Redistribution of Sumatran orangutan in the Leuser ecosystem due to dispersal constraints and climate change

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Abstract. Sumatran orangutan (Pongo abelii) is one of the great apes that lives in Asia. The species' population suffered a significant reduction due to altered habitat and climate shifting; thus, this species is critically endangered (CR) based on The International Union for Conservation of Nature (IUCN) red list. Nowadays, the vast majority of the species only occur in the Leuser ecosystem (LE). The population estimation of Sumatran orangutan towards ground-truthing methods still became a challenge to carry out conservation planning; therefore, the ecological niche modeling (ENM) will be an excellent alternative to evaluate this species' population dynamics. Here we present the potential distribution changes of the Sumatran orangutan in the LE under mitigation and business as usual (BAU) scenarios of climate change. This study also conducted the effects of environmental constraint (i.e., deforestation and rivers) on the Sumatran orangutan's future dispersal in LE. We collected the Sumatran orangutan occurrences data from the Global Biodiversity Information Facility (GBIF) and literature reviews of orangutan inventory in the Leuser ecosystem. The ENM and dispersal constraints have been conducted using ENMTML and MigClim R package script-codes, respectively. This study provides novel information regarding future orangutan distribution.

1. Introduction

A country with a tropical climate has a major vast habitat for non-human primates due to its food abundance within the rainforests [1,2]. Indonesia is one of the most countries with a high diversity of non-human primates [2]. Sumatran orangutan (Pongo abelii) is one of three orangutan species from the great apes family (Hominidae) that found in Indonesia [3]. Pongo abelii is endemic to the Sumatera Island, Indonesia, restricted only in the Northern part of Sumatera—e.g., the Leuser ecosystem. Orangutans play important roles in livelihoods, human health, and ecosystem services as seed dispersal agents [4–6]. Unlike the Kalimantan species, the Sumatran orangutan is tended to be more arboreal than Bornean orangutan due to predatory factors in Sumatera [7]. The prior study shows that Sumatran orangutans are also more vulnerable to habitat disturbance than other orangutan species [8]. However, Sumatran orangutan suffered a significant population declining over the past years due to environmental changes [9,10].
The previous study shows that altered habitat was the most essential factor for species contraction due to anthropogenic activities [9] – e.g., road network and infrastructure developments [10,11]. Moreover, Sumatran orangutans are also killed in human-wildlife conflicts in the cultivation areas, e.g., oil palm or fruit crops and poaching activities as well [3,12]. Climate change also will likely amplify the risk of extinction of this non-human primate species [13–16]. Global climate change affects food distribution that implies a reproductive rate reduction on Sumatran orangutan [11, 17] that also led to species contraction at the local or regional scales. Therefore, this species was considered to become critically endangered (CR) based on The International Union for Conservation of Nature (IUCN) red list of threatened species [3].

Understanding the population dynamics of Sumatran orangutans is essential to support conservation management planning. Nevertheless, estimating the Sumatran orangutan population in the wild is still quite challenging. The recent study about population estimating explained that Sumatran orangutan’s total is 13,846 individuals in 2016 [9]. It was higher than the previous study in 2008 [18] that Sumatran orangutan estimated around 6,600 individuals remaining. Many studies related to ecological niche modeling or species distribution modeling [19, 20] have been carried out to overcome the challenges of field survey of species populations – e.g., species records, habitat evaluation, restoration, spatial prioritization, etc. [21]. The ecological niche modeling has been widely used for explanation, prediction, or projection context towards species distribution in two periods of time [22]. Nowadays, there are new scenario frameworks of climate change that integrate the energy, land-use, and emissions trajectories based on shared socioeconomic approaches. This new scenario has been employed to the new generation of earth system models as part of the 6th climate model intercomparison project (CMIP6; [23]). Here we present the current and future distributions of Sumatran orangutan using a new approach of species distribution model (i.e., ensemble machine learning) under a shared socioeconomics pathway scenario to support conservation management of Sumatran orangutans.

More than fifty percent of Sumatran orangutans in the wild are only found in Aceh Province, specifically across the Leuser ecosystem [3]. The Leuser ecosystem covering 37% of protected forests, 37% of conservation areas, 12% of production forests, and 14% of other land use based on forest concession from the Ministry of Environment and Forestry of Indonesia [24]. Moreover, this ecosystem (i.e., Gunung Leuser National Park) also considered to be a part of the Tropical Rainforest Heritage of Sumatera along with Kerinci Seblat and South Bukit Barisan National Parks by the United Nations Educational, Scientific, and Cultural Organization (UNESCO) and defined as one of the irreplaceable landscapes in the world due to its essential biodiversity [25]. Therefore, this study focuses on the dynamics of the biodiversity distribution in the Leuser ecosystem.

The objectives of this study are: (1) to assess environmental changes in the Leuser ecosystem due to climate change; (2) to predict current (1970 – 2000) and future (2041 – 2060) spatial distribution of Sumatran orangutan in the Leuser ecosystem using ensemble model of machine learning under mitigation and business as usual (BAU) scenarios and perform the model evaluation; and (3) to assess the redistribution of Sumatran orangutan in the future under those two scenarios.

2. Material and methods

2.1. Study area

The study was carried out in the Leuser ecosystem, located in the Northern part of Sumatera Island, Indonesia (figure 1). Leuser ecosystem was the last landscape on earth where tigers, elephants, rhinos, and orangutans were co-existing with the total areas of about 26,501 km² [26]. The Leuser ecosystem covered two provincial administrative areas: i.e., North Sumatera Province and Aceh Province.
2.2. Data

2.2.1. Sumatran Orangutan occurrence data. We compiled all of the available Sumatran Orangutan records within Leuser ecosystem from the following sources: 1) Global Biodiversity Information Facility database (GBIF; www.gbif.org) with the basis of records filtered by human observations; 2) iNaturalist database (www.inaturalist.org); and 3) scientific and reliable publications [3,9,18]. We used “Sumatran orangutan” and “Pongo abelii” as the keywords to search in online databases, collected from 2010 to 2020 observations. The records were geo-positioned in decimal degrees based on WGS 1984 datum [27]. Finally, we collected 127 total Sumatran Orangutan records from the data compilations.

2.2.2. Bioclimatic and environmental constraint data. We used 19 BIOCLIM variables from WorldClim v.2.0 [28] and Global Climate Model (GCM) ensemble models [29–31] to represent the current (1970 – 2000) and the future (2041 – 2060) climatic conditions, respectively. We used three GCM data from Assessment Report 6th Inter-governmental Panel on Climate Change (IPCC) – i.e., MRI-ESM2-0 [31], MIROC-ES2L [29], and MIROC6 [30] under mitigation and business as usual (BAU) scenarios within Shared Socioeconomic Pathways (SSPs; [23]). However, the spatial resolution of the available GCM data was still relatively coarse (~5 km resolution) – thus, we performed the statistical downscaling for those GCM data using Delta Methods to retrieve better spatial resolution (~1 km resolution) of the data [32]. We also considered deforestation and river networks as the restrictions to Orangutan dispersal ability in the future [33].
Table 1. Datasets used in species distribution modelling.

| Data used     | Sources                                      |
|---------------|----------------------------------------------|
| Presence data | Sumatran Orangutan records GBIF; scientific  |
|               | and reliable publications [3,9,18]           |
| BIOCLIM variables | Current climatic conditions (1970 – 2000)  |
|               | WorldClim v.2.0 [28]                        |
|               | Future climatic conditions (2041 – 2060)     |
|               | MIROC-ES2L [29]                             |
|               | MIROC6 [30]                                 |
|               | MRI-ESM2-0 [31]                             |
|               | i.e., SSP2 and SSP5 scenarios                |
| Dispersal constraints variables | Current deforestation (e.g., 2000) |
|               | Global Forest Change [34]                   |
|               | Future deforestation (e.g., 2050)           |
|               | Prepared by the author                      |
| River barrier  | River networks, Geospatial and Information  |
|               | Agency of Indonesia (BIG)                   |

2.3. Ecological niche modelling

This study was performed ecological niche models (ENMs) using the ENMTML R package for ENMs [35]. The package contains comprehensive methods from the pre-processing to post-processing steps. In the pre-processing stage, unique records per cell were performed as the response variable with a thinning process to reduce sampling bias using Moran Variogram [36]. Then, we also performed Principal Component Analysis (PCA) using 95% of the total variance in the predictors to control the collinearity in the predictors [37]. We conducted the linear regression between the principal components as response and future predictors as independent variables to create the future covariates for the model. Random allocation was used to retrieve background points or pseudo-absence data in this model [38].

The most common model evaluation is to perform the partition to the occurrence data [35]. This study used a geographical partitions method based on a checkerboard or block for model fitting and evaluation [39]. An ensemble model retrieved from several different algorithms – i.e., Support Vector Machine (SVM; [40]), Random Forest (RDF; [41]), Maximum Entropy (Maxent; [42]), Bioclim [43], Ecological Niche Factor Analysis (ENFA), Generalized Linear Model (GLM), and Boosted Regression Tree (BRT; [43]) was used for the ecological niche modelling (ENM) technics. We applied the weighted mean ensemble method; i.e., an average of suitability values weighted by the True Skill Statistics (TSS; [44]).

To evaluate the model, we used several different metrics: Area Under the Curve (AUC), Kappa coefficient, True Skill Statistic (TSS), Jaccard, Sorensen, OR, and Feb [35]. We select the best algorithm from the highest value of the accuracy metrics that have been carried out on the models for further analysis. All of the modeling steps have already fulfilled the ODMAP (Overview, Data, Model, Assessment, Prediction) species distribution modeling protocol [19]. We describe the general scheme of the ENMs in the following flowchart (figure 2).
Figure 2. General workflow of the species distribution model for Sumatran Orangutan.

2.4. Dispersal constraints

Sumatran orangutans are dominantly arboreal and rely on canopy trees to lives [3]. Deforestation within the Leuser ecosystem may disrupt potential dispersal routes for climate-driven migratory [9,10]. Therefore, deforested areas will become a barrier to Sumatran orangutan dispersal in response to climate change. The broad rivers are also known as delimiter [33] for Sumatran orangutan distribution. To capture deforestation within areas, we used global forest change data [34], and we performed cellular automata to simulate future deforestation using the MOLUSCE module in Quantum GIS 2.18 [45]. The previous study shows a good agreement for global forest change data to represent Indonesia's deforestation [46]. To simulate future deforestation, we used determinant factors of forest loss – i.e., slope, elevation, and distance to the road. MigClim R package was used to implements species-specific restrictions into projections of Sumatran orangutan distributions under environmental change [33,47,48]. We used ArcGIS 10.5 and RStudio to perform the spatial analysis and modeling as well. Range shift of Sumatran orangutan distribution was calculated as the percent variation in the number of suitable cells for a species, comparing the current and future potential distributions [33].

3. Results

3.1. Climate shifting

The results showed the current mean annual temperature in the Leuser ecosystem (21.8 ± 3.68) °C. Future mean annual temperature in the Leuser ecosystem (i.e., 2050) under mitigation scenario (SSP2) and business as usual (BAU) scenario (SSP5) of about (23.0 ± 3.66) °C and (23.3 ± 3.67) °C, respectively. The annual temperature variations have no significant changed both in current or future scenarios, ranging from 3.66 to 3.68 °C. However, we found a significant increase in the mean annual temperature of about 1.24 °C under mitigation scenario and 1.50 °C under BAU (figure 3).

Figure 3. Statistical distributions of mean annual temperature within Leuser ecosystem under (A) current condition (1970 – 2000), (B) mitigation scenario, and (C) BAU scenario.
The Leuser ecosystem will likely occur future increases in precipitation, whether annually or monthly precipitation. The Northeast part of the Leuser ecosystem (LE) will gain annual precipitation of more than \(~195\) mm. Besides, future annual precipitation has a slight increase or no change, particularly in the Southwest part of LE under the mitigation scenario and Northeast part of LE under the BAU scenario (figure 4A). The result shows that SSP2 has more surplus in annual precipitation (+127 mm) than the SSP5 scenario (+85 mm). Generally, monthly precipitation will likely increase in the future (2050), ranging from 6 mm to 46 mm per month. We found a monthly precipitation decreasing on March and May 2050 under mitigation scenario (figure 4B).

**Figure 4.** Precipitation shifting within the Leuser ecosystem. (A) Spatial distributions of annual precipitation changes (2000–2050) under mitigation (SSP2) and business as usual (BAU; SSP5) scenarios; (B) Monthly precipitation changes under the Shared Socioeconomic Pathways (SSPs) scenarios.

### 3.2. Model evaluation

We evaluate seven different algorithms (i.e., BIOCLIM, Generalized Linear Model/GLM, Ecological Niche Factor Analysis/ENFA, Maximum Entropy/Maxent, Support Vector Machine/SVM, Random Forest/RF, and Boosted Regression Tree/BRT) along with the ensemble model from those algorithms (with the weighted mean techics) using seven different metrics of model performance as well (i.e., Area Under the ROC Curve (AUC), Kappa coefficient, True Skill Statistic (TSS), Jaccard Index, Sorensen Index, OR, and Feb). We present the average of the metric values for all algorithms used in this study.

Area Under the ROC Curve (AUC) is the common-use metric of model performance that is used for ecological niche modeling (ENM) or species distribution modeling (SDM). The result shows that the Random Forest algorithm has the highest model performance with an AUC of about \((0.58 \pm 0.013)\) than the other algorithms and also the ensemble model with AUC of about \((0.50 \pm 0.000)\). BIOCLIM has the lowest model performance with an AUC of about \((0.36 \pm 0.056)\). This study shows that the ensemble algorithm (WMEA) has a lower performance than Random Forest (RDF) algorithm, except OR metric shows the higher value of WMEA than RDF \((\Delta\text{AUC} = -0.08, \Delta\text{Kappa} = -0.21, \Delta\text{TSS} = -0.21, \Delta\text{Jaccard} = -0.48, \Delta\text{Sorensen} = -0.64, \Delta\text{Feb} = -0.95, \Delta\text{OR} = 0.72)\). Therefore, we used the Random Forest algorithm for further analysis. The average of another model performance metrics for each algorithm can be seen in table 2.
Table 2. Model evaluation using seven different metrics of accuracy. BIO: Bioclim or Climate Envelope, GLM: Generalized Linear Model, ENFA: Ecological Niche Factor Analysis, MXD: Maximum Entropy, SVM: Support Vector Machine, RDF: Random Forest, BRT: Boosted Regression Tree, and WMEA: Weighted Mean Ensemble Algorithm.

| Algorithm | AUC  | Kappa | TSS   | Jaccard | Sorensen | Feb  | OR  |
|-----------|------|-------|-------|---------|----------|------|-----|
| BIO       | 0.36 | 0.00  | 0.00  | 0.50    | 0.67     | 1.00 | 0.00|
| GLM       | 0.39 | 0.02  | 0.02  | 0.27    | 0.38     | 0.55 | 0.48|
| ENFA      | 0.47 | 0.00  | 0.00  | 0.00    | 0.00     | 0.00 | 1.00|
| MXD       | 0.56 | 0.20  | 0.20  | 0.51    | 0.67     | 1.01 | 0.16|
| SVM       | 0.49 | 0.11  | 0.11  | 0.50    | 0.67     | 1.00 | 0.10|
| RDF       | 0.58 | 0.21  | 0.21  | 0.48    | 0.64     | 0.95 | 0.28|
| BRT       | 0.55 | 0.25  | 0.25  | 0.54    | 0.70     | 1.07 | 0.13|
| WMEA      | 0.50 | 0.00  | 0.00  | 0.00    | 0.00     | 1.00 | 1.00|

3.3. Sumatran Orangutan distributions

Based on the Random Forest algorithm, we found a suitable habitat for Sumatran Orangutan in the Leuser ecosystem of about 11,136 km² or covered 42% of the study area. For the climate change scenario only (no dispersal constraints), future Sumatran Orangutans indicated dominantly will expand their range on both scenarios (i.e., mitigation and BAU). Future suitable habitat for Sumatran Orangutan under mitigation and BAU scenario were 11,702 km² (range shift = +5%) and 12,078 km² (range shift = +8%), respectively. Moreover, we also found further detailed conditions of future Sumatran Orangutans for potential migration, non-analog, and climate refugia of about 4,346 km², 3,780 km² and 7,356 km² under mitigation scenario and 4,349 km², 3,407 km² and 7,729 km² under BAU scenario. In this scenario, there is unlimited dispersal and allows Sumatran Orangutans to colonize all new suitable environments.

If dispersal was limited only by rivers, future Sumatran orangutans’ distribution will likely decrease with the range shifts of about -6% and -3% under mitigation and BAU scenarios from the current distribution. We also found future Sumatran orangutans’ potential migration, non-analog, and climate refugia of about 4,007 km²; 4,670 km²; and 6,466 km² under mitigation scenario and 3,982 km²; 4,314 km²; and 6,822 km² under BAU scenario. This scenario (include rivers as barriers to dispersal of Sumatran orangutans) represents a Pre-Anthropocene case when the human disruption did not already occur in the study areas [49].

If dispersal was limited only by deforestations, future Sumatran orangutans' distribution will slightly increase with the range shifts of about +2% and +5% under mitigation and BAU scenarios from the current distribution. We also found future Sumatran orangutans’ potential migration, non-analog, and climate refugia of about 4,164 km²; 3,995 km²; and 7,141 km² under mitigation scenario and 4,188 km²; 3,624 km²; and 7,512 km² under BAU scenario. In this case, future Sumatran orangutans’ dispersal was restricted by rivers and deforested areas. In this case, future Sumatran orangutans’ distribution will likely decrease with the range shifts of about -9% and -6% under mitigation and BAU scenarios from the current distribution. We also found future Sumatran orangutans’ potential migration, non-analog, and climate refugia of about 38,27 km²; 4,869 km²; and 6,262 km² under mitigation scenario and 3,822 km²; 4,516 km²; and 6,620 km² under BAU scenario. If no dispersal was allowed so that Sumatran orangutans’ distribution did not move as a response to climate change, Sumatran orangutans would likely have suffered to extirpate by a large proportion of their distribution. Future Sumatran orangutans’ distribution will strongly decline with the range shifts of about -39% and -36% under mitigation and BAU scenarios from the current distribution. Non-analog and climate refugia of Sumatran orangutans’ distributions were 8,696 km² and 6,267 km² under mitigation scenario; 8,338 km² and 6,620 km² under BAU scenario (figure 5).
Figure 5. Dispersal-restricted potential distribution of Sumatran Orangutan in 2000 – 2050 period within the Leuser ecosystem for unlimited dispersal, limited by rivers only, limited only by deforestation, limited by both rivers and deforestation, and no potential migration. (A) Mitigation scenario and (B) business as usual (BAU) scenario.

Red cells in figure 5 indicate the cells that suitable in the present but will become unsuitable in the future and blue cells represent newly suitable cells accessible via dispersal. Moreover, grey cells indicate climate refugia (i.e., always suitable), and black cells represent unsuitable habitat in current and future conditions.
4. Discussion

Sumatran Orangutan distributions in the Leuser ecosystem encountered many issues and problems towards biodiversity conservation [3,9,10]. In this study, firstly, we emphasized the climatic shifting effects as the fundamental factors to Sumatran Orangutan movements and metabolisms [4,50,52,52]. This study found a rapidly rising mean annual temperature within the Leuser ecosystem of about 0.025 °C per year and 0.030 °C per year under mitigation and BAU scenarios. Trend fossil-fuelled development (SSP5) has a higher trend of mean temperature than the middle of the road scenario (SSP2) where community taking the highway to climate change mitigation, particularly in biodiversity conservation aspects [53,54]. Temperature increases may occur in the reproductive rate, reducing the Sumatran Orangutan, which implies a population decline [17].

Surprisingly, we found that most of the future landscapes in the Leuser ecosystem will gain more precipitation in 2050 both under SSP2 and SSP5 scenarios. The previous study also suggests that most of the world will suffer a 16% to 24% increase in heavy precipitation intensity by 2,100 [55], particularly across the tropical regions. This result will give either positive or negative impacts on the Leuser ecosystem. Climate-driven dispersals will only allow species migratory if the dispersal route requirements were full-filled [56]. Therefore, this study also explored the effects of deforestation and climate change to redistribute Sumatran Orangutan. In a worst-case scenario where species are unable to migrate and only can stay within the climate refugia, Sumatran Orangutan would be expected to suffer the ecological bottleneck. The Southern part of the Leuser ecosystem would be likely suffered more range contractions (non-analog climate) than the northern part of the study area. This study suggests that Northern Leuser ecosystem would be gained a more favourable climate in the future (2050; e.g., annual precipitation), particularly for the BAU scenario. We also found a new suitable habitat for Sumatran Orangutan mainly in the Northwest Leuser ecosystem, covered by lowland cultivation areas that would lead to human-wildlife conflicts in the future [57].

The model performances were ranging from low to moderate accuracy based on the metrics (table 2). We used the block method in data partitioning to avoid over-fitting on the model outputs. However, the results suggest that block or checkerboard methods for data partitioning created an underestimate output for all of the algorithms [39]. A previous study also shows that the ensemble model gave a lower performance than a single algorithm [58]. Moreover, performing the other data partition methods (e.g., jackknife, bootstrap, or K-folds) should be performed to obtain more realistic model performances [35, 59].

As an arboreal primate, Sumatran orangutan has a poor migratory ability in deforested landscape matrix [11] – thus, deforestation creates another constraint to the distribution of Sumatran orangutan in the future. Future deforestation in the Leuser ecosystem mainly focuses on the road network development that connects West Aceh with East Aceh "The Ladia Galaska Project" [10,18,60]. However, this result suggests that the river barriers have more significant effects on the range contractions of Sumatran orangutan. The previous studies also investigated riverine effects as a strong barrier to orangutan dispersal and evolutionary [61,62]. Moreover, we found a significant range contraction within Sumatran orangutan based on rivers and deforestation dispersal constraints.

This study also provides redistribution of Sumatran orangutans within the Leuser ecosystem if there is no opportunity for the species to migrate to the new suitable habitat. This result suggests that the range of Sumatran orangutans would significantly decline with no dispersal scenario (ranging from -36 to 39%) habitat will be lost due to coupled climate change and dispersal constraints effect. We separated the effects of climate change and deforestation, in which deforestation created non-suitable areas [33]. However, climate change also can amplified deforestation through wildfires [63] that creates a more depressing scenario of conservation. Future deforestation also induced temperature rises [64]. The synergism between climate change and deforestation towards Sumatran orangutan redistribution should be considered to avoid over-conservative output to these projections [33].
5. Conclusion
This study shows that the machine learning algorithm (i.e., Random Forest) was relatively useful to describe the current and future distribution of Sumatran Orangutan. However, the model performance was still underestimated due to data partitioning method selections. We found that the block method was not significant to evaluate the species distribution modelling or ecological niche modelling. Business as usual scenario of climate change (SSP5) will likely provide more positive impacts to the distribution of Sumatran Orangutans in the study area due to the precipitation gain from its scenario that leads to new suitable habitat for Sumatran Orangutan. However, we found the temperature rises that implied range contractions in the future. Sumatran Orangutan's redistribution within the Leuser ecosystem will be highly relying on the existence of permeable migratory routes across the habitat patch. If Sumatran Orangutans were able to migrate towards suitable environments, most of the species would cope with the species contraction. However, deforestation disrupts Sumatran Orangutans' dispersal routes, confining them to unsuitable areas. If the species cannot migrate to the potential migration areas, the ecological bottleneck will likely happen to the Sumatran orangutan in the future.

Furthermore, wildlife corridor development as the basis of future conservation planning to cope with global climate change should be considered to enhance the permeability of the population flow of Sumatran orangutan and enabling efficient migration to suitable climates in the future. This could prevent the bottleneck effects on the Sumatran orangutan population or the local extinction of this species in the Leuser ecosystem. This study should support Sustainable Development Goals (SDGs) related to SDG13 and SDG15 about climate action and life on land, respectively.

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Acknowledgements
We would like to thanks to the Ministry of Research Technology and Higher Education through PMDSU Scholarship, for their financial aid under “Non-Human Primates Distributions Dynamics: Climate Change and its Implication to Conservation Management” Research Project with grant number 1/E1/KP.PTNBH/2020.