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Crucial Habitats for the Spangled Ebony Langur: The Role of Former Production Forests in Alas Purwo National Park

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ABSTRACT

Land use conversion into production forests has led to habitat degradation for primates. On the other hand, most primates have started adapting to the presence of these habitats and have forced conservation efforts to focus on the production forests. Our study at the Kucur Resort, Alas Purwo National Park, reported the population estimates using distance sampling, composition and diversity of vegetation, and habitat suitability of *Trachypithecus auratus* using multi-algorithm approach in former production forests consisting of jungle and rehabilitation zones. Our study estimated the population density of *T. auratus* at around 1.29 individuals per km^2. We found an association between the number of encounters and the diversity of vegetation in each zone, although it was dominated by *Tectona grandis*. In addition, we predict that the area of suitable habitat is always smaller than the unsuitable habitat and suggest the model from Boosted Regression Tree as a management reference. We assume that the presence of *T. auratus* in this habitat is influenced by food availability, distance from settlements, and slope. This study provides reliable information on the potential of reforesting production forests as a habitat for *T. auratus* and deserve conservation attention.

1. Introduction

The worldwide issue of deforestation is particularly critical in Southeast Asia, where approximately 80,000 km^2 of forest were lost between 2005 and 2015. Indonesia was responsible for almost two-thirds of this loss during that period and is expected to continue being the primary contributor to deforestation through 2050 (Estoque *et al.* 2019). Deforestation in Indonesia has been driven by land use, which increased around the 1970s-1980s, starting in Java when the Government was committed to developing the economy through the wood processing industry (Tsujino *et al.* 2016). These land use conversions primarily involved the establishment of production forests, with teak (*Tectona grandis*), pine (*Pinus merkusii*), and mahogany (*Swietenia* spp.) being major commodities, providing precious commercial benefits (Pratiwi and Lust 1994; Pandey and Brown 2000). Recently, production forests are no longer a major driver of deforestation in Java (Austin *et al.* 2019). Nevertheless, regardless of their socioeconomic advantages (Buongiorno and Zhu 2014), the existence of remaining former production forests continues to provoke discussions about their ecological impact (Bowen *et al.* 2007; Gardner *et al.* 2009), such as biodiversity loss and habitat degradation (Barlow *et al.* 2007; Alroy 2017; Burivalova *et al.* 2020).

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Production forests are frequently planted with non-native species, which can present challenges when restoring the original composition, diversity, and population during reforestation (Brook *et al.* 2006; Gardner *et al.* 2007). However, with the forecast of slow human population growth and decreasing deforestation rates, reforestation in production forests to create secondary forests is expected to prevent species extinction (Wright and Muller-Landau 2006a, 2006b). Recent studies have shown that numerous mammal species, including primates, have adapted to inhabit this type of forest (McShea *et al.* 2009; Bernard *et al.* 2014, 2016; Wong *et al.* 2022). Unfortunately, around 87% of primates also inhabit this habitat dominantly (Galán-Acedo *et al.* 2019). The condition may have implications for carefully managing the former production forests and their reforestation as secondary forest for conservation strategies (Edwards *et al.* 2014; Estrada *et al.* 2017).

The spangled ebony langur (*Trachypithecus auratus*) is an endemic primate of Indonesia distributed in Java, Bali, and Lombok (Nijman 2000). Over the past 36 years (1984-2020), its population has decreased by around 30% (Nijman 2020). As a result, *T. auratus* is now protected by the Indonesian Government under the Regulation of the Minister of Environment and Forestry No. P.106/Menlhk/SETJEN/KUM.1/12/2018 and categorized as a Vulnerable species by the IUCN (PermenLHK 2018; Nijman 2020). *T. auratus* is known as a folivorous arboreal primate, so it depends on the existence of forests. It can be found in various habitats, including lowland and montane forests, mangrove forests, deciduous forests, and savannas (Nijman 2014; Supriatna 2019; Hansen *et al.* 2020). Research has shown that *T. auratus* can adapt to logged production forests, such as those in the Pangandaran Nature Reserve (Kool 1993; Tsuji *et al.* 2019) and West Bali National Park (Leca *et al.* 2013). The previous study of *T. auratus* was also conducted explicitly in the former production forest of Kucur Resort Alas Purwo National Park (APNP) and reported that these areas have potentially suitable habitats (Maulahila *et al.* 2023). However, the information about the population and vegetation condition of the *T. auratus* habitat in Kucur Resort is limited. It has become essential to investigate the factors and the habitat conditions that attract *T. auratus* to inhabit this habitat, which may be facing anthropogenic impact.

With technological advancements, ecological studies have become more comprehensive. The utilized niches have been measured through species distribution modeling, explaining the environmental factors influencing species existence and habitat suitability (Guisan and Zimmermann 2000; Guisan *et al.* 2017). However, the scarcity of information on occurrence poses challenges for wildlife studies, especially with cryptic and rare species (Pearson *et al.* 2007). Recent studies have utilized presence data to predict the distribution of species such as *Bos javanicus* (Siddiq *et al.* 2023), *Rusa timorensis* (Rahman *et al.* 2017), *Hylobates moloch* (Widyastuti *et al.* 2020), and *T. auratus* (Hansen *et al.* 2020). Although predicting distributions using presence-only data is debatable, it sometimes provides better results than the presence-absence approach (Cianfrani *et al.* 2010). Nonetheless, the presence-pseudoabsence approach can also be realistic if the number of pseudoabsences and the algorithm type are appropriately selected (Elith *et al.* 2006; Barbet-Massin *et al.* 2012). Recently developed algorithms employing advanced machine learning techniques, such as random forests and boosted regression trees, have significantly enhanced the accuracy of presence-pseudoabsence approaches in predictive modeling (Li and Wang 2013). Furthermore, the adoption of ensemble models is increasingly recognized for their potential to generate robust predictions by integrating insights across a diverse array of predictive algorithms (Araujo and New 2007; Hao *et al.* 2019, 2020).

The primary goal of this study is to report on the potential of reforested former production forests as habitats for *T. auratus*, which will be referred to in this study as secondary forests. Our specific objectives are (1) to estimate the density population of *T. auratus* in the study area using line transect distance sampling, (2) to survey the composition and diversity of vegetation that comprises *T. auratus* habitat in the study area that consists of jungle and rehabilitation zone, and (3) to predict the suitability habitat and identify the factors that influence *T. auratus* to inhabit the study area using multiple algorithms framework. This study augments the information for the conservation efforts of *T. auratus*, especially the management of the Kucur Resort, APNP.

2. Materials and Methods

2.1. Study Area

We collected data from March to July 2023, which falls during the dry season at the Kucur Resort APNP, covering an area of approximately 22.5751 Km^2. Part of Kucur Resort was previously a production forest planted with Tectona grandis as its primary commodity. Since 2010, it has shifted to become part of the APNP as a secondary mixed forest and is immediately adjacent to Perhutani's production forest. Currently, the Kucur Resort has five zones, but we focused on collecting data in the Jungle Zone and Rehabilitation Zone due to accessibility (Figure 1). The resort is categorized as a lowland forest with elevation conditions ranging from 0 to 322 meters above sea level (m.a.s.l.) and varying slopes, from flat (0°) to steep (>40°). In addition, the resort has a tropical climate that tends to be dry, with precipitation varying between 1,000-1,500 mm/year (Awang *et al.* 2011).

2.2. Density Population Estimation

We surveyed the *T. auratus* population using the distance sampling method, which assumes that animals can be detected via transects with a decreasing detection rate as the distance from the transect increases (Buckland *et al.* 1993, 2010). We walked along six transects, each spanning approximately 1-2 km through the study area, with five repetitions for each transect (Figure 1). We conducted surveys twice a day, in a single direction, during the morning (~06:00 WIB) and late afternoon (~14:30 WIB) (Peres 1999; Plumptre *et al.* 2013). The data we recorded are encounter time, number of individuals, and perpendicular distance. Specifically, we measure the perpendicular distance between the observer and the species using the laser pathfinder Edkor. We did not identify the individual or the group of *T. auratus* precisely since they were non-habituated. Therefore, we use assumptions to minimize double counting bias, i.e., (1) conduct the consecutive surveys on the same transect at least after two different days and (2) define a group as two or more individuals within the ~50 m (Kyes *et al.* 2013; Leca *et al.* 2013).

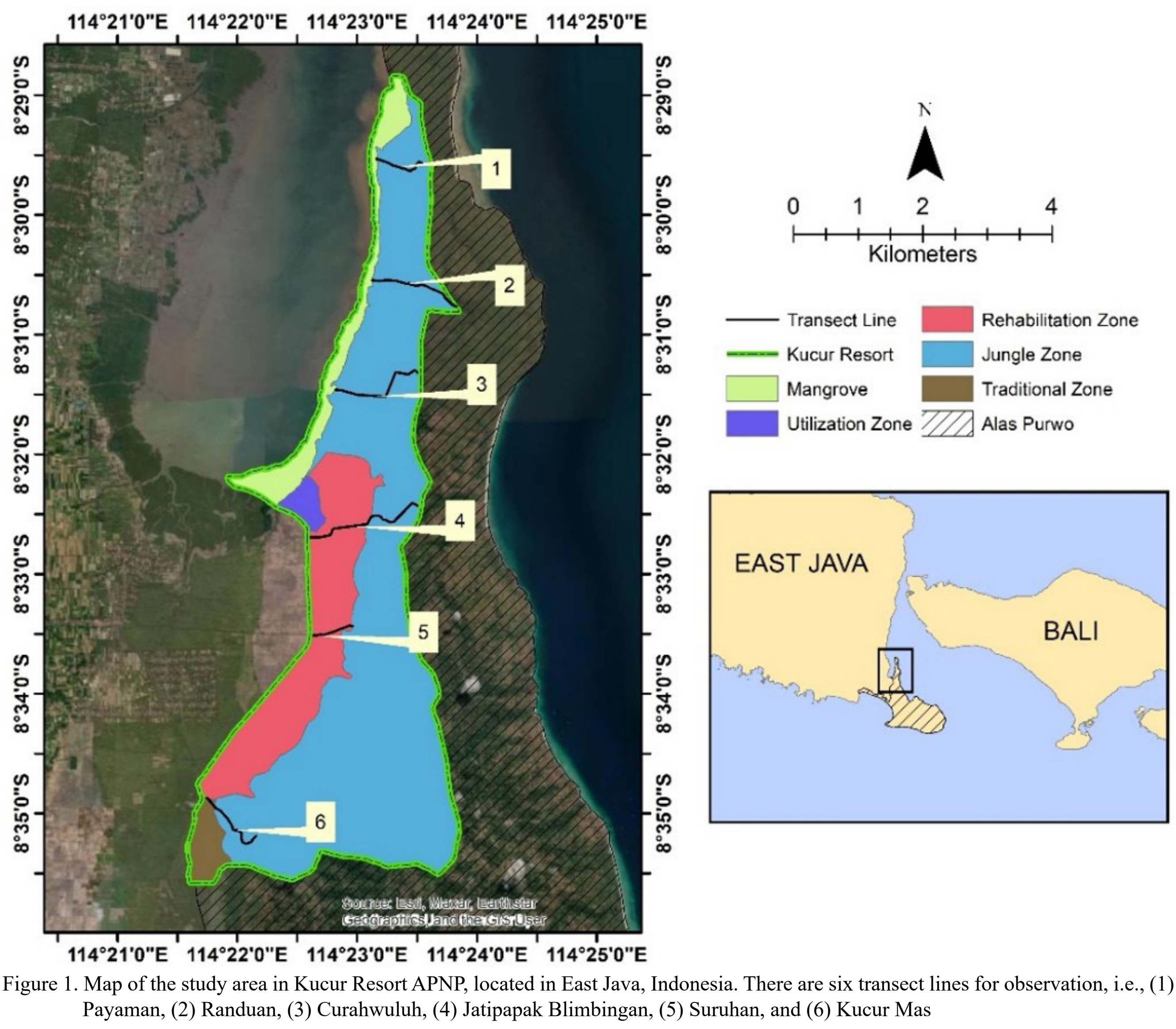

Figure 1. Map of the study area in Kucur Resort APNP, located in East Java, Indonesia. There are six transect lines for observation, i.e., (1) Payaman, (2) Randuan, (3) Curahwuluh, (4) Jatipapak Blimbingan, (5) Suruhan, and (6) Kucur Mas

We calculate statistically the number of encounters between the jungle zone and the rehabilitation zone using the 'ggstatsplot' package in the R programming language (Patil 2021; R Core Team 2022). Furthermore, we analyze the estimation population of *T. auratus* using Distance 7.3 software (Thomas *et al.* 2010). During the analysis process, we tested all combinations of detection functions (i.e., Uniform, Half-normal, Hazard rate) and adjustments (i.e., cosine, simple polynomial, and hermite polynomial). The best combination was determined based on the lowest Akaike information criterion (AIC) or the best Goodness of Fit (GOF) (Buckland *et al.* 1993).

2.3. Vegetation Composition Survey

We focused on surveying the composition of vegetation in the tree-growing phase. We chose this growing phase because *T. auratus* exhibits predominantly arboreal feeding activity (Tsuji *et al.* 2019; Asyrofi *et al.* 2022; Siddiq *et al.* 2024). We used 10 m × 10 m quadrat plots to record tree species, number of trees, and basal stem diameter (DBH) (Oosting 1948; Curtis and McIntosh 1950; Mueller-Dombois and Ellenbergh 1974). The plots were placed randomly following the transect, i.e., 18 in the jungle zone and 16 in the rehabilitation zone. Furthermore, we calculated the Importance Value Index (IVI) to determine the dominant vegetation species, the Shannon-Weiner diversity index (H'), and the Pielou evenness index (E) (Pielou 1966; Mueller-Dombois and Ellenbergh 1974; Magurran 2004).

2.4. Habitat Suitability Model

2.4.1. Occucucrance Data

We compiled the presence occurrence record of *T. auratus* from the following sources: (1) a fieldwork survey, 2) a research article (Maulahila *et al.* 2023), and 3) Alas Purwo National Park field guidebooks (BTNAP 2017). We obtained 43 presence-only coordinates, then resampled and rarefied the coordinates to avoid pseudo-replication and spatial autocorrelation (Phillips *et al.* 2009; Naimi 2011, 2012). Finally, we use 31 presence-only coordinates of *T. auratus* to generate a habitat suitability model (Supplementary Table 1).

2.4.2. Environmental Covariate

This study uses four environmental groups of data as predictor variables, i.e., (1) climate, (2) topography, (3) biophysical, and (4) anthropogenic (Guisan and Zimmermann 2000; Sanderson *et al.* 2002). We retrieved The data of environmental groups from Climatologies at High Resolution for the Earth's Land Surfaces (CHELSA) in 1981-2010 (Karger *et al.* 2021). The Shuttle Radar Topography Mission (SRTM) in 2000, Landsat 8 OLI/TRIS collection-2 level-2 in 2023, the land cover map of Indonesian Ministry of Environment and Forestry (MoEF) in 2019, and ESRI Sentinel-2 land use/land cover time series of the world in 2023 (Karra *et al.* 2021). Overall, we obtained 24 environmental data and extracted them using ArcMap 10.7.1 with a spatial resolution of ~100 meters (Supplementary Table 2). We used the Pearson test from the 'usdm' package in the R program language and excluded the environmental variables with threshold $|r|>0.7$ to reduce the multicollinearity (Dormann *et al.* 2013; Naimi and Araújo 2016; Feng *et al.* 2019). Therefore, we considered six environmental covariates to generate species distribution modeling based on multicollinearity selection and the ecological characteristics of *T. auratus* (Table 1). We combined the environmental covariate map with the occurrence coordinates in ArcMap 10.7.1 and then explained it descriptively.

2.4.3. Model Fitted and Evaluation

We generate all modeling processes using the 'sdm' package in the R programming language (Naimi and Araújo 2016; R Core Team 2022). The model was run in a single framework with various algorithms, i.e., the Boosted Regression Tree (BRT) (Friedman 2001), the Generalized Linear Model (GLM) (Nelder and Wedderburn 1972), Maximum Entropy (MAXENT) (Phillips *et al.* 2004, 2006), and Random Forest (RF) (Breiman 2001). We generated these five single models

Table 1. Description of the selected environmental covariate for generating the habitat suitability model of *T. auratus*

Group	Code	Covariates	Unit	Description
Climate	bio1	Mean annual air temperature	°C	Mean annual daily mean air temperatures averaged over 1 year
	bio12	Annual precipitation amount	kg m^{-2} year^{-1}	Accumulated precipitation amount over 1 year
Topography	bio20	slope	degree	-
Biophysical	bio21	Normalized different vegetation index (NDVI)	-	-
				-
Anthropogenic	bio22	Distance from settlement	km	-
	bio24	land cover/land use	-	

five times in repetition by randomly splitting the data into a 75% training set and a 25% testing set. The training and test dataset consists of occurrence presence data coupled with 100 randomly sampled pseudo-absence points within a defined study area (Barbet-Massin *et al.* 2012). In addition, we combine those five single models for the ensemble framework with the weighted approach (EN) (Araujo and New 2007).

We evaluated the performance of each modareasing three discrimiareaon metrics, i.e., the area under the ROC curve (AUC), Cohen's Kappa Coefficient (KAPPA), and the True Skill Statistical (TSS) (Cohen 1960; Swets 1988; Allouche *et al.* 2006). The AUC ranges from 0 to 1, with values of 0.5–0.7 indicating low accuracy, 0.7–0.9 indicating moderate accuracy, and values greater than 0.9 indicating excellent accuracy (Swets 1988). Meanwhile, the KAPPA and the TSS range from -1.00 to 1.00, where <0.00 indicates no agreement, 0–0.20 is slight, 0.21–0.40 is fair, 0.41–0.60 is moderate, 0.61–0.80 is substantial, and 0.81–1.00 indicates a perfect agreement (Landis and Koch 1977).

We generate the importance and response of *T. auratus* to environmental covariates to identify the factors that influence the habitat suitability model. The study also identified suitable and unsuitable habitats for *T. auratus* in Kucur Resort using the 10-percentile value. We use it as a threshold to convert the distribution probability from the single and ensemble models into a binary habitat suitability map. Furthermore, we visualize the habitat suitability map of *T. auratus* using ArcMap 10.7.1.

3. Results

3.1. Population Estimation

We observed 27 encounters of *T. auratus* across all six surveyed transects. The highest and lowest were Kucur Mas and Suruhan, i.e., 11 and 2 encounters, respectively (Supplementary Table 3). We found a significant difference (p-value = 0.01, twelch = 3.67, df = 5.99) in the *T. auratus* occurrences according to the zonation, where the jungle zone was higher than the rehabilitation zone (Supplementary Figure 1). Furthermore, the combination of uniform key with cosine is the best detection function model with the lowest AIC value (AIC 193.86). The goodness-of-fit (GOF) test also confirmed a good fit between the observed data and the selected model (p-value>0.05). Therefore, we selected this detection function combination model to estimate the probability of detection in this population. The estimated group density of *T. auratus* was 2.74 groups per km^2, and the population density of *T. auratus* was 12.60 individuals per km^2. The total number of *T. auratus* present in Kucur Resort was estimated to be around 284 individuals (Table 2).

3.2. Composition and Diversity of Vegetation

Kucur Resort features 18 species of tree-level vegetation. The jungle zone is the habitat with a higher richness of species compared to the rehabilitation zone, which has 15 and 6 species, respectively. Both zonations have identically dominant and codominant species, i.e., *T. grandis* and *Schleichera oleosa*. Meanwhile, *Lepisanthes rubiginosa* and *Ficus hipsida* are isolated in the jungle and rehabilitation zones, respectively (Figure 2). The Shannon-Wiener and Evenness indices indicate that the jungle zone (H' = 1.74, E = 0.64) is a habitat with more diverse and even vegetation species than the rehabilitation zone (H' = 0.9, E = 0.5).

3.3. Habitat Suitability Model

3.3.1. The Evaluation of Model Performance

The habitat suitability models generated for *T. auratus* in Kucur Resort had varying levels of accuracy among matrices (Figure 3). The AUC reveals that GLM (0.63±0.029) and MAXENT (0.70±0.022) have low accuracy, while BRT (0.71±0.017), EN (0.72±0.016), and RF (0.84±0.020) have moderate accuracy levels. The KAPPA revealed that the accuracy of GLM (0.27±0.041), MAXENT (0.32±0.031), BRT (0.36±0.022), and EN (0.37±0.021) is fair, while RF (0.53±0.023) has moderate accuracy. Meanwhile, the TSS revealed that the accuracy of GLM (0.36±0.045) is fair, EN (0.48±0.023), BRT (0.47±0.022), and

Table 2. The estimated population and group density of *T. auratus* from Distance 7.3

Parameters	Estimation	Standart error	Coefficient of variation	95% confidence intervals
Encounter rate	0.67	-	15.07	0.49-0.92
Group density estimation	2.74	0.47	17.34	1,93-3,83
Mean group size estimation	4. 59	0.50	10.93	3,67-5,75
Individual density estimation	12.60	2.58	20.49	8,40-18,88
Abundance	284	58.19	20.49	190-426

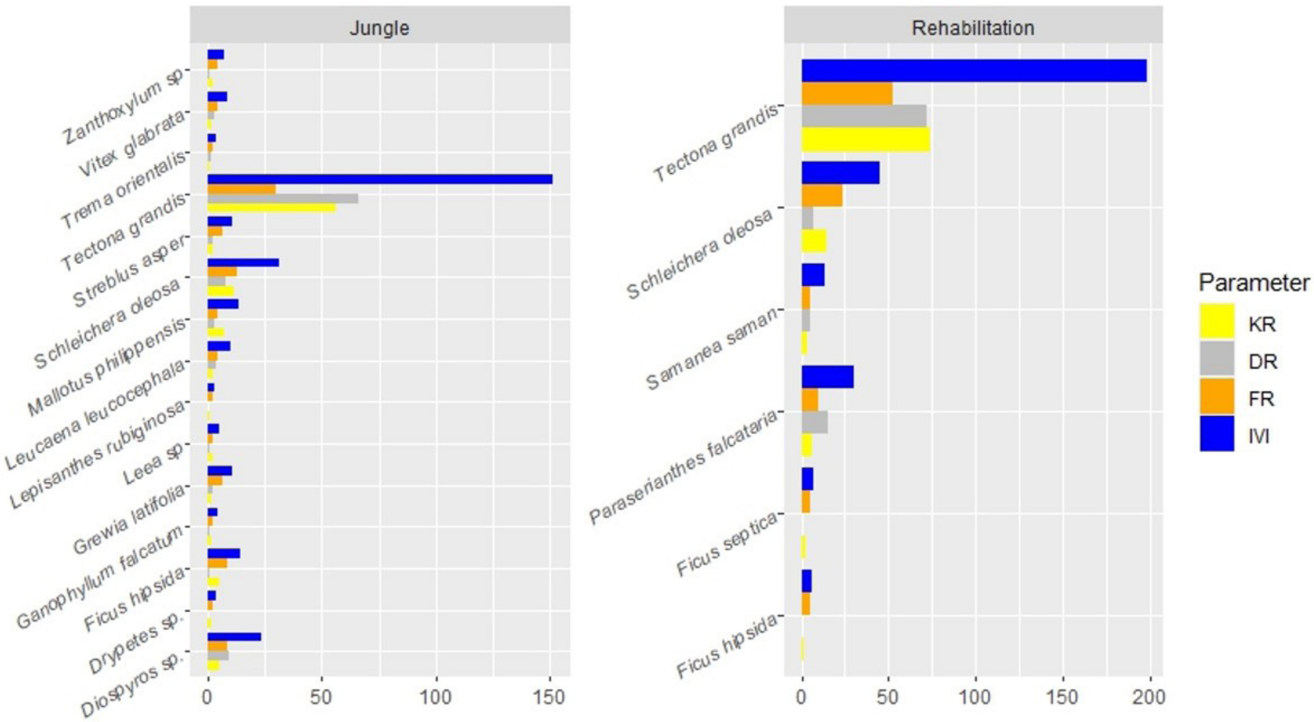

Figure 2. Composition of tree-level vegetation in the jungle and rehabilitation zones. The parameters include relative density (KR), relative dominance (DR), relative frequency (FR), and importance value index (IVI)

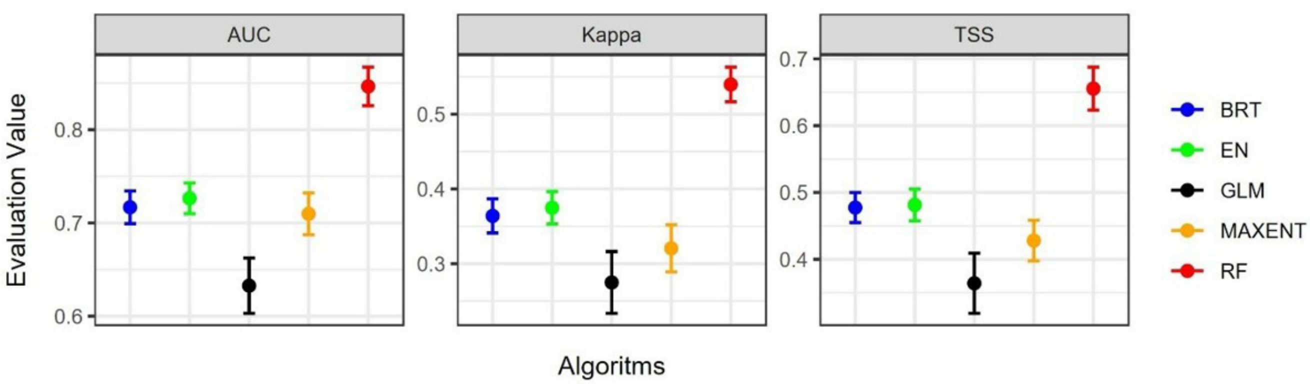

Figure 3. The mean performance evaluation values of the habitat suitability of *T. auratus* from five algorithms, i.e., boosted regression tree (BRT), ensemble (EN), generalized linear model (GLM), maximum entropy (MAXENT), and random forest (RF) according to three evaluation matrices, i.e., area under ROC curve (AUC), cohen's kappa (Kappa), and true skill statistic (TSS)

MAXENT (0.42±0.030) have moderate accuracy, while RF (0.65±0.032) has substantial accuracy. Overall, RF has the best accuracy in predicting the habitat suitability model of *T. auratus*, followed by EN, BRT, MAXENT, and GLM.

3.3.2. The Influence of Environmental Covariates

The results of importance permutation revealed that all environmental covariates contribute to the langur habitat suitability model, and we identified two patterns of environmental covariate contribution. The first pattern shows that slope, NDVI, and distance from settlements are the three covariates with the most significant contribution to the langur habitat suitability model in the BRT, EN, MAXENT, and RF algorithms. However, the contribution values of the three covariates varied among the four models. The prediction results of suitability models built using BRT and EN showed that distance from settlements was the most influential covariate (15.7% and 12.1%, respectively). Furthermore, the model from BRT placed NDVI (9.3%) and slope (8.5%) in the second and third positions, respectively, while the EN model placed NDVI (8.1%) and slope (11.1%) in the opposite positions (Supplementary Figure 2A and B). The models built with MAXENT and RF were similar in that they placed slope (17% and 14.4% respectively) as the most influential covariate followed by distance from settlements (9.1% and 14.3% respectively) and NDVI (8.9% and 10.8% respectively) (Supplementary Figure 2D and E). The second pattern (2) was identified in the habitat suitability model built with the GLM algorithm alone. This model identified annual precipitation amount (13%), followed by distance from settlement (9.3%) and mean annual air temperature (8.2%) (Supplementary Figure 2C).

We obtained the distribution of *T. auratus* descriptively according to each environmental covariate map. Both climate covariate maps indicate a narrower range of mean annual temperature and annual precipitation amount, leading to *T. auratus* not favoring specific climate conditions (Supplementary Figure 3A and B). Therefore, we do not make any future forecasts regarding climate change on this scale. The topography of Kucur Resort varies from flat to steep, and we found that *T. auratus* occurred in all topography classes, but predominantly in gentle slope areas (Supplementary Figure 3C). The NDVI in Kucur Resort did not exceed 0.7, indicating that the vegetation was not very dense. At the same time, the land cover was mainly identified as trees and rangeland. Our findings showed that all *T. auratus* occurrence points were located in areas with moderate vegetation density, but were more abundant in areas with trees (Supplementary Figure 3D and F). Lastly, Kucur Resort is not directly adjacent to settlements, with the closest and furthest distances between Kucur Resort and each settlement being 10.63 km and 18.26 km, respectively. The presence of T. auratus that we recorded mainly was distributed more than 14 km away from settlements (Supplementary Figure 3E).

Furthermore, our models also predicted the response of *T. auratus* to each of the environmental covariates. All algorithms predict that Javan langurs tend to be distributed in areas with lower mean annual air temperature. The pattern shown by the BRT and MAXENT models (Supplementary Figure 3D and 4) tends to show an insignificant decrease in distribution probability compared to the EN and GLM models (Supplementary Figure 4B and C). At the same time, the RF model shows a fluctuating pattern with the decrease occurring first at the beginning of the curve. Then, the probability increases in the range of 25.25 to 25.75 °C and decreases again thereafter (Supplementary Figure 4E). The same pattern is also observed in the annual precipitation amount covariate, which indicates that Javan langurs are more distributed in areas with low rainfall. The prediction from BRT, MAXENT, and RF showed a slight decrease in the annual precipitation amount covariate. However, in BRT, the probability remained stagnant in the range of 2000 to 2200 kg m^{-2} $year^{-1}$ (Supplementary Figure 4A, D, and E), whereas the decrease shown by EN and GLM was more significant than that of the previous three algorithms (Supplementary Figure 4B and C).

The probability of Javan langur distribution based on slope tends to be optimum at certain slope levels. Models from the BRT, EN, MAXENT, and RF algorithms show that langurs occupy areas with gentle slopes ranging from 8-15° (Supplementary Figures 4A, B, D, and E). However, GLM has a different pattern, showing that Javan langurs tend to inhabit areas with flat slopes of <8° (Supplementary Figure 4C). All algorithms also predict that Javan langurs in Kucur Resort tend to be distributed in areas with low to moderate canopy density. GLM shows a very different pattern where there is a decrease with increasing vegetation density from NDVI (Supplementary Figure 4C). At the same time, the other four algorithms tend to show relatively stagnant distribution probabilities with a slight decrease at NDVI values ranging from 0-0.35 and then a significant decrease thereafter (Supplementary Figures 4A, B, C, and D), except for RF which increases first at NDVI values of 0.4 (Supplementary Figure 4D). All five algorithms predicted that the distribution of Javan langurs consistently increased as the distance from settlements increased. Meanwhile, none of the algorithms showed differences in the probability of Javan langur distribution between land cover classes.

3.3.3. Prediction of Habitat Suitability

In this study, we found that the predicted area of the suitable habitat varies across the models (Table 3). Interestingly, we consistently observed that the unsuitable habitat was expected to be larger than the suitable habitat in all models. Specifically, the MAXENT model predicted the largest habitat suitability, followed by BRT, EN, GLM, and RF, with the opposite trend for unsuitable habitats. It's worth noting that the north and east sides of the Kucur Resort are consistently identified as a suitable habitat in all prediction maps (Figure 4).

4. Discussion

We report the presence of *T. auratus* populations inhabiting both lowland secondary forests and former production forests. The population of *T. auratus* in this resort is predicted to have a higher density compared to West Bali National Park (7.11 individuals per km^{-2}; Leca *et al.* 2013) and Sokokembang (7.46 individuals per km^{-2}; Al-Huda *et al.* 2024) which have relatively similar habitat types. However, the estimates at this resort are still lower than population densities in other habitat types, such as Baluran National Park (14.9 individuals per km^2; Hansen *et al.* 2020) and Mount Dieng (23 individuals per km^2; Nijman and Van Balen 1998).

The estimation results may be difficult to compare directly due to differences in observers' abilities (Mitani *et al.* 2000) and the application of methodologies by each observer, such as the size and randomness of transect lines, the size of the study area, and the ecological conditions of the study area. However, we are sure that our observations meet the necessary assumptions for distance sampling (Buckland *et al.* 2010). The histogram of detection probabilities supports a high proportion of *T. auratus* encounters near the transect lines (Supplementary Figure 5). We acknowledge that our estimation still has limitations, as we used trails as transects and were unable to reach the entire Kucur Resort due to the challenging topography. Our data is also relatively low compared to the recommended range of 30-80 encounters for more accurate estimation. However, as long as the data distribution assumptions of distance sampling are met, 20 encounters can still be tolerated, and this has been proven by our GOF test results (Peres 1999; Plumptre *et al.* 2013). Therefore, it cannot be denied that there is still a possibility of bias that may lead to underestimated or overestimated estimation results. However, this information can serve as preliminary information for the management of *T.*

Table 3. The total area of the suitability model of *T. auratus* in Resort Kucur predicted by the five algorithms

Algorithms	Area (Km^2)	
	Suitable	Unsuitable
Boosted regression tree	9.191	13.110
Ensemble	7.666	14.615
Generalized linear model	7.624	14.611
Maximum entropy	10.097	12.144
Random forest	6.584	15.739

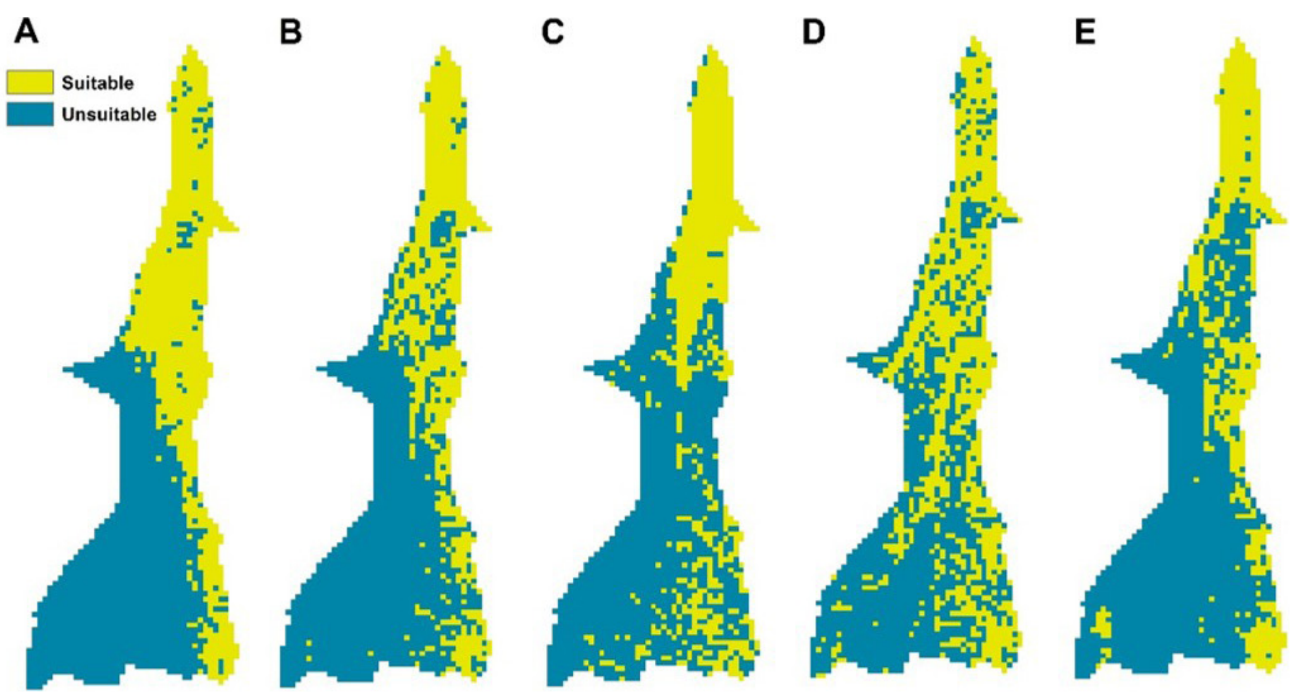

Figure 4. Prediction map of habitat suitability model for Javan Langur in Kucur Resort APNP. Predicted using five algorithms, i.e., (A) boosted regression tree, (B) ensemble, (C) generalized linear model, (D) maximum entarea, and (E) random foarea

auratus conservation in Kucur Resort of APNP. Long-term monitoring efforts are needed in the future to ensure that information on the Javan langur population in the resort can be reported with greater precision.

Although it cannot be confirmed due to the unavailability of longitudinal data on *T. auratus* in this resort, we assume the presence of *T. auratus* is due to two scenarios. The first is that the *T. auratus* population already inhabited Kucur Resort when it was still a production forest, but later declined in size due to increased anthropogenic activities. Second, the *T. auratus* population is a group that reoccupied the area after the forest was rehabilitated. The results of the habitat suitability prediction, which indicate that suitable habitat conditions for *T. auratus* are still limited and tend to be located at the edge of the jungle zone, away from other resorts without natural barriers, seem to support our second assumption (Figure 4). We suspect that the suitable habitat is a transition area between the rehabilitated mixed secondary forest and the primary forest, allowing the Javan Langur to move between Kucur Resort and the primary forest. These results align with a study conducted by Supartono *et al.* (2020) in Kuningan, which found that *Presbytis comata* tends to prefer mixed secondary forests and transition to primary forests over homogeneous plantations. Therefore, we comprehensively report on the habitat's condition to determine the factors influencing its existence. The results indicate that well-rehabilitated production forests provide resources for *T. auratus* to occupy. We assume the occupancy of *T. auratus* is due to the Kucur Resort having 1) adequate food sources, 2) not directly adjacent to settlements, and 3) an undulating topography.

The availability of food sources is one of the fundamental factors that primates need in their habitat. In this study, we assume that the abundance of *T. grandis* likely attracts *T. auratus* to occupy the Kucur Resort. Even though *T. grandis* has a rough leaf surface, *T. auratus* uses it as a food source, particularly for young leaves, petioles, and midribs (Kool 1993; Tsuji *et al.* 2019). This assumption is also supported by a study from Tsuji *et al.* (2019) in the Pangandaran Nature Reserve, which showed a significant positive correlation between food species and the abundance of trees available in the Javan langur habitat. Further study is still needed on the role of *T. grandis* as a main or substitute food source that affects the presence of Javan langurs in Kucur Resort.

We also presume that the abundance of *T. grandis* is not the only determining factor concerning food sources because our survey records indicate that *T. auratus* is uncommon in rehabilitation zones where *T. grandis* is more abundant (Supplementary Figure 1 and Figure 2). Another possible reason is the diversity and richness of vegetation species in the jungle zone, which perhaps increases the interest of *T. auratus* in obtaining more varied food sources. At least eight of the 18 species identified in this study are thought to be utilized as food sources by Javan langurs in Kucur Resort, including *T. grandis, S. oleosa, G. latifolia, V. glabrata, F. hipsida, F. spetica, M. philippensis, T. orientalis*, and *S. saman* (Kool 1993; Ihsanu and Setiawan 2013; Tsuji *et al.* 2019; Djamil Wardhana *et al.* 2022). We realize that the number of species identified is relatively small compared to studies in other locations because the plots placed on the transect lines have not been able to access most of the jungle zone. Therefore, we still lack data on the specific vegetation consumed by *T. auratus* at Kucur Resort. However, our assumption aligns with the studies on *Colobus guereza* in Ethiopia, where the groups inhabiting natural forests utilize more diverse feeding plant species than those in plantation forests (Yazezew *et al.* 2024). Diverse vegetation also provides a positive relationship with occupancy and population density of primates, as shown in studies of *Presbytis comata, Presbytis rubicunda, Alouatta palliata*, and *Aotus miconax* in Indonesia, Malaysia, Mexico, and Peru, respectively (Davies *et al.* 1988; Cristóbal-Azkarate *et al.* 2005; Campbell *et al.* 2019; Supartono *et al.* 2020). These facts underscore the importance of increasing the number of trees and enhancing vegetation diversity in primate conservation efforts.

Diverse vegetation can also provide a variety of canopy architecture that can support Javan langur activities. The NDVI map constructed shows that Resort Kucur has a moderate vegetation canopy density (Supplementary Figure 3D). Field observations also indicate that areas with higher vegetation diversity within Resort Kucur have higher NDVI values. The rehabilitation zone has NDVI values of 0.1-0.3, with almost the entire area covered by homogeneous *T. grandis* and a small canopy volume. Meanwhile, the jungle zone, with more varied vegetation, has a higher NDVI of 0.3-0.5 because it also provides a varied canopy volume. The presence of Javan langur populations in Kucur Resort indicates that these primates have adapted to these canopy conditions. Considering these canopy conditions, we suspect that *T. grandis* utilizes Kucur Resort for foraging activities rather than sleeping trees. This assumption is supported by the research of Subarkah *et al.* (2011) and Tsuji *et al.* (2019), which showed that trees with smaller canopy volumes are preferred for foraging, while trees with wider canopy volumes tend to be used by Javan langurs as sleeping trees.

The position of the Kucur Resort, which is not directly adjacent to settlements, seems to offer an advantage to *T. auratus* by protecting it from anthropogenic pressure. Based on our findings, *T. auratus* tends to avoid human settlements by inhabiting deeper areas in Resort Kucur (Supplementary Figure 3E and Supplementary Figure 4). The same pattern is also observed in studies of *A. palliata* and *P. thomasi* in Mexico and Indonesia, respectively, where the occupancy of this primate is very low in areas close to human settlements (Arroyo-Rodríguez *et al.* 2008; Hankinson *et al.* 2023). We suspect this is related to the production forests around the Kucur Resort, where *T. auratus* avoids both. Due to high-intensity human activities, this active production forest may act as a barrier preventing *T. auratus* from approaching settlements and direct interaction with the community. We also observed no movement of *T. auratus* into this production forest during the survey. Generally, *T. auratus* is known as a sensitive primate but also has the flexibility to adapt to various habitat conditions (Hansen *et al.* 2020). Therefore, this finding needs to be considered in the future conservation efforts of *T. auratus* as their adaptive flexibility could lead them to approach areas with high intensity of human activity, similar to what has occurred with *Rhinopithecus roxellana* in China (Dong *et al.* 2019), *P. comata* in Kuningan (Supartono *et al.* 2020), and *T. auratus* in West Bali National Park (Leca *et al.* 2013). However, further studies on the behavior of *T. auratus* in response to human presence in Kucur Resort still need to be conducted because in several tourist sites, such as Pengandaran Nature Tourism Park (Wahyu 2021) and Pancur Resort of APNP (Personal observation), *T. auratus* are also found quite close to humans, although they tend to maintain a considerable distance.

Protection for *T. auratus* also appears to be provided by several areas in Kucur Resort through undulating slope conditions. Based on field observations, it was found that such undulating regions are often found on the eastern side of Kucur resort, which is also predicted to be a suitable habitat for Javan langurs. This species was also observed and predicted to dominate areas that are gentle to steep, compared to flat (Supplementary Figures 3C and Supplementary Figure 4), which may allow them space to avoid human disturbances (i.e., tourists and anglers) and predators (e.g., Paareara pardus melas; Ariyanto *et al.* 2024). The area with gentle and steep slopes usually provides tall trees and is not easily accessible terrestrially, allowing *T. auratus* to monitor and move quickly. Therefore, they utilized this slope condition for defense against predators and facilitated vocal communication between individuals such as *Pan troglodytes* (Chitayat *et al.* 2021), *Papio ursinus* (Hoffman and O'Riain 2012), and *T. francois* (Zeng *et al.* 2013).

Despite several environmental conditions supporting *T. auratus* to occupy the Kucur Resort, our five models confirm that the availability of suitable habitat is still limited (Figure 4 & Table 3). Moreover, our predations prediction that the area of *T. auratus* suitable habitat is smaller than in previous studies conducted at the Kucur Resort (Maulahila *et al.* 2023). Habitat quality significantly affects the population size, daily activity, and social organization of primates (Pinto *et al.* 2009; Abel *et al.* 2023; Biswas *et al.* 2024). We assume Kucur Resort supports some of the basic needs of *T. auratus*, but perhaps it does not entirely fulfill them. The population of *T. auratus* likely uses Kucur Resort as a temporary rather than a permanent habitat. This assumption is more reasonable when considering the location of suitable habitats within Kucur Resort, primarily on the north and east sides, directly adjacent to the jungle zone of other resorts. However, more specific research on the habitat selection and use of *T. auratus* in APNP is still required.

Furthermore, each models have varying evaluation values due to the statistical approach of the algorithm, which depends on parametric or nonparametric analyses of the relationship between variables to generate the model (Segurado and Araújo 2004; Elith and Graham 2009). We recommend the habitat suitability prediction from RF as the primary reference in *T. auratus* conservation efforts at Kucur Resort. The RF model had the most accurate prediction and was supported by ecological information on Javan langurs and observations during field surveys. RF is an algorithm of machine learning with a nonparametric approach. This algorithm has gained popularity due to its robust capabilities, ability to accommodate multiple variables, and capacity to overcome non-linear interactions (Cutler *et al.* 2007; Strobl *et al.* 2009; Valavi *et al.* 2022). However, the use of RF needs to be executed carefully so that the predictions obtained are optimal and do not experience overfitting (Freeman *et al.* 2016). It is also important to note that our study results are specific to this location. The prediction of the model depends on the environmental covariate conditions, such as environmental covariate bias and grain size, as well as the occurrence coordinates, including prevalence, sample size, uncertainty error, and occurrence type (Segurado and Araújo, 2004; Graham and Hijmans 2006; Loiselle *et al.* 2008; Elith and Graham 2009; Syphard and Franklin 2009). In the future, conducting additional studies on habitat suitability models using various algorithms at the regional level may offer different perspectives for *T. auratus* habitat suitability.

Overall, our study revealed that the availability of food sources and shelter are essential factors in attracting *T. auratus* to inhabit a habitat, and reforested former production forests can provide these. Moreover, our study has also indirectly demonstrated the potential for remaining production forests in Java to be inhabited by Indonesian primates. This phenomenon can be a double-edged sword: primates' existence in production forests can offer hope for reforestation, but threatens their survival if not adequately managed. For instance, the role of *T. auratus* in endozoochory will aid the process of forest rehabilitation (Tsuji *et al.* 2017). However, its presence in a habitat with high human activity will increase the likelihood of being poached, roadkilled, and zoonosis-infected. Primates are crucial as flagship species in forest restoration initiatives (Chapman *et al.* 2020). Therefore, it is essential to engage various stakeholders in collaborative conservation efforts.

Furthermore, we need to expand the geographical scale of this study to identify the distribution and remaining habitats of *T. auratus*. The wide-scale prediction will enable us to determine which habitats can be potentially and efficiently managed by conservation efforts (Wibisono *et al.* 2018; Rahman *et al.* 2020, 2022). In addition, we need more extensive fine-scale studies on their feeding behavior, habitat use, and dynamic population in production or rehabilitation forests, considering seasonal variations. We recommend using our research for future studies and conservation efforts, especially for the local management of APNP.

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Supplementary Materials

Supplementary Table 1. Coordinate occurance of *T. auratus* for generating the habitat suitability model in Kucur Resort Alas Purwo National Park

Species	Latitude	Longitude	*References
Trachypithecus auratus	-8.50144	114.3869	Maulahila *et al.* 2023
Trachypithecus auratus	-8.50796	114.3868	Maulahila *et al.* 2023
Trachypithecus auratus	-8.52059	114.3829	Maulahila *et al.* 2023
Trachypithecus auratus	-8.52059	114.3861	Maulahila *et al.* 2023
Trachypithecus auratus	-8.54251	114.3869	Maulahila *et al.* 2023
Trachypithecus auratus	-8.52495	114.3873	Field Observation
Trachypithecus auratus	-8.50908	114.3895	Field Observation
Trachypithecus auratus	-8.5408	114.3901	Field Observation
Trachypithecus auratus	-8.5408	114.3821	Field Observation
Trachypithecus auratus	-8.58192	114.3645	Field Observation
Trachypithecus auratus	-8.58458	114.3657	Field Observation
Trachypithecus auratus	-8.54274	114.3909	Field Observation
Trachypithecus auratus	-8.58731	114.3684	Field Observation
Trachypithecus auratus	-8.54274	114.3842	Field Observation
Trachypithecus auratus	-8.50979	114.3911	Field Observation
Trachypithecus auratus	-8.55739	114.3816	Field Observation
Trachypithecus auratus	-8.54213	114.3852	Field Observation
Trachypithecus auratus	-8.52351	114.3819	Field Observation
Trachypithecus auratus	-8.49299	114.3918	Field Observation
Trachypithecus auratus	-8.58603	114.367	Field Observation
Trachypithecus auratus	-8.49293	114.3879	Field Observation
Trachypithecus auratus	-8.51037	114.3935	Field Observation
Trachypithecus auratus	-8.5574	114.3871	Officer statement and BTNAP 2017
Trachypithecus auratus	-8.53573	114.3767	Officer statement and BTNAP 2017
Trachypithecus auratus	-8.55254	114.3831	Officer statement and BTNAP 2017
Trachypithecus auratus	-8.55137	114.3884	Officer statement and BTNAP 2017
Trachypithecus auratus	-8.58463	114.3923	Officer statement and BTNAP 2017
Trachypithecus auratus	-8.58446	114.3896	Officer statement and BTNAP 2017
Trachypithecus auratus	-8.58591	114.3847	Officer statement and BTNAP 2017
Trachypithecus auratus	-8.58347	114.383	Officer statement and BTNAP 2017
Trachypithecus auratus	-8.58345	114.3938	Officer statement and BTNAP 2017

*[BTNAP] Balai Taman Nasional Alas Purwo, 2017. Panduan Lapang Mamalia Taman Nasional Alas Purwo. Balai Taman Nasional Alas Purwo, Banyuwangi, Indonesia.

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Supplementary Table 2. Description of the environmental variables for generating the habitat suitability model of *T. auratus* in Kucur Resort Alas Purwo National Park

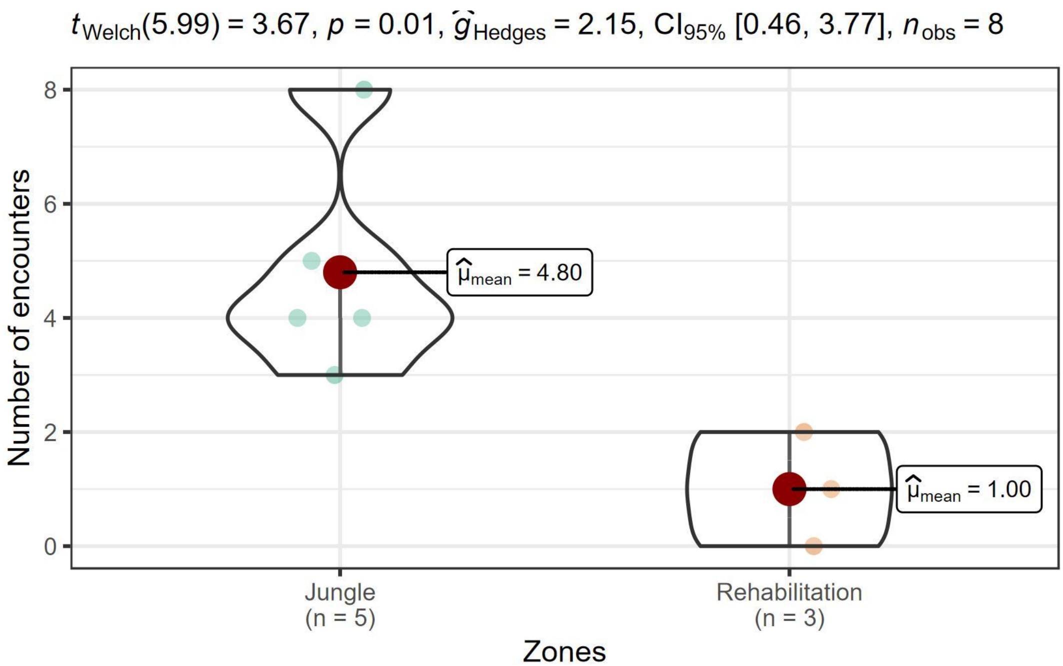
Group	Variable	Description	Unit
Climatic	BIO1	Mean annual air temperature	°C
	BIO2	Mean diurnal air temperature range	°C
	BIO3	Isothermality	°C
	BIO4*	Temperature seasonality	°C
	BIO5	Mean daily maximum air temperature of the warmest month	°C
	BIO6	Mean daily maximum air temperature of the warmest month	°C
	BIO7	Mean daily maximum air temperature of the warmest month	°C
	BIO8	Mean daily maximum air temperature of the warmest month	°C
	BIO9	Mean daily mean air temperatures of the driest quarter	°C
	BIO10	Mean daily mean air temperatures of the warmest quarter	°C
	BIO11	Mean daily mean air temperatures of the coldest quarter	°C
	BIO12	Annual precipitation amount	kg m^{-2} $year^{-1}$
	BIO13	Precipitation amount of the wettest month	kg m^{-2} $month^{-1}$
	BIO14	Precipitation amount of the driest month	kg m^{-2} $month^{-1}$
	BIO15*	Precipitation seasonality	kg m^{-2} $month^{-1}$
	BIO16	Mean monthly precipitation amount of the wettest quarter	kg m^{-2} $month^{-1}$
	BIO17	Mean monthly precipitation amount of the driest quarter	kg m^{-2} $month^{-1}$
	BIO18	Mean monthly precipitation amount of the warmest quarter	kg m^{-2} $month^{-1}$
	BIO19	Mean monthly precipitation amount of the coldest quarter	kg m^{-2} $month^{-1}$
Topography	BIO20*	Slope	degree
Biophysical	BIO21*	Normalized different vegetation index (NDVI)	-
Anthropogenic	BIO22*	Distance from settlement	Km
	BIO23	Distance from production forest	Km
	BIO24*	Land cover/land use	-

*Environmental variables that were considered for generating the habitat suitability model after multicolinearity test (threshold ≥0.7)

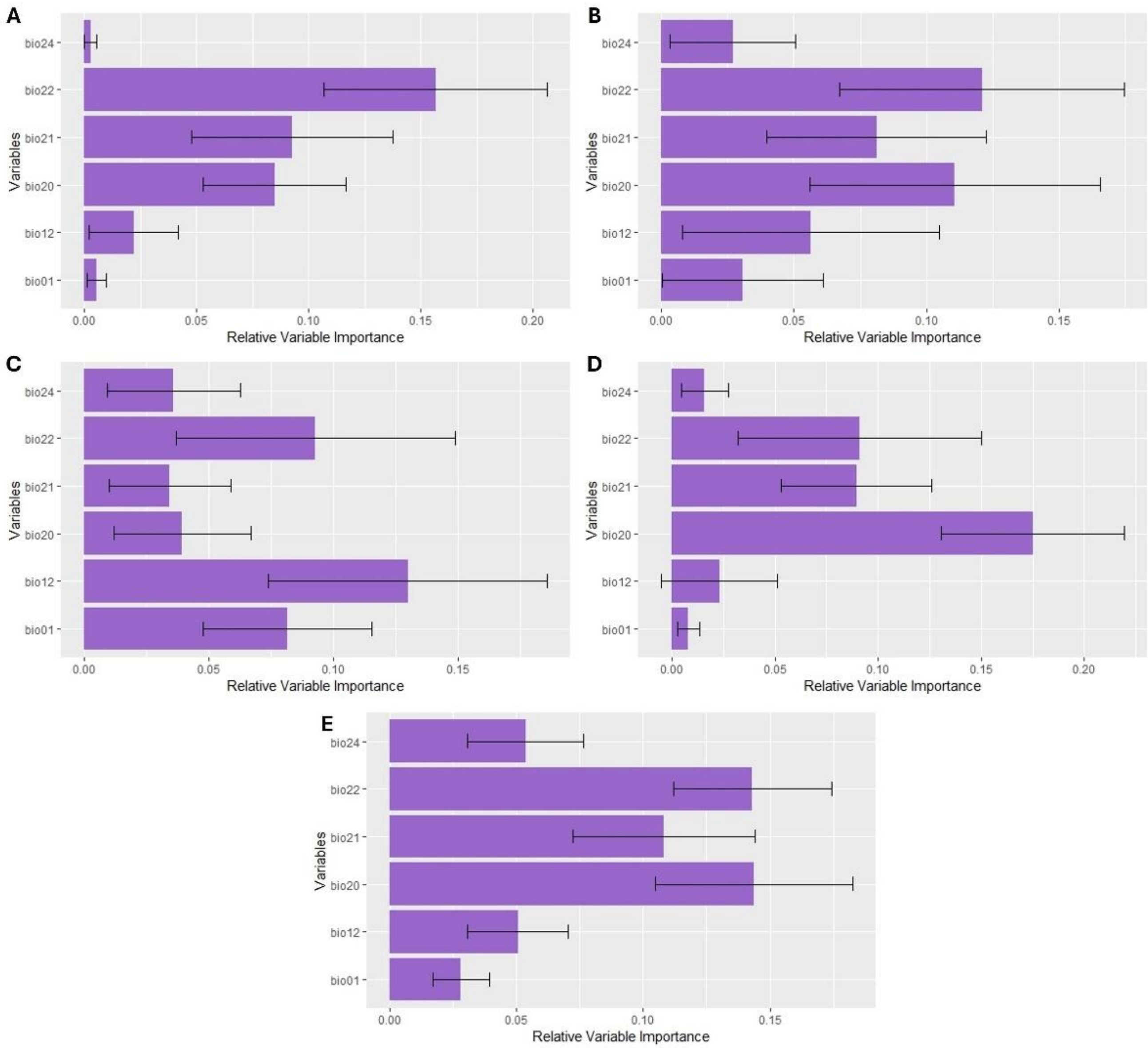
Supplementary Table 3. The encounters number of *T. auratus* in Resort Kucur TNAP according to the transect line and zone

Transect line	Zones	
	Jungle	Rehabilitation
Payaman	5	-
Randuan	4	-
Curahwuluh	3	-
Jati papak blimbingan	4	2
Suruhan	0	1
Kucur mas	8	0

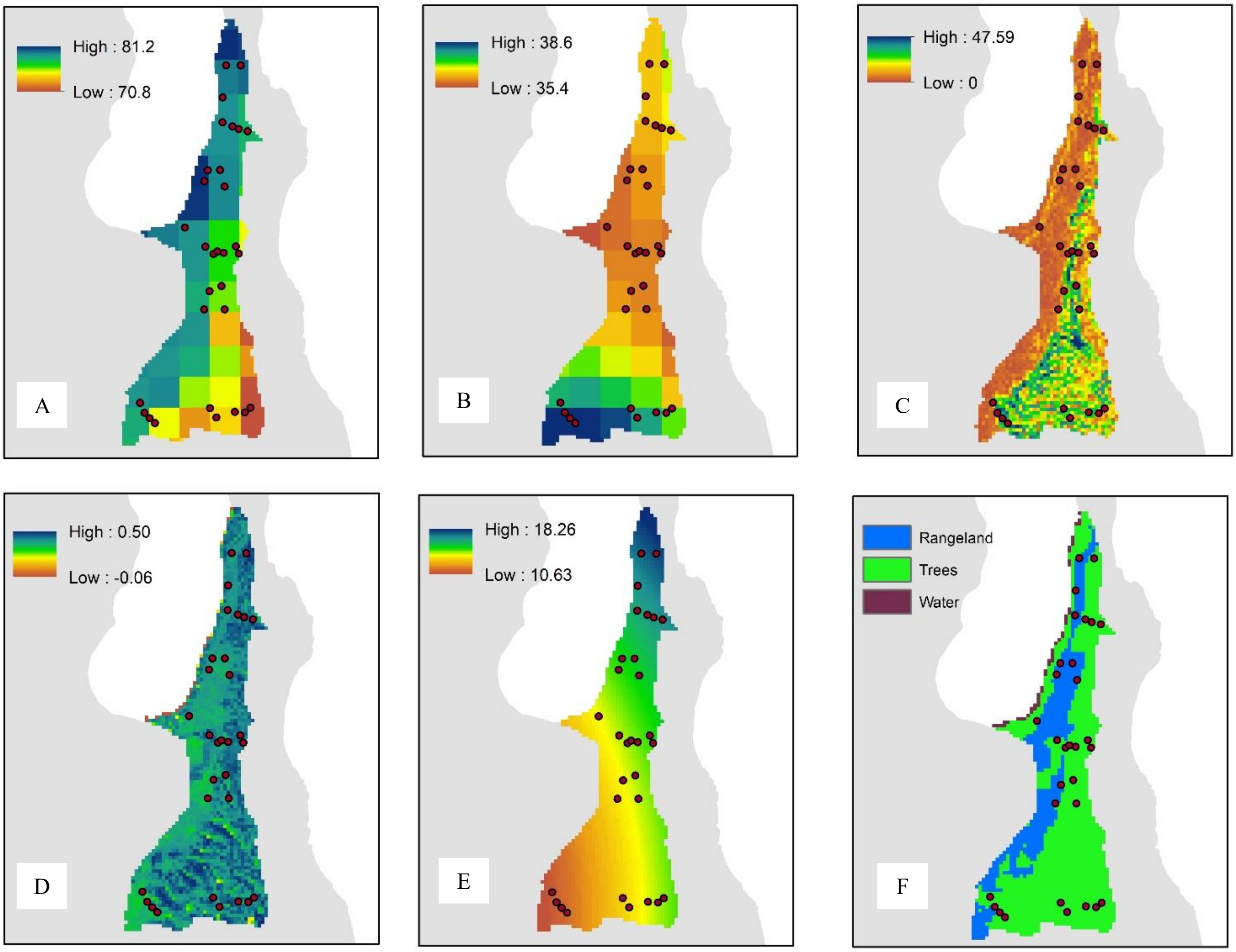
(-) There is no type of zone on the transect line



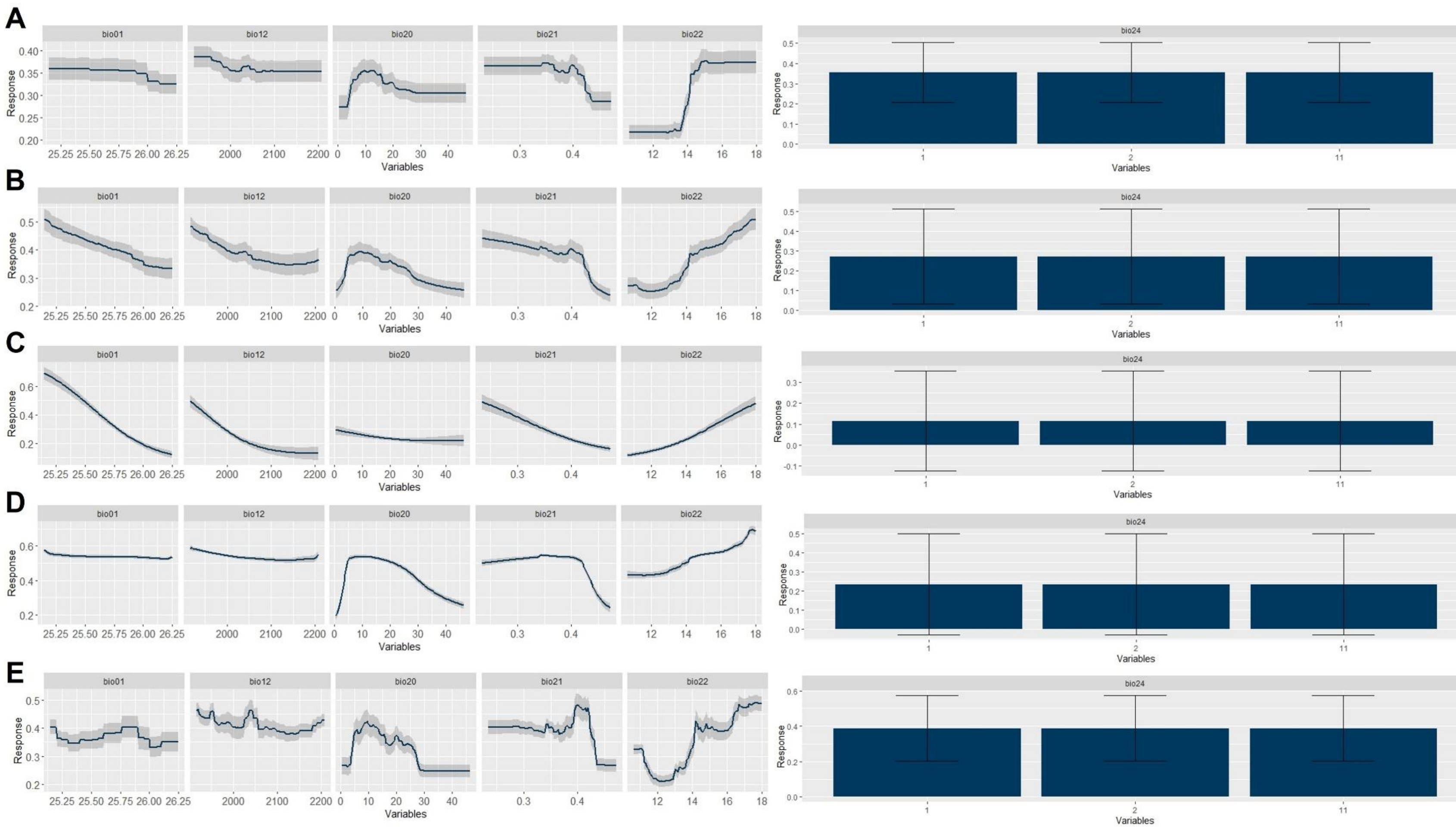
Supplementary Figure 1. The average number of *T. auratus* encounters in the jungle zone was higher than in the rehabilitation zone. Based on Welch test, there was a significant difference (p-value = 0.01, twelch = 3.67.) between the two zones. The filled red circle is the average number of *T. auratus* encounters in each zone. The transparent green and orange circles are the number of *T. auratus* encounters in the forest and rehabilitation zone, respectively



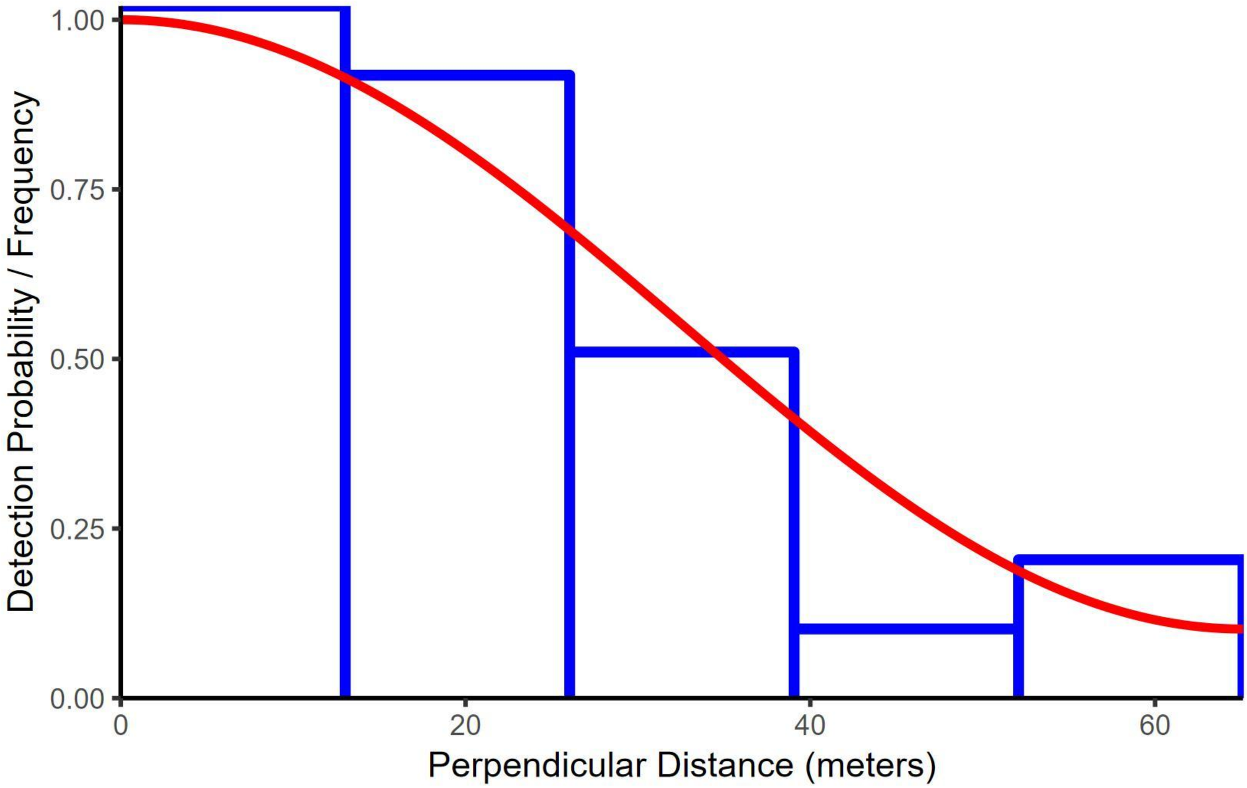
Supplementary Figure 2. The permutation value of environmental covariates contribution to habitat suiatbility model of *T. auratus* in Kucur Resort Alas Purwo National Park from (A) Boosted Regression Tree, (B) Ensemble, (C) Generalized Linear Model, (D) Maximum Entropy, and (E) Random Forest. The environmental factors listed are used to create the habitat suitability model, including mean annual air temperature (bio1), annual precipitation amount (bio12), slope (bio20), normalized difference vegetation index (bio21), distance from settlement (bio22), and land cover/ land use (bio24). The purple bar is the relative value of the variable permutation importance



Supplementary Figure 3. The distribution of *T. auratus* occurance (black filled circles) according to six environmental covariate maps in Kucur Resort Alas Purwo Natioanl Park, i.e., (A) temperature seasonality (°C), (B) precipitation seasonality (kg m^{-2} $year^{-1}$), (C) slope (degree), (D) normalized different vegetation index, (E) distance from settlement (kilometers), and (F) land cover/land use



Supplementary Figure 4. The probability of *T. auratus* occurance to environmental covariates in Kucur Resort Alas Purwo National Park generated from (A) Boosted Regression Tree, (B) Ensemble, (C) Generalized Linear Model, (D) Maximum Entropy, and (E) Random Forest. The environmental factors listed are used to create the habitat suitability model. These factors include temperature seasonality (bio4), precipitation seasonality (bio15), slope (bio20), normalized difference vegetation index (bio21), distance from settlement (bio22). However, for land cover/land use (bio24) specifically contain Waters (code: 1), Tree (code: 2), and Rangeland (code: 11) that there are no differences probability of *T. auratus* occurance



Supplementary Figure 5. The histogram of detection probability as a function of the perpendicular distance from the transect line to the *T. auratus*