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Original Research Article

Thermal infrared imaging from drones can detect individuals and nocturnal behavior of the world's rarest primate

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A B S T R A C T

Escalating anthropogenic pressures now threaten ~60% of primate species across the world with extinction. Developing effective evidence-based conservation for threatened primate species requires accurate and precise information on their population abundance. However, standard ecological field techniques are costly in terms of time, resources and manpower, meaning that the effectiveness of alternative survey and monitoring methods must be investigated. Thermal infrared imaging using drones may be able to improve ability to detect individuals and accuracy of population abundance estimates for primate species at lower cost. Here we use a drone with a thermal infrared sensor to survey the largest social group (Group C) of the Hainan gibbon (*Nomascus hainanus*), the world's rarest primate species, which survives as a remnant population in Bawangling National Nature Reserve, Hainan, China. Group C is known to currently contain nine Hainan gibbon individuals based on regular visual monitoring. Drone surveys conducted over two consecutive days and nights in April 2019 demonstrated that thermal infrared imaging can detect the presence of different gibbon individuals in this social group, with comparable group size estimates to regular visual monitoring, and provides the first information about Hainan gibbon sleeping behavior and the range of nocturnal body temperatures for the species. This method can therefore be used to monitor other Hainan gibbon groups in the future, and can also be used to survey individuals and study nocturnal behaviors in other threatened or cryptic primate species.

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1. Introduction

Nonhuman primate species, our closest biological relatives, are of central importance to tropical biodiversity and can provide insights into human evolution, biology, behavior, and the threat of emerging diseases (Estrada et al., 2017). Escalating anthropogenic pressures (e.g., forest loss resulting from regional and global economic pressures, hunting and illegal trade) now threaten ~60% of the world's primate species with extinction (Estrada et al., 2017). There is therefore an urgent need to develop evidence-based conservation strategies for threatened primate species. Effective conservation decision-making requires accurate and precise information on key population parameters, notably abundance (Groombridge et al., 2004; Segan et al., 2011). However, standard ecological field techniques are sometimes unable to determine presence and population size for species of extreme rarity that have declined to only a handful of surviving individuals and can be extremely hard to detect, meaning that alternative data collection methods may be needed to inform conservation (Turvey, 2017).

Most primate species are arboreal mammals, which live in the canopy and flee before they can be studied by observers on the ground (Munari et al., 2011; Neilson et al., 2013). As a result, they are often difficult to survey, and population information for a wide range of arboreal primate species is currently incomplete or lacking. Recently, several studies have used drones to detect primates, mostly focusing on surveying nests built by hominid apes (van Andel, 2015; Wich, 2016; Bonnin et al., 2018). Many studies have also recently demonstrated that thermal infrared cameras mounted on drones can be used to survey arboreal mammals, including monkeys (*Alouatta palliata* and *Ateles geoffroyi*) (Burke et al., 2019; He et al., 2020; Kays et al., 2019; Spaan et al., 2019). Drones carrying thermal infrared sensors may therefore represent an important new avenue for surveying highly threatened primates.

The Hainan gibbon (*Nomascus hainanus*) is the world's rarest primate species (IUCN, 2019). Due to historical habitat loss and hunting, currently only about 27 Hainan gibbon individuals comprising four social groups are thought to survive in a ~15 km^2 forest fragment within Bawangling National Nature Reserve, Hainan, China (Chan et al., 2005; Fellowes et al., 2008; Zhang et al., 2010; Turvey et al., 2015; Bryant et al., 2016a). Effective and systematic monitoring of the surviving population is recognized as a key priority for conservation management of the species, to understand individual and group movements, habitat use and social dynamics, and to detect the possible existence of cryptic non-singing solitary individuals outside the known social groups (Chan et al., 2005; Turvey et al., 2015). However, standard monitoring of gibbons using monitoring teams is costly in terms of time, resources and manpower. There is therefore an urgent need to assess the effectiveness of alternative monitoring approaches for detecting the presence of Hainan gibbons at Bawangling (Turvey et al., 2015).

Successful use of drones for detecting spider monkeys requires information on nocturnal behavior such as sleeping location (Spaan et al., 2019). However, whereas sleeping behavior is known for other gibbon species in China and elsewhere in southeast Asia, and provides important information on the ecological requirements and habitat selection of these highly

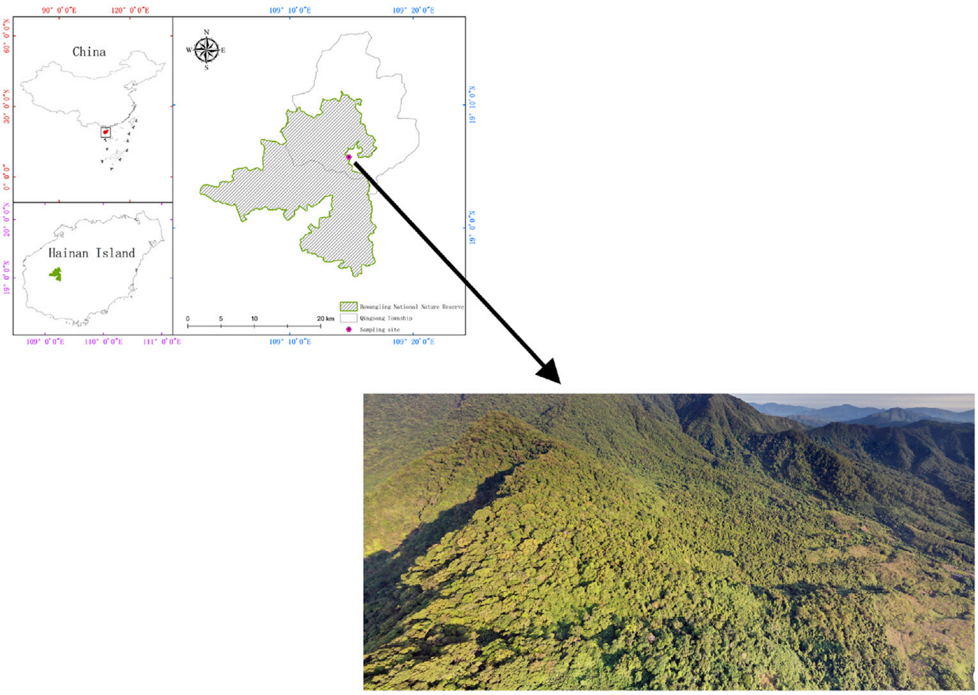

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Fig. 1. Map and landscape of survey site at Bawangling National Nature Reserve, Hainan, China, showing the process of flying a drone with a thermal infrared sensor.

threatened primates (e.g., Tenaza and Tilson, 1985; Cheyne et al., 2012; Fei et al., 2012, 2017, 2019), there is currently no field information available on sleeping tree selection or other nocturnal behavior for the Hainan gibbon (Turvey et al., 2015). Moreover, other relatively large-bodied arboreal mammal species also occur in Bawangling, including giant squirrels (Indian giant flying squirrel *Petaurista philippensis*, black giant squirrel *Ratufa bicolor*; body mass >1.5 kg), several species of civet that are arboreal to varying degrees (masked palm civet *Paguma larvata*, common palm civet *Paradoxurus hermaphroditus*, large Indian civet *Viverra zibetha*, small Indian civet *Viverricula indica*), and a second native primate, the rhesus macaque (*Macaca mulatta*) (Kadoorie and Botanic, 2001; Smith et al., 2010). As a result, drone-based detection of Hainan gibbons may be not straightforward or feasible.

Here we use a drone with a thermal infrared sensor to survey the largest social group (Group C) of the Hainan gibbon. This group is known to currently comprise nine individuals (four males including two subadults and two adults, four females including two subadults and two adults, and one infant), and its distribution is well understood based on regular long-term visual monitoring by forest rangers employed by Bawangling National Nature Reserve Management Office (Zhang et al., 2010; Turvey et al., 2015; Bryant et al., 2016a, 2017; Bawangling National Nature Reserve Management Office, pers. comm.). Specifically, we aimed to test: 1) whether thermal infrared imaging with a drone can detect the presence of Hainan gibbons; 2) whether the total number of Hainan gibbon individuals found by this method is consistent with the known size of this social group; 3) whether effectiveness of surveying Hainan gibbons with thermal infrared imaging varies between different times of day or night.

2. Materials and methods

2.1. Study site

The study was carried out at the border of Bawangling National Nature Reserve and Miaocun (Miao Village), Qingsong Township, Baisha County, in the northeastern corner of the reserve (109°14′47.35″E, 19°5′45.17″N) (Fig. 1; see also https://720yun.com/t/8a9jr0yvta7?scene_id = 26513452). The mean yearly home range of a Hainan gibbon group has been estimated at 1–2 km^2 (Bryant et al., 2017). Group C was estimated to have a home range of between 0.06 and 0.2 km^2 (median estimate = 0.11 km^2) based on 11 h of fieldwork conducted in 2010–2011 (Bryant et al., 2017), and longer-term monitoring by forest rangers indicates a total home range area for this group of approximately 0.5 km^2 (Bawangling National Nature Reserve Management Office, pers. comm.) This area is covered by tropical evergreen rainforest, with trees reaching a maximum of 30 m in height. The terrain is relatively rough and mountainous, with a vertical elevation difference of about 500 m within the home range of Group C.

2.2. Survey methods

Since flying a drone is associated with a potentially high risk of disturbance for the Critically Endangered Hainan gibbon, and the technique has not previously been shown to be feasible for detecting this species in the wild, Bawangling National Nature Reserve Management Office only gave approval to investigate the effectiveness of using this approach to survey Group C (see Fig. S1). We mounted a thermal infrared sensor (Fig. S2) to an industrial drone (DJI M600Pro, DJ-Innovations, China; Fig. S3) via a gimbal, which kept the camera steady during drone flights. Detailed information about the thermal infrared sensor is given in Table S1. To survey the entire home range of Group C, we conducted preprogrammed grid flights covering the whole 0.5 km^2 area, subdivided into four different sub-areas that varied between 0.1 and 0.2 km^2. We set up grid flights in DJI GS Pro app (DJ-Innovations, China) by drawing an outline polygon on a satellite image and utilizing the Automatic Waypoint–Survey (Grid) feature. Grid flight duration ranged between 15 and 18 min depending on area of the site surveyed, flying height, and percentage of overlap selected for the footage. We fixed sidelap for all grid flights at 60%; increasing sidelap decreases overall flight area but may increase count accuracy for a smaller survey area. For all sites and days, we flew the drone 380 m above the ground level of the take-off point, equivalent to approximately 50 m above canopy height at the study sites inside the forest. With the guidance of three local rangers from the reserve who are responsible for surveying Group C every day, we carried out three flights each day, in early morning (6:00–7:00 a.m., corresponding with the time when Hainan gibbons can be located by monitoring teams using standard visual/acoustic detection methods in fixed-point surveys; Chan et al., 2005; Bryant et al., 2017), afternoon (4:00–5:00 p.m.) and night (8:00–9:00 p.m.), respectively, on 23 and 24 April 2019.

2.3. Statistical analysis

2.3.1. Detecting gibbons and calibrating body and surface temperature in thermal infrared sensor data

Thermal infrared imaging using drones cannot directly measure gibbon body temperatures, as gibbons stay under the canopy, whereas the drone must fly over the canopy. As a result, body temperatures measured by the infrared thermal sensor can be affected by the canopy and might not represent true gibbon surface temperature. However, detecting Hainan gibbons and calibrating body temperatures in thermal infrared sensor data can help us focus on the hotspots in the captured images

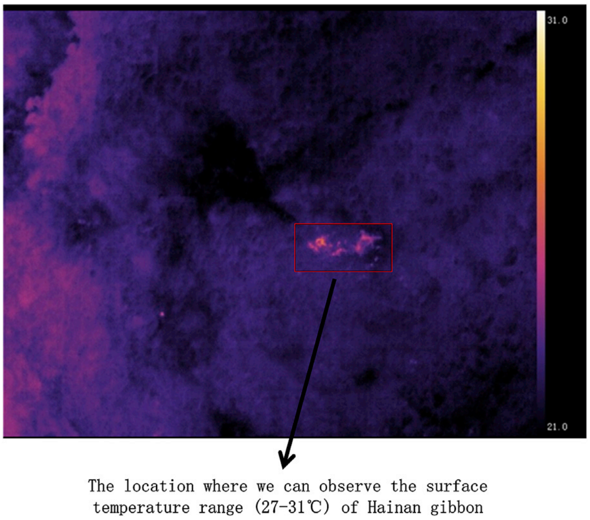

Fig. 2. Thermal infrared image showing the presence of Hainan gibbon Group C, with temperature detection range of 21–31 °C.

that show the same body and surface temperature as gibbons, thereby eliminate interference from other pixels and quickly filtering thousands of images.

The thermal infrared footage from the drone flights was firstly cut and edited into 100 videos each of 30 s in length. These videos were studied for evidence of arboreal mammal heat signatures in the forest canopy; videos containing arboreal mammals were then re-exported from the TC64 thermal camera as images for analysis.

The thermal imager captured data as raw TMC files that were then imported into ThermoViewer software. Calibrating gibbon body temperatures in thermal infrared sensor data enables identification of hotspots that show the same body temperature ranges as Hainan gibbons in captured images, thereby screening pixels and quickly filtering the thousands of images captured during drone flights. We therefore used the drone and thermal infrared sensor to measure the body and surface temperature of all human participants involved in fieldwork as a comparative reference range for gibbons (range = 27–31 °C; Fig. S4), and we used this temperature range to screen for potential gibbon individuals in the thermal images within ThermoViewer, with images containing this reference range exported as jpg files. We detected four tree canopies within the study area that exhibited this comparative reference range across both survey dates (two different trees on both dates). We then determined the temperature range at which both tree canopy and gibbon individuals could be detected in thermal images, increased the temperature to determine the temperature at which only gibbons could be detected (lower detection temperature threshold), and further increased the temperature to determine the temperature at which gibbons could no longer be detected (upper detection temperature threshold). This approach enabled us to estimate Hainan gibbon body and surface temperature range. Specifically, this temperature range is not the same as the core body temperature range of Hainan gibbon.

2.3.2. Deducing numbers of Hainan gibbon individuals from the detected temperatures

Accurate numbers of Hainan gibbon individuals can be determined easily if the infrared sensor can detect individual outlines clearly. However, this process may require flying the drone low above the canopy, thereby having a high risk of causing disturbance to the highly threatened Bawangling gibbon population. Instead, by flying the drone higher above the canopy we only detected different temperature signals but no clear individual gibbon body shapes. We therefore used *X*-means clustering (Pelleg and Moore, 2000) to automatically cluster all detected temperature data points and estimate the number of different gibbon individuals; if multiple temperature data points group into a single cluster, these points can be interpreted as representing a single gibbon individual, with the total number of clusters representing the estimated number of different gibbons detected by the drone.

X-means is an extension of *K*-means clustering (Duda and Hart, 1973; Bishop, 1995), which categorizes data points into k groups based upon similarity following a three-step algorithm: 1) k points are randomly initialized as group means; 2) Each given data point is categorized to its closest mean based on Euclidean distance, and the mean's coordinates are then updated based upon the values of other data points also categorized within that mean; 3) Repeat step 2 until the new mean's co-ordinates do not change further, to give a final set of k clusters. Whereas the *K*-means algorithm requires the number of clusters (k) to be provided as an input parameter, the *X*-means algorithm can search for the best k value automatically, and only needs to have an initial range specified within which the true k is expected to lie; the final predicted value for k within this range is then determined by the Bayesian Information Criterion (BIC) (Kass and Wasserman, 1995). Since Group C contains nine gibbon individuals, we defined k as 1–9. The *X*-means algorithm was applied to temperature data points that

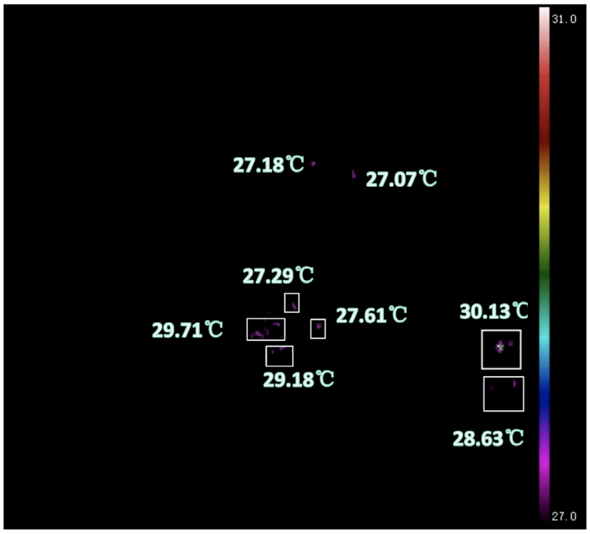

Fig. 3. Thermal infrared image showing the presence of Hainan gibbon Group C, with temperature detection range of 27–31 °C and showing specific temperatures of separate identified Hainan gibbon individuals.

represent one-dimensional data, so the distance between two data points represents the difference of the corresponding temperature values, and the mean's coordinates are the means of all temperature values within one cluster. We used the WEKA software platform (https://www.cs.waikato. ac.nz/ml/weka/) to conduct the *X*-means computing process.

We determined that the gibbon-specific temperatures we detected remotely were indeed Hainan gibbons, by visiting the specific location where these temperatures were detected from 5:30 a.m. (sunrise) to 8:00 a.m. on 24 April 2019, and used binoculars to visually detecting gibbons in Group C when they left their sleeping trees.

3. Results

During each of the night survey flights, only one video showed a temperature range of 21–31 °C, which we interpret as indicating the presence of arboreal mammals. On each night, these individuals were situated in the canopy of two adjacent mature Chinese sweet gums (*Liquidambar formosana*), located at 800 m elevation and almost 60 m apart, with two different trees occupied each night (Fig. 2 and S5). When we increased the temperature to 27 °C, we could still detect individuals but not the surrounding tree canopy (Fig. 3), and we could no longer detect individuals when we increased the temperature above 31 °C.

Because Group C contains nine Hainan gibbon individuals, representing seven adult/subadult gibbons and one adult female holding an infant, we would expect to detect eight discrete temperature groups. When setting the temperature detection range on the thermal infrared sensor to 27–31 °C, we detected 102 different temperatures (red dots). *X*-means clustering detected eight discrete temperature groups, which had mean temperatures ranging from 27.07 °C to 30.13 °C. We then used the pixel x, y value for the eight discrete temperature groups to show the location of these eight groups (see Fig. 3). We interpret these eight groups as representing the eight adult/subadult individuals of Group C. We and the local rangers also used binoculars to clearly observe 9 Hainan gibbon individuals for Group C, when the gibbons left from the specific location where we detected the eight temperature groups between 6:30 a.m. and 8:00 a.m. on 24 April 2019 from 100 m away. In addition, we had photographed the infant present in the group being held by an adult female (Fig. 5). We therefore interpret the eight detected temperature groups as representing all nine individuals of Group C. Thermal infrared imaging using drones at night can therefore detect Hainan gibbons and provide the same gibbon group size estimate as diurnal visual monitoring.

Conversely, in the morning and afternoon there are large areas of canopy pixels between 27 and 31 °C, and we were unable to detect gibbons during these time periods (Fig. S6). Canopy temperature was also heterogeneous across different elevations within the study area, ranging from 30.2 to 36.9 °C at lowest elevations (630 m) to 22.5–26.9 °C at mid-elevations (800 m) and to 16.5–22.2 °C at highest elevations (900 m) (Fig. 4).

4. Discussion

By using a drone with a thermal infrared sensor, we demonstrate for the first time that it is possible to detect the presence of Hainan gibbons, with evidence of detection of eight different temperature groups ranging from 27 to 31 °C within the known home range of Group C in Bawangling National Nature Reserve. However, in contrast to Spaan et al. (2019), we were unable to detect the clear shapes of Hainan gibbon individuals using this method. This is possibly an inevitable restriction of

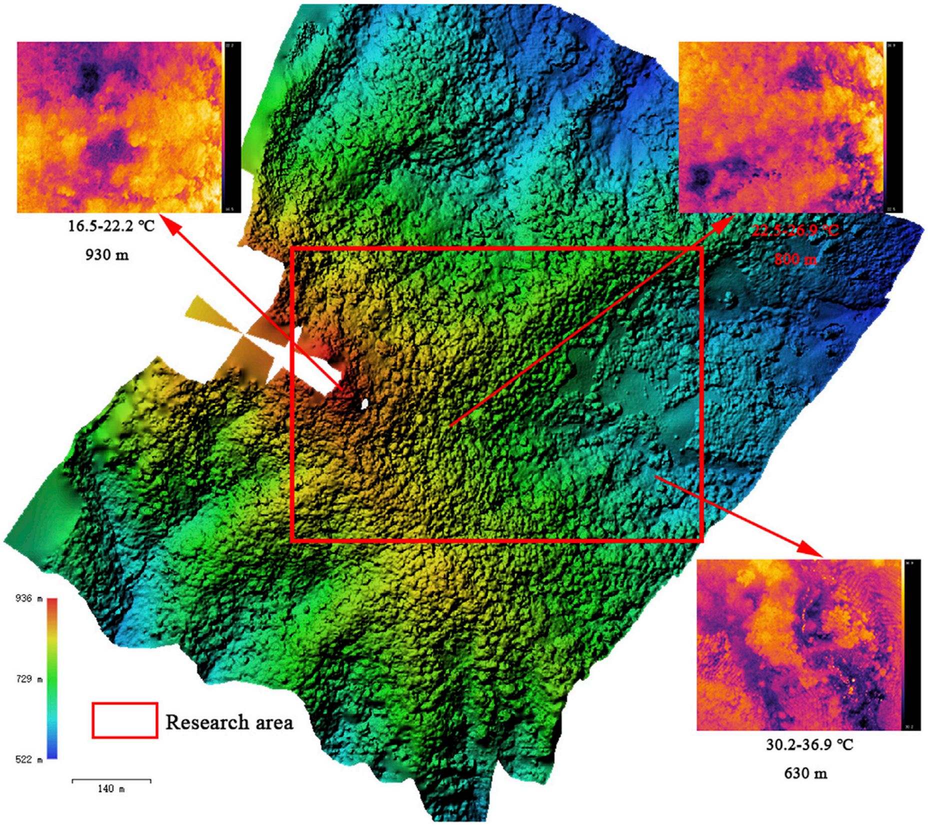

Fig. 4. Canopy temperatures across different elevations within the survey site: lowest elevation (630 m), mid-elevation (800 m), and highest elevation (930 m).

the need to fly the drone relatively high above the canopy at Bawangling, which was necessary for two reasons. First, the canopy is structurally complex, with the risk that flying lower at night could damage the drone. Furthermore, the drone is noisy, so flying lower will pose a serious risk of disturbing gibbons, which is to be avoided at all costs given the critical conservation status of the tiny remnant population of this species (Mulero-Pázmány et al., 2017). Disturbance to gibbons at Bawangling is a very real concern, and other Hainan gibbon social groups are thought to have shifted their home ranges due to human disturbance in recent years (Turvey et al., 2015; Bryant et al., 2016b). Any future aerial survey or monitoring work conducted using drones at Bawangling must therefore follow strict protocols to minimize any risk of disturbing the last surviving Hainan gibbon population.

We were unable to detect clear shapes of gibbon individuals using a thermal infrared sensor, and there are multiple large-bodied arboreal mammal species present at Bawangling. However, giant squirrels and civets are solitary, so are very unlikely to represent the large group of individuals that we detected (Smith et al., 2010). Rhesus macaques live in social groups and can occur sympatrically with gibbons in China (e.g., Chan et al., 2008), but they are relatively rare at Bawangling (Turvey, 2017) and were not otherwise observed within the known home range of Group C during fieldwork. Furthermore, the eight temperature groups we detected using thermal imagery within the known home range of Group C are very likely to represent gibbons due to the known composition of this gibbon group (eight adults/subadults, with one holding an infant), and as confirmed by our follow-up direct visual observations of gibbons moving away from the location of the detected temperature groups. The known close pairing of two gibbon individuals within this group (mother holding an infant) may possess a slightly higher temperature than single gibbon individuals, and we therefore suggest that the "individual" that we detected with a temperature of 30.13 °C may represent the mother-infant pair. The other three Hainan gibbon groups at Bawangling (A, B and D) also contain mature females with infants, and so future work could investigate whether the total number of individuals detected in these groups using drones with thermal infrared sensors are also one individual lower than indicated through visual monitoring by field survey teams.

Several important aspects of Hainan gibbon biology, behavior and ecology (e.g., home range and spatial requirements, social structure, feeding ecology, calling behavior, reproductive biology and genetic diversity) have already been documented in previous studies, and have been used to guide conservation planning for this Critically Endangered species (Chan et al., 2005; Fellowes et al., 2008; Zhou et al., 2008; Liu et al., 1989; Bryant et al., 2016a, 2017). However, no published data are available on the species' nocturnal behavior. Importantly, in this study we can provide the first information on Hainan gibbon sleeping trees. We demonstrate that Group C slept together for two consecutive nights in the canopy of two adjacent mature

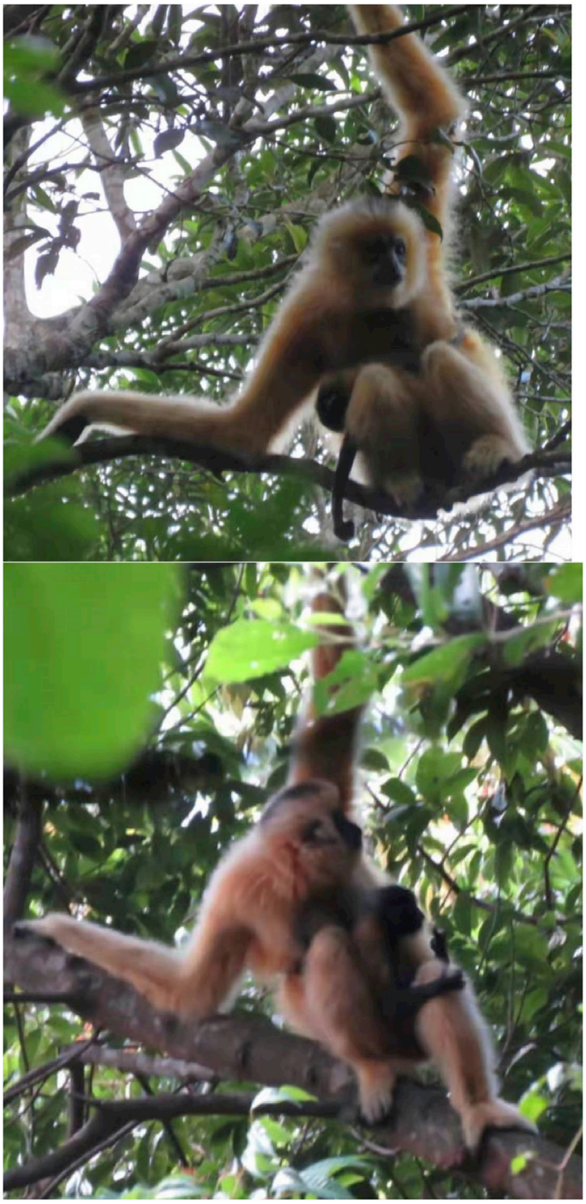

Fig. 5. Mature Hainan gibbon female with infant in Group C.

Chinese sweet gums, a dominant tall canopy tree at Bawangling that is abundant within Group C's home range, and that the group changed trees overnight. These specific trees were among the highest trees across the survey area, and were located at 800 m elevation, which has a recorded canopy temperature closest to observed Hainan gibbon body temperature. Local forest rangers reported to us that Group C typically sleeps in this tree species at this elevation. It is therefore likely that Hainan gibbons choose sleeping sites with a comparable temperature to their own body temperature to help reduce thermoregulatory costs, a behavioral pattern also seen in other primate species living at lower altitudes (Cui et al., 2006; Xiang et al., 2010; Fei et al., 2019). Further nocturnal surveys are required to investigate general sleeping patterns and other nocturnal behavior in Hainan gibbons.

Drones with thermal infrared sensors have been used to detect presence and determine number of individuals for a range of ecologically and taxonomically distinct primates, now including the world's rarest primate species. Our results demonstrate that thermal infrared imaging using drones is a feasible tool for detecting Hainan gibbons at night, and for providing important insights into their nocturnal behavior. This method therefore represents a useful tool for detecting other Hainan gibbon social groups and potentially also solitary individuals, and for investigating other nocturnal gibbon behaviors across Bawangling in the future. A single drone and thermal infrared sensor is expensive, costing almost 150,000 USD for this study, so surveying the whole Hainan gibbon population may cost at least 300,000 USD if two drones are required. Moreover, drones cannot be flown low over the canopy at Bawangling, to prevent potential disturbance to gibbons, limiting the available data resolution that can be obtained from this method. The number of gibbon individuals represented by temperature groups detected by the thermal infrared sensor must be checked against the number of individuals observed in visual surveys, and it is also necessary to check whether gibbons can be observed directly at locations where temperature groups have been detected. However, drones and thermal infrared sensors can provide new evidence of specific gibbon distributions and important nocturnal behaviors that have not been obtained from standard monitoring of gibbons by monitoring teams. Further nocturnal drone surveys can also determine dynamic variations in preferred gibbon sleeping trees and locations.

Our results demonstrate that thermal infrared imaging using drones can provide comparable estimates for Hainan gibbon group size to those provided by regular visual monitoring. We recommend that as long as there is definitely no disturbance to gibbons, drone-based surveys should also be used to investigate group size in groups A, B and D, to complement ongoing direct visual and acoustic monitoring and provide a more comprehensive monitoring system for Hainan gibbons in both day and night. Longer-term survey and monitoring data obtained through this new method will be able to provide additional important biological and ecological information that can be used to support effective Hainan gibbon conservation management. This method can also potentially save time, resources and manpower in the long-term, compared to the ongoing investment required to support standard monitoring of Hainan gibbons using multi-person monitoring teams. We also recommend further research using Lidar and other remote sensors on drones to investigate the body mass of the Hainan gibbon, whether the species exhibits a fixed or flexible sleeping location, and how gibbons select sleeping tree locations based on species, canopy structure, and/or other factors such as temperature. This approach can also potentially be applied to survey other threatened primates, and provide important and novel information to assist their conservation.

Ethics statement

Experimental protocol adhered to the local laws of China and was approved by Bawangling National Nature Reserve.

Authors' contributions

H.Z., W.X.L. and Z.Y.S. designed research; H.Z., W.X.L., Z.Y.S, C.W., S.T.T., Z.Y. T., X.M.W., D.H.Y. and S.M. performed research; H.Z., W.X.L, Z.Y.S. and C.W. analyzed data; H.Z., W.X.L., Z.Y.S., C.W. and S.T.T. wrote the paper.

Declaration of competing interest

The work is all original research carried out by the authors and all authors agree with the contents of the manuscript and its submission to the journal. No part of the research has been published in any form elsewhere. The manuscript is not being considered for publication elsewhere while it is being considered for publication in this journal. All sources of funding are acknowledged in the manuscript, and authors have declared any direct financial benefits that could result from publication. Experimental protocol adhered to the local laws of China and has been approved by the Bawanglin Natural Reserve, China.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gecco.2020.e01101.

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