A drone-based population survey of Delacour's langur (*Trachypithecus delacouri*) in the karst forests of northern Vietnam

Highlights

The Delacour's langur population in Kim Bang Forest is globally significant and larger than previously estimated, emphasizing the forest's vital role in the conservation of this Critically Endangered species.

Delacour's langur abundance was correlated negatively with the presence of macaques and positively with vegetation productivity. We propose further research into the langur's interactions with sympatric competitor species and the relationship with habitat quality for effective species management.

The drone survey method is an effective and resource-efficient choice for surveying Delacour's langur with potential applicability to other mammals in difficult-to-access karst habitats.

Abstract

The Critically Endangered Delacour's langur (*Trachypithecus delacouri*) is presently found only in a few isolated karst areas in northern Vietnam, where conducting field surveys has proven challenging due to the difficult terrain. Accurate population estimates from a scientifically sound method are needed to inform management of the species. From October to December 2022, we used a drone equipped with optical and thermal cameras to survey the species in Kim Bang Forest, a critical site for the species. We estimated langur abundance from the resulting point count data using N-mixture models including abiotic and biotic variables. We also compared the effectiveness and efficiency of the drone method with two commonly used ground-based methods. The drone survey recorded 16 groups with 104 individuals. We estimated a density of 0.87 groups per km^2 and a population of 25 groups and 175 individuals. This estimate is 80-113% higher than previous ground-based estimates, attributed primarily to the higher area coverage by the drone survey. The estimate reaffirms the conservation importance of Kim Bang Forest for the species. The modelling also indicated that Delacour's langur abundance was correlated negatively with Assamese macaque *Macaca assamensis* presence and positively with vegetation productivity. Other variables (elevation, terrain ruggedness and distance to forest edge) were much less important in explaining langur abundance. Compared to the ground-based methods, the drone approach proved effective and resource-efficient for surveying Delacour's langurs. We recommend the drone method for future Delacour's langur surveys, with potential applicability to other arboreal mammals in difficult-to-access karst forests.

Key words: Unoccupied aerial vehicle, drone survey, *Trachypithecus delacouri*, abundance, N-mixture model, inter-specific interaction

1. Introduction

Karsts, accounting for 15%-20% of the Earth's land area (Jones and White, 2008), exhibit complex geomorphology such as subsurface streams, sinkholes, and caves, fostering high biodiversity and species endemism (Clements et al., 2006; Jones and White, 2008; Mičetić Stanković, 2023). However, anthropogenic threats, including deforestation, quarrying, mineral extraction, dumping of illegal waste and poorly regulated cave tourism (Parise and Pascali, 2003) have, in many areas, resulted in extensive degradation of the original habitat, causing the decline and extinction of several endemic species (Clements et al., 2006). These include sardina ciega (*Astyanax Jordani)* (García, 2019), fountain darter (*Etheostoma fonticola)* (NatureServe, 2015), turquoise dwarf gecko *(Lygodactylus williamsi)* (Flecks et al., 2015), forest musk deer (*Moschus berezovskii caobangensis*) (Groves et al., 1995; Wang and Harris, 2017), cao vit gibbon (*Nomascus nasutus*) (Chan et al., 2008; Ma et al., 2020) and several species of limestone langur (*Trachypithecus* genus) (Groves, 2007). Although being recognized as important for their biodiversity, karsts are still little studied worldwide (Mičetić Stanković, 2023), in large part due to the extreme difficulty associated with accessing and travelling within them.

Restricted to the limestone karst evergreen forests of north-central Vietnam (Nadler and Brockman, 2014), Delacour's langur (*Trachypithecus delacouri*) is a diurnal and primarily arboreal primate (Harding, 2011). It is predominantly folivorous (Harding, 2011; Workman, 2010) and lives in groups of 5–30 individuals (Harding, 2011) with home ranges estimated at around 46 ha (Nguyen, 2008). The species is currently listed as Critically Endangered (CR) on the IUCN Red List due to population extirpations and decline caused by hunting, habitat loss from mining and quarrying, and tourist infrastructure development (Nadler, 2015; Nadler et al., 2020). In addition, the presence of several macaque species (Macaca genus) has been reported from the remaining sites occupied by Delacour's langur (Nadler et al., 2007). Given potential overlaps in their habitat and diet, macaques may be important competitors.

Within the species' restricted range, Kim Bang Forest in Ha Nam Province is considered as an important area for the species since it is home to one of only two known viable populations (Nguyen et al., 2021). The langur population size in Kim Bang Forest was estimated to be 73-100 individuals by an intensive ground survey conducted in 2018 (Nguyen et al., 2021). However, the accuracy of the survey was thought to be limited because it only took place in the areas reported by local people to be inhabited by the species. The survey likely missed langurs in areas of the forest that the interviewees either had never visited or in areas they had visited but had not detected any resident langurs. In addition, the mixed-methods approach (interviews and field surveys) used in the survey is difficult to repeat in a standardised way across space and time, due to its unsystematic nature. Furthermore, some of the langur records were from second-hand interview data that is difficult to verify. Moreover, it is difficult to conduct and repeat line transects and point counts in the rugged habitat (Dawson, 1981; Li and Rogers, 2007). The terrain inaccessibility makes it impossible to meet the requirement of random sampling (Li and Rogers, 2007).The accuracy in ground surveys is also likely compromised due to difficult accessibility, slow pace of travel by survey teams, low detectability due to the need for observers to pay attention to the terrain underfoot and due to physiographic features blocking the view of observers, distance estimate errors caused by the uneven terrain (Dawson, 1981). Given the importance of reliable population estimates for Delacour's langur, for tracking the population status over time and assessing the impact of conservation work, a new method is needed.

We propose that many of the drawbacks of previous methods can be overcome by using an Unoccupied Aerial Vehicle (UAV) or drone. Drones are increasingly being used for surveying and monitoring wildlife, including aquatic mammals, terrestrial ungulates, carnivorans, primates, elephants, bats, birds, reptiles and fish (Aniceto et al., 2018; Beaver et al., 2020; Fischer et al., 2023; He et al., 2023; Hodgson et al., 2017; Mo and Bonatakis, 2022). The advantages of using drones over traditional ground surveys include: quick access to areas that are difficult-to-access on foot, the ability to cover a much larger area during a similar time period (He et al., 2019; Spaan et al., 2019), reducing human effort (Elmore et al., 2023) and collect accurate information by causing minimal disturbance to the habitat (Mazumdar, 2022). In addition, drones equipped with a thermal-imaging camera are able to spot camouflaged animals based on their body heat and can be used at all times of the day or night (Burke et al., 2019), and obtain more accurate group size counts (He et al., 2019; Spaan et al., 2019; Wearn et al., 2023; Zhang et al., 2020). The main challenges, besides the legal visual line of sight limit regulation and technical low resolution of camera sensors for thermal camera drone surveys, include high dependence on weather (strong wind, rain, strong sunlight, high ambient temperature) and obstacles constituted by dense/thick tree crowns and canopy; therefore, it is important to consider survey timing to account for changes in the thermal characteristics of the environment during the day and suitable habitat types (Beaver et al., 2020; He et al., 2023; Witczuk et al., 2018).

Kim Bang Forest is currently managed by the commune-level governments of Thanh Son, Lien Son, and Ba Sao. The provincial government of Ha Nam, with support from Fauna & Flora (FFI), is in the process of establishing a protected area specifically for the conservation of the Delacour's langur population. To support conservation management in the area, it is necessary to obtain reliable estimates of Delacour's langur abundance and identify influencing environmental factors. Therefore, our study objectives were to: establish accurate baseline population estimates for Delacour's langur in Kim Bang Forest; identify important environmental variables that explain variation in the langur abundance; and compare the proposed drone-based method with previous survey methods that have been used for the species, in order to provide recommendations for future surveys.

2. Materials and methods

2.1 Study area

The study was conducted between 4th October and 18th December 2022 in Kim Bang Forest, Ha Nam Province, northern Vietnam (Fig. 1). The area is approximately 29 km^2 and is covered with degraded limestone evergreen forest, having been heavily impacted by past timber exploitation and charcoal production (Trinh Dinh and Le, 2016). The rugged terrain is characterized by high ridgetops, inaccessible cliffs, deep gorges and narrow, deep valleys. The altitude ranges from 0 m to 450 m above sea level. Besides Delacour's langur, other primates and large mammals reported to occur in the study area include: Assamese macaque (*Macaca assamensis*) directly observed (Trinh Dinh and Le, 2016); Stump-tailed Macaque (*Macaca artoides*) from past camera trap survey. Rhesus macaque (*Macaque mulatta*), Slow Loris (*Nycticebus bengalensis),* Pygmy Loris (*Nycticebus pygmaeus*) and mainland serow (*Capricornis milneedwardsii*) from interviews with local communities (Nguyen et al., 2018).

[Figure 1 Map of study area and drone survey sites]

Kim Bang District exhibits a humid subtropical climate. The temperature varies throughout the year, with daily maximums of around 20.7°C in January to 34°C in June. The daily minimums vary from 16.5°C in January to 27.1°C in June. Humidity values also show variation throughout the year, decreasing from 86% in January to 69% in June. Rainfall is lowest in February (20 mm/month) and increases later in the year, particularly in August and September (100 and 169 mm/month respectively). Consequently, the number of rainfall days increases correspondingly, with 11.4 days in February and reaching up to 18.8 days in September. The sunlight hours vary as well, with 11 hours per day in January, increasing to 13.4 hours in June (Weather Atlas, 2023).

2.2 Methods

2.2.1 Drone flights and estimation of langur abundance

Data on Delacour's langur presence were collected using a multi-rotor drone, the Mavic 2 Enterprise Advanced manufactured by Shenzhen DJI Sciences and Technologies Ltd. The drone was outfitted with both an optical and thermal camera. The optical camera utilized a 1/2" CMOS sensor capable of capturing 4K videos and 48 megapixel photos. Meanwhile, the infrared thermal camera contained an Uncooled VOx Microbolometer to record 640×512 pixel video. The drone was also capable of digitally zooming the live feed on the display by up to 32 times. We used six batteries, which were recharged in the field by a Honda Elemax SHX1000 generator. Our preliminary trials of the method showed that the best ambient temperature for thermal-imaging of the species was 23^{o}C or below, reducing the suitable period for thermal camera drone survey from mid-October to mid-March.

Using QGIS (QGIS Development Team, 2021), the sampling area was defined by overlaying a systematic grid of points with a spacing of 1 km over the entirety of Kim Bang Forest. The 1 km spacing was to avoid double counting as it represents over twice the estimated Delacour's langur group home range radius (383 m) (Nguyen, 2008). For each point, we manually delineated the nearest/overlapping valleys bordered by peaks and ridges, which would constitute our actual target area for sampling (Fig. 1). We excluded areas of no-flight zone. One day was divided into two survey occasions, morning and afternoon. We surveyed Delacour's langurs early in the morning (5:30 – 9:30) and late in the afternoon (15:30 – 17:30) to avoid sunlight and high temperatures, which reduces thermal detection. Before 5:30 and after 18:00, the light condition was insufficient for identifying species with the visual camera. On cold and cloudy days, we finished the morning session as late as 9:30 and started the afternoon section as early as 15:30. Conversely, on warmer and sunnier days we finished the morning session as early as 7:30 and started the afternoon section as late as 16:30. We did not survey Delacour's langur from 9:30 to 15:30 due mostly to the strong sun at this time, which reduces the efficacy of thermal detection, and also to ensure a time interval of at least four hours between two occasions at a survey site.

In order to correctly identify and count individuals detected, an active detection approach was used, with flights flown manually. After starting the drone and controller and recording mode on both devices, the drone flew to the survey site at a height of 50 m above the terrain. While moving to the survey site, the surveyors monitored the controller screen with the optical (RGB) camera mode. At the survey site, the controller screen was switched to thermal (infrared, IR) mode to find warm objects. The optical mode was used to identify any objects detected using the thermal mode. Depending on the situation, if needed for species identification, the drone could move as close as 50 m to the langurs. Once the warm objects (Fig. 3a) were identified as Delacour's langurs (Fig. 3b) by the visual camera, the thermal mode would again be activated to count the number of individuals and the drone moved back away from the langurs if they react to the drone presence. For each langur group detection, we collected GPS coordinates by flying the drone directly above the group center with the gimbal pointing straight down.

Neighbouring groups were differentiated (i) if they are recorded at the same survey site and at the same time, or (ii) if they are recorded at different survey sites but within a short time frame (either within the same morning or afternoon survey session). If a langur group is recorded at two sites, we removed its detections at one site from modelling data to avoid double counting.

We used N-mixture models to estimate animal abundance from replicated count data in two ways. First, we used the N-mixture model with a binomial/Poisson mixture (Royle, 2004) to model the count data for groups. In a second approach, we attempted to model the individual count data, accounting for the non-independence of individuals within a group using a beta-binomial/Poisson model (Martin et al., 2011). We fitted more complex models to account for overdispersion, such as zero-inflated Poisson and Poisson-lognormal. We did not include the results from the negative binomial models because of the unrealistic high abundance estimates (Joseph et al., 2009).

We examined the effects of four abiotic variables and one biotic variable that we hypothesised to be important for explaining variation in Delacour's langur abundance, specifically: 1) vegetation productivity (normalized difference vegetation index, NDVI), as Delacour's langur is a forest-dwelling and folivorous species (Harding, 2011; Workman, 2010); 2) elevation; 3) terrain ruggedness, as the species is presently confined to limestone mountains/outcrops with difficult accessibility (Nadler et al., 2020) thought as factors protecting the species from anthropogenic threats; 4) distance to the nearest forest edge, as a proxy of human disturbance (Pfeifer et al., 2018); and 5) presence of macaques, since their distributions reportedly overlap with Delacour's langur (Nadler et al., 2007) and local people have reported langur-macaque fights (Annex 2). We downloaded a 10 m resolution Sentinel 2 image from the Sentinel Scientific Data Hub for 21st August, 2022 and calculated NDVI from the near infrared (NIR) and red bands (NIR-Red)/(NIR+Red). Terrain ruggedness was calculated from a 30 m resolution digital elevation model (USGS, 2018) using the 'Terrain Ruggedness

Index' function in QGIS (QGIS Development Team, 2021). Distance from the survey sites to the forest edge was measured by manually creating a layer of forest edge based on the Global Land Cover for 2021 (Karra et al., 2021), and then using the 'Join Attributes by Location' function in QGIS to calculate nearest distance from the survey sites to the forest edge. We used macaque detected/non-detected data recorded in the drone survey. Their locations were recorded in the drone flights using the same method as we used for Delacour's langurs. The survey recorded only Assamese macaques (*Macaca assamensis*). The macaque's home range of 0.55 km^2 (Khatiwada et al., 2020) is a 418.5 m radius area if assumed to be a circular. We buffered the macaque locations with this home-range radius and identified the survey sites overlapping with the macaque buffered areas (Figure 2). We assigned values of 1 to sites having overlap with the macaque area and values of 0 otherwise. Due to the relatively sparse data, we fit each of these variables one at a time in single-variable models, then additive models including only the variable for macaque presence. The variables were standardized (z-score) before running the models by subtracting the mean and dividing by the standard deviation. The site area was included as an offset to account for the varying search area by site. The log of the areas was used to ensure a linear effect on the scale of the linear predictor.

We used a Bayesian mode of inference, running models in the *jagsUI* package (Kellner and Meredith, 2021) in program R version 4.2.3 (R Core Team, 2023). The models were run with vague priors for all parameters, except for the theta parameter. We tested prior sensitivity for theta and found that it had no discernible effect on the posterior distribution. Posterior Markov chain Monte Carlo samples were taken using six chains, each with 2,900,000 iterations (including 900,000 burn-in iterations, 3,000 adaptation iterations and a thinning rate of three). The number of iterations was deemed sufficient for inference by checking that the Monte Carlo standard error was less than 1.5% (Lunn et al., 2013). Model convergence was assessed using the R-hat criterion, with values <

1.05 indicating sufficient convergence (Gelman and Hill, 2006) and by examining the trace plots of the chains (Gelman et al., 2014). To assess goodness-of-fit, we used a posterior predictive check plot based on the Freeman-Turkey Discrepancy Criterion with Bayesian p-value of around 0.5 (and not < 0.05 or > 0.95) indicating reasonable model fit. We accounted for the 95% credible interval (CrI) by adjusting ad hoc overdispersion correction of the model's lack of fit from unstructured noise (e.g. a large variance). First, we estimated the magnitude of overdispersion (c-hat) from a posterior prediction based on a Chi-square discrepancy (Kéry and Royle, 2015). Second, we calculated overdispersion correction by multiplying the standard deviation by two times the square root of c-hat. Lastly, we computed an approximate 95% CrI by adding and subtracting the overdispersion correction from the mean (mean± 2*sd*sqrt(c-hat)). We used the Deviance Information Criterion (DIC) for model selection with models having smaller DIC being preferred (Royle et al., 2014; Spiegelhalter, D. J. et al., 2002).

After identifying the top model, we calculated group densities for each survey site and then average density across the sites. In each Markov Chain Monte Carlo (MCMC) iteration we calculated the density for each site by dividing N by the “effective sampling areas" in km^2. We calculated effective sampling areas by buffering each of the survey sites by one home-range radius (Kéry and Royle, 2015) and then clipping the buffered polygons to the forest layer acquired from the Global Land Cover (Karra et al., 2021). We estimated the total number of langur groups for Kim Bang Forest by multiplying the average density across sites by the total area of the forest. The estimate for the total number of groups was then converted to an estimate of the number of individuals by multiplying by the median group size. The median was chosen instead of the mean because it is appropriate for integer data and less affected by outliers.

2.2.2 Additional ad-hoc surveys

Besides the 26 survey sites used for formal estimation of the population size, we also flew the drone above additional areas known or suspected to have Delacour’s langurs based on our available data from previous ground-based surveys (2016 and 2018), drone test (March 2022) and community patrols (SMART data 2020- 2022), in order to collect more information on Delacour's langur group sizes in the study area. The data recorded outside the survey sites were not input to the modelling. However, combining with the data inside the survey sites, they contribute to more comprehensive first-hand information on the population such as total number of groups, group sizes and total number of individuals recorded by the drone.

2.2.3 Comparing survey method effectiveness

We compared the drone-based point count method with the ground-based methods previously used to survey the Delacour's langur, namely regular community patrolling and an intensive survey last carried out in 2018. Community patrols took place between January 2020 and July 2022 and used the Spatial Monitoring and Reporting Tool (SMART) to record survey data. The method with the lowest total score was indicated to be the most effective method overall. We ranked each of the three methods from worst (rank = 3) to best (rank = 1) along 10 different dimensions (see Table 2 for details on the 10 dimensions and effectiveness of the different methods). Five of the dimensions were judged based on expert opinion of the authors and, whilst subjective, allowed us to incorporate a wider range of considerations than would have been possible using quantitative criteria only.

All datasets are from the same study area. We calculated data collection efficiency by dividing total efforts (total cost in US Dollar, and total time in hour) by the total number of detections. We used the exchange rate of 1 USD = 23,290 VND (Vietcombank, 2023) for converting currency from Vietnamese Dong to US Dollar. For details of all dimensions used to compare the methods, we would like to refer to Table 2 and Annex 3.

Drone survey 2022

Data collection and analysis of the drone survey was presented in the section of method of abundance estimation. To measure flight way length, we used Flight Reader 1.5.5 developed by Mike Singer (https://www.phantomhelp.com/LogViewer/upload/) to convert flight records (flight tracks) from .txt files to .kml files, which were then input to QGIS for mapping and measuring the track length. For the calculation of survey costs, we noted the number of working days, accommodation nights, number of participants, number of person days, daily salary, food allowance, travel costs, equipment and materials (drone, batteries, generator and gasoline). The drone survey time was the sum of the flight time.

Ground survey 2018.

The ground survey was conducted by Center for Nature Conservation and Development for 38 days in August-October 2018. The survey team consisted of one primate expert, one student assistant, seven local surveyors and three logistic support staff. The survey was carried out by three teams, 2-3 members each, simultaneously. Equipment and materials include a Camera Nikon P900, two Garmin 64S units powered by AA batteries. Surveys were carried out from fixed survey posts from 6:00 to 17:00 for each survey day and by walking slowly in the forest. Once a langur group was found, the time of detection, group size, compass bearing and estimate of distance from the surveyors were recorded. Data on the survey time, number of personnel and field costs were obtained from the report (Trinh Dinh and Nguyen, 2018). Salary costs for organisational staff (primate expert and student assistant) were not included in the cost calculation, for comparability with the drone method. The ground survey time was calculated by multiplying the number of survey days by the hours daily spent surveying Delacour's langurs.

Community patrolling (SMART data) 2020-2022

SMART data were collected by three community-based monitoring teams. The teams, usually consisting of three people each, walked in the forest 15 -22 days per month and collected information on any langurs that they encountered, as well as human impacts such as trapping, logging and non-timber forest product collection. Each team had a Camera Nikon P900 and a GPS Garmin 64S powered by AA batteries. They recorded both auditory and visual detections of langurs, including the time, location and group size. Their efforts (time, tracks) were recorded automatically by the SMART application running on smartphones. We used two datasets collected before the drone survey, one collected by Fauna & Flora from 1st January 2020 to 31st December 2021 and one from the Center for Nature Conservation and Development from 01st January 2020 to 30 July 2022. These organizations worked in parallel in different forest sections. Thus, the datasets are supplementing to each other, they together provide more comprehensive data of the study area. The SMART data included the number of days, numbers of hours, number of kilometers walked and Delacour's langur detections. In order to quantify the community-based monitoring costs, we first calculated a daily cost norm for labour by dividing the sum of (i) the monthly salary, (ii) allowance and (iii) insurance by the total number of 22 working days required a month. This daily labour cost norm was then multiplied by the total number of field person-days in SMART to estimate the total cost for labour. The costs for equipment and materials – including cameras, GPS units and batteries – were also added to calculate the total cost for SMART data collection.

3. Results

3.1 Abundance estimation and covariate effects

Across the 26 survey sites in our systematic design, we flew for a total of 74.6 hours over 48 days. This encompassed 217 flights over a total distance of 871.7 km. A survey occasion, which included one to five flights depending on the survey site area, lasted 29 minutes on average (ranging from 10.25 to 122 minutes). We surveyed two sites on two occasions; eight sites on three occasions; 11 sites on four occasions; three sites on five occasions; and two sites on six occasions. We recorded 20 detections of 12 groups from 11 survey sites and 15 sites generated no detections. We recorded one group at two sites (12 and 11) since we observed the group moving from Site 12 to Site 11. For estimating population abundance, we removed the detection at one site (Site 12) from the data to avoid double counting (Annex 2).

The individual count models showed poor fit to the data (Bayesian p-values ~ 0) (Table 1). The best individual count model (beta-binomial/Poisson-lognormal with NDVI and macaque presence as site covariates) exhibited slightly overdispersion (c-hat 2.65). The model estimated detectability of 0.03 (95% CrI 0.00 – 0.10), average density of 21 (95% CrI 1 – 41) langurs per km^2 and total number of langurs of 606 (adjusted 95% CrI 29 – 1,183) individuals, with a coefficient of variance (CV) = 0.49. We did not consider these estimates credible.

The group abundance models exhibited a good fit with the group count data, as evidenced by Bayesian p-values close to 0.5. Among these, the zero-inflated Poisson model incorporating macaque presence as a covariate had the smallest DIC value (Table 1). According to this model, the probability of detecting a group in a single survey was 0.23 (95% CrI 0.03 – 0.42); the average density, 0.85 (95% CrI 0.31 – 2.96) langur groups per km^2 (CV = 2.05); and the number of langur groups for Kim Bang Forest, 25 (95% CrI 9 – 86) groups.

[Table 1. Model selection of Delacour's langur abundance estimation from N-mixture models and Bayesian P-value]

[Figure 2. Location of Delacour's langur and macaque detections by the drone survey 2022]

Additional 31 flights (8.09 hours, 98.92 km) took place outside the survey sites, recording 13 detections of four groups. Overall, we recorded 33 detections of 16 groups and 104 animals (Annex 1). The median group size was seven langurs, with a mean of 6.5 and a standard deviation of 2.6. Utilizing the median group size of seven langurs, we extrapolated an individual abundance estimate of 175 (95% CrI 63 – 602) langurs for the entire Kim Bang Forest.

3.2 Method comparison

The drone survey method was ranked higher than the other two ground-based methods along most of the 10 dimensions of effectiveness that were assessed, although it was ranked as the least effective for financial cost and understanding the threats to the langur population occurring on the ground (Table 2, additional comparative information is presented in Annex 3).

[Table 2. Effectiveness and efficiency of drone survey, SMART work and ground survey]

4.1 Discussion

Firstly, using our novel drone-based survey method, we have better enumerated the Delacour's langur population in Kim Bang Forest than was previously done. With an estimate of 25 groups and 175 individuals, our drone flights directly observed 64% and 59% of the estimated group and individual counts, respectively. We attribute the substantially larger size of this population size estimate (80-113% larger than previously thought) primarily to our new, more effective approach, rather than a very large increase in the actual population since the last surveys, although we cannot discount the fact that the population may have grown slightly between 2018 (the last survey) and 2022. The Kim Bang population was first recorded in the 1990s with 1-2 groups and 20 individuals, and then in 2013-2014 with seven groups and 24-32 individuals in total (Nadler, 2015). In 2016, (Trinh Dinh and Le, 2016) reported seven groups with 40 individuals. Most recently in 2018, (Nguyen et al., 2021) recorded 13 groups with at least 73 individuals and an estimated 82-97 individuals. Those varying results could be the direct consequence of these ground-based surveys being not complete in terms of coverage and biased to areas previously reported to have species presence and being accessible. Now with our new estimates, Kim Bang Forest is reaffirmed as one of the most important areas globally for the conservation of the species, ranking alongside Van Long Nature Reserve – Dong Tam Forest, which is believed to harbour the largest population (Nadler, 2015; Nguyen et al., 2021) with 25 groups and a total of 207 – 222 individuals (Nguyen et al., 2019).

Secondly, our estimates could be improved for future monitoring as they are still relatively imprecise due to the small sample size and low detectability of the species. On average, each survey site was surveyed only four times. The probability of detecting a group on a single survey was 0.23. Thus, the probability of missing Delacour's langurs if present (i.e., a false negative) after four survey occasions was (1-0.23) ^ 4 = 0.35. To be 95% certain that langurs are detected if present, the minimum number of occasions needed for each survey site is about 12 (log(1-0.95)/log(1-0.23) = 11.46) (Tobler et al., 2008). Increasing the number of survey occasions would generate a considerably larger dataset that allows N-mixture models to fit individual counts and integrate more covariates that might influence langur abundance and detection.

Furthermore, since Delacour's langur has a large variation in group size (Harding, 2011), estimating only group numbers might not fully represent the population, especially in cases where average group size changes but the number of groups does not. Where data make it possible, individual abundance modelling should complement group-based estimates. However, in cases where it is logistically difficult to collect the accessory information on group sizes, the number of groups can still serve as a useful metric for making informed management decisions about a population.

Moreover, regarding the influence of other factors on langur abundance, we found that the presence of macaques was correlated with lower langur abundance. This finding, along with informal reports from local ex-hunters about macaque-langur fights (Le Van Hien and Nguyen Van Bien pers. comm. to author TDH), likely helps explain the lack of langur detections in the southern part of Kim Bang Forest (Fig. 2). In this southern area, Assamese macaques were found and Delacour's langur was not detected in either the ground-based survey or the drone survey. Additionally, the SMART data only show five detections over the past two and a half years. Potential reasons for this include: (a) macaques are driven to the area of low langur density as langurs have been reported to chase macaques (*Macaca mulatta*) (Bist, 2017); (b) the macaques (*Macaca assamesis*) in Kim Bang Forest are bigger than *Macaca mulatta*, and might be able to displace Delacour’s langur away from the area they occupy, and-or (c) the lack of key resources for langurs that inhabit limestone, such as caves for sleeping in at night and cliffs for protection from predators. Langurs visit the forests without these conditions occasionally, or even never, while macaques, who do not require those structures, frequently use these places. Additionally, as macaques are known to raid crops for food (Ghimirey et al., 2018), they tend to be distributed in the areas close to farms in the arable valleys further south of Kim Bang Forest. This could explain their concentration in those areas and the consequent absence, or low abundance, of Delacour’s langurs. Besides macaque presence, langur individual abundance was found to correlate positively with vegetation productivity (NDVI). More individuals, or larger group sizes, were detected in the sites with higher NDVI values which presumably had more food resources for a folivorous species like Delacour’s langur. Given the significance of macaque presence and NDVI in explaining langur abundance, they should be considered as covariates in understanding the results from future langur surveys. Further research into the langur’s interactions with sympatric competitor species, particularly macaques, and the relationship with habitat quality is essential for effective species management.

Lastly, comparing our drone-based method with previous ground-based community patrolling and the intensive survey, we found that the drone-based method is more effective along most of the dimensions that we compared (Table 2 and Annex 3), with key benefits being the reduced demands in terms of required field personnel and time in the field and, crucially, the higher objectivity and robustness of population estimates. However, the drone-based method (a) generates limited data on threats to the population, particularly from snares and other human disturbances occurring on the ground, for which it is necessary to do ground-based surveys, and (b) is initially relatively expensive due to equipment costs. As technology advances and costs decrease, making drones affordable, our new method has a lot of promise to provide accurate population estimates for Delacour's langur, as well as other mammals in poorly-accessible karst habitats. We foresee that the use of drones will increase in future.

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Table 1. Model selection for Delacour's langur abundance estimation from N-mixture models.

We used the log of the size of the sampling unit log(Area) as an additive offset in all models

No.	Model	DIC	P-value
	Group abundance model		
1	lambda(offset(Area) +Macaques), p(.)[a]	101.91	0.47
2	lambda(offset(Area) +Macaques + NDVI), p(.)[a]	103.3	0.22
3	lambda(offset(Area)+Ruggedness), p(.)[a]	104.27	0.45
4	lambda(offset (Area)+Distance to forest edge), p(.)[a]	104.62	0.54
5	lambda(offset(Area), p(.)[a]	104.68	0.49
6	lambda(offset(Area)+Elevation), p(.)[a]	105.41	0.49
7	lambda(offset(Area)+NDVI), p(.)[a]	105.68	0.45
8	lambda(offset(Area) +Macaques), p(.)[b]	106.1	0.44
9	lambda(offset(Area)), p(.)[b]	111.11	0.47
	Individual abundance model		
10	lambda(offset (Area) + NDVI + Macaque), p(.)[c]	267.11	0.01
11	lambda(offset (Area) + NDVI), p(.)[c]	268.99	0.01
12	lambda(offset(Area) + Distance), p(.)[c]	269.23	0.01
13	lambda(offset (Area) + Ruggedness), p(.)[c]	269.25	0.01
14	lambda(offset (Area) + Macaques), p(.)[c]	269.44	0.01
15	lambda(offset (Area), p(.)[c]	271.21	0.01
16	lambda(offset (Area) + Elevation), p(.)[c]	269.41	0.01
17	lambda(offset(Area) + Ruggedness), p(.)[d]	275.15	0.01
18	lambda(offset(Area) + Distance to forest edge), p(.)[d]	277.65	0.01
19	lambda(offset(Area) + Elevation), p(.)[d]	289.66	0.01
20	lambda(offset(Area) + NDVI), p(.)[d]	289.82	0.01
21	lambda(offset(Area) + Macaque), p(.)[d]	290.2	0.01
22	lambda(offset(Area)), p(.)[d]	291.71	0.01
23	lambda(offset(Area) + Macaques) p(.)[e]	319.44	0.01
24	lambda(offset(Area)+Distance to forest edge) p(.)[e]	320.94	0.01
25	lambda(offset(Area))p(.)[e]	321.93	0.01
26	lambda(offset(Area)+Elevation) p(.)[e]	322.37	0.01
27	lambda(offset(Area)+NDVI) p(.)[e]	322.67	0.01
28	lambda(offset(Area)+Ruggedness) p(.)[e]	322.75	0.01

[a] Binomial/zero-inflated Poisson mixture model

[b] Binomial/Poisson mixture model

[c] Beta-binomial/Poisson-lognomal mixture model

[d] Beta-binomial/zero-inflated Poisson mixture model

[e] Beta-binomial/Poisson mixture model

Table 2. Effectiveness and efficiency of drone survey, community patrolling and ground survey. In each case, we rank the methods from 1 (best) to 3 (worst). Ranks are indicated in parentheses.

No.	Criteria	Drone survey 2022	Community patrolling 2020 - 2022	Ground survey 2018
1	No. of data collectors required	2 (1)	9 (3)	8 (2)
2	No. of detections	33 (2)	201 (1)	14 (2)
3	No. of survey hours	83 (1)	7,149 (3)	399 (2)
4	Total cost in Dollars	15,662 (2)	52,462 (3)	5,589 (1)
5	Coverage of study area	Medium (2)	High (1)	Low (3)
6	Suitability for population size estimation	High (1)	Low (3)	Medium (2)
7	Robustness of statistical approach	Medium (1)	Low (3)	Low (3)
8	Objectivity and verifiability of data	High (1)	Low (3)	Medium (2)
9	Suitability for monitoring threats (snares and deforestation)	Low (3)	High (1)	Medium (2)
10	Safety for field teams	Medium (1)	Low (3)	Low (3)
	Sum of ranks	**15 (1)**	**24 (3)**	**23 (2)**

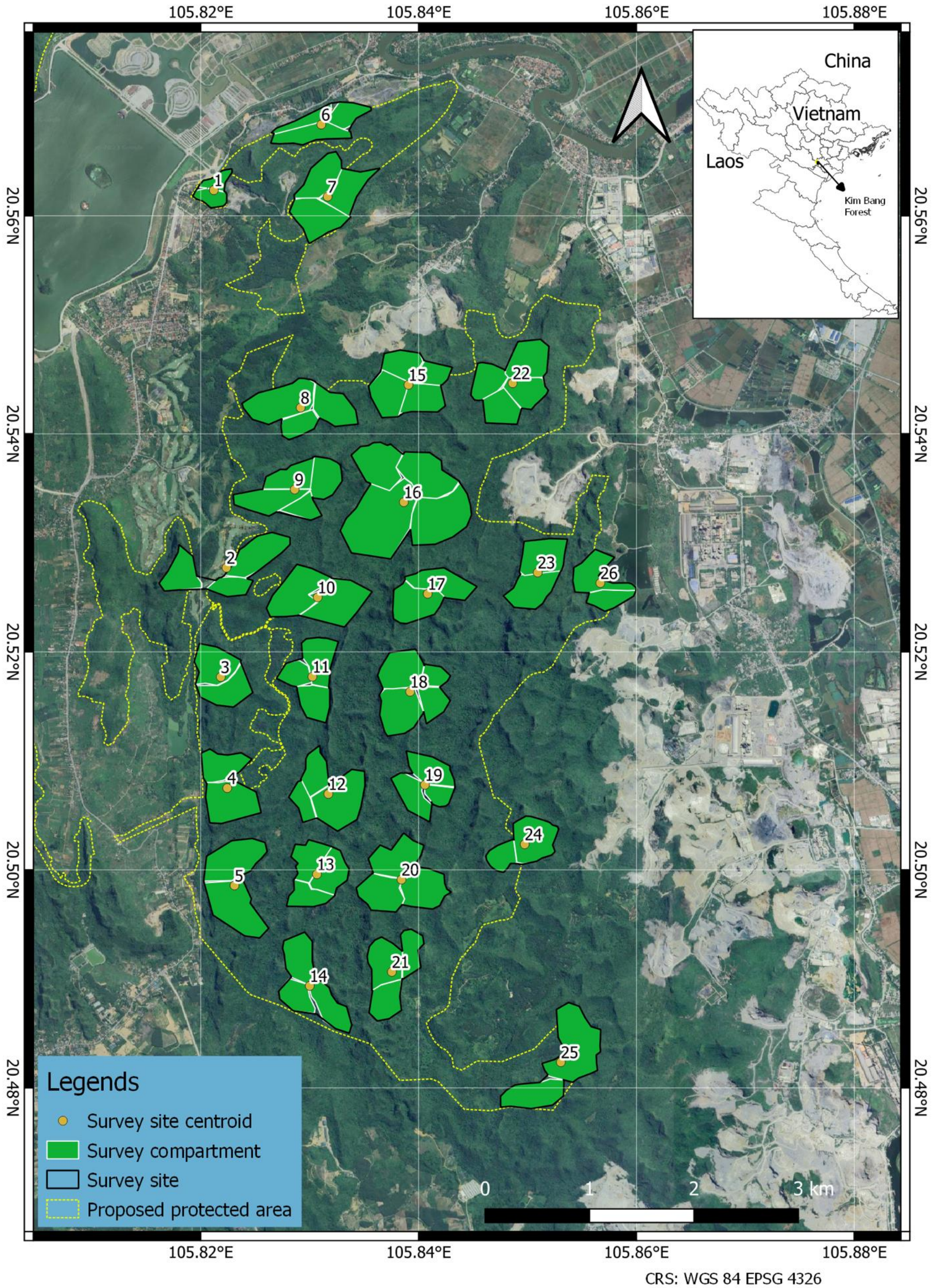

Figure 1: Drone survey sites in Kim Bang Forest between October to December 2022

Note: The white-buffered black numbers in the map are ordinal numbers of the survey sites.

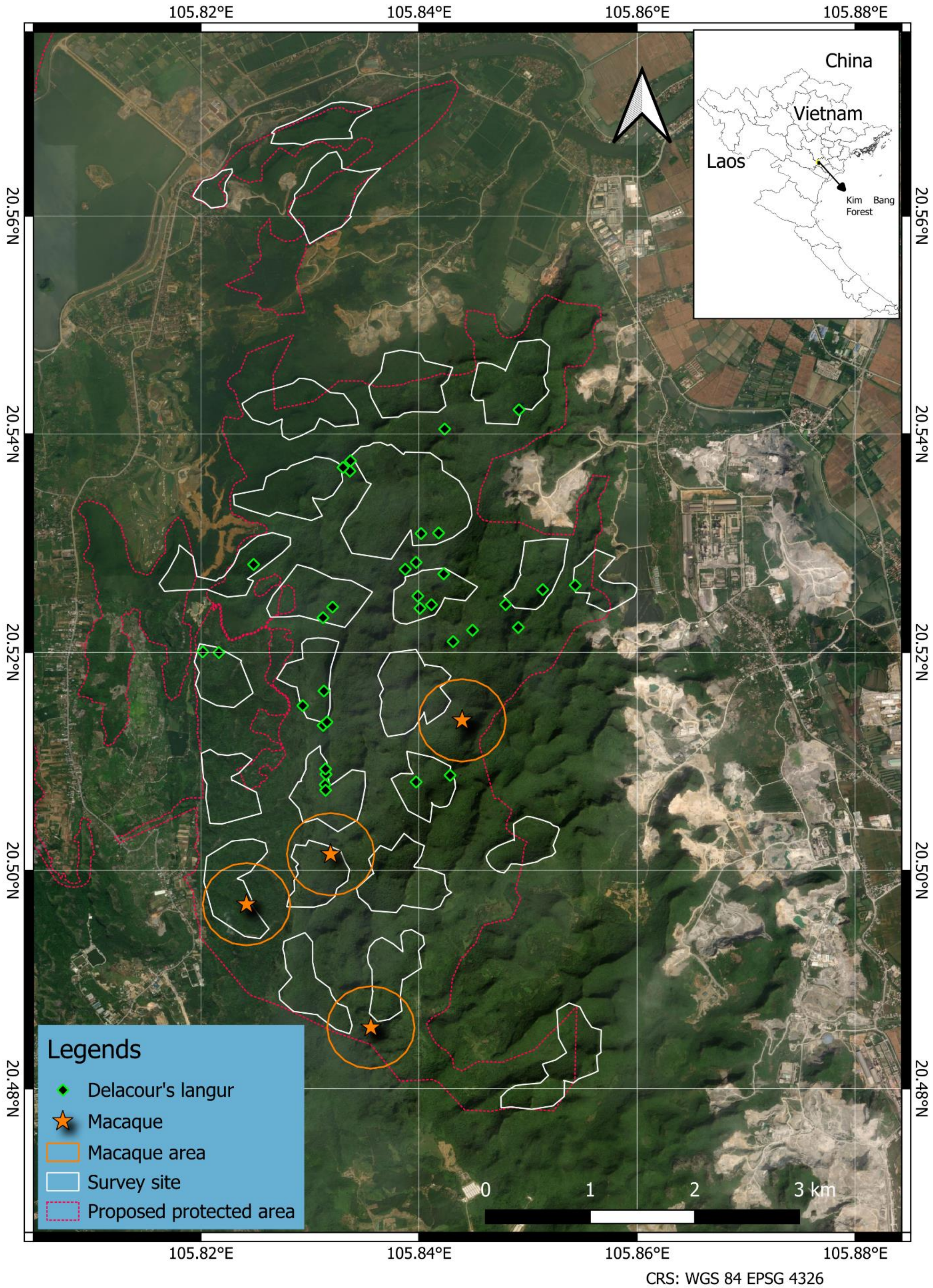

Figure 2. Location of Delacour's langur and macaque detections by the drone survey 2022.

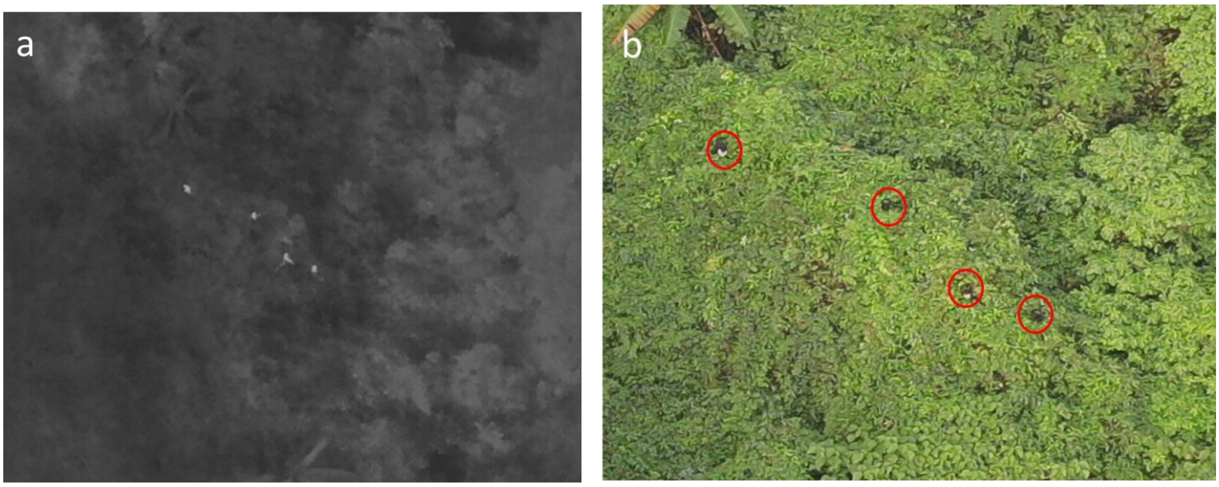

Figure 3. (a) Thermal photo and (b) visual photo of Delacour's langur by Mavic 2 Enterprise Advanced

Annex 1. Delacour's langur groups recorded by the drone survey. Group size was the maximum number of individuals observed.

No.	Group ID	Group size	Site ID	Notes
	Within 26 survey sites			
1	D1	4	22	
2	D4	8	16	Recorded at the same time as D5
3	D6	8	26	Recorded at the same time as D7
4	D7	3	23	Recorded at the same time as D6
5	D8	7	17	Recorded at the same time as D9 and D5
6	D9	1	17	Recorded at the same time as D8 and D5
7	D12	8	12	Recorded at the same time as D13
8	D13	7	12 and 11	Recorded at the same time as D12 and D14
9	D14	8	10	Recorded at the same time as D13
10	D15	5	3	
11	D16	8	2	
12	D17	4	19	
	Outside 26 survey sites			
13	D2	10	Outside sample	Recorded at the same time as D3
14	D3	7	Outside sample	Recorded at the same time as D2
15	D5	11	Outside sample	Recorded at the same time as D4
16	D10	5	Outside sample	Recorded at the same time as D6
	Total	104		
	Mean group size = 6.5			
	Median=7			

Standard deviation = 2.6

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Annex 2. Covariate data used for N-mixture models of Delacour's langur abundance estimation

Site	Area (ha)	Macaque detection	Distance to forest edge (m)	Elevation (m)	Ruggedness	NDVI	Effective survey area (ha)
1	8.24	0	0.00	64.80	45.55	0.45	37.20
2	33.69	0	0.00	155.59	42.57	0.56	204.31
3	25.11	0	13.53	180.20	41.56	0.61	141.94
4	28.87	0	15.74	156.48	44.56	0.60	156.70
5	39.68	1	21.62	194.28	30.96	0.60	181.78
6	23.51	0	0.00	135.99	63.61	0.42	105.51
7	39.65	0	0.00	124.21	32.62	0.59	168.73
8	39.77	0	37.36	218.98	35.26	0.61	191.06
9	39.25	0	0.00	206.94	41.39	0.61	187.16
10	38.62	0	482.25	231.24	35.04	0.63	183.01
11	28.26	0	797.44	210.29	48.74	0.59	165.12
12	35.45	1	810.43	271.99	41.46	0.62	181.45
13	28.42	1	834.88	238.15	46.74	0.62	156.26
14	32.00	1	285.85	162.15	45.11	0.67	184.73
15	38.80	0	0.00	239.29	31.78	0.54	154.72
16	99.31	0	322.44	219.89	36.06	0.64	301.82
17	27.64	0	737.48	319.18	43.47	0.62	156.86
18	43.09	1	1118.80	316.00	50.56	0.59	189.24
19	26.31	0	952.32	281.84	44.03	0.62	152.10
20	42.98	0	260.17	281.47	55.25	0.61	195.25
21	30.62	1	119.72	171.92	45.14	0.67	172.90
22	42.23	0	90.09	124.42	43.17	0.61	182.40
23	26.90	0	115.18	131.57	39.20	0.60	146.84
24	22.60	0	183.77	270.42	50.45	0.60	144.28
25	41.29	0	230.26	244.89	50.71	0.57	217.29
26	19.77	0	0.00	86.04	50.08	0.55	85.94

Annex 3. Drone, community patrolling and ground survey method comparison

Criteria	Drone survey 2022	Community patrolling 2020 - 2022	Ground survey 2018
# Visual detections	33	133	6
# Auditory detections	NA	68	8
# groups and individuals directly recorded	16 groups with a total 104 langurs	No synthesis available	11 groups with 35-36 langurs
# teams	1	3	3
# people involved	5	9	12
# days	48	777	38
# team*days	48	1,212	114
# hours	82.72	7,148.5	399
# Flight km	970.6	NA	NA
# Ground walking Km	NA	8,696.88	NA, mainly vantage point method
Financial cost (USD)	15,662	52,462	5,589
Equipment cost (USD)	9,252.90	2,581.37	1,273.08
Time efficiency (Hours/detection)	2.51	35.56	28.5
Financial efficiency (USD per detection)	475	394	931
Time of first detection (minute)	5.69 (0.02 - 16.83)	NA	NA
Survey documentation	The whole survey recorded on video (RGB/thermal), providing historical visual data of Delacour's langurs and the habitat.	Photos and videos were taken with narrow view field mainly focussing on Delacour's langurs after being seen.	Photos and videos were taken with narrow view field mainly focussing on Delacour's langurs after being seen.

Criteria	Drone survey 2022	Community patrolling 2020 - 2022	Ground survey 2018
Effort distribution	Relatively equal effort distribution throughout the study area	Unequal effort distribution in the study area, biased towards areas/trails of logistic convenience	Unequal effort distribution, concentrated on the areas reported to have Delacour's langurs
Group detection independence	Visual detections only were independent	DL groups could be heard and then seen or vice versa	DL groups could be heard and then seen or vice versa
Double counting issue	Minimal double counting	Potentially many double counts due to visual and auditory records of a group by different survey teams or on different days.	Double counting was probably minimal because of small number of detections
Ability to work in dark and misty condition	Thermal camera worked well in misty, dim light and dark condition	It is hard or impossible to detect and/or count DLs by naked eyes and RGB cameras /Binoculars in misty, dim light or dark condition	It is hard or impossible to detect and/or count DLs by naked eyes and RGB cameras /Binoculars in misty, dim light or dark condition
Energy issue, recharging equipment	A generator required to recharge drone batteries	Simple with AA batteries for GPS and power banks to recharge camera batteries	Simple with AA batteries for GPS and power banks to recharge camera batteries
Determination of DL location	Directly recorded with the drone above Delacour's langurs	Indirectly determined by estimated distance and compass bearing, which possibly cause error (Dawson, 1981; Rawson, 2010)	Indirectly determined by estimated distance and compass bearing, which possibly cause error (Dawson, 1981; Rawson, 2010)
Accessibility and safety for surveyors	Easily accessible regardless of how rugged the surface terrain is. It took 1-2 minutes for 1 km	Difficult to access rugged terrain, even inaccessible to vertical cliffs or deep gorges. Walking takes 60 minutes for 1 km	Difficult to access rugged terrain, even inaccessible to vertical cliffs or deep gorges. Walking takes 60 minutes for 1 km
Daily survey time, location records and occupancy	To avoid sunlight and high temperature, early morning and late afternoon flights probably recorded DLs at/near their	The field workers did not start early morning or finish late afternoon, especially in middle of the forest if it was a one-day mission. DLs were probably recorded while	Started from early morning until late afternoon. DLs could be recorded throughout the day.

Criteria	Drone survey 2022	Community patrolling 2020 - 2022	Ground survey 2018
	sleeping places, which do not reflect well the area of occupancy	foraging and noon resting, which might not reflect well DL occupancy.	
Flight permits and no flight zone	Flight permit required No-flight areas contributed to smaller number of sites	No problem of flight permit and no flight zone	No problem of flight permit and no flight zone

Title Page (with Author Details)

A drone-based population survey of Delacour's langur (*Trachypithecus delacouri*) in the karst forests of northern Vietnam

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