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Effectiveness of thermal infrared drone surveys in detecting the diurnal primate community in Cat Tien National Park, South Vietnam

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Summary

Thermal infrared (TIR) imaging and drone technology have recently emerged as valuable tools in wildlife monitoring, offering advantages over traditional survey methods. We conducted manual and systematic TIR drone surveys from April 2022 to May 2023 in Cat Tien National Park, Dong Nai Province, southern Vietnam, to assess their effectiveness in detecting and counting six diurnal sympatric primate species at their sleeping sites. Our study revealed successful detections of black-shanked douc langurs (*Pygathrix nigripes*), Annamese silvered langurs (*Trachypithecus margarita*), southern yellow-cheeked gibbons *Nomascus gabriellae*), long-tailed macaques (*Macaca fascicularis*), and pig-tailed macaques (*Macaca leonina*). However, detection reliability varied among species, with arboreal langurs showing higher reliability compared to semi-terrestrial macaques or gibbons. Ecological and behavioral factors influenced species' detection effectiveness, with large-bodied, arboreal species being more reliably detected. For instance, black-shanked douc langurs exhibited distinct thermal signatures, facilitating their detection and count. In contrast, gibbons showed avoidance behavior during drone surveys, posing challenges for detection. We developed a scoring system based on these factors to assess thermal detection reliability, which could assist in evaluating detectability in multispecies studies and the reliability of TIR drone surveys. The low resolution of TIR drone imagery also limited species differentiation, particularly for species with similar morphology or behavior. We recommend combining TIR drone surveys with ground-truthing methods, camera trap surveys, and passive acoustic monitoring for comprehensive primate monitoring research. Our findings underscore the potential of TIR drone technology for detecting and monitoring large arboreal species like langurs, while highlighting the need for developing global scoring system to assess TIR detection reliability for different primate species. This study contributes to understanding sympatric primate behavior and ecology, aiding conservation efforts, and emphasizes the importance of innovative technologies in primate monitoring.

Hiệu quả của khảo sát bằng máy bay không người lái hồng ngoại nhiệt trong việc phát hiện quần thể linh trưởng ban ngày ở miền Nam Việt Nam

Tóm tắt

Công nghệ hình ảnh hồng ngoại tầm nhiệt (TIR) và công nghệ Drone đã trở thành các công cụ có giá trị trong việc giám sát động vật hoang dã, mang lại lợi ích cao so với các phương pháp khảo sát truyền thống. Chúng tôi đã tiến hành các cuộc khảo sát Drone TIR thủ công và có hệ thống từ tháng 4 năm 2022 đến tháng 5 năm 2023 tại Vườn Quốc gia Cát Tiên, tỉnh Đồng Nai, Nam Việt Nam, để đánh giá hiệu quả của thiết bị trong việc phát hiện và đếm kiểm sáu loài linh trưởng cùng phân bố tại các địa điểm ngủ của chúng. Kết quả nghiên cứu cho thấy đã ghi nhận thành công các loài như Chà vá chân đen, Voọc bạc An Nam, Vượn má vàng miền Nam, Khỉ đuôi dài, Khỉ mặt đỏ và Khỉ đuôi lợn. Tuy nhiên, độ tin cậy phát hiện khác nhau giữa các loài, đối với các loài voọc sống trên cây cho thấy độ tin cậy cao hơn so với các loài khỉ hoặc vượn ở tầng dưới của tán rừng. Các yếu tố sinh thái và hành vi đã ảnh hưởng đến hiệu quả phát hiện loài, đối với các loài sống trên cây mà có cơ thể lớn, sự phát hiện loài có độ tin cậy cao hơn. Ví dụ, voọc Chà vá chân đen thể hiện dấu hiệu nhiệt riêng biệt, tạo điều kiện thuận lợi cho việc phát hiện và đếm chúng. Ngược lại, vượn có ứng xử tránh né trong suốt quá trình khảo sát bằng thiết bị Drone TIR, gây ra những thách thức cho việc giám sát bằng thiết bị này. Một hệ thống điểm đã được thiết lập dựa trên các yếu tố này để đánh giá độ tin cậy của việc phát hiện loài bằng cảm biến nhiệt. Hệ thống này có thể hỗ trợ đánh giá khả năng phát hiện loài trong các nghiên cứu đa loài và độ tin cậy của các khảo sát bằng Drone TIR. Độ phân giải thấp của hình ảnh từ Drone TIR cũng hạn chế khả năng phân biệt các loài, đặc biệt là đối với các loài có hình dáng hoặc hành vi tương tự nhau. Chúng tôi khuyến nghị kết hợp phương pháp khảo sát bằng thiết bị Drone TIR với các phương pháp xác minh trên thực địa, khảo sát bằng bẫy ảnh và âm sinh học để có một hệ thống giám sát động vật linh trưởng toàn diện. Các kết quả của chúng tôi nhấn mạnh tiềm năng của công nghệ Drone TIR trong việc phát hiện và giám sát các loài linh trưởng lớn sống trên tầng cao của tán rừng như voọc, đồng thời nhấn mạnh sự cần thiết phát triển hệ thống điểm toàn cầu để đánh giá độ tin cậy của phương pháp phát hiện loài bằng TIR đối với các loài linh trưởng khác nhau. Nghiên cứu này đóng góp vào việc hiểu biết về hành vi và sinh thái của các loài linh trưởng cùng sinh sống với nhau, hỗ trợ các nỗ lực bảo tồn, và nhấn mạnh tầm quan trọng của các công nghệ đổi mới trong giám sát động vật linh trưởng.

Introduction

In recent years, the application of thermal infrared (TIR) imaging and drone technology has gained prominence in the field of wildlife monitoring (Wich & Koh 2018). TIR drones enable the detection of animals by capturing their thermal signatures, facilitating wildlife surveys and identification of species that may not be discernible to the naked eye or through conventional imagery (Wich et al. 2021). This innovative approach offers significant advantages over traditional survey methods. It enabled researchers to conduct aerial surveys with improved efficiency and accuracy, particularly in detecting various forest-dwelling primate families, such as Atelidea and Cebidae families in the Neotropics (Kays et al. 2019; Spaan et al. 2019; Whitworth et al. 2022), and Cercopithecidae, Hylobatidae and Hominidae families in Asia (Burke et al. 2019; He et al. 2023; Mirka et al. 2022; Rahman et al. 2022; Zhang et al. 2023). Specifically, in Southeast Asian countries, Vietnam is increasingly using TIR drones to monitor and count threatened Vietnamese primates such as the ‘Critically Endangered’ Delacour’s langurs (*Trachypithecyus delacouri*, Trinh Dinh Hoang 2022), Tonkin snub-nosed monkeys (*Rhinopithecus avunculus*, Le Khac Quyet 2022), eastern black gibbons (*Nomascus nasutus*, Wearn et al. 2023), grey-shanked douc langurs (*Pygathrix cinerea*) and the ‘Endangered’ Hatinh langurs (*Trachypithecus hatinhensis*, Gazagne et al. 2023).

Cat Tien National Park in southern Vietnam encompasses a rich primate community that includes seven sympatric species: the ‘Critically Endangered’ black-shanked douc langur (Hoang Minh Duc et al. 2021), the ‘Endangered’ Annamese Silvered Langur (Hoang Minh Duc et al. 2022), the ‘Endangered’ southern yellow-cheeked gibbon (Rawson et al. 2020), the ‘Endangered’ long-tailed macaque (Hansen et al. 2022), the ‘Vulnerable’ northern pig-tailed macaque (Boonratana et al. 2022), the ‘Vulnerable’ stump-tailed macaque (*Macaca arctoides*) (Chetry et al. 2020), and the ‘Endangered’ pygmy loris (*Xanthonycticebus pygmaeus*) (Blair et al. 2021). The current study is part of a broader project aimed at studying the distribution and sleeping site selection of the diurnal primate community via systematic TIR drone nocturnal surveys in Cat Tien National Park. However, before proceeding, it is imperative to assess the effectiveness of TIR drones in detecting and counting the six diurnal primate species at their sleeping sites.

By combining data, collected through manual and systematic TIR drone surveys in the lowland dry-evergreen forests of the eastern sector of Nam Cat Tien (< 100 km^2), we aimed to assess the reliability of TIR drones in detecting black-shanked douc langurs, Annamese silvered langurs, southern yellow-cheeked gibbons, long-tailed macaques, pig-tailed macaques, and stump-tailed macaques. We hypothesize that inter-species variations in the effectiveness of TIR drone detectability at a short scale will be influenced by primate physiological factors (e.g. body and tail length), ecological factors (e.g. group size and home range size), and behavior at their sleeping site (e.g. sleeping position in the canopy strata and species' behavioral response to the drone). For instance, we predicted that large-bodied and highly arboreal species, with smaller home range such as black-shanked douc langurs (Hoang Minh Duc et al. 2021), would be easier to detect and identify locally through TIR imagery than semi-terrestrial species with large home ranges and elusive behavior such as stump-tailed macaques (Chetry et al. 2020). Finally, we aimed to build a local scoring system to assess thermal detection reliability that could be adapted to other study sites with similar sympatric species to assess viability of TIR drone use.

Study site

Cat Tien National Park (738.78 km^2; 11°2' to 11°48'N; 107°10' to 107°34'E), located in southern Vietnam, comprises three sectors (Cat Tien National Park 2020): Nam Cat Tien in Dong Nai Province (383.02 km^2), Tay Cat Tien in Binh Phuoc Province (51.41 km^2) with both moderate terrain (elevation ranging from 200 to 300 m asl), and Cat Loc in Lam Dong Province (304.35 km^2) with high mountain topography (elevation ranging from 200 to 600 m asl) (Fig. 1). Our study focused on the lowland Eastern Nam Cat Tien forest complex, covering approximately 100 km^2 with elevations reaching a maximum of 150 m above asl (Fig. 2). The area experiences a tropical monsoon climate with two distinct dry (November to April) and rainy seasons (May to October). The average annual temperature is 26.7°C, average annual rainfall is 2,227 mm, and average humidity level is 82% (Cat Tien National Park 2020). Habitat types include primary and secondary evergreen forest, semi-evergreen forest, mixed forest (including bamboos and other plants), bamboo forest, grassland, wetlands and lakes (Fig. 3).

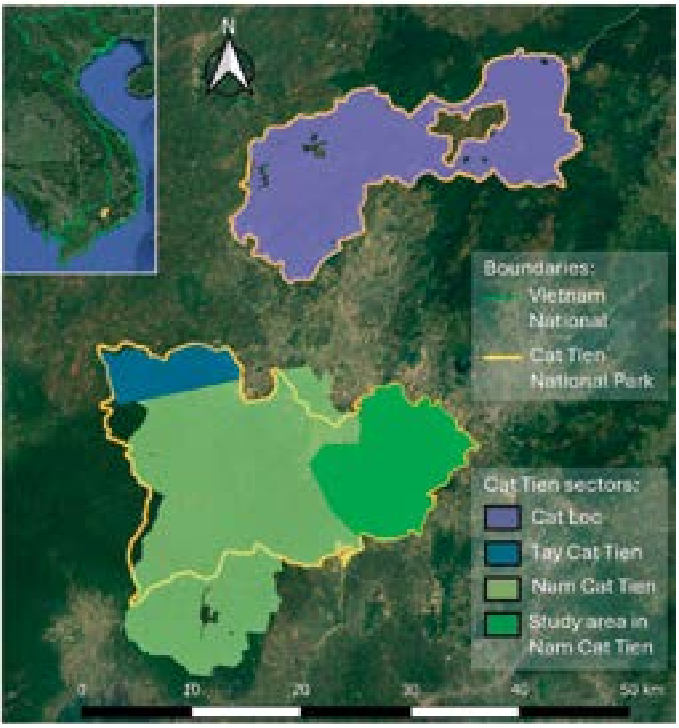


Fig.1. Satellite image of Cat Tien National Park and its three sectors located in southern Vietnam: Cat Loc, Tay Cat, and Nam Cat Tien. The study area is covering approximately 100 km^2 within the lowland dry-evergreen forests of Eastern Nam Cat Tien.

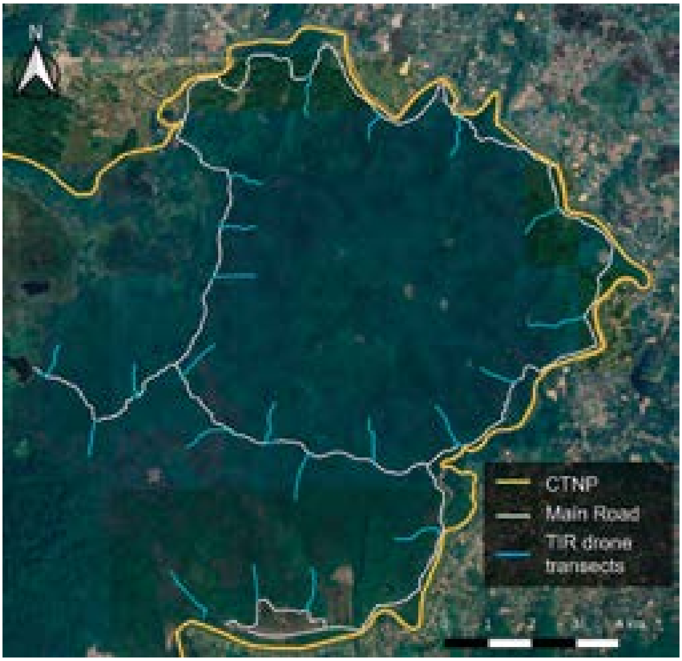


Fig.2. Zoomed-in satellite image of the study area in Cat Tien National Park. We conducted Thermal Infrared drone surveys along 22 <1-km aerial transects, spaced more than 1 km apart, and overlapping with ground transects adjacent to the main road.

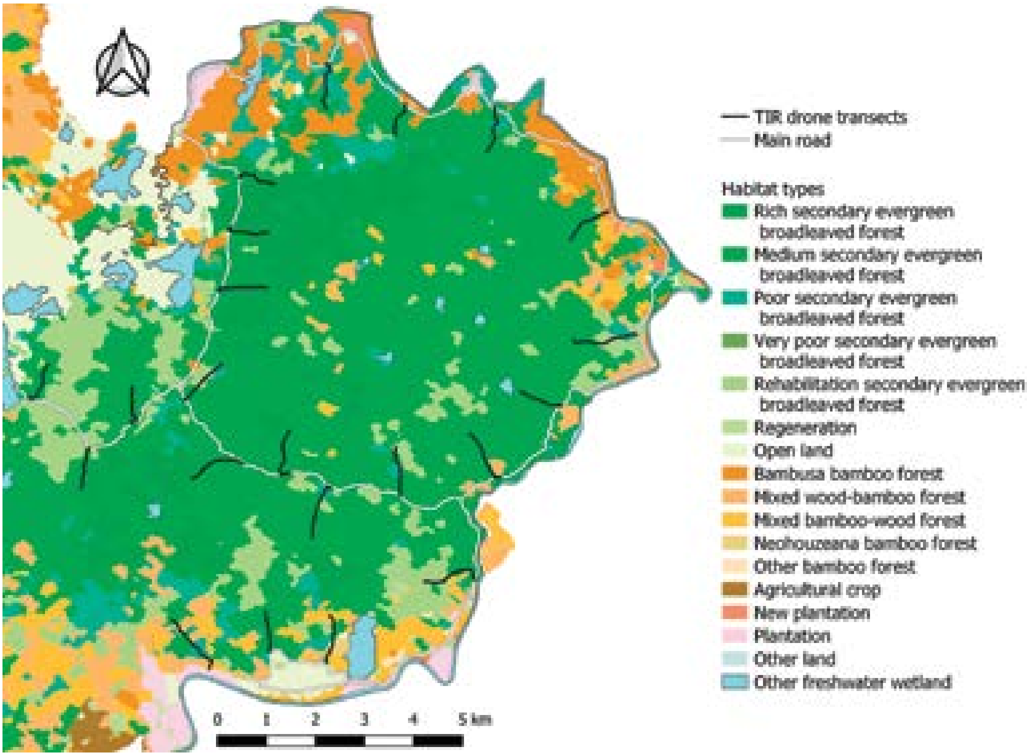


Fig.3. Habitat types within the study area which is predominantly characterized by secondary evergreen forests, including ‘rich’, ‘medium’, ‘poor’, ‘very poor’, and ‘rehabilitation’ secondary evergreen broadleave forests on soil mountains, as well as mixed bamboo forests, comprising both bamboo and evergreen trees.

Material and Methods

Material

For pilot surveys conducted in 2022, we used a DJI Mavic 2 Enterprise Advanced Drone (M2EA) equipped with a thermal camera. For systematic surveys in 2023, we employed a DJI Mavic 3 Thermal (M3T) drone. Both drones featured a 12-μm pixel pitch, uncooled VOx microbolometer sensor operating within a 8–14 μm spectral band, a 640x512-pixel resolution at 30 Hz framerate, and a 48 megapixel standard camera. The M2EA is equipped with a 35 mm lens providing a 84° field of view and a 16x digital zoom, while the M3T possesses a 61° diagonal field of view and a 56x hybrid zoom. We captured still images and videos of primate detections using the Ironbow color palette (Gazagne et al. 2023).

Primate species detection and identification with TIR drones

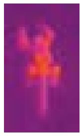
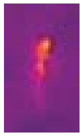
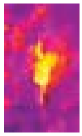
To test TIR drone detectability of the six diurnal primate species inhabiting Cat Tien National Park, we conducted pilot surveys from April 2022 to November 2022. For these exploratory surveys, we executed 34 TIR drone flights manually at 40 m to 80 m Above Ground Level (AGL), during night-time (nocturnal surveys) and sunrise (diurnal surveys), over locations where the principal investigator (E.G.) had previously observed various primate species during daylight hours. Each TIR detection was validated through subsequent ground-truthing: (i) either primate groups were followed to or near sleeping sites before conducting targeted aerial surveys above this location, or (ii) unknown sleeping sites were identified through nocturnal TIR drone surveys, with species confirmation achieved after sunrise through direct observation. We recorded the detected species, counted detected individuals, evaluated the number of groups present, and collected ad *libitum* sleeping behavior (e.g. sleeping position height in the canopy, number of sleeping trees used etc.).

We conducted 132 nocturnal systematic TIR drone surveys along 22 transects (6 replicates per transect) from January to May 2023, using flight routes programmed with the DJI RC Pro Enterprise control unit (Fig. 1.). The drone maintained a flight speed of 3 m/s, oriented toward the flight route, and a flight altitude of 60 m (94 surveys) or 70 m AGL (38 surveys), depending on the canopy height (respectively <30 m or >30 m). The altitude was set to ensure a distance >30 m between the drone and the top canopy, providing sufficient resolution for animal visibility in the upper canopy while minimizing disturbance (Burke et al. 2018; Kays et al. 2019). The length of flight routes averaged 940 ± 155 m, ranging from 656 m to 1,269 m based on drone signal capacities. Each flight lasted on average 14’33’’± SD 00’02’’ minutes. Nocturnal flights were conducted when the temperature difference between primates and the surrounding canopy was greater, and allowed for more visible thermal detections: before sunrise at 5:08 AM ± SD 00:21 (n=99) or at dusk at 7:46 PM ± SD 00:34 (n=21). Similar to pilot surveys, nocturnal detections were verified through ground-truthing during diurnal ground surveys conducted the same day and along the same flight route as each aerial survey. Suspected species detected via TIR drone were confirmed if primate species were detected and identified in the same area a few hours later or earlier, corresponding to early morning or evening nocturnal surveys. However, unconfirmed TIR detections were classified as unknown species. We recorded the detected species, the count of individuals and groups. Finally, to assess drone disturbance, we documented whether detected individuals were inactive (i.e. no visible response), in movement (i.e. at least one individual exhibited movement but remained within the sleeping site), or exhibited flight response (i.e. rapid movement and departure from the sleeping sites).

Local Thermal Detection Reliability Score

We developed a local Thermal Detection Reliability Score to assess the likelihood of successful thermal detection for the diurnal primate species in Cat Tien National Park (Table 1). Due to the elusive nature and low abundance of *M. arctoides*, we were unable to collect sufficient behavioral data or confirm thermal detections during this study. As a result, this species was not included in the scoring system. This scoring system, ranging from 1 to 5 (i.e. low to high detectability), integrates ecological influences and behavior on detectability. We considered physiological characteristics such as body length and tail length, with larger species and longer-tailed species deemed easier to detect and identify. Additionally, we incorporated ecological factors like average group size and home range size, with larger group size making detection easier, and species with smaller home range sizes being considered easier to detect locally (based on previous knowledge of the target species range). Finally, based on observations from ground-based surveys and TIR drone survey in this study, we integrated primate sleeping behavior and responses to the drone in our detectability scoring system: species sleeping in emergent trees and high canopy strata were considered easier to detect, while those exhibiting flight or movement behaviors during drone flights were more difficult to detect. The cumulative scores provide an assessment of thermal detection reliability for each species (Table 1).

Table 1. Annual Forest Appreciation Program participation.

Species	**Body length (cm)**[a]	**Tail length (cm)**[a]	**Group size**[b]	**Home Range (km^2)**[b]	**Sleeping site selection and sleeping position**[c]	**Behavioural response to drone**	**Thermal signature**[c]	**Thermal detection reliability**
Pygathrix nigripes	54-67	65-85	7	0.25	Sleep in emergent trees, One Male Units (OMU) use few sleeping trees, sometimes OMUs reunite into large bands.	No visible response or movement in sleeping tree.		Very high
Score	***5***	***5***	***2***	***5***	***5***	***4***		***26***
Trachy-pithecus margarita	42-58	60-80	18	1.34	Sleep in low to high strata in the canopy, use few sleeping trees.	No visible response.		High
Score	***3***	***4***	***3***	***3***	***3***	***5***		***21***
Macaca fascicu-laris	31-63	31-71	22	1.57	Sleep in low to medium strata in the canopy in subgroup, use low to high number of sleeping trees.	Movement in sleeping site.		Medium
Score	***1***	***3***	***4***	***2***	***2***	***3***		***15***
Macaca leonina	47-62	14-25	53	4.50	Sleep in low to medium strata in the canopy in subgroup, use low to high number of sleeping trees.	Movement in sleeping site.		Medium
Score	***4***	***2***	***5***	***1***	***2***	***3***		***15***
Nomas-cus ga-briellae	45-50	NA	4	0.52	Sleep in high stra-ta in the canopy in family group, use few sleeping	Avoidance and flight but stay in-or-return to sleeping site		Low
Score	***2***	***1***	***1***	***4***	***4***	***1***		***13***

Note. [a] Nadler & Brockman 2014; [b] Galan-Acedo et al. (2019); [c] This study. Due to the variability in TIR sensor readings and the strong influence of environmental conditions on thermal signatures, we did not incorporate thermal intensity measurements into our scoring system.

Results

Pilot survey

We detected black-shanked douc langurs in 16 surveys, pig-tailed macaques in 11 surveys, long-tailed macaques and yellow-cheeked gibbons in five surveys, silvered langurs in three surveys, and stump-tailed macaques in zero survey. On three occasions, TIR detections could not be identified to species level. We observed douc langurs sharing sleeping sites with pig-tailed macaques twice and with silvered langurs once.

In total, we observed 188 black-shanked douc langurs, distributed across 26 distinct groups. Each group averaged 7.2 individuals and utilized three sleeping trees on average, with group sizes ranging from 1 to 35 individuals. Douc langurs slept in emergent trees or on upper branches in the canopy strata. Pig-tailed macaques were more challenging to detect as they slept in the lower strata of the canopy or on lower branches of large emergent trees. We counted an average of 8.8 individuals per group, ranging from 4 to 18 macaques over more than five sleeping trees. Similarly, we observed long-tailed macaque sleeping in medium strata of the canopy and in bamboo patches, potentially reducing detection reliability. Detected group averaged 11 individuals (ranging from 8 to 15 individuals), spanning three to eight sleeping trees. While gibbons were initially easier to detect as they slept in emergent trees or high canopy strata, they exhibited the most movement in response to the drone flying over their sleeping trees. Each gibbon group averaged 4.2 individuals (ranging from 3 to 7 individuals) and used one to three sleeping trees. All detected groups exhibited movement or flight behaviours, but subsequent surveys over the same sleeping trees revealed individuals returning to their original location after the disturbance event. Finally, silvered langurs were repeatedly detected at the same location, with counts of 7, 22, and 19 individuals utilizing two to five sleeping trees.

Systematic surveys

In total, we detected 1,756 primate individuals via TIR imagery during systematic surveys, belonging to 283 groups (Table 2). This total count may include potential re-detection across survey replicates. Black-shanked douc langurs accounted for 65% of detections with 1,138 individuals, demonstrating the effectiveness of TIR drone surveys in detecting and counting this arboreal species (Fig 4 a). In comparison, we observed lower numbers of long-tailed macaques and pig-tailed macaques (Fig. 4 d, e) and fewer gibbons and silvered langurs (Fig. 4 b, c) (Table 2). Unfortunately, we could not confirm whether we detected stump-tailed macaques or not. We collected 162 individuals that we could not identify to species via TIR imagery and ground-truthing. However, although some detections could not be identified at the species level (classified as unknown), we could attribute a genus to some detections based on our ecological knowledge of those primate species. For instance, we identified *Macaca* due to the high number of individuals detected within a group spanning many sleeping trees in the same areas (Fig. 5, 6). During ground surveys, although we were unable to identify the species (i.e. long-tailed macaques, northern pig-tailed macaques, or stump-tailed macaques), we heard contact calls and observed movement within branches similar to travelling macaques, confirming the genus detected.

Table 2. Thermal infrared (TIR) detections of the diurnal primate community in Cat Tien National Park at their sleeping sites during nocturnal TIR drone surveys. We conducted 132 systematic surveys along 22 transects from January 2023 to May 2023. The table presents the total number of individuals and groups detected per species, as well as the percentage of detections where at least one individual exhibited movement or a flight response.

Species	Individuals	Groups	Movement (%)
Pygathrix nigripes	1138	283	21
Trachypithecus margarita	15	2	0
Nomascus gabriellae	22	8	67
Macaca leonina	258	35	33
Macaca fascicularis	138	20	31
Macaca arctoides	0	0	-
Unidentified	162	96	35

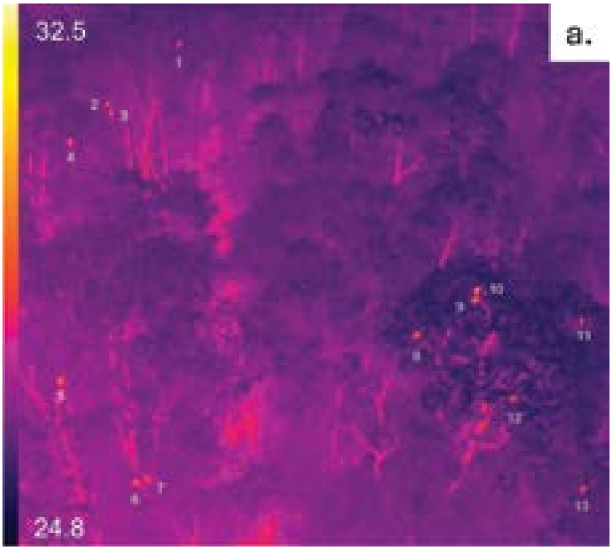


Fig.4a. Illustrations of Thermal Infrared (TIR) detections of five diurnal primate species at their sleeping sites obtained with a DJI Mavic 2 Enterprise Advanced (M2AE) and a Mavic 3 Thermal (M3T) drone during nocturnal surveys conducted in the lowland dry-evergreen forests of Eastern Nam Cat Tien National Park, from April 2022 to May 2023. a. Black-shanked douc langurs (*Pygathrix nigripes*),

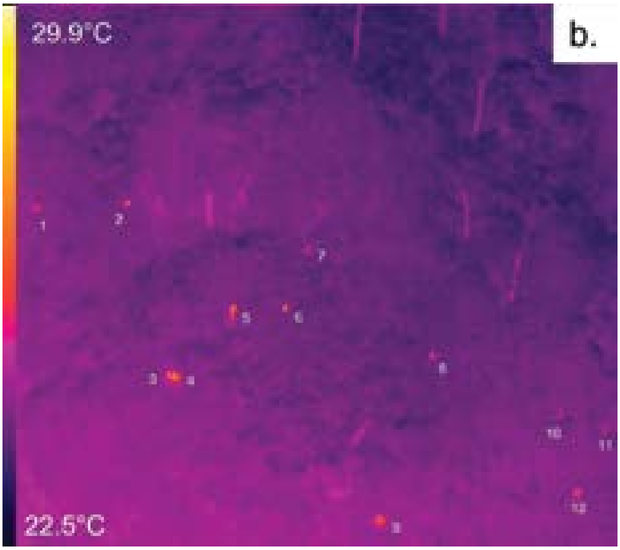


Fig.4b. Annamese silvered langur (*Trachypithecus margarita*).

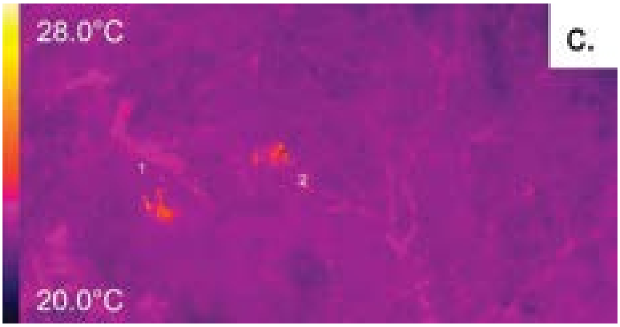


Fig.4c. Southern yellow-cheeked gibbon (*Nomascus gabriellae*).

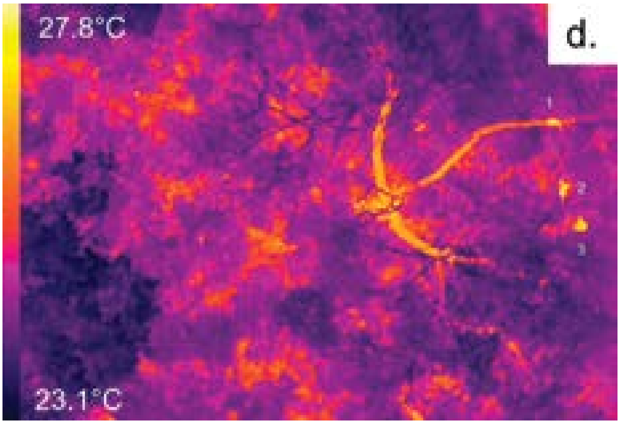


Fig.4d. Long-tailed macaque (*Macaca fascicularis*).

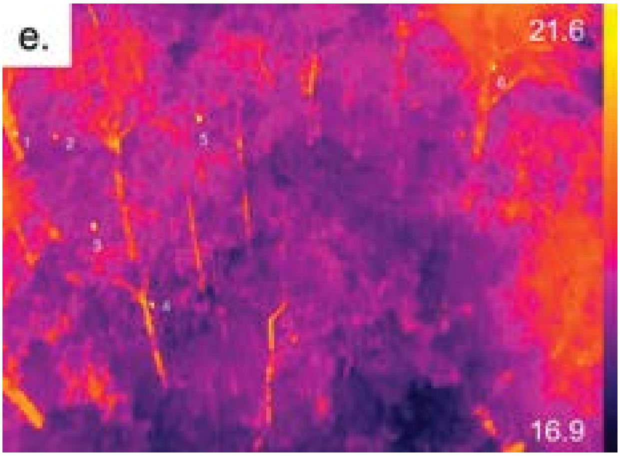


Fig.4e. Northern pig-tailed macaque (*Macaca leonina*). TIR primate detections correspond to the hotter thermal spots or body shapes (in yellow or orange color) highlighted with the white numbering. Note: all primate species in the given images were also visually verified from the ground.

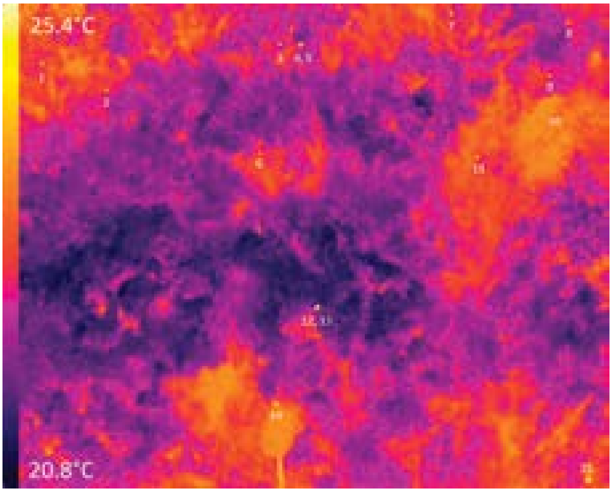


Fig.5. The detection of two unidentified groups of macaques within rehabilitation secondary evergreen forest mixed with bamboo patches using a DJI Mavic 3T. Individuals are highlighted with numbering but could not be identified via TIR imagery due to the low-resolution of the detections (drone flight about 50 m above the canopy) and the absence of visible response from the individuals (no movement or flight response). Image captured on April 19th 2023 (we detected a total of 35 macaques belonging to this group) at 05:07.

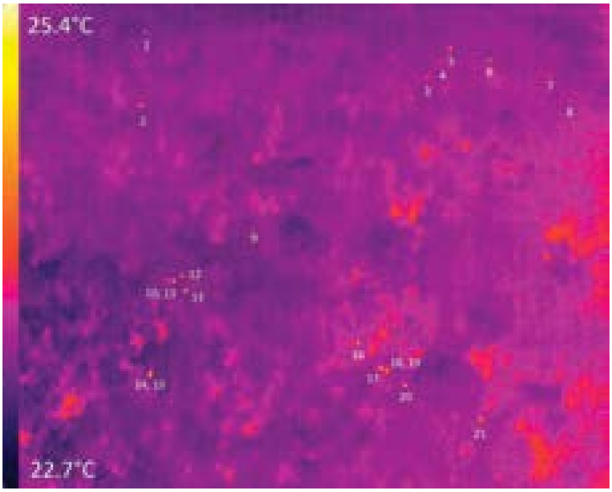


Fig.6. Image captured on May 9th 2023 at 05:09 am (we detected a total of 36 macaques belonging to this group) on the same transect segment.

Local Thermal Detection Reliability Score

Based on data collected through our pilot and systematic TIR drone surveys, we assigned higher scores for sleeping behavior to douc langurs, gibbons, and silvered langurs as they exhibited more arboreal sleeping position than macaque species (Table 2). Additionally, langurs showed no or little response to flying drones so we assigned them the highest score, compared to gibbons that exhibited disturbance response (Table 3). Our final thermal detection reliability score indicates that langurs, especially black-shanked douc langurs, are ideal candidates for monitoring with TIR drones compared to macaques or gibbons (Table 2). This finding is consistent with our field data, where we could be identifying this species solely based on TIR imagery due to their body size, characteristic body shape (e.g. tail-size, arms-size, sitting position), locomotion pattern, combined with their social behavior and organisation at sleeping sites, as well as their arboreal behavior.

Discussion

We conducted manual and systematic TIR drone surveys from April 2022 to May 2023 and successfully detected populations of five of the six diurnal primate species present in the lowland dry-evergreen forests of eastern Nam Cat Tien: black-shanked douc langurs, Annamese silvered langurs, southern yellow-cheeked gibbons, long-tailed macaques, and northern pig-tailed macaques. However, within a multispecies study site, the reliability of TIR drone detection for monitoring and counting primates varied among species. It was higher for arboreal langurs compared to semi-terrestrial macaque species or gibbons, which were less tolerant to drone surveys.

Consistent with our hypothesis, ecological and behavioral factors influenced the effectiveness of the detection and counting of primate species at sleeping sites: large-bodied species with characteristic features such as a long tail, sleeping in emergent trees (or high strata in the canopy), and exhibiting minimal movement during drone flight, such as black shanked langurs, were more reliably detected and counted using TIR drone imagery (Table 1, 2). For instance, through pilot manual flights above black-shanked douc langur sleeping sites, we observed an average of 7.2 individuals per One Male Units (OMUs), with social structures ranging from single males to bands of 35 individuals. These results align with findings from ground-based surveys, where OMUs averaged 7.5 individuals, ranging up to groups comprising more than 40 individuals (Rawson 2009; O'Brien 2014). Although we detected a few Annamese silvered langur groups, TIR drone surveys appeared effective in monitoring this species (Table 1, 2). Since silvered langurs were detected at the same sleeping trees across several surveys, this may suggest re-detection of the same group or sub-group consistently using the same sleeping sites (Nijman 2022). The low detection rates may be attributed to the low abundance of this species within Cat Tien National Park, but ground-based census data are necessary for validation (Hoang Minh Duc et al. 2022). As predicted, semi-terrestrial macaques, which live in large groups spanning numerous sleeping trees and occupying lower strata in the canopy, were less reliably detected and counted with TIR drone surveys (Table 1). For example, we observed an average of 8.8 individuals per group of pig-tailed macaques sleeping over five trees, significantly fewer than the known groups sizes of the species, which can range from 30 to 153 individuals across several trees while sleeping (Gazagne et al. 2020).

Additionally, macaque species tend to sleep in lower canopy strata, or under thick canopy vegetation, making them challenging to detect via TIR imagery. However, reliable identification to the species level was sometimes unattainable with TIR drones for macaques; we could still identify the *Macaca* genus based on their sleeping behavior, such as high number of individuals detected within a group spanning many sleeping trees in the same areas (Fig. 5, 6). Unfortunately, we could not confirm whether some unidentified TIR drone detections belonged to stump-tailed macaques due to their low abundance and elusive nature during ground surveys. However, this does not imply that this species cannot be surveyed with TIR drone surveys, but possibly their low abundances in the area. In fact, it may be more feasible in study sites with fewer sympatric macaque species or with prior knowledge on group ranges. Overall, in Cat Tien National Park, we recommend conducting camera trap surveys to monitor the macaque community (Masseloux et al. 2022; 2023) in combination with TIR drones to capture behaviors that are difficult to observe via traditional ground-based surveys, such as spatial organization at sleeping sites (Gazagne et al. 2020). Although other studies have detected gibbon species with diurnal TIR drones (*Hylobathes moloch*, *Nomascus hainanus* and *N. nasutus* in Rahman et al. 2022; Zhang et al. 2023; Wearn et al. 2023), we encountered challenges in monitoring southern yellow-cheeked gibbons in Cat Tien. Similar to our previous study in semi-wild enclosures in the Endangered Primate Rescue Center (EPRC) in northern Vietnam (Gazagne et al. 2023), Southern yellow-cheeked gibbons exhibited avoidance behavior during drone surveys, even with drone flying more than 30 m above the canopy. Our findings suggest aerial surveys might induce disturbance to *N. gabriellae* (Table 1, 2). Additionally, unless gibbons were in motion during the survey (identifiable locomotion behavior), inactive thermal spots of gibbons were impossible to identify based solely on TIR imagery. While TIR drone survey effectiveness on gibbons may be species- and site-specific, we recommend favoring passive acoustic monitoring surveys to monitor southern yellow-cheeked gibbons in Cát Tiên (Vu Tien Thinh & Tran Manh Long 2019). Lastly, although we did not include the nocturnal pygmy loris in our study, applying our scoring system to the species (Table 1) would likely yield the lowest thermal detection reliability score due to their small body length, low density, solitary behavior, habitat preferences such as vine entanglements and bamboo thickets, and tendency to sleep at low heights (Blair et al. 2021; Kenyon et al. 2014). To assess the effectiveness of TIR drones on lorises, tests should be conducted directly above the known locations of radio-collared individuals (Kenyon et al. 2014).

As we conducted replicates on the same transects, it is likely that we re-detected the same groups. Therefore, our individual and group counts do not aim to provide population abundance or distribution. However, our study demonstrates that TIR drone surveys can effectively detect and count large arboreal species such as langurs and could be utilized for long-term monitoring. Therefore, we encourage conservation managers to integrate TIR drone surveys with RGB drone surveys and/or traditional ground-based surveys to determine the distribution and population size of *Pygathrix* species, *Rhinopithecus* species, *Trachypithecus* species or other Cercopithecoidea with similar arboreal behavior and identifiable morphotypes such as proboscis monkey (*Nasalis larvatus*), with minimal disturbance (Burke et al. 2019; Gazagne et al. 2023; Le Khac Quyet 2022; Trinh Dinh Hoang 2022). These technologies could be used not only to assess species behavior and habitat selection but also to monitor long-term population trends, as well as the integration and survival of released individuals as part of population reintroduction and recovery activities.

The choice of nocturnal, pre-programmed TIR drone surveys in this study was driven by the benefits of consistency and the enhanced thermal contrast provided by lower ambient temperatures at night. This approach allowed us to systematically survey the area and detect primates at their sleeping sites. However, this method has trade-offs, such as reduced flexibility compared to manual diurnal surveys, which offer real-time adjustments and the potential for visual confirmation through RGB cameras, reducing the risk of misidentification. Diurnal surveys can be particularly effective for detecting active primates during early morning or late afternoon periods. Understanding these trade-offs allows future studies to adapt their approaches based on the specific requirements of their study area and target species (Table 3).

Table 3. Comparison of nocturnal versus diurnal Thermal Infrared (TIR) imaging and systematic (pre-programmed) versus manual drone surveys, summarizing key factors in TIR drone surveys for diurnal primate detection.

FACTOR	NOCTURNAL TIR	DIURNAL TIR	SYSTEMATIC FLIGHT	MANUAL FLIGHT
THERMAL CONTRAST	**High:** Greater temperature difference improves detection.	**Low:** Reduced contrast in daytime temperatures.	**High:** Consistent imaging across surveys.	**Low:** Varies with operator decisions and conditions.
SPECIES IDENTIFICATION	**Low:** No RGB images lead to potential misidentification.	**High:** Daylight allows RGB images facilitating identification.	**Low:** Fixed paths limit adjustments for optimal identification.	**High:** Manual adjustments improve identification accuracy.
DISTURBANCE TO PRIMATES	**Low:** Less disturbance while diurnal primates are sleeping.	**High:** Active primates may exhibit avoidance behaviors.	**Moderate:** Fixed paths may cause disturbance but less noise overall.	**Moderate:** Can adjust for minimal disturbance but generates more noise.
DETECTION RELIABILITY	**High:** Easier to detect stationary primates and prevent overcounting.	**Low:** Active primates may be harder to detect or lead to inaccurate/ duplicate counts.	**Low:** Fixed paths may miss individuals or behavioral cues.	**High:** Real-time adjustments improve detection of moving primates.

COUNT ACCURACY	**Moderate:** May undercount individuals hidden.	**Low:** Active primates increase risk of missed or double counts.	**High:** Consistent paths reduce observer bias in counting.	**Moderate:** Variability in counting, but can detect dispersed individuals.
URVEY FLEXIBILITY	**High:** Can survey entirety of night time hours.	**Low:** Small window where TIR surveys can be conducted.	**Low:** Fixed routes with no real-time adjustments.	**High:** Adjustments of flight paths based on real-time observations and conditions.
SURVEY EFFICIENCY	**High:** Stationary primates may increase efficiency.	**Low:** Primate activity may reduce efficiency.	**High:**: Automated path covers larger areas in less time.	**Low:** Requires active control, reducing coverage per unit time.
SURVEY CONSISTENCY & AUTOMATION	**High:** Usually more stable nighttime conditions.	**Moderate:** Variable daylight conditions and primate activity reduce consistency.	**High:** Consistent coverage and data collection with fixed parameters.	**Low:** Operator variability and manual adjustments introduce inconsistencies across surveys
OPERATOR SKILL REQUIREMENT	**Moderate:** Requires night flight expertise but less active control.	**Moderate:** More skill needed for navigation with active primates but increased visibility.	**Low:** Minimal operator input needed as flights are automated.	**High:** Requires skilled operators for real-time adjustments.

Lastly, we encountered challenges during aerial surveys that should be considered for further studies. While our study area had lowland terrain with minimal risk of tree collisions during nocturnal surveys, we recommend conducting diurnal drone flights beforehand to identify any potential obstacles, such as elevated terrain or structures, especially when conducting systematic flights. Additionally, the low resolution of TIR drone imagery limited our ability to differentiate species with similar morphology or behavior, especially when flying high above the canopy (Burke et al. 2018; Kays et al. 2019). We recommend adjusting drone flight height based on habitat type. Although maintaining a constant flight height was convenient, it compromised image resolution in habitats with lower canopy heights, such as the rehabilitation secondary evergreen forest mixed with bamboo patches (Fig. 3). Consistent with previous studies, we suggest flying at approximately 30 m above the canopy to achieve sufficient resolution for detecting animals in the upper canopy (Burke et al. 2018; Kays et al. 2019; Rahman et al. 2022; Spaan et al. 2019). However, species-specific disturbance studies are needed to assess tolerance to drone surveys, particularly for species that are vulnerable to raptors as predators and may exhibit increased fear of flying animals and objects (Fam & Nijman 2011; Schad & Fischer 2022). Additionally, in multispecies studies where misidentification is a risk, a combination of TIR and RGB image drone surveys or ground-truthing surveys is recommended (Rahman et al. 2021). Thermal intensity analysis could potentially enable clearer species-specific insights, especially when considering fur thickness and color, which can significantly affect body surface temperature. As TIR imaging technology advances, incorporating thermal intensity into the scoring system could enhance detection reliability across species. Finally, we were unable to survey interior forest areas not adjacent to roads due to the limited reception range of drones in dense forests, as signal loss frequently occurred beyond 1 km. Therefore, we recommend focusing monitoring efforts on species with smaller ranges or ranges that include roads or open areas, considering logistical constraints like drone takeoff, landing, and reception range.

Conclusions

We found that TIR drone surveys can be effectively used to monitor large arboreal primate species, such as black-shanked douc langurs. In study areas with multiple species, if species-level identification is not possible, combining sleeping behavior with ecological knowledge can help identify species at the genus level (e.g. *Macaca, Pygathrix, Rhinopithecus, Trachypithecus, Nomascus, Hylobates*, etc.). This preliminary knowledge can serve as a starting point for identifying areas of interest for further ground-based studies. Alternatively, combining diurnal TIR and image drone surveys can identify species without ground-truthing. We also recommend developing a universal scoring system to assess TIR detection reliability for different primate species. Finally, our research contributes to the understanding of sympatric primate behavior and ecology, thereby making a substantial contribution to conservation efforts, and highlights the potential of innovative technologies in primate monitoring.

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