

RESEARCH ARTICLE

Assessing population structure and body condition to inform conservation strategies for a small isolated Asian elephant (*Elephas maximus*) population in southwest China

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Abstract

The Asian elephant (*Elephas maximus*) population in Nangunhe National Nature Reserve in China represents a unique evolutionary branch that has been isolated for more than twenty years from neighboring populations in Myanmar. The scarcity of information on population structure, sex ratio, and body condition makes it difficult to develop effective conservation measures for this elephant population. Twelve individuals were identified from 3,860 valid elephant images obtained from February to June 2018 (5,942 sampling effort nights) at 52 camera sites. Three adult females, three adult males, one subadult male, two juvenile females, two juvenile males and one male calf were identified. The ratio of adult females to adult males was 1:1, and the ratio of reproductive ability was 1:0.67, indicating the scarcity of reproductive females as an important limiting factor to population growth. A population density of 5.32 ± 1.56 elephants/100 km² was estimated using Spatially Explicit Capture Recapture (SECR) models. The health condition of this elephant population was assessed using an 11-point scale of Body Condition Scoring (BCS). The average BCS was 5.75 (n = 12, range 2–9), with adult females scoring lower than adult males. This isolated population is extremely small and has an inverted pyramid age structure and therefore is at a high risk of extinction. We propose three plans to improve the survival of this population: improving the quality and quantity of food resources, removing fencing and establishing corridors between the east and wet parts of Nangunhe reserve.

Introduction

The Asian elephant (*Elephas maximus*), as the largest terrestrial mammal in Asia, is considered an ecosystem engineer because it can modify its habitat and aid in seed dispersal [1, 2]. As an umbrella species, its conservation contributes to the preservation of biodiversity in the tropical moist and tropical dry broadleaf forests of Southeast and South Asia [3–5]. It is also considered

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a flagship species that can attract interest in the protection of biodiversity [6]. It is a Class I Key Protected Species in China and listed as Endangered under the IUCN Red List [7, 8]. China sustains a population of around 300 wild Asian elephants, divided into seven geographic populations [9, 10]. Most of these populations are located in Mengyang, Mengla and Shangyong areas of Xishuangbanna National Nature Reserve, while there are also a few populations in Simao, Jiangcheng and Lancang counties of Pu'er city and one small isolated population in the Nangunhe National Nature Reserve (NNNR) of Lincang city [9, 11].

The conventional methods used for tracking Asian elephants in dense forest are difficult to accomplish and usually fail to provide accurate estimation of population size and age structure [12, 13]. Although it is relatively easy to detect signs of elephant presence, such as dung or footprints, during sign surveys [14], estimates of the number of individual Asian elephants derived from signs are highly inaccurate and unreliable [15]. Individuals can be identified using non-invasive DNA methods, but this requires relatively fresh fecal samples and the lab costs can be quite high. Population size can only be estimated from DNA using genetic capture-mark-recapture methods, which can be time and labor intensive [16, 17]. Furthermore, since elephant calves have lower defecation rates than adults, this method can underestimate the number of young individuals in a population [18].

Infrared-triggered camera technology can make up for the above-mentioned disadvantages [19, 20]. Cameras cause minimal disturbance to animals and their habitat, can be used continuously for long periods of time, can withstand harsh weather conditions, and are relatively cheap [19, 21, 22]. They are widely used to conduct baseline surveys of protected species [23, 24], to monitor endangered wildlife [25], to study habitat use [26], to observe animal behavior [27], and to study the mechanisms of coexistence in sympatric species [28, 29]. Moreover, infrared cameras can also be used to estimate population size and density in conjunction with Spatially Explicit Capture-Recapture models (SECR) [30–33]. This technology has been used extensively to estimate the population density of multiple species, especially those possessing easily observed markings, such as the snow leopard (*Panthera uncia*), the leopard cat (*Prionailurus bengalensis*), the Sumatran tiger (*Panthera tigris* ssp. *Sumatrae*), and the serval (*Leptailurus serval*) [33–36]. For species without natural markings, individual identification can still be conducted using morphological features. A number of studies have identified individual elephants in this way by directly photographing them or by obtaining images from infrared cameras [17, 37–39].

Effective conservation strategies for small, threatened populations need detailed baseline information on both the population size and its habitat. Population structure and density estimation are other essential features that can be used to study the ecology of wildlife populations [40, 41] while, the Body Condition Scoring (BCS) is an index of an animal's health that reflects habitat quality [42]. It can be used in conjunction with population structure and density estimation to obtain a more accurate picture of the health of a population. Furthermore, it can be used for both longitudinal and cross-sectional studies, is comparatively inexpensive, and is easy to use [43]. While BCS is individual-based, it is most meaningful when applied to a population as an early indicator of the impact of management actions on the average health of the population [43, 44]. For Asian elephants, the BCS obtained through photographs can be as accurate as an ultrasonic subcutaneous fat measurement, thus providing a safer and non-invasive method to evaluate the health condition of wild populations [43, 45].

In China, population studies on Asian elephants have mainly been concentrated in Xishuangbanna National Nature Reserve [17, 37]. These studies were limited to population size and none have assessed the health condition of the population [13, 46]. Although it is a unique evolutionary unit in China, the isolated Nangunhe National Nature Reserve population has been poorly studied. The lack of scientific data and information on its population

structure, genetic relatedness, and health status prevent the development of efficient conservation strategies. Additionally, this population is facing threats from habitat loss, fragmentation and illegal hunting [47–49]. An accurate understanding of the current situation of the elephant population in NNNR, especially its structure and health condition, is key to establishing a baseline for the development of more effective protection and management schemes.

In this study, our aim was to determine the size, density, demographic structure and health condition of the NNNR Asian elephant population using SECR and BCS with data from infra-red camera trapping. We sought to understand which factors might have affected the population size in recent years in order to develop targeted and effective protection strategies.

Material and methods

Ethics statement

Both National Forestry and Grassland Administration of China and Yunnan Forestry and Grassland Administration reviewed all sampling procedures and approved permits for the work conducted in NNNR. Non-invasive methods were applied and approval from an Institutional Animal Care and Use Committee or equivalent animal ethics committee was therefore not required.

Study area

The study area is located in the western part of the Nangunhe National Nature Reserve, Yunnan, where elephants are found [47, 48] (Fig 1). It occupies 70.82 km² at latitude 23° 13'–23° 19'N, longitude 98° 54'–99° 05'E, and the altitude ranges from 510 m to 1747 m. Rainfall is highly seasonal, with a dry season between November and April, and a rainy season between May and October. Mean precipitation is 351.3 mm in the dry season and 1983.3 mm in the rainy season, while the temperature varies at different altitudes. The average monthly temperature is hottest in July, varying between 12.3–25.5°C and it is coldest in January, with values between 2.8–14.3°C [50]. Vegetation and climate also vary across elevation zones. Tropical forest and tropical monsoon forest are located at altitudes below 600 m, middle elevation ranges are dominated by subtropical monsoon evergreen broad-leaf forests, and evergreen broadleaf forests are found above 1700 m [48]. Bamboo forest, shrub, and grasslands are scattered throughout the area. Deforestation along the China and Myanmar border has disrupted the connectivity between elephant populations that are found in both countries [47]. An iron fence in the southern part of the reserve is used to protect the surrounding villages from wildlife (Fig 1).

Camera trap set-up

We carried out the survey for four months between February and May 2018 using automatically triggered camera traps (Ltl Acorn 6210). 52 camera stations recorded for 43–129 camera-trap nights totaling 5,942 trap nights (114.27±19.83) (Fig 1). All camera stations were located in either evergreen broadleaf forest, broadleaf and bamboo forest, bamboo forest, pine forest or nearby brush forest, which represents the preferred habitat of elephants in NNNR. We systematically deployed camera traps along trails and spaces where there were signs of elephants, including lying sites, foraging sites, footprints, dung, and urine marks. We attempted to deploy cameras throughout the reserve according to a 1 km² grid. We increased the number of cameras in the grid cells where many elephant signs were found, but always with a minimum of 200 m between any two cameras. We avoided the northwestern part of the reserve as the topography is rough, with steep cliffs of up to 1747 meters high, and has no records of elephants [51, 52].

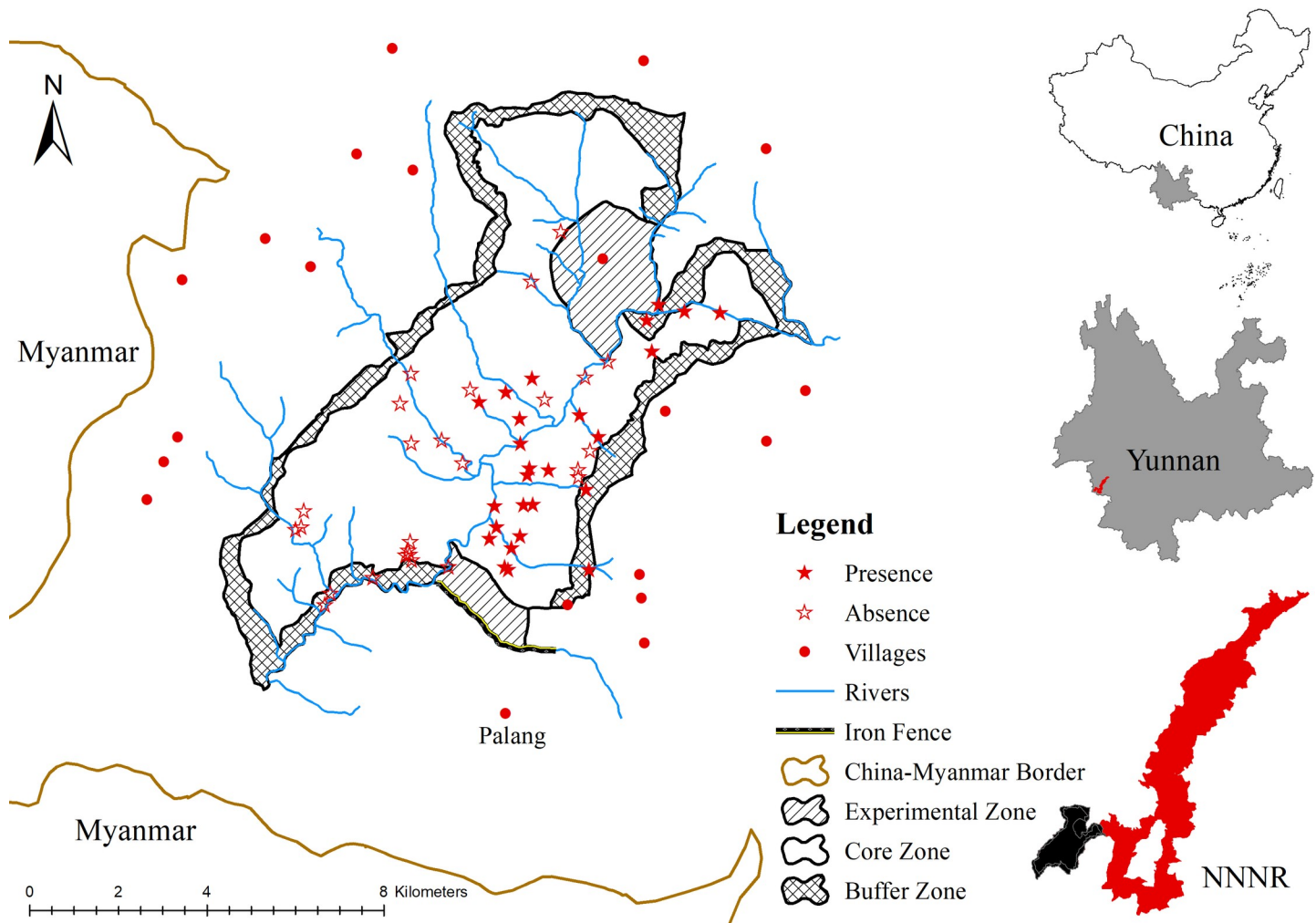


Fig 1. Map of study area in NNNR showing the camera sites with or without elephant detections.

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Cameras were strapped onto trees at approximately 1.5 m above the ground with the sensor parallel to the ground to maximize the extension of the detection zone. The positions of all the camera sites were recorded by GPS. To avoid blank images caused by sunlight, the cameras were never placed facing east. Camera traps were hidden as much as possible to reduce the disturbance to wildlife and the probability of being stolen. Camera traps were set to operate 24 hours per day and programmed to take three photographs and one 12-second video in a sequence without delay. Cameras registered the date and time for each exposure. All camera traps were left operating continuously for a maximum of four months. SD cards and batteries were replaced every month. We recorded the time of installation and retrieval of each camera and calculated the total duration of sampling.

Individual identification

The images obtained from the camera traps were categorized into independent events, which were defined as “sequences” of adjacent images. For one elephant unit (defined as all or the maximum number of individuals in a group), the sequence included all the images from the first individual entering the field to the last one exiting it, making it possible to identify

Table 1. Morphological characteristics used for individual identification of elephants photographed in NNNR, between February and May 2018.

Characteristics	Categories	Description
Age	Adult (>15years)	With the highest shoulder height
	Subadult (5-15years)	Shoulder height reaches an adult's eyes
	Juvenile (1-5years)	Shoulder height reaches half the height of an adult
	Calf (0-1year)	Below an adult's knee
Sex	Female	Without obvious tusks but with prominent breasts, belly swelling or the presence of nursing offspring
	Male	With visible testicles or penis, and/or obvious tusks
Facial bones	Wisdom tumor	Size
	Bones between the eyes	Extent of prominence
	Upper margin of eyes	Extent of depression
Tusks	Length	Very short/short/long compared with trunk
	Thickness	Thick/normal/slender
	Shape	Straight/bent
	Crack	Yes/no
Ear	Upper edge	Fold/unfold
	Lobe	V-acute/U-rounded
	Lobe tear	Yes/no
	Ear hole	Yes/no
Tail brush	Standard	Present/both sides/both-continuous
	Nonstandard	Absent/single side/both-discontinuous
Others	Old scars and injuries	-

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different individuals based on distinct features. For solitary individuals, a sequence was a series of captured images of the same individual within a continuous time period [53]. Only images from which age and sex classification was possible were used for individual identification [39, 53]. Animals were classified as either adult, subadult, juvenile or calf using approximate shoulder height as recommended by previous studies, and sex was mainly determined by secondary sexual characteristics [54–56] (Table 1). We defined the age structure as the ratio of adults, subadults, juveniles and calves. Reproductive ability was defined as the ratio of age structure between adult and juvenile females [39], due to the absence of subadult and calf females in this reserve. Male elephants living completely or mostly outside the herd were classified as solitary males [12]. Based on individual events, a capture-history event database was established to record the individuals and their characteristics. Individuals were identified based on morphological features including facial bone structures, ear shape and size, tusks, presence of back and tail hair, old scars and injuries, as well as physical characteristics related to sex and age classes [17, 37, 38, 57] (Table 1).

Density estimation

We used a spatially explicit capture-recapture models (SECR) to estimate density of elephants in NNNR. The population is small and isolated and without any migrants, thus conforming to the “closed population” assumption of SECR [58]. The model accounts for movement and detect ability when estimating density by combining a state model and an observation model, which together describe how the observed data were generated [58]. The state model describes statistically the mechanisms determining the distribution of the animals in the study area, while the observation model quantifies the probabilities of detection or capture, given the surveyed region, the animals' locations and characteristics during different sessions [59]. SECR models can be described as generalized linear mixed models that assume that each individual i

in the population has its own unobserved activity center S_i , and that all activity centers $S_1 \cdots S_N$ are distributed across the study area [60, 61].

The encounter rate of an individual i with a given trap j located at X_j is a monotonically decreasing function of the distance from S_i to j . Y_{ij} , the number of times individual i is detected by trap j during a sampling occasion, is a random variable following a Poisson distribution and with mean λ_{ij} [62]:

$$Y_{ij} \sim \text{Poisson}(\lambda_{ij})$$

For an elephant i captured by a trap j , the model assumes a log-linear form [63]:

$$\text{Log}(\lambda_{ij}) = \text{Log}(\lambda_0) - \left(\frac{1}{2\sigma^2}\right) \|S_i - X_j\|^2$$

Here, λ_0 is the baseline encounter probability, the function $\|S_i - X_j\|^2$ is the distance between the activity center and the trapping station, and σ is the Gaussian scale parameter for the distance function between activity centers and trap locations; assuming a bivariate normal model of space use, sigma can be used to calculate a 95% activity area radius.

SECR models estimate the density of animal activity centers in an area large enough that animals residing beyond it have a negligible chance of being detected [58]. The maximum distance between the east and west boundaries of elephant distribution was 10 km, and so we defined our study area as extending 5 km beyond all camera stations, corresponding to an area of 255.8 km² [64].

SECR 3.1.5 package in R 3.6.1 was used for density estimation. Data were prepared as an R object of class “caphist”. This object included both the capture data and the detector layout. The file named “capture histories” contained data on individual identified at each sampling occasion from the specific detector (camera). The detector file contained data on cameras’ ID, and x-y coordinates. Five different sessions, corresponding to each of the months and one corresponding to the whole survey period, were used to run the model to see the estimation accuracy under different detection efforts.

Body condition scoring

We established a database of each identified individual and the images with the best angle of each individual elephant were used to score the body condition. Compared to previous studies, our target population size was small, and the sample size was limited, therefore we used a simple method which can rapidly and more easily be applied to wild elephant populations. In this study, we applied a BCS method that focuses on six physical characteristics and ranks the elephant’s body condition according to an 11-point scale [42, 43]. Five of the clearest images for each physical characteristic were selected to assess the body condition. Thirty images were used to calculate the comprehensive scores for each individual. This scoring method is based on the extent of visibility of depressions around bone structures. Depressions around bones become visible as an animal loses its subcutaneous fat deposits and muscles in the region concerned, thereby making bones appear more prominent. Skull, pectoral girdles in shoulders, vertebral column, ribs and pelvic girdles are prominent bone structures. Thick rolls of skin that fold below the neck can accumulate fat, and thus, also represent a criterion of good body condition. We created a reference scale of 5 scored elephants with rankings of 1, 3, 5, 7, 9, with numerically higher values corresponding to better body condition (Table 2). However, the range of scores extended from 0 to 10 due to the possibility of greater variation. For example, if all the ribs of an elephant were visible, it meant that this individual presented a worse body condition than 1 and thus, it would be assigned 0. If an individual presented a fatter condition than 9 and had very thick rolls of skin fold below the neck, it would be assigned a score of 10.

Table 2. Diagnostic characteristics pertaining to scores in photographic scale.

Score	Characteristics
1	Ribs from shoulder to pelvis are visible, some ribs prominent (spaces in between sunken in)
3	Some ribs visible (spaces in between not sunken in), shoulder and pelvic girdles prominent
5	Ribs not visible, shoulder and pelvic girdles visible
7	Backbone visible as a ridge, shoulder and pelvic girdles not visible
9	Backbone not visible or difficult to differentiate and pelvic bones not visible

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Scores ranging from 0–3 were considered poor, 4–7 were considered medium and 8–10 were considered good [44]. Pearson's correlation coefficient (r) was used to study the relationship between BCS and three covariates: sex, age, and whether an individual was solitary or in a herd.

Results

Population size and density

70,902 images were obtained, of which 7.34% (5,207) contained Asian elephants. There was a total of 134 independent events, including 40 events of elephants in a herd and 94 events of solitary elephants. Excluding the image data that could not be used for individual identification, there were 3,860 valid Asian elephant images belonging to 85 independent events (26 events of individuals in a herd and 59 events of individuals). Generally, all herds and individuals had similar frequencies of recapture histories during the study period, particularly herds. However, solitary elephants were image-captured with a minor difference: a minimum of 16 capture times for AE12 compared to a maximum of 25 capture times for AE10 (Table 3).

A total of 12 individuals were identified among these valid independent events (Fig 2; S1 Dataset). The elephant population size in each session was consistent, except in February. Moreover, the population size estimated by SECR was 12.00 ± 0.71 (95%CI 12.00,12.11; Table 4). The estimated density by SECR was 5.32 ± 1.56 elephants/100km² (95%CI 3.02,9.36). April had the lowest monthly density estimation at 6.07 ± 1.79 elephants/100km², while May had the highest density estimation at 24.43 ± 7.20 elephants/100km². The movement parameter σ was twice as large in April ($6643 \text{ m} \pm 2356 \text{ m}$) than in May ($3771 \text{ m} \pm 1471 \text{ m}$).

Table 3. Number of capture events per individual per month.

Individual No.	Age	Gender	Tusk	Type	Number of Capture events				
					Feb.	Mar.	Apr.	May	Total
AE01	Juvenile	Male	Yes	Herd	2	6	5	8	21
AE02	Adult	Female	No	Herd	3	5	6	6	20
AE03	Adult	Female	No	Herd	3	5	6	7	21
AE04	Juvenile	Female	No	Herd	2	6	5	7	20
AE05	Calf	Male	No	Herd	3	6	8	5	22
AE06	Adult	Female	No	Herd	4	6	8	5	23
AE07	Juvenile	Female	No	Herd	4	6	9	6	25
AE08	Juvenile	Male	Yes	Herd	4	7	6	7	24
AE09	Sub-adult	Male	No	Solitary	3	9	2	9	23
AE10	Adult	Male	Yes	Solitary	2	3	13	7	25
AE11	Adult	Male	No	Solitary	3	5	8	5	21
AE12	Adult	Male	No	Solitary	2	6	1	7	16
Total	-	-	-	-	35	70	77	79	261

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Fig 2. Asian elephants individually identified in NNNR, China. Each individual’s most distinguished characteristic was emphasized, except for the easily identified AE05 and AE10, the only calf and adult male with tusks respectively.

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Demographic structure

We identified an inverted pyramid age structure for this population: three adult females, three adult males, one subadult male, two juvenile females, two juvenile males and one male calf, with a sex ratio of 1:1.4 using females as a reference (Table 4). The three adult males comprised

Table 4. Population density estimation using SECR models for five sessions.

Sessions	Occasions	Density			λ_0		sigma		Population size		
		estimate	SE.estimate	95% CI	estimate	SE.estimate	estimate	SE.estimate	estimate	SE.estimate	95% CI
February	11	10.71	3.31	5.91–19.38	0.15	0.04	2983	664	14.00	2.19	12.35–23.43
March	26	6.57	1.94	3.73–11.58	0.07	0.02	4193	700	12.20	0.87	12.00–17.95
April	22	6.07	1.79	3.45–10.70	0.02	0.004	6643	2356	12.05	0.75	12.00–16.87
May	26	24.43	7.20	13.87–43.03	0.01	0.003	3711	1471	12.03	0.74	12.00–16.48
Total	85	5.32	1.56	3.02–9.36	0.02	0.003	6474	1065	12.00	0.71	12.00–12.11

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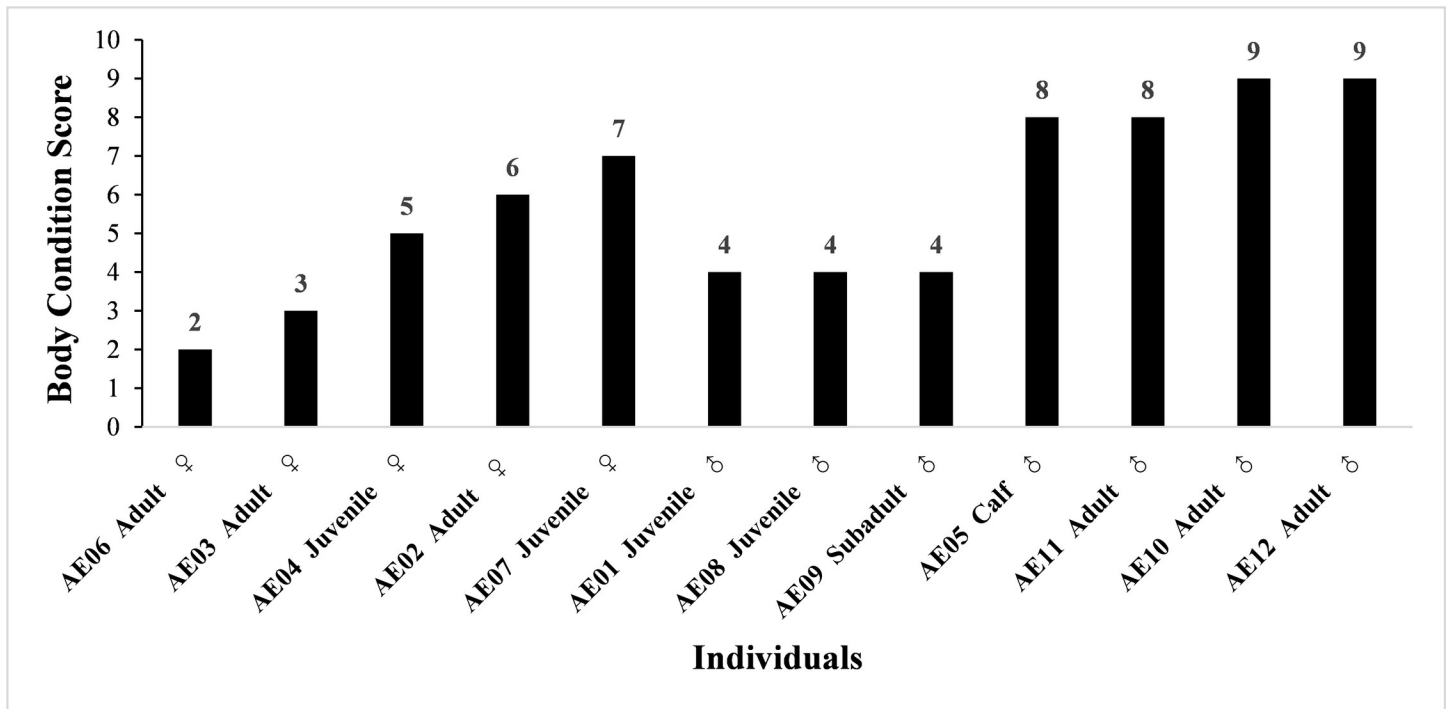


Fig 3. Body condition score of the 12 individuals identified in NNNR.

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one tusker and two without tusks (known as makhna), giving an adult tusked to tuskerless male ratio of 1:2. The subadult male was also a makhna, increasing the tusker to tuskerless male ratio to 1:3. The ratio of reproductive ability was 1:0.67.

The social network was comprised by AE01-AE08 that formed a joint-family unit. Calf AE05, adult female AE06 and juvenile female AE07 formed a mother-calf unit which occasionally departed from the large family unit. AE06 was the mother of AE05, evidenced by images of the calf nursing from the female. The solitary subadult male AE09 and adult male AE10 occasionally joined the family unit.

Body condition scoring

The average population BCS was 5.75 ($n = 12$, range 2–9; Fig 3). 33.3% of the elephants were in a good body condition, while 50% and 16.7% were in medium and poor body conditions, respectively (Fig 3). Age was not strongly correlated to BCS ($r = 0.03$), but sex was ($r = 0.42$), as adult males had better body conditions than adult females. None of the only three fertile females in this population was classed as having a good BCS. AE02 had a BCS of 6 just above the average score, while AE03 and AE06 were in poor body conditions with a low BCS of 3. Individuals that were part of the herd had a lower BCS than solitary individuals ($r = 0.53$).

Discussion

Population size and density

Accurate assessment of population size is essential for species conservation and management [65]. Identification from captured images was robust enough to identify individuals [66], unlike dung and footprints which are easily influenced by slope, soil quality and climatic factors [67]. This study used cameras installed in elephant preferred habitats that covered most of

Table 5. Unnatural deaths of Asian elephant since the establishment of NNNR.

Year	Number of individuals	Cause of death	Data resources
1987	Two: One female and one male	Illegal killing	[50, 71]
1988	Four: Two adult males, one adult female and one calf	Poaching, electrocuting and unknown reason	[47]
1995	One male	Unknown	[49]
1996	One male	Retaliatory killing by local people	[48]
1997	Three: One female, one male and a calf	Unknown	[50]
2003	A Subadult male (about 10 years old)	Unknown	[50]
2008	One subadult male	Unknown	Communication with local residents and rangers
2011	One juvenile	Unknown	[50]
2016	One adult male	Unknown, but the tusks showed visible saw marks	Communication with local residents and rangers

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the western part of the reserve. This provided a higher chance of obtaining data reflecting the real population, leading to a more reliable population assessment than in the study that used drone surveys [49]. Previous studies have estimated this population to be around 20 individuals. Although population estimation using different methods could generate bias in direct comparison, research has shown that this elephant population has remained small during the last few decades [49, 67–69] (S1 Table). The NNNR population is an extremely small and isolated population, compared with other elephant populations found around the world [3, 9, 10, 12]. Historic illegal hunting has had a direct impact on this population with a total of 15 unnatural deaths recorded since 1987 (Table 5). Additionally, 3 of 4 elephants found dead since 2003 have been immature individuals (Table 5). Moreover, the fact that elephants have a long adolescence and long inter-birth intervals means it takes time for elephants to recover and they are more vulnerable to local population extinction [12, 70], especially if young individuals are being poached or dying from other unnatural causes. All these facts result in the current small population size that could lead to the extinction of this local population.

SECR modelling has become a powerful tool to estimate the size of small populations like the one in NNNR [32]. The model defines the activity center according to the range of the species activities [72], so it is easy to overestimate the population density in a short survey period, which was confirmed by the monthly estimates in this study (Table 4). We first used single monthly sessions to run the SECR models, with which we obtained a strong difference in density estimation. The SECR models simulated a larger movement buffer ($\sigma = 6643$ m) in April, which resulted in the smallest population density. May presented the highest density because 8 cameras captured elephants, and the distance between each one was less than 800 m, which is smaller than their daily movements [73, 74]. The fluctuation in estimates from single month session results by SECR prompted us to use the combined four months' data as the fifth session to run the model. Parameter estimates from this session were the most accurate of the five [39].

We compared these results with those from other populations in order to improve our understanding of elephant ecology and develop more detailed management and conservation plans [75]. However, with no other SECR analyses conducted on other populations in China, we used the crude density estimation (estimated population number/study area) to draw comparison between the NNNR population and others in Yunnan [39]. The crude density estimation of Asian elephants in NNNR was the highest at 16.9 elephants/100 km², compared with that in Shangyong (69 individuals, 646 km²), Mengyang (82 individuals, 998.4 km²) and Mengla (40 individuals, 939.9 km²) with a density of 10.68, 8.21, and 4.26 elephants/100 km², respectively [13, 17]. The relatively high population density might lead to more intensive competition among individuals for limited natural resources, and even greater human-elephant

conflict as elephant resort to crop raiding for food, which could be further studied in the future.

Population structure in NNNR

The juveniles in this population accounted for 33% of the population, higher than the minimum of 20% needed for the population to be self-sustaining over a short period [18]. However, a previous study confirmed these individuals were related to each other [76]. Inbreeding will be more serious in the near future due to the small population size.

We could not match adult females with their offspring in the groups relying on observed behaviors alone, even though we captured intimate interaction between AE02 and AE08, as well as between AE03 and AE04. In recent years, the death of adult females has not been recorded in the reserve (Table 5). Therefore, we assumed that all the current juveniles were the offspring of these three adult females. Genetic studies are urgently needed to better understand the lineage and degree of inbreeding depression in the NNNR population.

Two tuskless juveniles were observed with body heights similar to that of the tusked juvenile males. These were identified as females, though it should be noted that tuskless males can occur in populations subjected to intensive historical poaching pressure [12, 77]. Since makhnas are common in this population, it would be helpful to conduct genetic studies on this population that can confirm the sex of these two juveniles.

The unbalanced sex ratio skewed towards males is not beneficial for population growth [78]. Male elephant can recognize kin and avoid inbreeding, and so male-biased populations usually indicate an increased genetic diversity and an ability to persist [79]. However, without introductions from elsewhere, such a small population with only 7 males is likely to go extinct in the near future. Females do not enter the breeding period until they are 10–14 years old and as such the two juvenile females in the NNNR population still need 3–7 years to become mature [9, 12, 80]. Currently, only females AE02, AE03 and AE06 are of reproductive age, but the latter was nursing a calf, leaving only two sexually active females in the reserve. In either case, the scarcity of fertile females would be the primary constraint on population growth due to their long birth intervals.

Health condition

We chose a simple but accurate body condition method to assess the health of this small population. Our results showed a higher body condition of adult males than adult females. This may be because adult males are known to have larger home ranges than adult females [74, 81], and are more tolerant to human disturbance [82]. This means they can more frequently forage in areas near the reserve boundary, where intensive anthropogenic activities like hunting, grazing, fishing and collecting mushrooms have also been recorded by cameras. Additional nutritional stress from lactation, as observed in AE06, can also cause a poorer body condition than in males [44]. Furthermore, the presence of a calf can limit movement for members of the female members of the herd [81], while the solitary males have no such limitations. Additionally, the other two adult females both presented a medium health condition, which would not be conducive for reproduction [42].

Eight individuals (66.7%) had medium or poor body conditions during the survey period, which corresponded to the dry season. Since the quantity and quality of food and availability of water are the primary factors determining the body condition of free-ranging elephants [42], both female and male individuals show an obviously thinner body condition during the dry season compared to the rainy season [83]. We did not have the opportunity to conduct camera trap surveys during the rainy season since many cameras failed to work in this season.

Additionally, the rainy season coincides with the harvest period. In the past, especially in recent years, NNNR elephant-damage compensation data has shown that the elephants forage for corn and rice during the rainy season from July to October (Li Zhimin, personal communication). Therefore, we assume that at least some males in this population are foraging crops to supplement their diet. Future studies should focus on determining how crops contribute to improving the body condition of elephants during the rainy season.

Body condition assessment in this study could have implications for the research and conservation of other elephant populations. Since the vast majority of Asian elephant populations, especially in China, are found outside of reserves and near cropland, the health of these populations is likely heavily influenced by access to crops [84]. Massive amounts of data have been collected by camera traps and drones in these areas [85, 86], but none have been used to determine the health of elephant populations. We have shown that using images to assess BCS is a simple and fast method for determining the health of free-ranging elephant populations. Therefore, future studies should consider analyzing the body condition of regional Asian elephant populations from these data sets to obtain early indications of the health of individuals and quality of food resources in their habitats [43]. This in turn can be used to guide conservationists and policymakers to evaluate the necessity for interventions, including the restoration of suitable habitat [42].

Conservation recommendations

The long-term placement of cameras in NNNR could be an efficient approach of monitoring to obtain valuable data on demography, fecundity and body condition variation across seasons and years. Our approaches can also be applied to other elephant populations with further implications for global Asian elephant conservation. Molecular biological approaches are also needed in further studies to determine the kinship and genetic health status of this population.

The results of this study match those observed in earlier studies which indicated providing more suitable habitat is urgently needed [13, 47, 48], this is especially imperative if the lower BCS scores are due to an inadequate supply of food. Attention should be paid to the low body condition in the dry season, and a follow-up surveys should be carried out in the rainy season to verify the health status of this elephant population throughout the year. To improve elephant survival in the short term, we recommend establishing more food sources and improving the quality of existing sources to increase individuals' body condition [87]. In the mid-term, fence dismantlement should be prioritized because it has partially blocked the movement of elephants and hindered their ability to find new food resources (Fig 1). Allowing the animals greater movement could provide more opportunities for the elephants to explore new suitable areas with enough food, eventually improving elephant body condition regardless of the season. Long-term objectives should include establishing ecological corridors to connect this isolated elephant population to other suitable habitat. Since the western part of this reserve (Fig 1. Red part of NNNR) has some suitable habitat [48], an ecological corridor could be created by planting bamboo forest or bamboo-broadleaf forests, allowing individuals to move between the eastern and western parts of the reserve. We also suggest conducting research on the availability of food resources during different seasons. We emphasize the urgency of implementing these recommendations, especially efforts to ensure a better body condition of females, which may improve reproductive success in the long run.

Supporting information

S1 Table. Historical elephant population in NNNR estimated by different methods.
(DOCX)

S1 Dataset. A simplified database of Asian elephant in NNNR.
(PDF)

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References

1. Campos-Arceiz A, Blake S. Megagardeners of the forest—the role of elephants in seed dispersal. *Acta Oecologica*. 2011; 37(6):542–553. <https://doi.org/10.1016/j.actao.2011.01.014>.
2. McConkey KR, Nathalang A, Brockelman WY, Saralamba C, Santon J, Matmoon U, et al. Different megafauna vary in their seed dispersal effectiveness of the megafaunal fruit *Platymitra macrocarpa* (Annonaceae). *Plos One*. 2018; 13(7):e0198960. <https://doi.org/10.1371/journal.pone.0198960> PMID: 30020929.
3. Riddle HS, Schulte BA, Desai AA, Meer Lvd. Elephants—A conservation overview. *Journal of Threatened Taxa*. 2010; 2(1):653–661.
4. Tan A, Yu L. Distribution and Protection of Asian elephant in China. *Protection Forest Science and Technology*. 2015;(5):89–91. <https://doi.org/10.13601/j.issn.1005-5215.2015.05.035>.
5. Platt SG, Bickford DP, Win MM, Rainwater TR. Water-filled Asian elephant tracks serve as breeding sites for anurans in Myanmar. *Mammalia*. 2019; 83(3):287–289. <https://doi.org/10.1515/mammalia-2017-0174>.
6. Bowen-Jones E, Entwistle A. Identifying appropriate flagship species: the importance of culture and local contexts. *Oryx*. 2002; 36(2):189–195. <https://doi.org/10.1017/S0030605302000261>.

7. Jiang Z, Jiang J, Wang Y, Zhang E, Zhang Y, Li L, et al. Red List of China's Vertebrates. *Biodiversity Science*. 2016; 24(5):500–551. <http://www.biodiversity-science.net/EN/10.17520/biods.2016076>.
8. Choudhury A, Lahiri Choudhury DK, Desai A, Duckworth JW, Easa PS, Johnsingh AJT, et al. *Elephas maximus*. The IUCN Red List of Threatened Species. 2008:e.T7140A12828813. <https://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T7140A12828813.en>.
9. Li Z. *Research on Asian elephant Conservation in China*. Beijing: Science Press; 2018.
10. Yu Z, Kun J. Distribution, Population, Habitat Status and Population Management of Asian Elephant. *World Forestry Research*. 2018; 31(2):25–30. <https://doi.org/10.13348/j.cnki.sjlyyj.2018.0002.y>.
11. Mingyong C. *Asian elephant research in China*: Science Press; 2006.
12. Sukumar R. A brief review of the status, distribution and biology of wild Asian elephants *Elephas maximus*. *International Zoo Yearbook*. 2006; 40(1):1–8. <https://doi.org/10.1111/j.1748-1090.2006.00001.x>.
13. Zhang L, Dong L, Lin L, Feng LM, Yan F, Wang LX, et al. Asian Elephants in China: Estimating Population Size and Evaluating Habitat Suitability. *Plos One*. 2015; 10(5):e0124834. <https://doi.org/10.1371/journal.pone.0124834> PMID: 25992617.
14. Yuan T, Yongjun F, Chunlan Z, Baocheng Y, Xiaoping T, Huijian H. Effectiveness of line transects during wild animal surveys in mountain forest of South China. *Biodiversity Science*. 2015; 23(1):109–115. <http://www.biodiversity-science.net/EN/10.17520/biods.2014128>.
15. Barnes RFW. The problem of precision and trend detection posed by small elephant populations in West Africa. *African Journal of Ecology*. 2002; 40:179–185. <https://doi.org/10.1046/j.1365-2028.2002.00376.x>.
16. Mills LS, Citta JJ, Lair KP, Schwartz MK, Tallmon DA. Estimating Animal Abundance Using Noninvasive DNA Sampling: Promise and Pitfalls. *Ecological Applications*. 2000; 10(1):283–294. <https://doi.org/10.2307/2641002>.
17. Zicheng Y, Ying C, Junsong L, Lifan W, You P, Zhiyong S, et al. Individual identification and population size assessment for Asian elephant based on camera-trapping techniques. *Acta Theriologica Sinica*. 2018; 38(1):18–27. <https://doi.org/10.16829/j.slx.150109>
18. Eggert L.S., Eggert J.A., Woodruff D.S. Estimating population sizes for elusive animals: the forest elephants of Kakum National Park, Ghana. *Molecular Ecology*. 2003; 12(6):1389–1402. <https://doi.org/10.1046/j.1365-294x.2003.01822.x> PMID: 12755869.
19. Liu X, Wu P, He X, Zhao X. Application and data mining of infra-red camera in the monitoring of species. *Biodiversity Science*. 2018; 26(08):850–861. <https://doi.org/10.17520/biods.2018053>.
20. Xiao W, Hu L, Huang X, Xiao Z. Using capture-recapture models in wildlife camera-trapping monitoring and the study case. *Biodiversity Science*. 2019; 27(3):257–265. <https://doi.org/10.17520/biods.2018194>
21. Zhang L, Cui S, Huang Y, Chen D, Qiao H, Li C, et al. Infrared camera traps in wildlife research and monitoring in China: issues and insights. *Biodiversity Science*. 2014; 22(6):696–703. <https://doi.org/10.3724/SP.J.1003.2014.14225>.
22. Wearn OR, Glover-Kapfer P. Snap happy: camera traps are an effective sampling tool when compared with alternative methods. *Royal Society Open Science*. 2019; 6(3):181748. <https://doi.org/10.1098/rsos.181748> PMID: 31032031
23. Jorge A A, Carlos E F S, Krisna G, Chris H, Johanna H, Emanuel M, et al. Community structure and diversity of tropical forest mammals: data from a global camera trap network. *Philosophical Transactions of the Royal Society of London*. 2011; 366(1578):2703–2711. <https://doi.org/10.1098/rstb.2011.0115> PMID: 21844049
24. Chengcheng Z, Jun W, Alexander JS, Zhigang D, Liji W, Wantao D, et al. Biodiversity Assessment of Mammal and Bird Species from Camera Trap Data in Yanchiwan National Nature Reserve, Gansu Province, China. *Journal of Resources and Ecology*. 2018; 9(5):566–574. <https://doi.org/10.5814/j.issn.1674-764x.2018.05.014>.
25. Broto B, Mortelliti A. The status of research on the mammals of Sulawesi, Indonesia. *Mammal Review*. 2019; 49(1):78–93. <https://doi.org/10.1111/mam.12141>.
26. Montalvo VH, Sáenz-Bolaño C, Luis D, Alfaro JCC1, Guimarões-Rodrigues FH, Carrillo E, Sutherland C, et al. Seasonal use of waterholes and pathways by macrofauna in the dry forest of Costa Rica. *Journal of Tropical Ecology*. 2019; 35(2):68–73. <https://doi.org/10.1017/S0266467418000457>.
27. Matsukawa A, Ahmad AH, Kohshima S. Social structure and reproduction of long-tailed porcupine (*Trichys fasciculata*). *Mammalia*. 2019; 83(1):23–33. <https://doi.org/10.1515/mammalia-2017-0104>.
28. Sunarto S, Kelly MJ, Parakkasi K, Hutajulu MB. Cat coexistence in central Sumatra: ecological characteristics, spatial and temporal overlap, and implications for management. *Journal of Zoology*. 2015; 296(2):104–115. <https://doi.org/10.1111/jzo.12218>.

29. Rich LN, Miller DAW, Muñoz DJ, Robinson HS, McNutt JW, Kelly MJ. Sampling design and analytical advances allow for simultaneous density estimation of seven sympatric carnivore species from camera trap data. *Biological Conservation*. 2019; 233:12–20. <https://doi.org/10.1016/j.biocon.2019.02.018>.
30. Blanc L, Marboutin E, Gatti S, Gimenez O. Abundance of rare and elusive species: Empirical investigation of closed versus spatially explicit capture-recapture models with lynx as a case study. *The Journal of Wildlife Management*. 2013; 77(2):372–378. <https://doi.org/10.1002/jwmg.453>.
31. Efford MG, Fewster RM. Estimating population size by spatially explicit capture-recapture. *Oikos*. 2013; 122(6):918–928. <https://doi.org/10.1111/j.1600-0706.2012.20440.x>.
32. Bashir T, Bhattacharya T, Poudyal K, Sathyakumar S, Qureshi Q. Estimating leopard cat *Prionailurus bengalensis* densities using photographic captures and recaptures. *Wildlife Biology*. 2013; 19(4):462–472. <https://doi.org/10.2981/12-098>.
33. Alexander JS. Advancing research and conservation of snow leopards in the Qilianshan mountains of China: management and methodological implications [Doctoral dissertation]: Beijing Forestry University; 2015.
34. O'Brien TG, Kinnaird MF, Wibisono HT. Crouching tigers, hidden prey: Sumatran tiger and prey populations in a tropical forest landscape. *Animal Conservation*. 2003; 6(2):131–139. <https://doi.org/10.1017/S1367943003003172>
35. Bohm T, Hofer H. Population numbers, density and activity patterns of servals in savannah patches of Odzala-Kokoua National Park, Republic of Congo. *African Journal of Ecology*. 2018; 56(4):841–849. <https://doi.org/10.1111/aje.12520>.
36. Park H, Lim A, Choi T-Y, Baek S-Y, Song E-G, Park YC. Where to spot: individual identification of leopard cats (*Prionailurus bengalensis euptilurus*) in South Korea. *Journal of Ecology and Environment*. 2019; 43. <https://doi.org/10.1186/s41610-019-0138-z>.
37. Zhiqiang Y, Li Z. Population and activity characteristic of wild Asian elephant in Wild Elephant Valley. *Acta Theriologica Sinica*. 2006; 26(4):359–367. <https://doi.org/10.3969/j.issn.1000-1050.2006.04.007>.
38. Goswami VR, Madhusudan MD, Karanth KU. Application of photographic capture-recapture modelling to estimate demographic parameters for male Asian elephants. *Animal Conservation*. 2007; 10(3):391–399. <https://doi.org/10.1111/j.1469-1795.2007.00124.x>.
39. Chaiyarat R, Youngpoy N, Prempre P. Wild Asian elephant *Elephas maximus* population in Salakpra Wildlife Sanctuary, Thailand. *Endangered Species Research*. 2015; 29(2):95–102. <https://doi.org/10.3354/esr00706>.
40. Gupta M, Joshi A, Vidya TNC. Effects of social organization, trap arrangement and density, sampling scale, and population density on bias in population size estimation using some common mark-recapture estimators. *Plos One*. 2017; 12(3):e0173609. <https://doi.org/10.1371/journal.pone.0173609> PMID: 28306735
41. Hedges S, Johnson A, Ahlering M, Tyson M, Eggert LS. Accuracy, precision, and cost-effectiveness of conventional dung density and fecal DNA based survey methods to estimate Asian elephant (*Elephas maximus*) population size and structure. *Biological Conservation*. 2013; 159:101–108. <https://doi.org/10.1016/j.biocon.2012.12.010>.
42. Wijeyamohan S, Treiber K, Schmitt D, Santiapillai C. A Visual System for Scoring Body Condition of Asian Elephants (*Elephas maximus*). *Zoo Biology*. 2015; 34(1):53–59. <https://doi.org/10.1002/zoo.21181> PMID: 25323789
43. Fernando P, Janaka HK, Ekanayaka SKK, Nishantha HG, Pastorini J. A simple method for assessing elephant body condition. *Gajah*. 2009; 31:29–31. <https://doi.org/10.5167/uzh-32262>.
44. Ramesh T, Sankar K, Qureshi Q, Kalle R. Assessment of wild Asiatic elephant (*Elephas maximus* indicus) body condition by simple scoring method in a tropical deciduous forest of Western Ghats, Southern India. *Wildlife Biology in Practice*. 2011; 7(2):47–54. <https://doi.org/10.2461/wbp.2011.7.17>
45. Morfeld KA, Lehnhardt J, Alligood C, Bolling J, Brown JL. Development of a body condition scoring index for female African elephants validated by ultrasound measurements of subcutaneous fat. *Plos One*. 2014; 9(4):e93802. <https://doi.org/10.1371/journal.pone.0093802> PMID: 24718304
46. Fan Y, Li Z. Population genetic structure and population genetic diversity analysis based on mitochondrial DNA of Asian elephant *Elephas maximus* in China. *Acta Theriologica Sinica*. 2012; 32(2):90–100. <https://doi.org/10.16829/j.slx.2012.02.002>.
47. Limin F, Zhisheng W, Liu L, Shaobing Y, Bin Z, Chunhua L, et al. Habitat selection in dry season of Asian elephant (*Elephas maximus*) and conservation strategies in Nangunhe National Nature Reserve, Yunnan, China. *Acta Theriologica Sinica*. 2010; 30(1):1–10. <https://doi.org/10.16829/j.slx.2010.01.001>.

48. Peng L, Hui W, Liu L, Jing L, Li Z. Habitat evaluation for Asian elephants (*Elephas maximus*) in Lincang: Conservation planning for an extremely small population of elephants in China. *Biological Conservation*. 2016; 198:113–121. <https://doi.org/10.1016/j.biocon.2016.04.005>.
49. Yong-jing T, Zhi-sheng W, Gui-lian J, Xuan Z, Yuan H, Zheng-ling L, et al. Population dynamics analysis of Asian elephant in Nangunhe river basin. *Forestry Construction*. 2019; 6:101–106.
50. Tang F, Du F, Sun G. Investigation report on background resources of Nangunhe National Nature Reserve, Yunnan. China Forestry Press. 2015.
51. Guo B, Lan D. Status of wildlife resources in Nangunhe reserve. *Chinese Journal of Wildlife*. 1999; (4):46–47.
52. Bohnett E, Riordan P, Kun S. Initial Assessment on Large and Medium Sized Terrestrial Mammal Assemblage Using Camera Trapping in Nangunhe Nature Reserve in Yunnan, China. *Journal of Resources and Ecology*. 2015; 6(5):331–344. <https://doi.org/10.5814/j.issn.1674-764x.2015.05.007>.
53. Varma S, Pittet A, Jamadagni HS. Experimenting usage of camera-traps-for population dynamics study of the Asian elephant *Elephas maximus* in southern India. *Current Science*. 2007; 6(1):81–95. <https://doi.org/10.12723/mjs.10.7>.
54. Sd Silva, Ranjeewa A, Weerakoon D. Demography of Asian elephants (*Elephas maximus*) at Uda Walawe National Park, Sri Lanka based on identified individuals. *Biological Conservation*. 2011; 144(5):1742–1752. <https://doi.org/10.1016/j.biocon.2011.03.011>.
55. Vidya TNC, Prasad D, Ghosh A. Individual Identification in Asian Elephants. *Gajah*. 2014; 40:3–17.
56. Sukumar R, Joshi NV, Krishnamurthy V. Growth in the Asian elephant. *Proceedings: Animal Sciences*. 1988; 97(6):561–571. <https://doi.org/10.1007/BF03179558>.
57. Goswami VR, Laretta MV, Madhusudan MD, Karanth KU. Optimizing individual identification and survey effort for photographic capture-recapture sampling of species with temporally variable morphological traits. *Animal Conservation*. 2012; 15(2):174–183. <https://doi.org/10.1111/j.1469-1795.2011.00501.x>.
58. Borchers DL, Efford MG. Spatially explicit maximum likelihood methods for capture-recapture studies. *Biometrics*. 2008; 64(2):377–385. WOS:000255959500007. <https://doi.org/10.1111/j.1541-0420.2007.00927.x> PMID: 17970815
59. Borchers DL, Buckland ST, Zucchini W. Estimating Animal Abundance: Closed Populations. Springer, London. 2002. <https://doi.org/10.1007/978-1-4471-3708-5>.
60. López-Bao JV, Godinho R, Pacheco C, Lema FJ, García E, Llaneza L, et al. Toward reliable population estimates of wolves by combining spatial capture-recapture models and non-invasive DNA monitoring. *Scientific Reports*. 2018; 8(1):2177. <https://doi.org/10.1038/s41598-018-20675-9> PMID: 29391588
61. Gardner B, Reppucci J, Lucherini M, Royle JA. Spatially explicit inference for open populations: estimating demographic parameters from camera-trap studies. *Ecology*. 2010; 91(11):3376–3383. <https://doi.org/10.1890/09-0804.1> PMID: 21141198
62. Royle JA, Chandler RB, Sollman R, Gardner B. *Spatial Capture-Recapture*: Academic Press; 2014.
63. Royle JA, Gardner B. Hierarchical spatial capture-recapture models for estimating density from trapping arrays. In: O'Connell A.F., Nichols J.D., Karanth K.U. (eds) *Camera Traps in Animal Ecology*. Springer, Tokyo; 2011.
64. Efford MG. Estimation of population density by spatially explicit capture-recapture analysis of data from area searches. *Ecology*. 2011; 92(12):2202–2207. <https://doi.org/10.1890/11-0332.1> PMID: 22352159
65. Silveira L, Anah TAJ, Diniz-Filho JAF. Camera trap, line transect census and track surveys: a comparative evaluation. *Biological Conservation*. 2003; 114(3):351–355. [https://doi.org/10.1016/S0006-3207\(03\)00063-6](https://doi.org/10.1016/S0006-3207(03)00063-6)
66. Li Z, Kang A, Lang J, Xue Y, Ren Y, Zhu Z, et al. On the assessment of big cats and their prey populations based on camera trap data. *Biodiversity Science*. 2014; 22(6):725–732. <https://doi.org/10.3724/SP.J.1003.2014.14079>
67. Ling Q. Habitat Selection by Asian Elephant (*Elephas maximus*) in Nangunhe Nature Reserve, Yunnan, China: Northwest University; 2007.
68. Yuming Y, Genmin W, Zhisheng Z, Zhongli W. Wild elephant population in Nangunhe reserve. *Forest Inventory & Planning*. 1982; 02.
69. Jiasheng T, Jianhao W, Xiaolin H. Summary of Nangunhe nature reserve. *Forest Inventory & Planning*. 1986;01.
70. Vidya TNC, Sukumar R. Social and reproductive behaviour in elephants. *Current Science*. 2005;89.
71. Guo B. Investigation and protection advice of wild elephant in Nangunhe reserve. *Yunnan Forestry*. 1989.

72. Royle JA, Nichols JD, Karanth KU, Gopalaswamy AM. A hierarchical model for estimating density in camera-trap studies. *Journal of Applied Ecology*. 2010; 46(1):118–127. <https://doi.org/10.1890/09-0804.1> PMID: 21141198
73. Alfred R, Ahmad A, Payne J, Williams C, Ambu L, Phua M-H, et al. Home Range and Ranging Behaviour of Bornean Elephant (*Elephas maximus borneensis*) Females. *Plos One*. 2012; 7(2):e31400. <https://doi.org/10.1371/journal.pone.0031400> PMID: 22347469
74. Leggett KEA. Home range and seasonal movement of elephants in the Kunene Region, northwestern Namibia. *African Zoology*. 2006; 41(1):17–36. [https://doi.org/10.3377/1562-7020\(2006\)41\[17:Hrasmo\]2.0.Co;2](https://doi.org/10.3377/1562-7020(2006)41[17:Hrasmo]2.0.Co;2).
75. Kumara H, Rathnakumar S, Mavatur A, Singh M. Estimating Asian elephant, *Elephas maximus*, density through distance sampling in the tropical forests of Biligiri Rangaswamy Temple Tiger Reserve, India. *Tropical Conservation Science*. 2012; 5(52):163–172. <https://doi.org/10.1177/194008291200500206>.
76. Lichao M. Conservation genetic path to understanding the structure of Asian elephant (*Elephas maximus*) group: Beijing Normal University; 2004.
77. Kurt F, Hartl G, Tiedemann R. Tuskless bulls in Asian elephant *Elephas maximus*. History and population genetics of a man-made phenomenon. *Acta Theriologica*. 1995; 40:125–143. <https://doi.org/10.4098/AT.arch.95-51>.
78. Paulraj S, Subramanian C. Skewed sex ratio in elephant population—How it may affect the demography and population growth? A case study in Mudumalai Wildlife Sanctuary and National Park, Tamil Nadu, Southern India. *Indian Forester*. 2000; 126:1046–1053.
79. Archie E, Chiyo P. Elephant behaviour and conservation: Social relationships, the effects of poaching, and genetic tools for management. *Molecular Ecology*. 2011; 21:765–778. <https://doi.org/10.1111/j.1365-294X.2011.05237.x> PMID: 21880086
80. Sd Silva, Webber CE, Weerathunga US, Pushpakumara TV, Weerakoon DK, Wittemyer G. Demographic Variables for Wild Asian Elephants Using Longitudinal Observations. *Plos One*. 2013; 8(12): e82788. <https://doi.org/10.1371/journal.pone.0082788> PMID: 24376581
81. Fernando P, Wikramanayake ED, Janaka HK, Jayasinghe LKA, Gunawardena M, Kotagama SW, et al. Ranging behavior of the Asian elephant in Sri Lanka. *Mammalian Biology*. 2008; 73(1):2–13. <https://doi.org/10.1016/j.mambio.2007.07.007>.
82. Srinivasaiah N, Kumar V, Vaidyanathan S, Sukumar R, Sinha A. All-Male Groups in Asian Elephants: A Novel, Adaptive Social Strategy in Increasingly Anthropogenic Landscapes of Southern India. *Scientific Reports*. 2019; 9:8678. <https://doi.org/10.1038/s41598-019-45130-1> PMID: 31273235
83. Pokharel SS, Seshagiri PB, Sukumar R. Assessment of season-dependent body condition scores in relation to faecal glucocorticoid metabolites in free-ranging Asian elephants. *Conservation Physiology*. 2017; 5(1):cox039. <https://doi.org/10.1093/conphys/cox039> PMID: 28721215
84. Guozheng S, Guangyuan Z, Zicheng Y, Mengjun W. Research progress and direction of human elephant conflict mitigation projects. *Forestry Construction*. 2019; 6:5–9.
85. Sheng-dong Y, Yun D, Ai-dong L, Mang-cai W, Bin W, De Z, et al. A preliminary study of wireless infrared camera technology in alleviating the human-elephant conflict. *Forestry Construction*. 2019;(6):61–66.
86. Zhi-hong W, Heng-zhen Z, Wen-lan Z, Xuan Z, Wen-bian Y, Zheng-ling L, et al. An analysis of population dynamic on the Xishuangbanna Menghai-Pu'er Lancang Asian elephant population. *Forestry Construction*. 2019;(6):79–84.
87. Xian-ming G, Lan-xin W. Thoughts on the construction of Asian elephant food source base in Xishuangbanna. *Forestry Construction*. 2019;(6):30–33.