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Cover: A female Javan Leopard *Panthera pardus melas* in rehabilitation phase at Cikananga Wildlife Center. © Yayasan Cikananga Konservasi Terpadu.

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ARTICLE

The Javan Leopard *Panthera pardus melas* (Cuvier, 1809) (Mammalia: Carnivora: Felidae) in West Java, Indonesia: estimating population density and occupancy

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Abstract: The Javan Leopard is endemic to the Indonesian island of Java and has been classified as Endangered. Reliable information about its population status, distribution, and density is lacking but are essential to guide conservation efforts and provide a benchmark for management decisions. Our study represents the first empirical density and occupancy estimates for the Leopard in West Java and provides baseline data for this region. We used camera trap data collected from February 2009 to October 2018 in six study areas comprising a sampling effort of 10,955 camera trap days in a total area of 793.5 km^2. We identified 55 individual Leopards in these areas and estimated Leopard density using spatially explicit capture-recapture. Population density estimates range from 4.9 individuals/100 km^2 in Gunung Guntur-Papandayan Nature Reserve to 16.04 individuals/100 km^2 in Gunung Gede Pangrango National Park. Latter is among the globally highest Leopard densities. Based on detection data, we modelled single-season Leopard occupancy using three sampling covariates and eight site covariates. Modelling revealed that the two covariates forest cover and presence of Wild Boar are the strongest predictors for Leopard occupancy in our study areas. We recommend assessing and monitoring Leopard distribution, density and occupancy in other areas of Java and emphasize that a landscape approach for conservation of the Javan Leopard is imperative.

Keywords: Camera trap, conservation management, habitat use, spatially explicit capture-recapture.

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INTRODUCTION

With a range extending from Africa to eastern and southeastern Asia, the Leopard *Panthera pardus* has the widest distribution of the wild Felidae (Stein & Hayssen 2013). It inhabits arid and rugged montane regions, savanna grasslands, shrubland, temperate forests and rainforests (Nowell & Jackson 1996). Despite its adaptability to a wide range of habitats, it is primarily threatened by habitat fragmentation and depletion of its natural prey base (Stein et al. 2020). Endemic to the Indonesian island of Java, the Javan Leopard *P. p. melas* is classified as Endangered in the IUCN Red List of Threatened Species (Wibisono et al. 2021). It is listed on CITES Appendix I and nationally protected by Indonesian law (Ministry of Environment and Forestry 2018). Yet, reliable information on the Javan Leopard's population status, habitat use and density is lacking (Wibisono et al. 2018).

Java is home to 141 million people, and with 1,115 people/km² (Badan Pusat Statistik 2020) has one of the highest human population densities in the world (Dsikowitzky et al. 2019). West Java is the most densely populated province in Indonesia with 1,394 people/km² (Badan Pusat Statistik 2020). Human pressure on the Leopard's remaining natural habitat continues to increase in Java and has restricted its distribution to an extent that remaining suitable landscapes has been estimated at 11,599 km², which corresponds to 8.9% of the island (Wibisono et al. 2018). Both the Leopard and its prey are threatened by retaliatory killing and poaching, habitat loss and fragmentation, large-scale degradation by plantation companies and human encroachment into protected areas (Ministry of Environment and Forestry 2016; Gunawan et al. 2017). Leopards increasingly approach settlements in search for prey, which results in conflict with people over livestock (Ministry of Environment and Forestry 2016). An annual average of 4.6 Leopards have been removed from the wild between 2007 and 2019 (Adhiasto et al. 2020). In this period, 29 Leopards were captured due to conflict, of which four individuals were released into the wild, five died in captivity, and 20 are still kept in zoos and rescue centres (Adhiasto et al. 2020). These incidents also fuel illegal trade in body parts with 51 Leopards confiscated in 41 seizures between 2011 and 2019 (Gomez & Shepherd 2021).

In 1990, Leopards were known to be present in 12 protected areas with a guesstimated population of 350–700 individuals (Santiapillai & Ramono 1992). By 2013, the Leopard population was estimated at 491–546 individuals occurring in 48 habitat patches across Java's remaining natural forests, based on data collated during a workshop in 2013 (Ministry of Environment and Forestry 2016). Occurrence records obtained from 2013 to 2018 in 22 sites across Java indicate a Leopard population of 188–571 individuals at most (Wibisono et al. 2021). As the potential population loss is uncertain, reliable data and robust analyses are essential for a better understanding of the present Leopard status and viability, and for guiding management decisions (Traylor-Holzer et al. 2020).

Assessing Leopard density is necessary to provide a baseline for future reference and is a useful way to increase the precision of island-wide Leopard status assessments (Ministry of Environment and Forestry 2016). Furthermore, information on population density and distribution are crucial for assessing the effectiveness of conservation interventions and provides considerations to help management authorities for making decisions on conservation planning. In view of suitable habitat patches being small and isolated, it is equally important to understand the distribution and habitat use of the Javan Leopard (Traylor-Holzer et al. 2020; Wibisono et al. 2021). With our study, we aimed at estimating Leopard population density and occupancy in six forest areas in West Java province using camera traps in a closed population spatially explicit capture-recapture (SECR) design and single-season occupancy modelling. These two methods complement each other by providing a more nuanced assessment of the population status than a density estimate alone. We anticipate that our results will form a basis for a comprehensive conservation management plan for the Javan Leopard.

STUDY AREAS

Our study areas were located in six protected areas in the province of West Java (Figure 1), comprising three national parks, one strict nature reserve, one wildlife reserve and one protected forest (Table 1). They are all situated in Java's Southern Mountains, which are part of the Sunda Volcanic Arc that derived from stratovolcano complexes with thermal springs and fumaroles emitting hot fumes, gases, and vapors (Carranza et al. 2008). These six protected areas constitute 14% of Java's Leopard priority landscape (Wibisono et al. 2018). They are located in eight districts with a total population of about 20.54 million people (Badan Pusat Statistik Provinsi Jawa Barat 2021).

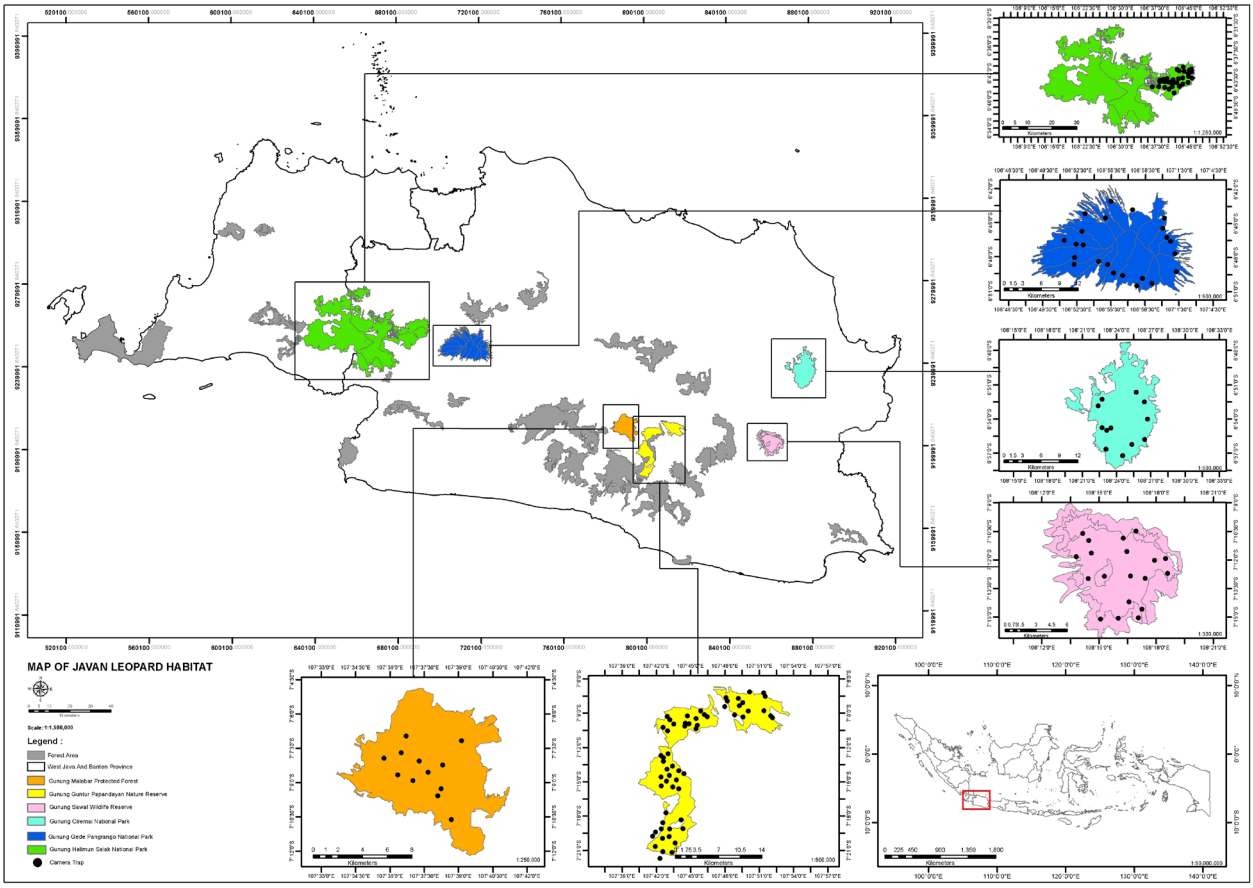

Figure 1. Map of study areas in West Java, Indonesia.

Table 1. List of protected areas in West Java, Indonesia, and their key characteristics.

Name	Size (km²)	Elevation (m)	IUCN Protected Area category	Description
Gunung Gede Pangrango National Park (GGPNP)	242.8	500–3,019	II	GGPNP was designated a biosphere reserve in 1977 and established as national park in 1980. It encompasses two stratovolcanoes with seven craters located at elevations of 2,600–2,927 m. Its topography is hilly and mountainous with forest cover classified as submontane, montane and subalpine forests; annual rainfall is 4,000–6,000 mm, and temperature ranges from 18–23°C (Harris 1996).
Gunung Ciremai National Park (GCNP)	155	500–3,078	II	GCNP was established in 2004. It surrounds a stratovolcano with a more than 20km² summit crater in its centre. The topography is hilly and mountainous with submontane, montane and subalpine forests; annual rainfall is 2,500–4,500 mm with temperatures ranging from 18–22°C (Kebun Raya Bogor 2001).
Gunung Malabar Protected Forest (GMPF)	88.9	1,000–2,300	VI	GMPF is a production forest managed by the Forestry State Enterprise Perhutani (Ario et al. 2018a). It encompasses a stratovolcano with fumaroles, hot springs, mud pools and altered ground on its southern slope (Bogie et al. 2008). The topography is hilly and mountainous with submontane and montane forests; annual rainfall is 2,000–2,500 mm with temperatures of 18–23°C (Ario et al. 2018a). It is disturbed due to encroachment for farming and hunting of wildlife (Ario et al. 2018a)
Gunung Sawal Wildlife Reserve (GSWR)	110	500–1,766	IV	GSWR was established in 1979. It encompasses an extinct volcano. The topography is hilly and mountainous with lowland and submontane forests; annual rainfall is around 2,000–2,500 mm with temperatures of 18–22°C (BBKSDA Jawa Barat 2018).
Gunung Guntur-Papandayan Nature Reserve (GGPNR)	153	773–2,678	IA	GGPNR was established in 2013. It encompasses two stratovolcanoes with active fumarole fields. Its topography is hilly and mountainous with submontane and montane forests; annual rainfall is 2,000–2,500 mm with temperatures from 19–27°C (BBKSDA Jawa Barat 2018).
Gunung Halimun Salak National Park (GHSNP)	877	500–2,211	II	GHSNP was established in 1992. It encompasses two stratovolcanoes with several cone craters at the summit. Its topography is hilly and mountainous with forest cover classified as lowland, submontane and montane forests; annual rainfall amounts to 4,000–6,000 mm, and temperature ranges from 19–23°C (Simbolon et al. 1998)

The tropical climate in the entire region is influenced by the southeastern Asian and Indo-Australian monsoon winds; the former brings rainfall from December to January, and the latter causes a dry season from June to August (Rahayu et al. 2018).

Potential prey species of the Leopard in the study areas include Wild Boar *Sus scrofa*, Red Muntjac *Muntiacus muntjac*, Javan Chevrotain *Tragulus javanicus,* Javan Gibbon *Hylobates moloch*, Javan Lutung *Trachypitecus auratus*, Javan Surili *Presbytis comata*, Long-tailed Macaque *Macaca fascicularis*, and Javan Slow Loris *Nycticebus javanicus* (Ministry of Environment and Forestry 2016; Ario et al. 2018b).

MATERIAL AND METHODS

Data collection

During the survey period from 2009 to 2018, we had three camera trap models at our disposal comprising Cuddeback® Digital Scouting Camera model 1125, Cuddeback® X-change white flash model 1279 (NonTypical Inc., Park Falls, WI, USA) and Bushnell Trophy Cam HD model 119547c. They were set to be active for 24 hours per day with one minute interval between consecutive photographs. We set them to take one to three photographs to select the best photograph for identification.

In each study area, we deployed camera traps in grids of 2 x 2 km^2 cells to maximize the chances that all individuals would be photographed, based on the smallest known Leopard home ranges in Asia (Grassman 1999; Ario et al. 2018b). Similar camera trapping designs were implemented by Borah et al. (2014), Noor et al. (2020) and Kittle et al. (2021). However, we excluded cells in the close perimeters of volcanoes that were difficult or potentially dangerous to access.

Most camera traps were positioned along animal trails where we found signs such as pugmarks, scrapes or faeces, and oriented in a north-south direction to avoid direct sunlight. They were mounted perpendicular to trails at a distance of 3–7 m from the trails' centre and at a height of 40 cm above ground to obtain photographs of the Leopard's flank, body and genitals. This height corresponds roughly with the shoulder height of an adult Leopard (Henschel & Ray 2003).

We surveyed each study area once using one camera trap per location due to the limited number of camera traps at our disposal. We did not use bait and covered all of GHSNP, GGPNP, GCNP, GSWR and GMPF in one survey block each, but two survey blocks in GGPNR. We determined coordinates and elevation of each location using a GPS device Garmin 64s that was set to WGS 84 datum. The distance between locations was 966–1,830 m. We kept camera traps at locations for 92 to 102 days to satisfy the assumption of population closure within each survey (Karanth 1995; Rostro-García et al. 2018). We tested population closure using the statistical program CAPTURE (Otis et al. 1978).

We consider photographs of single individuals and social units of several individuals as one detection of the species. Our definition of the term 'independent detection' refers to a) successive photographs of different individuals or social units of the same species, b) non-consecutive photographs of the same species, and c) one or several consecutive photographs of the same individual taken at the same location within an interval of 30 minutes.

Spatially Explicit Capture–Recapture

We identified individual Leopards by their distinct rosette patterns on both flanks, gauged their age class and sexed them by the size of their heads and bodies, and the presence of testes and dewlaps in males as described by Balme et al. (2012) (Image 1). Six observers independently verified identification of individuals. Blurred photographs were excluded for analysis.

Due to using a single camera trap per location, we separated photographs showing left and right flanks and used the flank with the highest number of identified individuals for analysis following O'Brien et al. (2003). We cross-checked identified individuals across neighbouring study areas, where surveys were conducted over the same period.

We estimated Leopard density in each of the six study areas using the spatially explicit capture-recapture (SECR) package in R version 3.1.5 (Efford 2018; R Core Team 2018). The SECR method combines information about the capture locations of individuals with their capture probability at point locations to estimate density (Efford et al. 2009; Royle et al. 2009). This method is less biased than conventional closed capture-recapture methods by study design, sample sizes and variation in detection probabilities for effective conservation and management (Sollmann et al. 2012; Ramesh & Downs 2013).

To avoid bias in determining the population size estimates for each study area, we used the effective sampled area and calculated SECR as the basis for the size of forest area. We analysed the spatial capture histories of camera traps in a likelihood-based density estimation framework, a method that does not require

the addition of a buffer to the trapping polygon for estimating effective trapping area resulting in less biased estimates (Efford et al. 2009).

As recommended by Tobler et al. (2013), we used sex covariates to improve density estimates and to show biologically important differences in movement patterns and detection probabilities between the two sexes. We used locations and detections of identified individuals on one or more sampling occasions, i.e. their detection histories, as input data for the SECR. We then separated the results of SECR analyses in group according to sex for each location.

The impact of sex on the parameter probability of capture at the activity centre of an individual (g0) and the spatial scale parameter describe the decline in probability of capture with distance from the activity centre (σ) (Efford et al. 2009). We tested g0 and σ through the comparison of four alternative models using the Akaike Information Criterion (AIC) adjusted for small sample size (AICc; Burnham & Anderson 2002): "secr.0" (null model), "secr.sex.g0" (g0 varies between males and females), "secr.sex.σ" (σ varies between males and females), and "secr.sex" (both g0 and σ vary between males and females) (Efford 2015; Boron et al. 2016). This model assumes that the detection of all individuals is governed by the same detection versus distance curve at all detectors on all occasions (Efford 2018).

Occupancy probability

We used single-season occupancy modelling to estimate occupancy probability (ψ) of Leopards at each site, with maximum likelihood estimation based on detection-nondetection data. The single-season model has three assumptions: 1) the method used to detect the species must generate non-equivocal presence data, 2) all the sampled sites must be 'closed' to change in occupancy for the duration of the survey period, and 3) detection of the species at a site should be independent from the detections at any other site. In order to allow for the estimator (ψ) to be interpreted as the proportion of area occupied, the following assumptions of an occupancy model were made: 1) sites are closed to changes in occupancy, i.e. they are either occupied or not by the species for the survey duration; 2) species are correctly identified; 3) detections are independent; and 4) heterogeneity in occupancy or detection probability are modelled using covariates (MacKenzie et al. 2006).

We reconstructed the Leopard camera trap history in each study area and divided the data into sampling occasions. We constructed a detection-nondetection matrix for all camera traps and occasions, with an entry of 1 if a Leopard had been detected at a particular location and occasion, and an entry of 0 otherwise. We categorized photographs into binary detection histories (1 = detected, 0 = not detected) by aggregating 15 survey days as a single survey occasion. The goodness-of-fit of the most complex model that included all contributing covariates (see below) was tested in four different collapsing scenarios (7-, 10-, 12-, and 15-day periods; MacKenzie & Bailey 2004). The 15-day period represented the optimum period length to maximize model fit (Tan et al. 2017). We entered the data into PRESENCE 2 version 12.41 (Hines 2006).

We used a constant model comprising the two components (ψ) and detection probability (p), and included three sampling covariates that potentially affect detection probability: camera traps were placed on animal trails (trail); trigger speed of camera trap model (camera) (Strampelli et al. 2018), and number of days the cameras traps were active in each location (effort) (Tan et al. 2017). We also included five site covariates, namely elevation, forest cover, distance to river, distance to village, and distance to road (Table 2), that potentially affect Leopard habitat use and detection probability (Ngoprasert et al. 2007; Erfanian et al. 2013; Mondal

Table 2. Covariates included in potential candidate detection and occupancy models.

Covariate name	Description
Sampling covariates	
Trail	Camera trap placed on animal trail (1) or not (0)
Camera	Trigger speed of camera trap models (range of 0.2–0.6 seconds)
Effort	The number of days a camera trap was active during each sampling occasion (range of 19–97 days)
Site covariates	
Elevation	Elevation of the camera trap location (range of 818–2,635 m) obtained from GPS device Garmin 64s and cross-checked with database of Badan Informasi Geospasial (2013)
Forest	Percentage of forest cover around camera trap locations (range of 65–98%) using values from Badan Informasi Geospasial (2013) database
River	Distance of the camera trap to the nearest river (range of 15–1,151 m) using values from Badan Informasi Geospasial (2013) database
Road	Distance of the camera trap to the nearest road (range of 215–4,943 m) using values from Badan Informasi Geospasial (2013) database
Village	Distance of the camera trap to the nearest human settlement (range of 481–6,152 m) using values from Badan Informasi Geospasial (2013) database
Boar	RAI of Wild Boar (range of 4.02–12.99 independent detections/100 camera trapping days)
Muntjac	RAI of Red Muntjac (range of 2.32–10.56 independent detections/100 camera trapping days)
Chevrotain	RAI of Javan Chevrotain (range of 1.58–6.07 independent detections/100 camera trapping days)

et al. 2013; Havmøller et al. 2019). We determined elevation using a GPS device Garmin 64s. We extracted values for forest cover and distances from the database of Badan Informasi Geospasial (2013) in ArcGIS version 10.4.1. We used the top ranked model on sampling covariates and site covariates with the lowest AIC score as a constant for building models that influenced habitat use and detection probability (Athreya et al. 2015).

Additionally, we included relative abundance index (RAI) values of three potential ungulate prey species from every camera trap location in each protected area as site covariates. RAI values are calculated as independent detections of these species per 100 days of camera trapping.

We ranked models based on the AICc values and identified those with the lowest AICc values as the best output models (MacKenzie et al. 2006). The best approximating models were selected based on the AICc and Akaike weights (wi). We then designated models with $\Delta AIC \leq 2$ as the top candidate (Burnham & Anderson 2002). From those models, we considered covariates to be important if they had relatively high-summed Akaike weights and outcompeted the null model [ψ(.), p(.)] with constant occupancy and detection to provide the most useful information regarding covariates that relate to Leopard occupancy.

RESULTS

Camera trapping

Between 1 February 2009 and 10 October 2018, we covered a total of 152 locations in an effective sampled area of 793.5km^2 with a total sampling effort of 10,955 camera trap days. We lost 12 camera traps due to theft, and seven were moved by people and covered with large leaves and branches. The surveys yielded 368 independent detections of 55 individual Leopards, comprising 161 of right flanks and 207 of left flanks; they were recorded at 85 locations at an elevation range of 818–2,635 m (Table 3). We discarded 69 blurred photographs for analysis. All identified individuals were adult (Images 2 to 5) and included five melanistic ones (Image 6).

Leopard density

Statistical tests support the population closure assumption for Javan Leopard in GGPNP (z = -0.31; p = 0.37), GCNP (z = 0.45; p = 0.67), GMPF (z = -0.01, p = 0.16), GSWR (z = -0.34, p = 0.37), GGPNR (z = -0.61, p = 0.27) and GHSNP (z = 0.28; p = 0.61).

For estimating Leopard density, the model based on no variation between sexes ranks top in three study areas, whereas variation between sexes ranked top in two study areas (Table 4).

Leopard density ranged from 4.92 ± 2.29 individuals/100 km^2 in GGPNR to 16.04 ± 6.29 individual/100 km^2 in GGPNP. The movement parameter (σ) was lowest in GGPNP with 1,070 m ± 1.81 for males and 676 m ± 1.24 for females, and highest in GGPNR with 4,227 m ± 1.21 and 2,564 m ± 6.69 for males and females, respectively. The probability of detection at home range centre (g0) was lowest in GSWR with 0.01 ± 0.012 for males and 0.031 ± 0.056 for females, and highest in GGPNR with 0.053 ± SE 0.051 for males and 0.064 ± SE 0.051 for females (Table 5).

Based on calculations, the analysis revealed an estimated population of about 20 Leopards in 125.8

Table 3. Sampling effort in six study areas with number of right (R) & left flanks (L), and adult male (M) & female (F) Javan Leopards detected. The bolded independent detections represent the flank used for identification of individuals.

Study area	Sampling period	Elevation	Effective sampled area in km^2	Locations	Camera trap days	Sampling occasion (days)	Independent detections	Adult individuals
GGPNP	01.ii.–03.v.2009	855–2,828	125.8	23	2,082	92	**R = 55**, L = 31	M = 8, F = 10
GCNP	14.i.–15.iv.2013	1,168–2,012	150	12	1,070	92	**R = 10**, L = 8	M = 1, F = 0
GMPF	01.xi.2013–04.ii.2014	1,500–2,226	85	12	1,102	96	**L = 56**, R = 30	M = 3, F = 4
GSWR	27.x.2016–01.ii.2017	818–1,766	86.9	14	1,317	98	**R = 21**, L = 9	M = 2, F = 3
GGPNR	01.vii.–10.x.2018	1,489–2,678	186.8	60	3,614	102	**L = 33**, R = 23	M = 3, F = 6
GHSNP	05.vii.–10.x.2018	964–1,962	159	31	1,770	98	**L = 70**, R = 22	M = 7, F = 8
		Total	793.5	152	10,955	578	R = 161, L = 207	M = 24, F = 31

Image 1. Male and female Javan Leopards in Gunung Gede Pangrango National Park. © Ministry of Environment and Forestry (MoEF) and Conservation International Indonesia (CI).

Image 2. Male Javan Leopard in Gunung Ciremai National Park. © MoEF and CI.

Image 3. Female Javan Leopard in Gunung Malabar Protected Forest. © MoEF and CI.

km² of GGPNP (95% CI: 9.68–42.38), seven Leopards in 85 km² of GMPF (95% CI: 2.62–18.87), five Leopards in 86.9 km² of GSWR (95% CI: 1.62–17.20), nine Leopards in 186.8 km² of GGPNR (95% CI: 3.98– 22.04), and 15 Leopards in 159 km² of GHSNP (95% CI: 7.47–30.04).

Detection probability

The estimated Leopard detection probability (p) ranges from 0.13 in GCNP to 0.22 in GMPF and GGPNP. The top ranked model showed that the detection probability of Leopard was affected by the distance of camera traps from animal trails in GGPNP, GCNP, GMPF, and GHSNP, but by the number of camera trap days in GSWR and GGPNR (Table 6).

Leopard occupancy

The estimated Leopard occupancy (Ψ) ranges from 0.51 (±SE 0.21) in GCNP to 0.94 (±SE 0.13) in GMPF, with a naïve estimate from 0.35 in GGPNR to 0.92 in GMPF (Table 7).

DISCUSSION

With an effective sampled area of 793.5 km² in six study areas, our camera trapping surveys covered about 6.8% of the total landscape identified by Wibisono et al. (2018) as suitable for the Javan Leopard. We identified 55 adult individuals during 578 sampling occasions in the period from February 2009 to October 2018. Although our surveys encompassed all seasons, none of the 31 identified female Leopards was recorded with a

Table 4. Model selection parameters for spatially explicit capture-recapture models.

Study area	Model	Description	AICc	ΔAICc	AICc wi	K
GGPNP	g0~1, σ~h2 (secr.sex.σ)	Variation between sexes affecting σ	179.34	0.00	0.90	5
	g0~1, σ~1 (secr.0)	No variation between sexes	184.40	5.07	0.07	4
	g0~h2, σ~1 (secr.sex.g0)	Variation between sexes affecting g0	186.83	7.50	0.02	5
	g0~h2, σ~h2 (secr.sex)	Variation between sexes affecting g0 and σ	188.71	9.38	0.01	5
GCNP		Not Applicable (NA)	NA	NA	NA	NA
GMPF	g0~1, σ~1 (secr.0)	No variation between sexes	242.47	0.00	1	4
	g0~h2, σ~h2 (secr.sex)	Variation between sexes affecting g0 and σ	280.23	37.76	0	5
	g0~1, σ~h2 (secr.sex.σ)	Variation between sexes affecting σ	284.06	41.59	0	5
	g0~h2, σ~1 (secr.sex.g0)	Variation between sexes affecting g0	284.44	41.97	0	5
GSWR	g0~1, σ~1 (secr.0)	No variation between sexes	270.78	0.00	0.60	4
	g0~1, σ~h2 (secr.sex.σ)	Variation between sexes affecting σ	265.01	5.64	0.24	5
	g0~h2, σ~1 (secr.sex.g0)	Variation between sexes affecting g0	264.37	8.19	0.12	5
	g0~h2, σ~h2 (secr.sex)	Variation between sexes affecting g0 and σ	260.10	10.20	0.04	5
GGPNR	g0~1, σ~1 (secr.0)	No variation between sexes	222.66	0.00	0.79	4
	g0~h2, σ~h2 (secr.sex)	Variation between sexes affecting g0 and σ	225.61	2.95	0.18	5
	g0~1, σ~h2 (secr.sex.σ)	Variation between sexes affecting σ	229.76	7.10	0.02	5
	g0~h2, σ~1 (secr.sex.g0)	Variation between sexes affecting g0	231.40	8.74	0.01	5
GHSNP	g0~h2, σ~h2 (secr.sex)	Variation between sexes affecting g0 and σ	317.14	0.00	0.48	5
	g0~1, σ~1 (secr.0)	No variation between sexes	317.38	0.24	0.43	4
	g0~1, σ~h2 (secr.sex.σ)	Variation between sexes affecting σ	321.93	4.78	0.04	5
	g0~h2, σ~1 (secr.sex.g0)	Variation between sexes affecting g0	322.01	4.87	0.04	5

Notes: the values probability of capture at the home range centre (g0), spatial parameter related to home range size (σ), Akaike information criterion adjusted for small sample size (AICc), difference from best ranking model (ΔAICc), model weighting (AICc wi), and number of model parameters (K).

Table 5. Results from SECR analyses for Leopard density in six study areas.

Study area	Gender	D (± SE) adult individuals/100 km²	LCL (CI 95%)	UCL (CI 95%)	σ (±SE) m	g0 (±SE)
GGPNP	M	4.94 (1.86)	2.46	10.12	1,070 (1.81)	0.026 (0.012)
	F	11.1 (4.43)	5.24	23.58	676 (1.24)	0.036 (0.012)
		16.04 (6.29)				
GCNP	M	Not Applicable (NA)	NA	NA	NA	NA
GMPF	M	3.42 (1.99)	1.19	9.85	2,091 (4.51)	0.023 (0.011)
	F	4.88 (2.47)	1.91	12.45	1,719 (3.59)	0.024 (0.006)
		8.30 (4.46)				
GSWR	M	1.96 (1.39)	0.56	6.8	2,120 (3.94)	0.010 (0.012)
	F	4.16 (2.62)	1.33	12.95	1,447 (5.66)	0.031 (0.056)
		6.12 (4.01)				
GGPNR	M	1.50 (0.85)	0.51	4.22	4,227 (1.21)	0.053 (0.051)
	F	3.42 (1.44)	1.57	7.58	2,564 (6.69)	0.064 (0.051)
		4.92 (2.29)				
GHSNP	M	4.36 (1.65)	1.25	7.51	1,996 (5.61)	0.025 (0.006)
	F	5.08 (1.80)	3.45	11.39	1,827 (3.57)	0.031 (0.008)
		9.44 (3.45)				

Notes: values for density (D), standard error (SE), confidence interval (CI), lower confidence limit (LCL), upper confidence limit (UCL), movement parameter (σ), the probability of detection at home range centre (g0).

cub, which is a matter of concern. In contrast, female Leopards with cubs were recorded between June and November in protected areas in Nepal and Iran (Odden & Wegge 2005; Farhadinia et al. 2009; Ghoddousi et al. 2010), and between February and May in southern Sri Lanka (Kittle et al. 2017).

We recorded only one Leopard in Gunung Ciremai National Park (GCNP) despite an effective sampled area of 150 km^2 in 1,070 camera trap days. Doubts about the small population led the GCNP management to continue the camera trap survey during 2014 to 2018, but not even a single photograph of a Leopard was obtained (R. Gumilang, pers. comm. 20 November 2018). For the recovery of a Leopard population in this area, a male Leopard was translocated to GCNP in July 2019 (Wibisono et al. 2021), and a female Leopard was released in March 2022 (R. Gumilang, pers. comm. 10 March 2022).

Leopard density

Our study provides the first estimate for Leopard density and distribution in montane protected areas of West Java using the spatially explicit capture-recapture method. Our study area in Gunung Halimun Salak National Park yielded the highest number of 70 independent detections (IDs). This is the only study area, in which the sex of 15 identified individuals affects both detection and spatial parameters as best model for estimating density. The slightly lower number of 55 IDs in Gunung Gede Pangrango National Park affects only the spatial parameter as top model, despite 18 identified individuals. The influence of the variation between sexes on density estimates is considerably lower in the remaining study areas, where we identified between five and nine individuals in 21 to 56 IDs. We therefore assume that a minimum of 56 IDs with at least 15–18 identified individuals represent the threshold necessary for modelling sex-specific Leopard density. A higher sample size facilitates modelling sex-specific differences in detectability and spatial patterns (Goldberg et al. 2015; Kittle et al. 2021; Vinks et al. 2021), whereas a smaller sample size is insufficient for this model (Strampelli et al. 2020).

Our study area in Gunung Gede Pangrango National Park covered about 52% of the park's total size and exhibited the highest Leopard density estimate of our study areas, followed by Gunung Halimun Salak National Park. Our study area in latter national park covered about 18.2% of its total size of 876.99 km². Giri & Munawir (2021) estimated that suitable Leopard habitat in Gunung Halimun Salak National Park is limited to about 476 km². Follow-up surveys are necessary to see whether our density estimates hold for all of the extents of these two national parks, and also to assess whether they can indeed support 50 and 100 Leopards, respectively, as assumed by Wibisono et al. (2018).

The Leopard density of 8.30 ± SE 4.46 in a non-conservation area like Gunung Malabar Protected Forest corroborates its suitability as Leopard habitat. The rather low Leopard density of 6.12 ± SE 4.01 and low detection probability at home range centre in Gunung Sawal Wildlife Reserve coincides with the highest frequency of conflict between local people and Leopards documented in Java; 48 cases were reported between 2001 and 2015 (Gunawan et al. 2017). Leopard density was lowest in Gunung Guntur-Papandayan Nature Reserve with 4.92 ± SE 2.29 individuals per 100 km^2 despite a high survey effort of 3,614 camera trap days at 60 locations.

Our density estimates for all study areas are bounded by wide confidence intervals, probably because of the low number of recaptures indicating that Leopards were not always detected when present. Several sampling covariates may have impacted differences in detection probabilities. The surveys were conducted during different seasons, and the sampling effort and duration differed between study areas. Habitat features around locations ranged from open to close vegetation. Avoiding disturbed sites is a common behaviour of the Leopard that has been documented across range countries and study areas (Ngoprasert et al. 2007; Khorozyan et al. 2008; Rosenblatt et al. 2016; Havmøller et al. 2019; Kittle et al. 2021; Islam et al. 2021).

With 16.04 ± SE 6.29 individuals/100 km², our study area in Gunung Gede Pangrango National Park holds a higher density than reported for Ujung Kulon National Park in southwestern Java by Rahman et al. (2018). At present, it ranks high in comparison with other study areas in Leopard range countries (Table 8).

Detection probability

The detection probability was positively correlated with proximity of camera traps to animal trails in Gunung Gede Pangrango National Park, Gunung Ciremai National Park, Gunung Malabar Protected Forest and Gunung Halimun Salak National Park. This reasserts the notion that animal trails facilitate Leopard movement (Borah et al. 2014; Ngoprasert et al. 2017), and that the placement of camera traps close to trails enhances the chances of detecting a Leopard (Strampelli et al. 2018). In contrast, the sampling covariate 'effort', i.e. number of camera trap days, was the principal predictor for detection probability in Gunung Sawal Wildlife Reserve

Table 6. Model selection for detection probability (p) analyses in six sites in West Java.

Study area	Model	AICc	ΔAICc	AICc wi	K	p (±SE)	−2 log likelihood
GGPNP	p(trail)	263.19	0.00	0.95	3	0.22 (0.03)	257.19
	p(effort)	270.92	7.73	0.02	3	0.22 (0.04)	264.92
	p(.)	271.35	8.16	0.02	2	0.22 (0.05)	267.35
	p(camera)	273.27	10.08	0.01	3	0.22 (0.05)	267.27
GCNP	p(trail)	79.97	0.00	0.76	3	0.13 (0.04)	67.97
	p(.)	77.68	3.71	0.12	2	0.12 (0.04)	73.68
	p(effort)	78.61	4.64	0.08	3	0.11 (0.04)	72.61
	p(camera)	79.68	5.71	0.04	3	0.11 (0.05)	73.68
GMPF	p(trail)	180.68	0.00	0.81	3	0.22 (0.04)	174.68
	p(effort)	184.72	4.04	0.11	3	0.22 (0.04)	178.72
	p(.)	186.00	5.32	0.06	2	0.21 (0.04)	182.00
	p(camera)	187.96	7.28	0.02	3	0.21 (0.05)	181.96
GSWR	p(effort)	125.24	0.00	0.41	3	0.16 (0.04)	119.24
	p(camera)	125.99	2.75	0.28	3	0.14 (0.03)	119.99
	p(.)	126.54	4.76	0.21	2	0.14 (0.03)	122.54
	p(trail)	128.00	5.30	0.10	3	0.14 (0.04)	122.00
GGPNR	p(effort)	267.99	0.00	0.63	3	0.16 (0.02)	261.99
	p(.)	270.14	2.15	0.21	2	0.16 (0.04)	266.14
	p(camera)	272.10	4.11	0.08	3	0.14 (0.04)	266.10
	p(trail)	272.13	4.14	0.08	3	0.14 (0.02)	266.13
GHSNP	p(trail)	344.69	0.00	0.70	3	0.17 (0.03)	338.69
	p(effort)	357.14	2.45	0.12	3	0.16 (0.02)	351.14
	p(.)	358.46	3.77	0.10	2	0.16 (0.03)	354.46
	p(camera)	360.20	5.51	0.08	3	0.16 (0.03)	354.20

and Gunung Guntur-Papandayan Nature Reserve. In these two study areas, the ratio of 21–33 independent detections per 5–7 identified individuals was lower than in afore-mentioned study areas. This lower detection rate may be the reason for the site covariate 'trail' being less significant than the sampling covariate 'effort'.

Leopards exhibited marked variation in movement parameters. The high detection probability and high movement parameters of both female and male Leopards in Gunung Guntur-Papandayan Nature Reserve may indicate that they used a high proportion of the surveyed area but avoid the central volcanic part. The lower movement parameters in Gunung Gede Pangrango National Park may indicate a high prey abundance in the surveyed area.

Leopard occupancy

Leopard occupancy in all our study areas was high in forests, a site covariate that has also been shown to be the preferred habitat type of the Leopard across Sri Lanka (Kittle et al. 2017). This stresses the importance of forest cover for Leopard distribution and persistence, especially in rather small isolated areas that do not afford the protection level of national parks like Gunung Sawal Wildlife Reserve and Gunung Malabar Protected Forest. As pointed out by Wibisono et al. (2018), the Javan Leopard has been under high pressure because of habitat isolation as a result of severe forest fragmentation since at least the turn of this century.

In Gunung Gede Pangrango National Park, the Leopard occupancy model based on the relative abundance index (RAI) of Wild Boar ranked even higher than the one based on forest cover. It also ranked high in four study areas, followed by RAI of Red Muntjac in three study areas. This result underscores the significance of integrating RAIs of potential prey species into modelling

Table 7. Single-season occupancy models for Javan Leopard distribution in six study areas in West Java, Indonesia.

Study area	Models	AICc	ΔAICc	AICc wi	K	Naïve estimate	Ψ (±SE)	p (±SE)
GGPNP	Ψ(boar),p(trail)	249.09	0.00	0.55	4	0.65	0.67 (0.13)	0.22 (0.03)
	Ψ(forest),p(trail)	251.91	1.82	0.22	4	0.65	0.67 (0.11)	0.22 (0.03)
	Ψ(muntjac),p(trail)	255.56	1.98	0.20	4	0.65	0.67 (0.12)	0.22 (0.03)
	Ψ(village),p(trail)	256.40	7.31	0.02	4	0.65	0.66 (0.12)	0.22 (0.03)
	Ψ(chevrotain),p(trail)	259.60	10.51	0.01	4	0.65	0.66 (0.11)	0.22 (0.03)
	Ψ(road),p(trail)	260.82	11.73	0.00	4	0.65	0.66 (0.12)	0.22 (0.03)
	Ψ(elevation),p(trail)	263.08	13.99	0.00	4	0.65	0.66 (0.14)	0.22 (0.03)
	Ψ(river),p(trail)	264.98	15.89	0.00	4	0.65	0.66 (0.14)	0.22 (0.03)
	Ψ(.),p(.)	271.35	22.26	0.00	2	0.65	0.67 (0.10)	0.22 (0.03)
GCNP	Ψ(forest),p(trail)	66.90	0.00	0.66	4	0.42	0.51 (0.21)	0.13 (0.04)
	Ψ(village),p(trail)	70.66	3.76	0.10	4	0.42	0.51 (0.21)	0.13 (0.04)
	Ψ(road),p(trail)	70.79	3.89	0.09	4	0.42	0.51 (0.21)	0.13 (0.04)
	Ψ(elevation),p(trail)	70.79	3.89	0.09	4	0.42	0.51 (0.21)	0.13 (0.04)
	Ψ(boar),p(trail)	74.44	7.54	0.02	4	0.42	0.50 (0.24)	0.12 (0.04)
	Ψ(muntjac),p(trail)	75.17	8.27	0.02	4	0.42	0.50 (0.24)	0.12 (0.04)
	Ψ(chevrotain),p(trail)	75.80	8.90	0.01	4	0.42	0.50 (0.24)	0.12 (0.04)
	Ψ(river),p(trail)	75.94	9.04	0.01	4	0.42	0.50 (0.24)	0.11 (0.04)
	Ψ(.),p(.)	77.68	10.78	0.00	2	0.42	0.50 (0.19)	0.11 (0.04)
GMPF	Ψ(forest),p(trail)	178.88	0.00	0.34	4	0.92	0.94 (0.13)	0.22 (0.04)
	Ψ(boar),p(trail)	178.88	1.78	0.13	4	0.92	0.94 (0.13)	0.22 (0.04)
	Ψ(muntjac),p(trail)	178.88	1.90	0.12	4	0.92	0.94 (0.13)	0.22 (0.04)
	Ψ(river),p(trail)	178.88	2.15	0.10	4	0.92	0.94 (0.13)	0.22 (0.04)
	Ψ(chevrotain),p(trail)	184.56	2.36	0.10	4	0.92	0.93 (0.14)	0.22 (0.04)
	Ψ(elevation),p(trail)	184.56	3.80	0.06	4	0.92	0.93 (0.15)	0.21 (0.04)
	Ψ(road),p(trail)	185.68	3.80	0.06	4	0.92	0.93 (0.15)	0.21 (0.04)
	Ψ(village),p(trail)	185.68	3.80	0.06	4	0.92	0.93 (0.15)	0.21 (0.04)
	Ψ(.),p(.)	186.00	7.12	0.03	2	0.92	0.93 (0.08)	0.22 (0.03)
GSWR	Ψ(forest),p(effort)	112.85	0.00	0.39	4	0.57	0.64 (0.15)	0.16 (0.05)
	Ψ(boar),p(effort)	112.85	1.98	0.20	4	0.57	0.64 (0.15)	0.16 (0.05)
	Ψ(river),p(effort)	126.09	3.24	0.09	4	0.57	0.63 (0.15)	0.14 (0.03)
	Ψ(muntjac),p(effort)	126.09	3.60	0.08	4	0.57	0.63 (0.15)	0.14 (0.03)
	Ψ(.),p(.)	126.54	3.69	0.08	2	0.57	0.63 (0.15)	0.14 (0.03)
	Ψ(chevrotain),p(effort)	127.01	5.16	0.06	4	0.57	0.63 (0.15)	0.14 (0.03)
	Ψ(elevation),p(effort)	127.01	5.16	0.01	4	0.57	0.63 (0.15)	0.14 (0.03)
	Ψ(village),p(effort)	127.13	5.28	0.05	4	0.57	0.63 (0.15)	0.14 (0.03)
	Ψ(road),p(effort)	127.24	7.39	0.04	4	0.57	0.63 (0.15)	0.14 (0.03)
GGPNR	Ψ(forest),p(effort)	241.55	0.00	0.34	4	0.35	0.60 (0.08)	0.16 (0.02)
	Ψ(boar),p(effort)	241.55	1.87	0.18	4	0.35	0.60 (0.08)	0.16 (0.02)
	Ψ(elevation),p(effort)	264.79	3.24	0.09	4	0.35	0.60 (0.15)	0.14 (0.02)
	Ψ(muntjac),p(effort)	264.79	3.40	0.08	4	0.35	0.60 (0.15)	0.14 (0.02)
	Ψ(chevrotain),p(effort)	264.79	4.87	0.07	4	0.35	0.60 (0.15)	0.14 (0.02)
	Ψ(village),p(effort)	266.47	4.92	0.07	4	0.35	0.59 (0.16)	0.14 (0.02)
	Ψ(road),p(effort)	268.53	6.98	0.06	4	0.35	0.59 (0.16)	0.14 (0.02)
	Ψ(river),p(effort)	269.91	8.36	0.06	4	0.35	0.58 (0.16)	0.14 (0.02)

Study area	Models	AICc	ΔAICc	AICc wi	K	Naïve estimate	Ψ (±SE)	p (±SE)
	Ψ(.),p(.)	270.14	8.59	0.05	2	0.35	0.58 (0.15)	0.14 (0.02)
GHSNP	Ψ(forest),p(trail)	339.57	0.00	0.51	4	0.74	0.80 (0.11)	0.17 (0.03)
	Ψ(muntjac),p(trail)	339.56	1.56	0.15	4	0.74	0.80 (0.11)	0.17 (0.03)
	Ψ(boar),p(trail)	349.56	1.98	0.12	4	0.74	0.80 (0.12)	0.17 (0.04)
	Ψ(river),p(trail)	349.52	3.95	0.04	4	0.74	0.80 (0.12)	0.17 (0.04)
	Ψ(chevrotain),p(trail)	349.52	3.95	0.04	4	0.74	0.79 (0.11)	0.16 (0.03)
	Ψ(road),p(trail)	346.57	7.00	0.04	4	0.74	0.79 (0.11)	0.16 (0.03)
	Ψ(elevation),p(trail)	346.66	7.09	0.04	4	0.74	0.79 (0.11)	0.16 (0.03)
	Ψ(village),p(trail)	346.69	7.12	0.04	4	0.74	0.78 (0.11)	0.16 (0.03)
	Ψ(.),p(.)	358.46	8.89	0.02	2	0.74	0.78 (0.11)	0.17 (0.03)

Image 4. Male Javan Leopard in Gunung Sawal Wildlife Reserve. © MoEF, TSI, Formata and CI.

Image 5. Female Javan Leopard in Gunung Guntur-Papandayan Nature Reserve. © MoEF and CI.

Leopard occupancy. Lamichhane et al. (2021) showed that the presence of the Wild Boar is a strong predictor of Leopard occupancy in a forested mountain range in Nepal. In several study areas in Asia, the Wild Boar constitutes a major proportion of the Leopard's diet (Sharbafi et al. 2016; Kandel et al. 2020), especially when other prey species are depleted (Ghoddousi et al. 2017). It also exhibits a higher temporal and spatial overlap with the Leopard than other ungulates (Ghoddousi et al. 2020; Kittle et al. 2021; Sehgal et al. 2022).

The remaining site covariates elevation, distance to road, village and river were less important predictors for Leopard occupancy in all our study areas.

Image 6. Male Javan Leopard in Gunung Halimun Salak National Park. © MoEF and CI.

Management implications and recommendations

Density estimates are not equally robust, and under- or over-estimating densities can have substantial implications for conservation management and policy (Foster & Harmsen 2012; Hayward et al. 2015). We recommend to maximise capture and recapture probabilities in future surveys by implementing a closer-knit camera trapping design with a maximum spacing of 1,500 m between locations and placing two opposite camera traps per location. Regular monitoring surveys in all our study areas and beyond are essential for

Table 8. Leopard densities in national parks (NP), wildlife sanctuaries (WS), and protected areas in range countries in Asia.

Study area	Leopard density per 100km²	Source
Rajaji Corbett NP, India	14.99 ± SE 6.9	Harihar et al. (2009)
Mudumalai NP, India	13.17 ± SE 3.15	Kalle et al. (2011)
Ujung Kulon NP, Java	12.8 ± SE 1.99 in dry season 11.24 ± SE 3.16 in wet season	Rahman et al. (2018)
Kuiburi NP, Thailand	12.6 ± SE 3.6	Steinmetz et al. (2009)
Ruhuna (Yala) National Park, Sri Lanka	12.1	Kittle et al. (2017)
Horton Plains NP, Sri Lanka	11.7 ± SE 5.5	Kittle & Watson (2017)
Kuno WS, India	11 ± SE 4.6	Pawar et al. (2019)
Wilpattu NP, Sri Lanka	10.4 ± SE 1.9	Kittle et al. (2021)
Sarigol NP, Iran	8.86 ± SE 3.60	Farhadinia et al. (2019)
Royal Manas National Park, Bhutan	6.25–15.93	Goldberg et al. (2015)
Mondulkiri Protected Forest, Cambodia	3.6 ± SE 1.0	Gray & Prum (2012)
Manas NP, India	3.4 ± SE 0.82	Borah et al. (2014)
Tembat Forest Reserve, Malaysia	3 ± SE 1.02	Hedges et al. (2015)
Bamu NP, Iran	1.87 ± SE 0.07	Ghoddousi et al. (2010)
Shaanxi Province, China	2.0 ± SE 0.53; 2.4 ± SE 0.67	Yang et al. (2021)
Kamdi Biological Corridor, Nepal	1.5 ± SE 0.49	Kandel et al. (2020)
Jigme Singye Wangchuck NP, Bhutan	1.04 ± SE 0.01	Wang & Macdonald (2009)
Srepok WS, Cambodia	1	Rostro-García et al. (2018)

assessing changes in Leopard densities as a baseline for readjusting management interventions.

Efforts to recover the Javan Leopard need focus on maintaining landscape integrity and reducing poaching (Wibisono et al. 2018). Integrated management of suitable Leopard habitat in West Java is utmost important, because Leopards inhabit forest types under three different management regimes, namely conservation forests, protected forests and production forests, which are currently managed by three different authorities. Priority management interventions inside and outside protected areas must be aimed at preventing further habitat fragmentation and decline of prey species. Degraded habitats need to be restored to improve habitat quality, ideally with the support of multiple stakeholders. Since a large part of landscapes suitable for Leopard survival includes production and secondary forests (Wibisono et al. 2018), we strongly recommend identifying and mapping potential wildlife corridors with low conflict risk that are suitable to increase connectivity between forest patches and protected areas. We emphasize that both a landscape approach and conflict mitigation is imperative to ensure the long-term viability of both Leopard and prey populations.

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Bahasa: Macan Tutul Jawa adalah satwa endemik pulau Jawa di Indonesia dan diklasifikasikan sebagai *Endangered species*. Informasi terpercaya tentang status populasi, distribusi, dan kepadatannya masih kurang, namun sangat penting sebagai pedoman dalam upaya konservasi dan memberikan tolok ukur untuk intervensi pengelolaan. Studi kami mewakili perkiraan kepadatan dan hunian empiris pertama untuk Macan Tutul di Jawa Barat dan menyediakan data dasar untuk wilayah ini. Kami menggunakan data *camera trap* yang dikumpulkan dari Februari 2009 hingga Oktober 2018 di enam wilayah studi yang meliputi upaya pengambilan sampel selama 10.955 hari rekam di total area seluas 793,5 km². Kami mengidentifikasi 55 individu Macan Tutul di seluruh wilayah studi dan memperkirakan kepadatan Macan Tutul menggunakan *spatially explicit capture-recapture*. Perkiraan kepadatan berkisar dari 4,9 individu/100 km² di Cagar Alam Gunung Guntur-Papandayan hingga 16,04 individu/100 km² di Taman Nasional Gunung Gede Pangrango, yang merupakan salah satu kepadatan macan tutul tertinggi secara global. Berdasarkan data deteksi, kami memodelkan hunian Macan Tutul satu musim menggunakan tiga kovariat pengambilan sampel dan delapan kovariat lokasi. Pemodelan mengungkapkan bahwa dua kovariat yaitu tutupan hutan dan keberadaan Babi Hutan adalah prediktor terkuat untuk hunian Macan Tutul di wilayah studi kami. Kami merekomendasikan untuk menilai dan memantau distribusi, kepadatan dan hunian Macan Tutul di wilayah lain di Jawa dan menekankan bahwa pendekatan lansekap sangat penting untuk konservasi Macan Tutul.

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