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Original Research Article

Identifying refuges for Borneo's elusive Hose's civet

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A B S T R A C T

Human-induced environmental changes, particularly climate change, pose a threat to many tropical montane species, making the identification of optimal future habitat a conservation priority. Here we used maximum entropy (Maxent) and boosted regression trees to predict suitable habitat of the threatened Bornean highland endemic Hose's civet (*Diplogale hosei*), that is currently available, and for future time periods (2050s and 2080s), considering future land cover and climate change predictions. Next, we identified areas that were consistently suitable under current and future model predictions as forest refuges. Our analysis predicted that Hose's civet is restricted mainly to the highlands of Borneo to an area less than 20,000 km^2 (about 2% of the entire island of Borneo). Changes in land cover have little impact on predicted suitable area for the species. However, we predicted habitat loss due to climate change to approximate 86% by 2080, except under a "green economy scenario" which showed stable or increasing suitable habitat. Refuges were small, about 11% of 2010 habitat, and mostly restricted to lower montane forest. About 28–35% of refuges lie within the current protected area network though much is designated as commercial forests within the proposed Heart of Borneo (HoB). For the conservation of Hose's civet and likely other Bornean highland endemics, we recommend increased wildlife and forest law enforcement in identified protected refuges and sustainable timber harvesting practices in surrounding commercial forests, both within the HoB and the extensions we identified. Results of our green model showed that efforts to reduce greenhouse gas emissions will likely contribute immensely to the long-term conservation of highland species such as Hose's civet.

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1. Introduction

Anthropogenic climate change was identified as one of the major causes of biodiversity loss in the next 100 years (Struebig et al., 2015a; Wiens, 2016). A changing climate is likely to increase variability in precipitation seasonality and temperature (Anderson et al., 2004). The possible impacts of climate change on species persistence remain highly uncertain, due to differences among climate models, uncertainty in modelling approaches, different hypotheses about species dispersal, varied species responses to climate change and indeed, uncertainty in these responses due to insufficient knowledge on species ecology (Wiens, 2016). Vulnerability to the effects of climate change may be strongest in tropical highland species because their current altitudinal ranges may not overlap with climatically suitable ranges of the future (so-called 'range-shift gaps'), and because warming may push climatically suitable conditions off mountain peaks leading to mountain-top extinction (Colwell et al., 2008). Both processes are further complicated by the decline and fragmentation of available habitat for dispersal (Sheldon et al., 2011). For example, the island of Borneo has lost more than 30% of its total forested area from the 1970s and almost half of the remaining forest is degraded through unsustainable logging practises, forest fires and encroachment (Gaveau et al., 2014). Much of the remaining intact forests on Borneo is allocated to be logged and converted to monoculture plantations under current forest-use designations (Gaveau et al., 2014). Moreover, although deforestation on Borneo previously occurred mainly in the lowlands, future land cover models predict additional lowland and increasingly upland forest have the highest probability to get deforested (Struebig et al., 2015a), thus likely reducing the ability of montane species to find and/or disperse to suitable habitat in the future. Species which are physiologically specialised to narrow environmental conditions may be most negatively affected by climate and land cover changes (Colwell et al., 2008). Assessing the impact of climate and land cover change on tropical mountain species in highland areas is thus critical to address their conservation needs.

One such tropical mountain species is the Bornean endemic Hose's civet (*Diplogale hosei)*. *Diplogale* is a monospecific genus and the species is genetically distinct from all other global carnivore forms (Wilting and Fickel, 2012). Hose's civet is listed as Vulnerable on *The IUCN Red List of Threatened Species* (Mathai et al., 2015) and nothing is known about population densities, home-range size or dispersal patterns, making specific conservation interventions difficult.

Earlier species distribution modelling efforts for this species concluded that it is forest-dependent and restricted to the higher elevations of Borneo predominantly above 1000m above sea level, a.s.l. (Jennings et al., 2013; Mathai et al., 2016a), whereas the latter more comprehensive study also summarised records from lowland forest (e.g. Samejima and Semiadi, 2012) and predicted Hose's civet to be patchily distributed within the highland interior of north-eastern Borneo (Mathai et al., 2016a). Overall the very low number of records (either from museum collections or camera trap surveys) strongly suggests that Hose's civet distribution used to be very localised, or its abundance very low, or both (Mathai et al., 2015). One reason for low population density might be the species' unusual microhabitat needs, as at fine spatial scales, Hose's civet occurrence was positively associated with mossy heath forest ('kerangas') (Mathai et al., 2017), a habitat scattered in distribution (Brunig, 1974). This specialised ecology and restricted core distribution area to highland forests emphasizes how important it is to understand the projected impacts of climate and land cover change on Hose's civet.

Here, we provide projections of habitat suitability for Hose's civet across its complete distribution range using land cover and climate change forecasts for the 21st century. We used a species distribution modelling framework that is based on statistical association between species presence and environmental factors (Elith et al., 2010). We first identified which global parameters (on the scale of Borneo) approximate best the fine-scale occurrence of Hose's civet, as determined by Mathai et al. (2017). Next, these global proxies were used to project the extent of suitable habitat into future time periods, while considering the influence of predicted changes in land cover and climate on the distribution of Hose's civet. We account for uncertainty arising from climate forecasts by using several general circulation models (GCM) and emission scenario combinations. Furthermore, we account for model structural uncertainty by using two different analytical frameworks, Maxent and generalised boosting model (GBM, commonly referred to as boosted regression trees). Our modelling frameworks identified areas that might serve as future refuges and where targeted management interventions could be implemented for Hose's civet in an era of rapid environmental change.

2. Methods

2.1. Species occurrence records used for modelling

We based our models both on records from the Borneo carnivore database (Kramer-Schadt et al., 2016) and more recent camera-trapping records until 2015, beyond which we are unaware of records from new locations. We only used records with a spatial precision of less than 5 km. Rapid deforestation occurs on Borneo (Gaveau et al., 2014) and could potentially lead to mismatch between species presences and current land cover classifications. Therefore, we cross-checked all records collected before 2005 with current land cover data (2010 PALSAR land-cover map validated for Borneo (Hoekman et al., 2009); see Table 1 for details) to ensure no records fell within habitat that was anthropogenically modified after the records were collected. This also enabled the direct use of land cover as an input variable for modelling. To reduce inaccuracy in model projections associated with spatial autocorrelation (Veloz, 2009; Kramer-Schadt et al., 2016) and to reduce possible search-effort bias, we applied spatial filtering as suggested in Kramer-Schadt et al. (2013) and used only one record within a radius of 2 km (greater than the assumed home range radii of similar-sized small carnivores on Borneo). We retained records with

Table 1
Full set of variables and the subset used in the final model for the species distribution modeling. Variables were calculated in R v.3.2.0 (R Core Team, 2015) and ArcGIS 10.1 using global GIS datasets. All data were resampled to 450m.

Variables (full set)	Variables (final set)	Source
2010 Land cover/elevation class, in 9 classes: 0. Bare areas; water and fishponds; water; burnt forest 1. Old plantations; young plantations and crops; mixed crops 2. Swamp forest; mangroves 3. Forest mosaics/fragmented or degraded forests, 501–1000m 4. Forest mosaics/fragmented or degraded forests, 0–500m 5. Upper montane forest above 1500m 6. Lower montane forest 1001–1500m 7. Upland forest 501–1000m 8. Lowland forest 0–500m	2010 Land cover/elevation class, in 9 classes: 0. Bare areas; water and fishponds; water; burnt forest 1. Old plantations; young plantations and crops; mixed crops 2. Swamp forest; mangroves 3. Forest mosaics/fragmented or degraded forests, 501–1000m 4. Forest mosaics/fragmented or degraded forests, 0–500m 5. Upper montane forest above 1500m 6. Lower montane forest 1001–1500m 7. Upland forest 501–1000m 8. Lowland forest 0–500m	Based on 2010 land cover data derived from 50m resolution PALSAR imagery by SarVision (Hoekman et al., 2009) but updated with DEM data in 500m elevation steps and reclassified into 9 classes.
Distance to logging roads	Distance to logging roads	Based on Gaveau et al. (2014) http://gislab.cifor.cgiar.org/wm/borneo/but applying a maximum threshold distance of 9 km
Bioclimatic maps bioclim variables 1–19	Bio 1 (annual mean temperature), Bio 2 (mean diurnal range), Bio 12 (annual precipitation), Bio 15 (precipitation seasonality)	Hijmans et al. (2005); http://www.worldclim.org/bioclim
Soil properties 1. Bulk density 2. Cation exchange capacity 3. Coarse Fragments 4. Organic Carbon 5. pH in H_20 6. % Sand 7. % Silt 8. % Clay	Bulk density Cation exchange capacity Organic carbon % Sand	http://www.isric.org/content/soilgrids These were given at six depth classes for each soil property. As all depth classes were almost perfectly correlated for every soil property, we took the mean of the top three classes for each property (0 − 5 cm, 5–15 cm, 15–30 cm).
Topographic Position Index (TPI) (the elevational difference between each cell of the DEM and the mean of its eight neighbours)	TPI	Calculated from the 90-m SRTM digital elevation model (DEM, http://srtm.csi.cgiar.org) using extraction method 'bilinear'

greatest location accuracy; when data clusters included two or more records with equal accuracy, we randomly selected the record to be retained.

2.2. Modelling approach

All analyses were done in R 3.2.0 (R Core Team, 2015) and ArcGIS 10.1 (ESRI, Redlands, CA, USA). All maps used during the analyses (Table 1) were resampled to an identical extent and cell size of 450 m. To model current habitat suitability of Hose's civet, we used occurrence records and environmental predictors (Table 1), and fitted the model with two algorithms: Maxent and GBM. We did not have 'true absences', and instead used a random sample of pseudo-absences. Models were fitted using the R package biomod2 (Thuiller et al., 2009). The following settings were used: random test percentage = 20; regularisation multiplier = 1; maximum number of background points = 10,000. The fitted model was used to project the habitat suitability to two future time periods (2050s and 2080s). We used three different scenarios for each time period, namely: (1) current climate but future projections for land cover (i.e. 'land cover only'); (2) current land cover but future climate projections (i.e. 'climate only'); and (3) both future projected climate and land cover (i.e. 'climate + land cover'). For each modelled algorithm and scenario, we ran ten replicates (representing ten random samples of absence points, to strengthen predictions) and three cross-validations (to assess model fit), and used the habitat suitabilities averaged across these replicates for further analyses. To identify potential refuges for Hose's civet over the course of the century, we identified forests that were consistently suitable under current and future model predictions. To place our projections into a historical context, we hindcasted habitat suitability to land cover conditions before the 1950s, a time when most data used to quantify current climate were first collected (Hijmans et al., 2005) and before major land cover changes occurred on Borneo (Gaveau et al., 2014).

We used the True Skill Statistic (TSS) as a measure of model performance and accuracy as it is neither affected by the prevalence of occurrence points nor size of the study region (Allouche et al., 2006). Values for this statistic range from 0 to 1, with 1 meaning good performance of the model.

2.3. Selection of input variables

We used the two identified fine-scale predictors of Hose's civet occurrence, mean moss cover and kerangas forest (Mathai et al., 2017) to detect corresponding global-scale predictors for the whole of Borneo. As no reliable analogous data exist on the

Borneo-scale for these two in-situ recorded variables, we tested 19 bioclimatic layers (Hijmans et al., 2005) and 8 soil property layers (Table 1), as candidate global proxies. We used correlation matrices and retained eight global predictors most correlated with the two in-situ predictors: annual mean temperature, mean diurnal (temperature) range, annual precipitation, precipitation seasonality (as global proxies of mean moss cover); percentage of sand, cation exchange capacity, bulk density and soil organic carbon (as global proxies of kerangas soils). In addition to these two fine-scale predictors, distance to roads, topographic position index (TPI) and forest disturbance also influence Hose's civet occurrence to a lesser degree (Mathai et al., 2017). For these we used the following corresponding global predictors: logging road data for Borneo (Gaveau et al., 2014; see Table 1) applying a maximum threshold distance of 9 km (because few surveys in Borneo have been conducted in isolated areas further than 9 km from the nearest logging road); a TPI raster for Borneo derived from a 90m SRTM digital elevation model; and land cover data (modified version of 2010 PALSAR land cover data, see Table 1). Hence, a subset of 11 variables was used for final modelling (Table 1).

2.4. Future projections

For future climate projections, we used eight scenarios to account for potential uncertainty associated with any single GCM and with source environmental data. We used the climate projections for two time periods (2050, 2070), obtained with two GCMs (http://www.metoffice.gov.uk/research/modelling-systems/unified-model/climate-models/hadgem2, HadGEM2-AO; and Commonwealth Scientific and Industrial Research Organisation, ACCESS1.0) under two emission scenarios (green/intermediate model and worst-case model). For HadGEM2-AO, we used RCP26 (green model which assumes global annual greenhouse gas (GHG) emissions peak between 2010 and 2020 and declines substantially thereafter) and RCP85 (worst case model which assumes global annual GHG emissions continue to rise throughout the 21st century). Because RCP26 was not available for ACCESS1.0, we instead used the intermediate model, RCP45 as our green model (which assumes global annual GHG emissions peak around 2040, then decline) and again, RCP85 for the worst-case model.

For future land cover projections, we used 2050 and 2080 predicted land cover maps for Borneo which assumed no reforestation and constant pace of deforestation typical for the period 2000–2010 (Gaveau et al., 2013; Struebig et al., 2015a, b: Supplementary Material). These scenarios represent the worst case scenario for land cover change against which to compare the influence of climate. For historical land cover, we used a modified version of the 2010 land cover data which was used for current habitat suitability models (Table 1), in which all non-forest or mosaic forest classes that were converted from forest were reclassified to their natural forested counterparts (Struebig et al., 2015a).

2.5. Refuge identification

To compare the extent of suitable habitat predicted by various models under different scenarios, we converted the habitat suitability predictions into binary predictions (i.e. suitable and unsuitable). We used a 25% threshold, calculated by assigning presence to all cells with suitability higher than 25% of habitat suitability predicted with the model for the current conditions. This threshold reflects a strict representation of primary Hose's civet habitat and was the consensus threshold agreed upon by researchers working on carnivores in the region during the 2015–2016 Red List evaluation for Hose's civet and other Bornean carnivores. Because area estimates are sensitive to threshold choice (Liu et al., 2005), we additionally provide estimates obtained with a 10% error threshold, a commonly applied criterion in distribution modelling studies (e.g. Pearson et al., 2007) to generate a liberal suitability classification insensitive to outliers and incorporate a larger predicted area (i.e. 90% of possible predicted values). Such a usage of fixed omission thresholds, although arbitrary, provides upper and lower bounds of possible habitat extent that could be reliably applied across environmental projections.

In our conservation planning approach, we wanted to include also areas of moderate suitability and the 25% error threshold, being strict, did not include such areas. Therefore, we used the 10% error threshold to select potential Hose's civet refuges. The use of this moderate threshold is also supported, as previous studies showed that species distribution forecasts under climate change often overestimate negative impacts, because SDMs assume stable ecological niches and do not allow for adaptation of species to changing environmental conditions (Stockwell and Peterson, 2002; Atkins and Travis, 2010).

To investigate the degree of agreement (similarity/dissimilarity) between the species predictions based on the two algorithms used, we overlaid binary threshold maps using Maxent only and GBM only, for each of the 12 models used (Appendix 1, Table S2). For each of these models, we calculated, at both thresholds (10% and 25%), the percentage agreement between pixels i.e. whether both modelling algorithms predicted the pixels as suitable or unsuitable (both either ‘1’ or ‘0’) against pixels that were only supported by one algorithm and not the other (i.e. ‘1’ in one case and ‘0’ in the other). Similarly, to investigate consensus between the species distribution predictions based on the two GCMs used, we overlaid binary threshold maps using HadGEM2-AO only and ACCESS1.0 only. However, because we used RCP26 (for HadGEM2-AO) and RCP45 (for ACCESS1.0) for our green/intermediate model, we compared percentage agreement in GCMs only for the RCP85 worst case scenario (4 models, Table S3).

3. Results

3.1. Species occurrence records

We collected 102 occurrence records for Hose's civet, of which 70 were recorded post-2011 (i.e., were not in the Borneo carnivore database). New records were all camera-trap records with high precision (<2 km). After using the 2 km filter to account for spatial autocorrelation and to reduce clumping, we included 64 records in the modelling, which is a large increase in the number of records compared to previous modelling studies (27, Jennings et al., 2013; 20 for Balanced Model covering the entire Borneo, Mathai et al., 2016a). Most records were collected from the mountainous interior of northern Sarawak and Sabah (Fig. 1).

3.2. Present-day model

Models fitted with both algorithms converged well and had good discriminatory power: TSS values for models fitted with Maxent and GBM were 0.855 ± 0.011 and 0.958 ± 0.001, respectively. Environmental parameters which most influenced Hose's civet occurrence using Maxent and GBM were quite consistent, although land cover contributed more in the GBM model: Maxent − annual mean temperature (42%), precipitation seasonality (15%), distance to roads (12%) and annual precipitation (7%); GBM − annual mean temperature (28%), precipitation seasonality (21%), land cover (20%), and distance to roads (16.4%). Much of the central highlands of Borneo exhibited modest to high suitability according to both algorithms. Using the more restrictive 25% error threshold, the ensemble (average of the two algorithms, Maxent + GBM) model predicted approximately 13,000 km^2 of Borneo to be currently suitable Hose's civet habitat (Maxent only: 20,000 km^2; GBM only: 12,750 km^2, Table 2). This represented a habitat reduction of approximately 2% of the habitat compared to the models hindcasting to conditions before the 1950s (Table 2).

3.3. Projected impacts of land cover change

The 2050 and 2080 predicted land cover maps used for future land cover projections only accounts for deforestation and does not include forest degradation e.g. through selective logging in upland forests. Under these projected land cover changes, models showed negligible change in suitable habitat for Hose's civet by the 2080s (Table 2 and S1).

3.4. Habitat decline under changing climate

The extent of suitable Hose's civet habitat in future climate conditions varied among the GCMs and emission scenarios used (Table 2 and S1), although there was consensus across models over most of the area (Fig. 2 and Appendix 1: Tables S2 and S3). Under future climate conditions, models predicted a drastic decline in suitable habitat, approximately 86% loss between 2010 and 2080 at the 25% error threshold (76% at the 10% error threshold: median across all models, including all scenarios

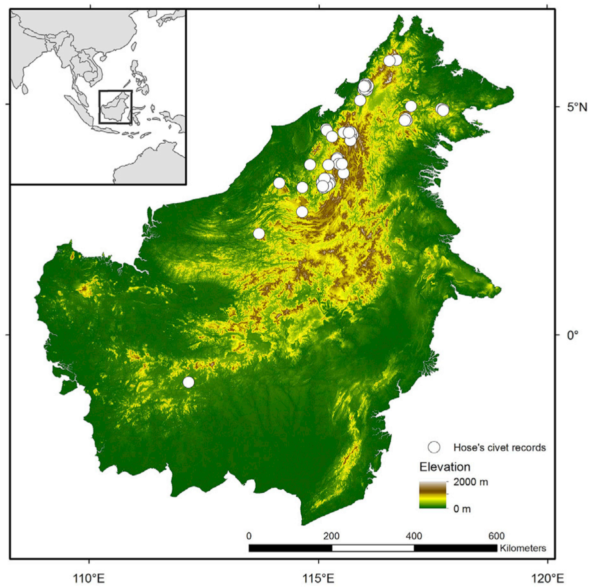

Fig. 1. Location of Hose's civet *Diplogale hosei* occurrence records used for the modelling study.

Table 2
Projected change in extent of suitable Hose's civet habitat over Borneo between the 1950s and 2080s under different environmental change scenarios and model predictions. The magnitude of habitat loss is calculated between the 1950s and 2010 for current conditions, and between 2010 and 2080s for the future. Projections are presented for the 25% error threshold.

	GBM			MAXENT			Ensemble (GBM + MAXENT)		
	Area (km2)		Suitable habitat loss (%)	Area (km2)		Suitable habitat loss (%)	Area (km2)		Suitable habitat loss (%)
Before major land-cover change (1950s)	13061			20422			13336		
Current (2010)	12755		2.3	20037		1.9	13021		2.3
Time slices	**2050**	**2080**		**2050**	**2080**		**2050**	**2080**	
Land cover only	12725	12723	0.2	19980	19982	0.3	12975	12975	0.3
Climate only									
HadGEM2-AO, green (RCP26)	7454	8402	34.1	19601	20199	−0.8	12342	13890	−6.7
ACCESS1.0, green (RCP45)	2099	1178	90.8	7193	4101	79.5	3307	2038	84.3
HadGEM2-AO, worst-case (RCP85)	3529	885	93.1	10745	4542	77.3	5769	1668	87.2
ACCESS1.0, worst-case (RCP85)	2061	51	99.6	15287	1752	91.3	5780	335	97.4
Land cover + climate									
HadGEM2-AO, green (RCP26)	7466	8413	34.0	19599	20170	−0.7	12318	13865	−6.5
ACCESS1.0, green (RCP45)	2117	1194	90.6	7214	4117	79.5	3331	2062	84.2
HadGEM2-AO, worst-case (RCP85)	3546	904	92.9	10710	4574	77.2	5789	1628	87.5
ACCESS1.0, worst-case (RCP85)	2082	54	99.6	15241	1720	91.4	5877	349	97.3

and both algorithms, Table 2 and S1). Interestingly, for the green model using the RCP26 scenario, the decline in suitable habitat was much less and predicted suitable habitat even increased, compared to present, for the Maxent and the ensemble (Maxent + GBM) model by 2080 at the 25% error threshold (up to 6.7%, Table 2). For all other models which incorporated climate change, huge losses in suitable habitat were projected (Table 2 and S1).

3.5. *Combined effects of land cover and climate change*

There was no major increase in habitat loss resulting from combining future changes in land cover and climate (Table 2 and S1, Fig. 2). Under this combined environmental change scenario, models predicted an 86% habitat loss at 25% error threshold between 2010 and 2080 (77% at 10% threshold; median across all models, Table 2 and S1).

3.6. *Consensus between algorithms and GCMs*

Variation among model outcomes is to be expected in forecasting studies (Araujo and Peterson, 2012) and our approach uncovered some variation although there was substantial consensus among models. There was 98% consensus between algorithms (96% at 10% error threshold; median across all models, Table S2) with a larger proportion of the area predicted using GBMs within the consensual regions of Ulu Padas – Lawas at the Sabah-Sarawak border, the Kelabit Highlands in Sarawak and the Crocker Range in Sabah. Models using Maxent consistently showed larger suitable areas (see Table 2 and S1). Similarly, there was 99% consensus between the species distribution predictions based on the two GCMs used (Table S3). A larger proportion of area predicted using ACCESS1.0 data was within the consensual regions described above and models using HadGEM2-AO generally showed larger suitable areas (Table 2 and S1).

3.7. *Hose's civet refuges*

By identifying forests that were consistently suitable under current and future model predictions, approximately 2900 km^2 of Borneo (or about 11% of 2010 habitat) was identified as potential refuges for Hose's civet over the course of the century, using the liberal 10% error threshold and the green model (greatest area among all scenarios, calculated from Fig. 3). This comprised mainly highlands (0% < 500 m a.s.l.; 7% 500–1000 m; 86% 1000–1500 m; 7% > 1500 m, Table 3), particularly the Kelabit Highlands in Sarawak, the Sarawak-Sabah border, and the western Sabah mountain massif. Though 35% of this area was in protected forests (Table 3), the rest lies outside the current protected area network, though largely within the northern regions of the Heart of Borneo (HoB) initiative (a tri-partite government agreement signed between Brunei, Malaysia and Indonesia to manage sustainably the remaining relatively less-encroached band of forests in the centre of the island).

4. Discussion

Very little is known about the response of tropical montane species to climate and land cover change. Moreover, montane regions are often remote and difficult of access, and generally less surveyed compared to tropical lowland forests. Hence a poorer knowledge and understanding of these ecosystems: Hose's civet is one such example of this knowledge gap, another

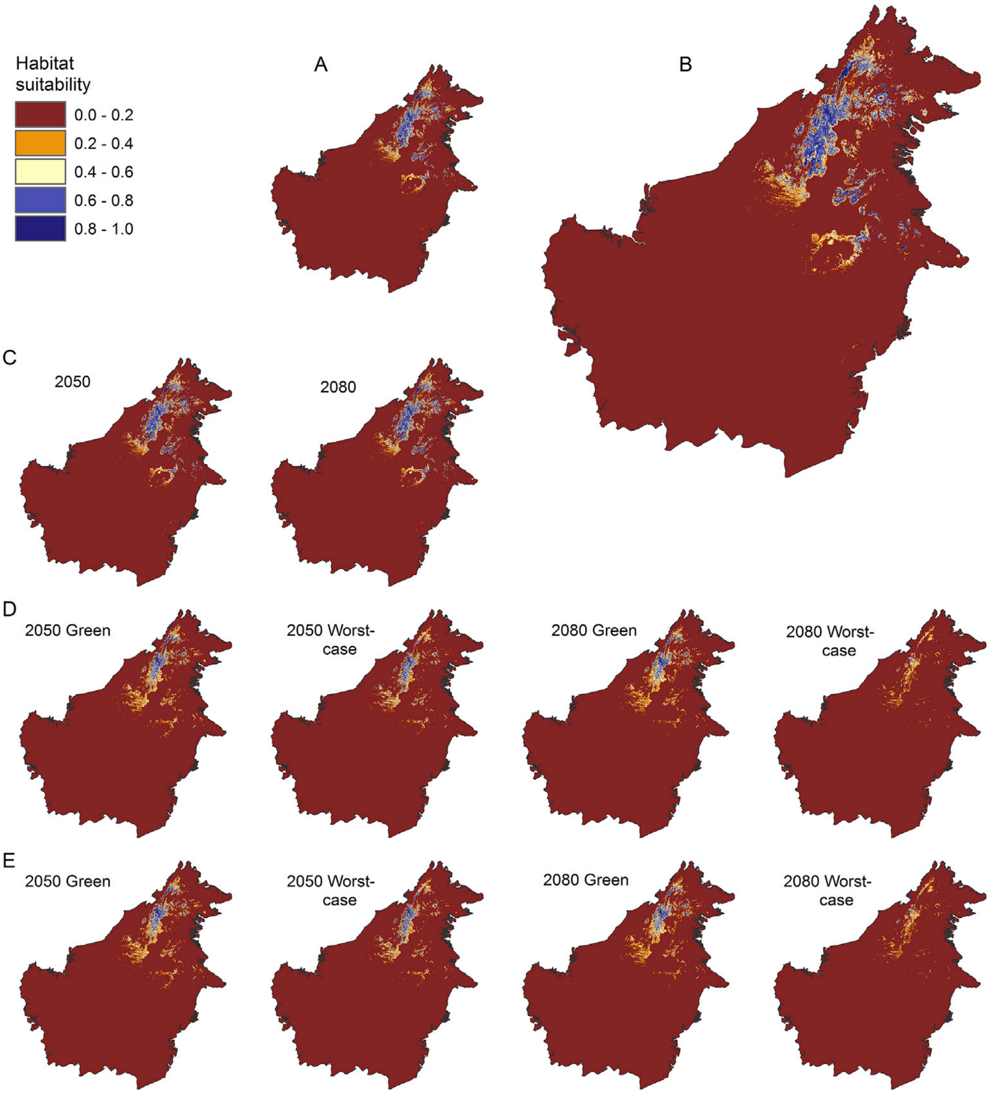

Fig. 2. Predicted suitable Hose's civet habitat following projected changes in land cover and climate. Suitability models derived from the ensemble model of Maxent and GBM at the strict 25% error threshold. Climate data are from two global circulation models (GCMs, HadGEM2-AO and ACCESS1.0) and two emission scenarios (green/intermediate model and worst-case model, see main text for details). (A) – Former (1950s) (B) – Current (2010) (C) – Land cover only (D) – Climate only (E) – Climate + land cover. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

example being the endemic Bornean ferret badger *Melogale everetti*. Most information in this study was derived from the mountainous interior of Sarawak and Sabah, with few records from Brunei and only one from Kalimantan, mainly due to the paucity of research in these regions. Our models therefore potentially underestimated the true occurrence of Hose's civet, particularly in the central mountain massif in Kalimantan. This is reflected by the fact that our models did not predict the Schwaner mountains of Central Kalimantan (where the sole record from Kalimantan was taken) as suitable habitat. This emphasizes the need for further basic inventory work using camera traps across Borneo, particularly from Kalimantan. Conversely, our models predicted Tawau Hills Park in the southeast of Sabah and species' presence has recently been confirmed by camera traps (AH, unpublished data). However, it seems possible that even within the predicted suitable areas, the actual distribution of the species is likely very discontinuous, as surveys in forest within the documented altitudinal and geographic range indicate (if at all, e.g. Cheyne et al., 2016), and native hunters seldom encounter the species (JM, pers. obs.).

Despite methodological limitations, low survey effort from certain regions such as Kalimantan and limited information about the ecology of the species, our results provide new insights into the occurrence and conservation management of this little known, threatened highland endemic. Our models suggest that only 1.7–2.7% of Borneo (12,700 to 20,000 km^2) was potentially suitable for Hose's civet in 2010. This figure is less than the area of occupancy (AOO) estimated for the IUCN Red List assessment in 2015 (28,000 km^2, Mathai et al., 2015), emphasizing that the species might be even more threatened than

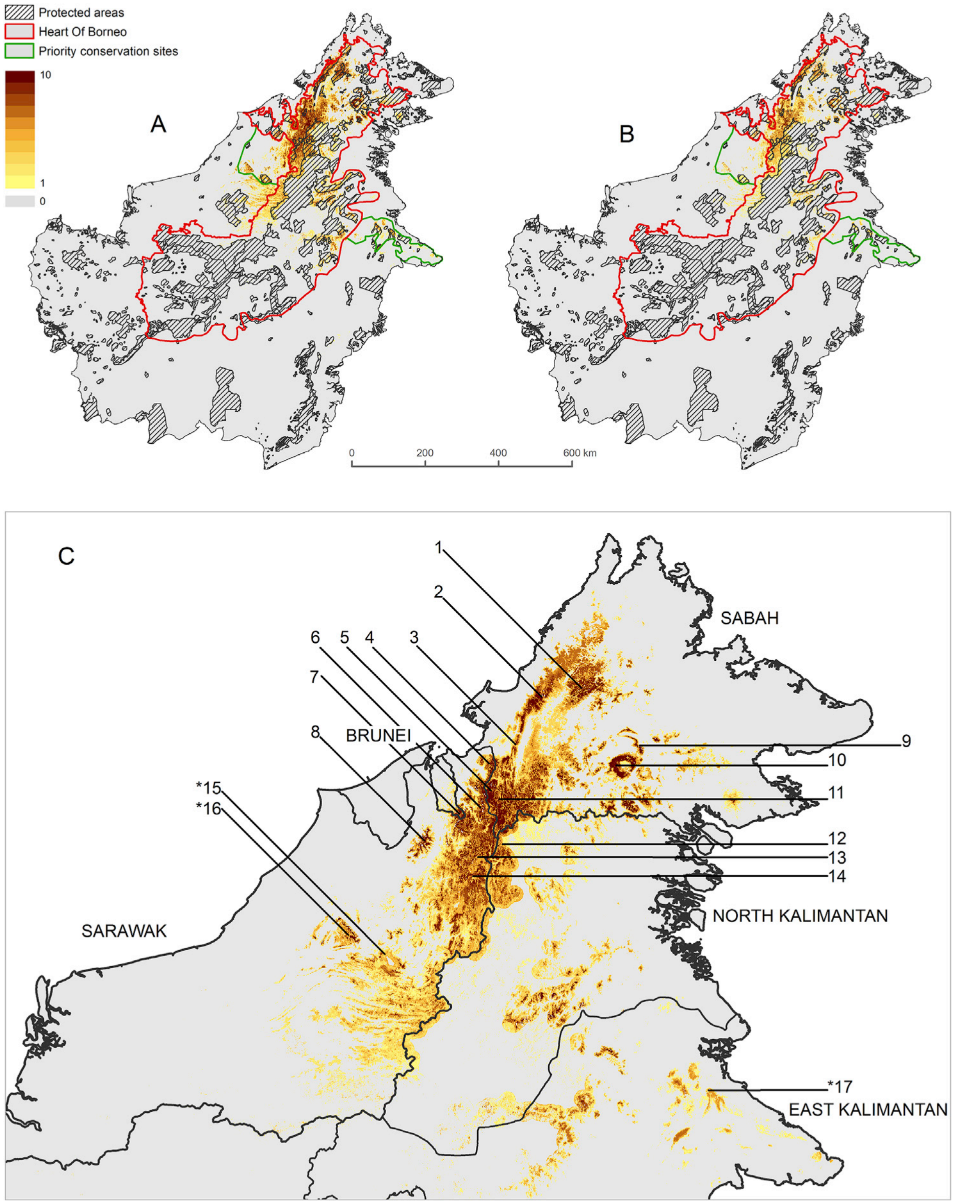

Fig. 3. Potential refuges for Hose's civet under predictions of both land cover and climate change. Refuge areas are suitable for Hose's civet between 2010 and 2080 according to 10% error (A) and 25% error (B) thresholds for the green/intermediate model (refuges for worst-case model are a subset of these and hence, are not shown here). Consensus among models is based on the overlay of ten models: (1) $\text{GBM}_{\text{Present}}$ (2) $\text{Maxent}_{\text{Present}}$ (3) GBM, $\text{Had}_{(\text{LC}\,+\,\text{CC})2050}$ (4) GBM, $\text{Access}_{(\text{LC}\,+\,\text{CC})2050}$ (5) Maxent, $\text{Had}_{(\text{LC}\,+\,\text{CC})2050}$ (6) Maxent, $\text{Access}_{(\text{LC}\,+\,\text{CC})2050}$ (7) GBM, $\text{Had}_{(\text{LC}\,+\,\text{CC})2080}$ (8) GBM, $\text{Access}_{(\text{LC}\,+\,\text{CC})2080}$ (9) Maxent, $\text{Had}_{(\text{LC}\,+\,\text{CC})2080}$ (10) Maxent, $\text{Access}_{(\text{LC}\,+\,\text{CC})2080}$, where Had = HadGEM2-AO, Access = ACCESS1.0, LC + CC = Land cover + Climate change. Consensus is indicated by overlays (red indicating 100% agreement). The protected area network on Borneo, the Heart of Borneo (HoB) initiative, and two extensions to the HoB, proposed in Mathai et al., 2016, and identified here as important for movement of Hose's civet between refuge habitats, are shown. (C) shows the refuge areas at the 10% error threshold only. Areas numbered 1–14 are within the HoB and areas numbered 15–17 (indicated with *) lie outside the HoB but within the proposed extensions to the HoB (see Table 4 for the names of the areas). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

originally thought. Although this shows the importance of conducting further studies on other taxa in montane regions, it is conceivable that our conclusions for Hose's civet could be applied to other montane species for which such comprehensive analysis of potential suitable habitat has not yet been performed.

4.1. Projected effects of land cover and climate change

Despite the high rates of deforestation reported on Borneo (Gaveau et al., 2014), our models predicted the trajectory of Hose's civet habitat loss to be negligible under land cover projections alone. This is due to two reasons. First, deforestation

Table 3
Percentage of area in each elevation class and under protection identified as potential refuges of Hose's civet. Refuge areas are both forested and predicted suitable for Hose's civet between 2010 and 2080 according to 10% and 25% error thresholds, under the green and worst-case scenarios. Percentages are shown if 8 or more models (see legend of Fig. 3 for model details) were consistent.

Model	Threshold	Consensus in number of overlays	% lowland forest (<500m)	% upland forest (500–1000m)	% lower montane forest (1000–1500m)	% upper montane forest (>1500m)	% under protection
Green model	10%	10	0	7	86	7	35
		9	0	30	62	8	33
		8	0	46	48	6	26
	25%	10	0	1	98	1	31
		9	0	6	86	8	34
		8	0	25	73	2	32
Worst-case model	10%	10	0	0	82	18	28
		9	0	0	85	15	32
		8	0	3	88	9	29
	25%	10	0	0	97	3	28
		9	0	0	95	5	22
		8	0	0	91	9	30

Table 4
Names of potential refuge areas for Hose's civet under predictions of both land cover and climate change at 10% error threshold, as mapped in Fig. 3C (see legend of Fig. 3 for more details).

No.	Political Unit/Location	Refuge
1	Sabah	Trus Madi Forest Reserve
2	Sabah	Crocker Range Park
3	Sabah	Gunung Lumaku Forest Reserve
4	Sarawak	Lawas highlands
5	Sabah	Maligan Virgin Jungle Reserve
6	Sarawak	Paya Maga highlands
7	Brunei	Ulu Temburong National Park
8	*Sarawak*	*Gunung Buda National Park*
9	*Sabah*	*Sungai Imbak Virgin Jungle Reserve*
10	*Sabah*	*Maliau Basin Conservation Area*
11	Sabah	Ulu Padas – Sipitang Forest Reserve
12	*North Kalimantan*	*(higher elevation areas of) Kayan Mentarang National Park*
13	Sarawak	Pulong Tau National Park
14	Sarawak	Kelabit highlands
**15*	*Sarawak*	*Usun Apau National Park*
**16*	*Sarawak*	*Dulit Range*
**17*	*East Kalimantan*	*Sankulirang-Mangkalihat Karst Mountains*

Areas in normal font lie within the core refuge area of Hose's civet. Areas in italics represent forests outside of this core refuge area that might also serve as potentially suitable habitat.

currently disproportionately affects the lowlands (<500 m a.s.l.) on Borneo (Struebig et al., 2015b; Mathai et al., 2016b) and under future land cover models, additional lowland and upland forest (500–1000 m a.s.l.) have the highest probability to get deforested via conversion to agricultural landscapes (Gaveau et al., 2014; Struebig et al., 2015a). Much of the suitable habitat for Hose's civet, on the other hand, was predicted in the highlands and thus, models did not consider deforestation of higher-elevation forest via conversion as a major threat. However, the deforestation projections regarded montane and upper montane forests, being more rugged, as not suitable for plantations due to higher erosion rates, but potential genetic modifications in cultivars (e.g. of oil palm, Cochard et al., 2005), or warming conditions at higher elevations, could enable cultivation at these altitudes. This will affect suitable habitat for Hose's civet, as there is currently no evidence that Hose's civet can persist in plantations and agricultural lands. Second, future land cover models only predicted deforestation and did not consider forest degradation. However, higher elevation forests often undergo degradation through intensive and unsustainable selective logging. Though Hose's civet has been found in logging concessions where there are areas of old-growth forest (Samejima and Semiadi, 2012; Mathai et al., 2017), the species' tolerance to more degraded habitat is still unknown. Thus, the inclusion of forest degradation into future land cover models may result in greater habitat loss due to land cover change. It is therefore important that logging practices, particularly within the distribution range of Hose's civet, be conducted in a sustainable manner to reduce potential impacts of forest degradation.

Our assessment of Hose's civet predicted a trajectory of severe habitat loss following anticipated future climate changes. The three climate predictors most affecting Borneo-wide Hose's civet distribution were annual mean temperature, precipitation seasonality, and annual precipitation, all linked to the fine-scale predictor of mean moss cover. How these climate predictors vary and to what degree, depend on GCMs and scenarios used though overall, models predict all three to increase on Borneo. The affinity of Hose's civet towards areas with higher mean moss cover (and hence, cool wet conditions with low seasonality) could be attributed to presence of potential food sources such as earthworms and amphibians, as suggested by Mathai et al. (2017). Projections of higher temperatures and greater seasonality may result in the drying out of such mossy areas, particularly during drier months and in areas which have been deforested, degraded or modified, as microclimate is disturbed due to increased canopy opening. Regarding annual mean temperature, increasingly warmer conditions will mean that individuals may need to move from existing habitats upslope. On Borneo, although altitudes go up to 4100 m, only 4.6% of the land area is above 1000 m (and only 0.6% > 1500 m, Mathai et al., 2016b), implying that loss of suitable habitat below 1500 m, due to changing climatic conditions, would restrict distributions to a tiny area, with drastic consequences to population size. The importance of climate has also been emphasized in a recent study of the endangered Bornean orangutan (*Pongo pygmaeus*), which, in contrast to Hose's civet, is a predominantly lowland species. Here, rates of habitat loss under climate change projections were expected to be more than triple those under land cover change projections alone (Struebig et al., 2015a).

An interesting aspect of the predictions is that in the green RCP26 scenario (where global annual GHG emissions peak between 2010 and 2020 and decline substantially thereafter), suitable habitat for Hose's civet increased up to 6.7%, compared to present, by 2080 (for the ensemble (GBM + Maxent) model). This implies that if concerted efforts are made to honour international commitments such as those under the United Nations Framework Convention on Climate Change (UNFCCC), then this will contribute immensely to the long-term conservation of highland species such as Hose's civet.

4.2. Potential future refuges for Hose's civet

We defined Hose's civet refuges as intact forests that were consistently suitable under current and future environmental change scenarios. At the 10% error threshold using the green model (the greatest area amongst all modelled scenarios), Hose's civet refuges is worryingly small at only 2900 km^2, consisting of a fairly narrow strip of mainly highland forest in the central spine of the mountainous interior of Borneo, stretching from Crocker Range Park and Trus Madi Forest Reserve in the western Sabah mountain massif to the Kelabit Highlands in northern Sarawak (see Fig. 3 and Table 4 for place names and localities). This refuge habitat, though fragmented among protected areas, lies within the larger extent of the HoB complex. Forests that fall under protection within this core refuge area range from approximately 28 to 35%. Forests outside the protected area network within this refuge area are mostly designated as forest reserves, i.e. logging concessions. It is imperative that these logging concessions are managed sustainably, in line with the vision of the HoB initiative, within which most of Hose's civet refuge habitat lies. Although the HoB vision expands well beyond wildlife conservation, a successful implementation of the vision on the ground has been shown for many Bornean taxa (Beck et al., 2011; Struebig et al., 2015b), including carnivores (Mathai et al., 2016b): these findings have now been reinforced here for Borneo's highland endemics, shown in the case of the Bornean endemic Hose's civet. Hence, it is imperative that more positive steps in implementing the vision of HoB need to be taken on the ground at a quicker pace than at present. We also highlight forests outside of this core refuge area that might serve as potentially suitable habitat. This includes scattered, mainly higher elevation areas in central Sabah, northern central Sarawak, along the Sarawak-Brunei border, and in North and East Kalimantan (see Fig. 3).

Although we can identify potentially suitable core refuge habitat, it is highly unlikely that the dispersal abilities of Hose's civet would enable individuals to move to these areas within the pace of environmental change predicted. Hence, to maximise the likelihood that Hose's civet could disperse from inferior to highly suitable areas, maintaining connectivity between existing stronghold species populations and the refuge areas we identified is crucial. For this, two conservation priority sites previously proposed as extensions to the HoB in Mathai et al. (2016b), play an important role: the extended Baram complex in Sarawak and the Wehea-Mangkalihat-Sangkulirang Complex in East Kalimantan (see Fig. 4 in Mathai et al., 2016b for all proposed extensions). The former will be critical in linking Usun Apau NP and the Dulit Range in Sarawak to the HoB whereas the latter will enhance connectivity between the Mangkalihat-Sangkulirang Karst Mountains and Wehea forest reserve, both in East Kalimantan, to the HoB, thereby providing connectivity among potential populations of Hose's civet (see Fig. 3 and Table 4). These conservation areas or corridors may also be suitable for other threatened species, as recent evaluations in northern Borneo are beginning to demonstrate (Brodie et al., 2015). However, present spatial and development planning in the different regions of Borneo does not yet include ecological principles such as forest connectivity. Consequently, a major change of planning systems and processes is required.

4.3. Hunting as a hidden threat

Much of the area identified as Hose's civet refuges is inhabited by indigenous human communities, in which hunting is widespread. Snares and nets are often used (JM, pers. obs.) during hunting activities and being indiscriminate in what they catch, it is suspected that carnivores which spend much of their mobile time on the ground such as Hose's civet, may be affected (Mathai et al., 2016b). Our models did not consider hunting pressure and hence, our predictions represent optimistic estimates. The intensity of hunting should not be under-estimated: regionally, this problem is so severe that trade in wildlife, including parts and derivatives, has been identified as the leading factor threatening species survival (Corlett, 2007; Harrison et al., 2016). In at least some of the logging concessions within Hose's civet refuges, human access, and therefore potential hunting activity, has been shown to negatively affect threatened small carnivores (Mathai et al., 2017). Although hunting levels of carnivores on Borneo are currently presumed lower than in other parts of Southeast Asia, particularly Indochina (Gray et al., 2017, 2018), high demand from China and neighbouring countries like Vietnam, can escalate illegal hunting and trade to become a serious threat (Zhang et al., 2015). Existing wildlife protection laws and ordinances are broadly appropriate on paper but implementation is highly patchy and rectifying this is a priority.

5. Conclusion

Although our modelling efforts presented here greatly increased our understanding of the distribution of Hose's civet, our models were constrained by two factors: 1) limited understanding of the ecology and the sensitivity of Hose's civet to forest degradation and the inability of incorporating degradation through selective logging in the model; and 2) lack of a spatial overview of hunting pressure on Borneo, which could have been directly included in the model.

The risk of decline or widespread local extinction of Hose's civet under environmental, particularly climate, change, is high. Within the refuge habitats identified in this modelling study, 1) enforcement should be prioritised to curb illegal logging, mining and poaching; 2) road expansion should be minimised to reduce fragmentation and effects of human access such as poaching, illegal logging and anthropogenic fires; 3) conversion of natural forest to plantations and agriculture should not be allowed; and 4) any logging should follow sustainable principles and only apply reduced impact logging strategies. Studies such as this, using range-wide projections of habitat suitability under land cover and climate change forecasts, are essential tools in planning the conservation of threatened species such as Hose's civet. Here we used a little known Bornean carnivore as an example, but a similar pattern of range shifts and contractions of suitable habitat can be expected with other tropical highland endemics and it is likely that areas of conservation priority for Hose's civet are also of conservation relevance for numerous other species on Borneo.

Declarations of interest

None.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2019.e00531.

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