also be explored. Given the urgent need for hornbill conservation in Asia, we suggest that our results be used as a case study to be built upon and adapted to support hornbill conservation prioritisation, especially in neighbouring South-east Asian countries facing similar challenges balancing forestry with conservation.

Ethics approval

Free Prior and Informed Consent was obtained from interviewees before interviews were conducted.

CRediT authorship contribution statement

Jelembai Hilda: Data curation, Formal analysis, Investigation, Methodology, Project administration, Validation, Writing – original draft. **Au Nyat Jun:** Project administration, Resources, Supervision, Validation. **Teo Jason J. H.:** Data curation, Investigation, Methodology, Validation. **Teepol Batrisyia:** Data curation, Investigation, Methodology, Validation, Writing – original draft, Formal analysis. **Wee Shelby Q.W.:** Data curation, Formal analysis, Project administration, Writing – original draft, Writing – review & editing, Methodology, Software, Visualization. **Yeap Chin Aik:** Data curation, Project administration, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. **Jain Anuj:** Conceptualization, Funding acquisition, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gecco.2024.e02828.

References

Ahmadi, M., Nezami, B., Jowkar, H., Hemami, M., Fadakar, D., Malakoutikhah, S., Ostrowski, S., 2017. Combining landscape suitability and habitat connectivity to conserve the last surviving population of cheetah in Asia. Divers. Distrib. 23 (6), 592–603. https://doi.org/10.1111/ddi.12560.

Alamgir, M., Campbell, M.J., Sloan, S., Engert, J., Word, J., Laurance, W.F., 2020. Emerging challenges for sustainable development and forest conservation in Sarawak, Borneo. PLoS One 15 (3). https://doi.org/10.1371/journal.pone.0229614.

Anggraini, K., Kinnaird, M.F., O'Brien, T.T.G., 2000. The effects of fruit availability and habitat disturbance on an assemblage of Sumatran hornbills. Bird. Conserv. Int. 10 (3), 189–202. https://doi.org/10.1017/s0959270900000174.

Barbosa, A.M., Pautasso, M., Figueiredo, D., 2013. Species-people correlations and the need to account for survey effort in biodiversity analyses. Divers. Distrib. 19 (9), 1188–1197. https://doi.org/10.1111/ddi.12106.

BirdLife International. 2023a. Malaysia IBAs. *Datazone.* ⟨https://datazone.birdlife.org/country/malaysia/ibas⟩ (accessed on 28 December 2023).

BirdLife International. 2023b. White-crowned Hornbill. *Datazone.* ⟨http://datazone.birdlife.org/species/factsheet/22682507⟩ (accessed 24 on September 2023).

BirdLife International. 2023c. Wrinkled Hornbill. *Datazone*. ⟨http://datazone.birdlife.org/species/factsheet/wrinkled-hornbill-rhabdotorrhinus-corrugatus⟩ (accessed on 24 September 2023).

BirdLife International. 2022. State of the World's Birds: 2022 Annual Update. *Datazone.* ⟨http://datazone.birdlife.org/2022-annual-update⟩ (accessed on 24 September 2023).

Clements, G.R., Rayan, D.M., Aziz, S.A., Kawanishi, K., Traeholt, C., Magintan, D., Yazi, M.F.A., Tingley, R., 2012. Predicting the distribution of the Asian tapir in Peninsular Malaysia using maximum entropy modeling. Integr. Zool. 7 (4), 400–406. https://doi.org/10.1111/j.1749-4877.2012.00314.x.

Corlett, R.T., 2017. Frugivory and seed dispersal by vertebrates in tropical and Subtropical Asia: an update. Glob. Ecol. Conserv. 11, 1–22. https://doi.org/10.1016/j.gecco.2017.04.007.

Datta, A., Patil, I., 2020. Red List status of hornbill species: ensuring updated species factsheets and review of threat assessments. Hornbill Nat. Hist. Conserv. 1 (2), 43–46.

Dayak Daily. 2023. Over 2 mln acres gazetted in NCR land surveys in Sarawak. 16 November 2023. ⟨https://dayakdaily.com/over-2-mln-acres-gazetted-in-ncr-land-surveys-in-sarawak/⟩ (accessed on 14 January 2024).

Department of Wildlife and National Parks Peninsular Malaysia. 2008. National Tiger Action Plan for Malaysia. Kuala Lumpur, Malaysia.

Department of Wildlife and National Parks Peninsular Malaysia. 2013. National Elephant Conservation Action Plan: Blueprint to Save Malaysian Elephants. Department of Wildlife and National Parks Peninsular Malaysia, Kuala Lumpur, Malaysia.

Diway, B., Yiing, L.C., Wasli, M.E., Takeuchi, Y., 2023. Forest structure and recovery in selectively logged forests in Sarawak, Malaysia. Tropics 32 (1), 1–14. https://doi.org/10.3759/tropics.ms22-07.

Donald, P.F., Fishpool, L., Ajagbe, A., Bennun, L., Bunting, G., Burfield, I.J., Butchart, S.H.M., Capellan, S., Crosby, M.J., Dias, M.P., Díaz, D., Evans, M.I., Grimmett, R. F., Heath, M., Jones, V.R., Lascelles, B.G., Merriman, J.C., O'Brien, M., Ramírez, I., Wege, D.C., 2018. Important bird and biodiversity areas (IBAs): the development and characteristics of a global inventory of key sites for biodiversity. Bird. Conserv. Int. 29 (2), 177–198. https://doi.org/10.1017/s0959270918000102.

Fick, S.E., Hijmans, R.J., 2017. WorldClim 2: new 1-km spatial resolution climate surfaces for global land areas. Int. J. Climatol. 37 (12), 4302–4315. https://doi.org/10.1002/joc.5086.

Forest Department Sarawak. 2023. Heart of Borneo (HoB) Initiative. ⟨https://forestry.sarawak.gov.my/web/subpage/webpage_view/993⟩ (Accessed on 28 December 2023).

Forestry Department of Peninsular Malaysia. 2023. Forest Type. ⟨https://www.forestry.gov.my/index.php/en/2016–06-07–02-31–39/2016–06-07–02-35–17/forest-type⟩ (Accessed 20 September 2023).

Gale, G., Thongaree, S., 2006. Density estimates of nine hornbill species in a lowland forest site in southern Thailand. Bird. Conserv. Int. 16 (01), 57. https://doi.org/10.1017/s0959270906000037.

Gaveau, D., Sloan, S., Molidena, E., Yaen, H., Sheil, D., Abram, N.K., Ancrenaz, M., Nasi, R., Quiñones, M., Wielaard, N., Meijaard, E., 2014. Four decades of forest persistence, clearance and logging on Borneo. PLoS One 9 (7), e101654. https://doi.org/10.1371/journal.pone.0101654.

GBIF.org, 2023a. GBIF occurrence download. GBIF. https://doi.org/10.15468/dl.u9etnm accessed on 03 March 2023.

GBIF.org, 2023b. GBIF occurrence download. GBIF. https://doi.org/10.15468/dl.uhuy7d accessed on 03 March 2023.

Geldmann, J., Heilmann-Clausen, J., Holm, T.E., Levinsky, I., Markussen, B., Olsen, K., Rahbek, C., Tøttrup, A.P., 2016. What determines spatial bias in citizen science? exploring four recording schemes with different proficiency requirements. Divers. Distrib. 22 (11), 1139–1149. https://doi.org/10.1111/ddi.12477.

Global Forest Watch. (n.d.). Sarawak, Malaysia. Global Forest Watch. https://www.globalforestwatch.org/dashboards/country/MYS/14/?map=eyJjYW5Cb3VuZCI6dHJ1ZX0%3D (Accessed on 20 September 2023).

Global Forest Watch. 2016b. Sarawak protected areas. *Global Forest Watch.* ⟨https://beta-gfw.opendata.arcgis.com/datasets/gfw::sarawak-protected-areas/about⟩ (Accessed on 20 September 2023) [dataset].

Global Forest Watch. 2016a. Tree cover (2000). *Global Forest Watch.* ⟨https://data.globalforestwatch.org/documents/5fb3275e080e497fa44174d2b14d4b7c/about⟩ *(Accessed on 20 September 2023)* [dataset].

Global Forest Watch. 2015. Sarawak logging concessions. *Global Forest Watch.* ⟨https://data.globalforestwatch.org/datasets/gfw::sarawak-logging-concessions/about⟩ (Accessed on 20 September 2023) [dataset].

Haimoff, E.H., 1987. A spectrographic analysis of the loud calls of Helmeted Hornbills *Rhinoplax vigil.* Ibis 129 (2), 319–326. https://doi.org/10.1111/j.1474-919x.1987.tb03175.x.

Han, X., Huettmann, F., Guo, Y., Mi, C., Wen, L., 2018. Conservation prioritization with machine learning predictions for the black-necked crane *Grus nigricollis*, a flagship species on the Tibetan Plateau for 2070. Reg. Environ. Change 18 (7), 2173–2182. https://doi.org/10.1007/s10113-018-1336-4.

Hayward, R., Banin, L.F., Burslem, D.F.R.P., Chapman, D.S., Philipson, C.D., Cutler, M.E.J., Reynolds, G., Nilus, R., Dent, D.H., 2021. Three decades of post-logging tree community recovery in naturally regenerating and actively restored dipterocarp forest in Borneo. For. Ecol. Manag. 488, 119036 https://doi.org/10.1016/j.foreco.2021.119036.

Hu, R., Gu, Y., Luo, M., Lu, Z., Wei, M., Zhong, J., 2020. Shifts in bird ranges and conservation priorities in China under climate change. PLoS One 15 (10), e0240225. https://doi.org/10.1371/journal.pone.0240225.

Huang, Z., Bai, Y., Alatalo, J.M., Yang, Z., 2020. Mapping biodiversity conservation priorities for protected areas: a case study in Xishuangbanna Tropical Area, China. Biol. Conserv. 249, 108741 https://doi.org/10.1016/j.biocon.2020.108741.

Jaafar, W.S.W.M., Said, N.F., Maulud, K.N.A., Uning, R., Latif, M.T., Kamarulzaman, A.M.M., Mohan, M., Pradhan, B., Saad, S.N., Broadbent, E.N., Cardil, A., Silva, C. A., Takriff, M.S., 2020. Carbon emissions from oil palm induced forest and peatland conversion in Sabah and Sarawak, Malaysia. Forests 11 (12), 1285. https://doi.org/10.3390/f11121285.

Jain, A., Lee, J.G., Chao, N., Lees, C., Orenstein, R., Strange, B.C., Chng, S.C.L., Marthy, W., Yeap, C.A.K., Hadiprakarsa, Y.Y., Rao, M., 2018a. Helmeted Hornbill (*Rhinoplax vigil*): status review, range-wide conservation strategy and action. Plan (2018 – 2027). https://doi.org/10.13140/RG.2.2.25467.16168.

Jain, A., Yeap, C.A., Miller, A., Kaur, R., Yong, D.L., Bidayabha, T., Simbolon, F.H., Aung, T.D.W., Lay, W., Razali, H., Lee, J.G.H., 2018b. Securing safe havens for the Helmeted Hornbill *Rhinoplax vigil.* BirdingASIA 30, 26–32.

Johns, A.D., 1987. The use of primary and selectively logged rainforest by Malaysian hornbills (bucerotidae) and implications for their conservation. Biol. Conserv. https://doi.org/10.1016/0006-3207(87)90084-x.

Johns, A.G., 1996. Bird population persistence in Sabahan logging concessions. Biol. Conserv. 75 (1), 3–10. https://doi.org/10.1016/0006-3207(95)00044-5.

Kaky, E., Nolan, V., Alatawi, A.S., Gilbert, F., 2020. A comparison between Ensemble and MaxEnt species distribution modelling approaches for conservation: a case study with Egyptian medicinal plants. Ecol. Inform. 60, 101150 https://doi.org/10.1016/j.ecoinf.2020.101150.

Kamlun, K.U., Goh, M.H., Teo, S.P., Tsuyuki, S., Phua, M.H., 2012. Monitoring of deforestation and fragmentation in Sarawak, Malaysia between 1990 and 2009 using landsat and SPOT images. J. For. Environ. Sci. 28 (3), 152–157. https://doi.org/10.7747/jfs.2012.28.3.152.
Karimi, A., Yazdandad, H., Reside, A.E., 2023. Spatial conservation prioritization for locating protected area gaps in Iran. Biol. Conserv. 279, 109902 https://doi.org/10.1016/j.biocon.2023.109902.
Kaur, R., Ramli, R., Ancrenaz, M., Hassan, H., Ahmad, E., Ratag, M., Elahan, B., Sinyor, H., Rajak, A., 2020. Estimating the availability of potential hornbill nest trees in a secondary forest patch in Kinabatangan, Sabah. Forktail 36, 56–62.
Kennedy, A.G., Ahmad, A.H., Klinck, H., Johnson, L.M., Clink, D.J., 2023. Evidence for acoustic niche partitioning depends on the temporal scale in two sympatric Bornean hornbill species. Biotropica 55 (2), 517–528. https://doi.org/10.1111/btp.13205.
Kéry, M., Gardner, B., Monnerat, C., 2010. Predicting species distributions from checklist data using site-occupancy models. J. Biogeogr. 37 (10), 1851–1862. https://doi.org/10.1111/j.1365-2699.2010.02345.x.
Klein, C.J., Wilson, K.A., Watts, M., Stein, J.L., Carwardine, J., Mackey, B., Possingham, H.P., 2009. Spatial conservation prioritization inclusive of wilderness quality: a case study of Australia's biodiversity. Biol. Conserv. 142 (7), 1282–1290. https://doi.org/10.1016/j.biocon.2009.01.035.
Kramer-Schadt, S., Niedballa, J., Pilgrim, J.D., Schröder, B., Lindenborn, J., Reinfelder, V., Stillfried, M., Heckmann, I., Scharf, A.K., Augeri, D.M., Cheyne, S.M., Hearn, A.J., Ross, J., Macdonald, D.W., Mathai, J., Eaton, J.A., Marshall, A.J., Semiadi, G., Rustam, R., Wilting, A., 2013. The importance of correcting for sampling bias in MaxEnt species distribution models. Divers. Distrib. 19 (11), 1366–1379. https://doi.org/10.1111/ddi.12096.
Lambert, F.R., 1992. The consequences of selective logging for Bornean lowland forest birds. Philos. Trans. R. Soc. B 335 (1275), 443–457. https://doi.org/10.1098/rstb.1992.0036.
Lehtomäki, J., Kusumoto, B., Shiono, T., Tanaka, T., Kubota, Y., Moilanen, A., 2018. Spatial conservation prioritization for the East Asian islands: a balanced representation of multitaxon biogeography in a protected area network. Divers. Distrib. 25 (3), 414–429. https://doi.org/10.1111/ddi.12869.
Li, Z.J., Liu, Y., Zeng, H., 2022. Application of the MaxEnt model in improving the accuracy of ecological red line identification: a case study of Zhanjiang, China. Ecol. Indic. 137, 108767 https://doi.org/10.1016/j.ecolind.2022.108767.
Loong, S., Sin, K.Y.C., Johns, P., Plowden, T., Yong, D.L., Lee, J., Jain, A., 2021. Nest predation by Oriental Pied Hornbills *Anthracoceros albirostris* in urban Singapore. BirdingAsia 35, 86–91.
Macdonald, D.W., Bothwell, H.M., Kaszta, Ż., Ash, E., Bolongon, G., Burnham, D., Can, Ö.E., Campos-Arceiz, A., Phan, C., Clements, G.R., Hearn, A.J., Hedges, L., Htun, S., Kamler, J.F., Kawanishi, K., Macdonald, E.A., Mohamad, S.W., Moore, J.H., Naing, H., Cushman, S.A., 2019. Multi-scale habitat modelling identifies spatial conservation priorities for mainland clouded leopards (*Neofelis nebulosa*. Divers. Distrib. 25 (10), 1639–1654. https://doi.org/10.1111/ddi.12967.
Mackenzie, D.I., Royle, J.A., 2005. Designing occupancy studies: general advice and allocating survey effort. J. Appl. Ecol. 42 (6), 1105–1114. https://doi.org/10.1111/j.1365-2664.2005.01098.x.
Mair, L., Ruete, A., 2016. Explaining spatial variation in the recording effort of citizen science data across multiple taxa. PLoS One 11 (1), e0147796. https://doi.org/10.1371/journal.pone.0147796.
Meijaard, E., Sheil, D., Nasi, R., Augeri, D., Rosenbaum, B., Iskandar, D., Setyawati, T., Lammertink, M., Rachmatika, I., Wong, A., Soehartono, T., Stanley, S., O'brien, T., 2005. Implication for forestry and concession management. In: Life after Logging: Reconciling wildlife conservation and production forestry in Indonesian Borneo (pp. 174–176). Center for International Forestry Research.
Merow, C., Smith, M.J., Silander, J.A., 2013. A practical guide to MaxEnt for modeling species' distributions: what it does, and why inputs and settings matter. Ecography 36 (10), 1058–1069. https://doi.org/10.1111/j.1600-0587.2013.07872.x.
Mudappa, D. & Raman, T.R.S., 2008. Hornbills and endemic birds: a conservation status survey across the Western Ghats, India. (NCF Technical Report No. 17). Nature Conservation Foundation, Mysore.
Musina. J. , 2007. Identifying Important Hornbill Areas (IHAs) in Kenya: priority setting for sites with high hornbill diversity. In The Active Management of Hornbills and their Habitats for Conservation, CD-ROM Proceedings of the 4th International Hornbill Conference. Kemp, A.C. and Kemp, M.I. (eds). Naturalists and Nomads, Pretoria. pp. 31–40.
Ng, S.C., Lai, H.M., Cremades, M., Lim, M.T.S., Tali, S.B.M., 2011. Breeding observations on the oriental pied hornbill in nest cavities and in artificial nests in Singapore, with emphasis on infanticide-cannibalism. Raffles Bull. Zool. 24, 15–222.
Ortega-Huerta, M.A., Peterson, A.T., 2004. Modelling spatial patterns of biodiversity for conservation prioritization in North-eastern Mexico. Divers. Distrib. 10 (1), 39–54. https://doi.org/10.1111/j.1472-4642.2004.00051.x.
Osman, N.B., Othman, H.T., Karim, R.A., Mazlan, M.A.F., 2014. Biomass in Malaysia: forestry-based residues. Int. J. Biomass Renew. 3 (1), 7–14.
Pandong, J., Gumal, M., Aton, Z.M., Sabki, M.S., Koh, L.P., 2019. Threats and lessons learned from past orangutan conservation strategies in Sarawak, Malaysia. Biol. Conserv. 234, 56–63. https://doi.org/10.1016/j.biocon.2019.03.016.
Pengiran, P., Mohd-Azlan, J., 2021. How do people in the "Land of Hornbills" perceive Hornbills? E5 Bird. Conserv. Int. 33. https://doi.org/10.1017/s0959270921000381.
Phillips, S.J., Dudík, M., Elith, J., Graham, C.H., Lehmann, A., Leathwick, J.R., Ferrier, S., 2009. Sample selection bias and presence-only distribution models: implications for background and pseudo-absence data. Ecol. Appl. 19 (1), 181–197. https://doi.org/10.1890/07-2153.1.
Poonswad, P., Chimchome, V., Mahannop, N., Mudsri, S., 2013. Conservation of hornbills in Thailand. Conservation Biology: Voices from the Tropics. John Wiley & Sons, Ltd eBooks, pp. 157–166. https://doi.org/10.1002/9781118679838.ch19.
Rahman, A.A., Mohamed, M., Tokiman, L., & Sanget, M.M., 2019. Species distribution modelling to assist biodiversity and conservation management in Malaysia. IOP Conference Series, 269(1), 012041. https://doi.org/10.1088/1755–1315/269/1/012041.
Saiful, I., Latiff, A., 2017. Stand profile topography of a primary hill dipterocarp forest in Peninsular Malaysia. J. Trop. For. Sci. 29 (2), 137–150.
Samling Timber Malaysia. (n.d.). Sustainable Forestry. Samling *Timber Malaysia*. ⟨https://www.samling.com/sustainability/environment⟩ (Accessed on 28 December 2023).
Sarawak Forestry Corporation. (n.d.). Gazetted Totally Protected Areas of Sarawak. *Sarawak Forestry*. ⟨https://sarawakforestry.com/layout2/wp-content/uploads/2022/05/Gazetted-TPAs-with-gazzetement-dates-u100522-for-MR.pdf⟩ (Accessed on 28 December 2023).
Sicacha-Parada, J., Steinsland, I., Cretois, B., Borgelt, J., 2021. Accounting for spatial varying sampling effort due to accessibility in citizen science data: a case study of moose in Norway. Spat. Stat. 42, 100446 https://doi.org/10.1016/j.spasta.2020.100446.
Sinclair, S.P., Milner-Gulland, E., Smith, R.J., McIntosh, E., Possingham, H.P., Vercammen, A., Knight, A.T., 2018. The use, and usefulness, of spatial conservation prioritizations. Conserv. Lett. 11 (6), e12459 https://doi.org/10.1111/conl.12459.
Sist, P., 2000. Reduced-impact logging in the tropics: objectives, principles and impacts. Int. For. Rev. 2 (1), 3–10.
Sullivan, B.L., Wood, C.L., Iliff, M.J., Bonney, R.E., Fink, D., Kelling, S., 2009. eBird: a citizen-based bird observation network in the biological sciences. Biol. Conserv. 142, 2282–2292. https://doi.org/10.1016/j.biocon.2009.05.006.
Syfert, M.M., Smith, M.J., Coomes, D.A., 2013. The effects of sampling bias and model complexity on the predictive performance of maxent species distribution models. PLoS One 8 (7). https://doi.org/10.1371/annotation/35be5dff-7709-4029-8cfa-f1357e5001f5.
Ting, C.H., Wira, A., Nadhir, K.A.T., William, C., Lamihati, G. (2022). Trials, tribulations and success of RIL – The Sarawak Experience. ⟨https://www.forestry.gov.my/images/pengumuman/2022/MFC/MFC2022/paperwork/KK06.pdf⟩ (Accessed 20 September 2023).
Trisurat, Y., Chimchome, V., Pattanavibool, A., Jinamoy, S., Thong-Aree, S., Kanchanasakha, B., Simcharoen, S., Sribuarod, K., Mahannop, N., Poonswad, P., 2013. An assessment of the distribution and conservation status of hornbill species in Thailand. Oryx 47 (3), 441–450. https://doi.org/10.1017/s0030605311001128.
Tulloch, A.I.T., Mustin, K., Possingham, H.P., Szabo, J.K., Wilson, K.A., 2012. To boldly go where no volunteer has gone before: predicting volunteer activity to prioritize surveys at the landscape scale. Divers. Distrib. 19 (4), 465–480. https://doi.org/10.1111/j.1472-4642.2012.00947.x.
Waliczky, Z., Fishpool, L., Butchart, S.H.M., Thomas, D., Heath, M., Hazin, C., Donald, P.F., Kowalska, A., Dias, M.P., Allinson, T., 2018. Important bird and biodiversity areas (IBAs): their impact on conservation policy, advocacy and action. Bird. Conserv. Int. 29 (2), 199–215. https://doi.org/10.1017/s0959270918000175.

Warton, D.I., Renner, I., Ramp, D., 2013. Model-Based control of observer bias for the analysis of presence-only data in ecology. PLoS One 8 (11), e79168. https://doi.org/10.1371/journal.pone.0079168.

Yackulic, C.B., Chandler, R., Zipkin, E.F., Royle, J.A., Nichols, J.D., Campbell Grant, E.H., Veran, S., 2012. Presence-only modelling using MAXENT: when can we trust the inferences? Methods Ecol. Evol. 4 (3), 236–243. https://doi.org/10.1111/2041-210x.12004.

Yamada, T., Moriwaki, Y., Okuda, T., Kassim, A.R., 2016. Long-term effects of selective logging on dipterocarp populations in the Pasoh Forest Reserve, Malaysia. Plant Ecol. Divers. https://doi.org/10.1080/17550874.2016.1185653.

Yeap, C.A., Perumal, B., 2018. Distribution of Hornbills and Important Hornbill Landscapes – setting site conservation priorities for Peninsular Malaysia. *Sarawak Museum*. J. LXXIX (N. S. 100, 197–242.

Yeap, C.A., Lim, K.C., Noramly, G., Carang, R., Carang, A., Pandak, M., 2016. The Malaysian Nature Society Hornbill Conservation Project. Malayan Nat. J. 68 (4), 149–159.