Research Square

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Monitoring sika deer population dynamics under culling on Nakanoshima island, Japan, using thermal infrared UAV survey

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Abstract

Wildlife management requires reliable assessment of animal populations. Over the last decade, unmanned aerial vehicles (UAVs) equipped with thermal infrared (TIR) cameras have been increasingly used to estimate wildlife population sizes. Although the effectiveness of UAVs with TIR camera surveys is well-established, most studies have been short-term with few monitoring population changes over multiple years. We conducted UAV surveys over a six-year period on a sika deer (*Cervus nippon*) population on Nakanoshima Island (5 km^2), northern Japan, where culling is employed for population control. UAV-based estimates were compared against harvest-based models for population estimation that integrated ground-based survey data, including cull numbers, camera traps, and drive counts. The UAV-based estimates correlated positively with harvest-based estimates (R = 0.67) and successfully detected a declining trend resulting from culling. Furthermore, the UAV surveys required only 20% of the effort compared to ground-based drive counts. Our results indicate that UAV surveys with TIR cameras provide a highly reliable and cost-efficient method for long-term wildlife monitoring, compared with traditional surveys, with potential applicability to similar environments globally.

INTRODUCTION

Reliable assessment of animal abundance is fundamental to effective wildlife management, including setting management targets, evaluating culling programs, and predicting damage. In particular, long-term evaluation of survey methods is essential for quantify their ability to track population trends under active management interventions such as culling. Conventional methods for monitoring population sizes include pedestrian sign counts, direct counts, and camera traps (Forsyth et al. 2022), most of which rely on ground-based observations. Although these methods have been widely applied, they are labor-intensive, time-consuming, difficult to implement in remote areas, and are often subject to low detection probability and observer bias (Beaver et al. 2014, Forsyth et al. 2022).

However, aerial surveys can overcome these limitations. Unmanned aerial vehicles (UAVs) have recently emerged as safe, convenient, and cost-effective tools for wildlife monitoring (Wang et al. 2019). UAVs provide access to challenging terrain and minimize disturbance to species that are sensitive to human approach (Chabot and Bird 2015). In addition, UAV surveys have achieved higher accuracy than ground-based methods in locations where visibility from the ground is obstructed by vegetation or terrain (Hodgson et al. 2018, Naugle et al. 1996, Preston et al. 2021). Among UAV techniques, thermal infrared (TIR) cameras have been widely used to monitor large terrestrial mammals (Baldwin et al. 2023, Povlsen et al. 2023). Thermal sensors detect animals based on their body heat, facilitating surveys under low-light conditions and in habitats where visual detection is challenging (Burke et al. 2018). TIR cameras provide a higher object detection accuracy than RGB cameras in forest environments (Gill et al. 1997, Matsuura et al. 2017). UAVs equipped with TIR cameras have been increasingly used to estimate the abundance and spatial distribution of large ungulates (McMahon et al. 2021, Baldwin et al. 2023, Larsen et al. 2023, Zabel et al. 2023, Finnegan et al. 2024), including sika deer (*Cervus nippon*) (Ito et al. 2020,

2023). Despite these technological advances, few studies have evaluated drone-based TIR camera surveys over extended timescales.

In this study, we focused on Nakanoshima Island, a closed population where long-term monitoring of sika deer has been conducted. On this island, continuous population culling has been implemented, resulting in dynamic changes in deer abundance over time. The combination of active population management and long-term monitoring data makes this site particularly suitable for evaluating different survey methods. Against this background, we estimated deer abundance over six years using a UAV equipped with a TIR camera. Our objective was to assess the effectiveness of UAV surveys under changing population sizes by comparing UAV-based estimates with harvest-based estimates derived from models that incorporate ground-based survey data.

STUDY AREA

This study was conducted on the Nakanoshima Island, located in Lake Toya, southwestern Hokkaido, northern Japan. The study area comprises a main island with an area of 4.978 km^2 and a circumference of 5 km, along with two small islets (0.230 km^2 and 0.038 km^2) (Fig. 1). The main island features three peaks: western (454 m a.s.l.), northern (363 m a.s.l.), and eastern (376 m a.s.l.). The center of the island is a flat plain with a ridge extending to the south. Although a walking trail exists on the island, it is inaccessible to vehicles. Nakanoshima Island is designated as a Shikotsu-Toya National Park Type 1 Special Area and a Hokkaido-designated Wildlife Protection Area; there are no permanent human residents. Originally, sika deer were not present on the island; however, three individuals were introduced between 1957 and 1965. The deer population subsequently fluctuated, reaching a maximum of 434 individuals (Kaji et al. 2009). Migration and immigration are considered negligible as the island is isolated from the lakeshore and the lake does not freeze. Sport hunting is prohibited, and the island lacks natural predators. Due to pronounced overgrazing and destruction of natural vegetation, population control began in 2012 and is ongoing, with the goal of eradication by the Ministry of the Environment. Drive-count surveys have been conducted almost every year since 1980 (Igota et al. 2024) and camera trap surveys have been utilized since 2010 to monitor herd composition and diel activity patterns (Ikeda et al. 2013, 2015, 2019). Although no other medium-to-large mammals originally inhabited the island, raccoons (*Procyon lotor*) have been recorded in recent years (Ikeda et al. 2025).

The vegetation primarily consists of deciduous broadleaf forests dominated by *Quercus crispula*, *Kalopanax septemlobus*, *Acer mono*, and *Tilia japonica*. A few evergreen coniferous forests were planted with *Abies sachahnensis* and *Picea glehnii*. Understory vegetation is dominated by plants unpalatable to deer, such as *Senecio cannabifolius*, *Pachysandra terminalis*, and *Chloranthus serratus* (Sukeno and Miyaki 2007). Between 2019 and 2023, the average maximum snow depth recorded at the nearest weather station in Ohgishi was 98.8 cm (ranging 47–162 cm) (Japan Meteorological Agency: https://www.data.jma.go.jp/stats/etrn/view/monthly_a1.php?prec_no=21&block_no=0128&year=2019&month=&day=&view=p1).

METHODS

UAV observation

The UAV surveys were conducted six times, once per year, from 2019 to 2024, during winter or spring, which is the defoliation season: January 14 and 15, 2019; January 11 and 12, 2020; April 24 and 26, 2021; March 25 and 27, 2022; April 23 and 24, 2023; and April 25 and 26, 2024. Surveys were conducted in the early morning (3:00–8:00) in 2019 and 2020, and at night (20:40–2:30) from 2021 to 2024. Early morning surveys were completed within 1 h of sunrise (7:00), while night surveys were initiated at least 2 h after sunset (18:00 in March; 18:30 in April). Ambient temperatures during the survey ranged from −11.3 to 1.7°C in 2019, -4.2 to -0.8°C in 2020, -2.4 to 11.4°C in 2021, 1.2 to 4.7°C in 2022, -1.8 to 6.6°C in 2023, and 6.3 to 10.4°C in 2024.

Two UAV models were employed: a TIR camera (Zenmuse XT ZXTB19FP, DJI Shenzhen; 270 g) on a UAV (Inspire 1 V2.0, DJI; 2845 g) and a UAV equipped with TIR sensors (Mavic 2 Enterprise Advanced, DJI; 909 g). The thermal sensor resolution, field of view, and instantaneous field of view for the Zenmuse XT ZXTB19FP camera and Mavic 2 Enterprise Advanced UAV were 336 × 256 pixels, 21°, and 0.895 mrad, and 640 × 512, 59°, and 1.334 mrad, respectively. The Inspire 1 was used for 2019–2022, and the Mavic 2 for 2023–2024. The battery life was 15–20 min.

Relatively inexpensive and versatile models have limitations such as short battery life and operational range. In addition, because the study area has three mountains and one ridge that can block radio signals, it is impossible to fly over the entire island at once. Therefore, considering its topography, the island was divided into four flight areas: northwest, northeast, southwest, and southeast. Landing points were set up at locations that allowed for a comprehensive survey of each area (Fig. 1).

Owing to the unavailability of vehicles, a pilot and assistant walked on foot between landing points. As it took time to move around, two flight areas were surveyed for one day, completing the entire area over two nights. The UAV observation protocol followed the methods described by Ito et al. (2020, 2023). This pilot manually controlled the UAV and camera while monitoring for heat sources on the controller screen, flying at an altitude of approximately 70–120 m above ground level. The spatial resolutions for the Zenmuse XT and the thermal sensor of Mavic 2 Enterprise Advanced at altitudes of 70 and 120 m were 6.3 and 9.3 cm, and 10.7 and 16.0 cm, respectively.

To minimize oversights and overlaps as much as possible, we made it a rule to fly on a line at the same elevation; if we left the route to check for deer or changed batteries, we returned to the former position as much as possible and restarted the survey. When a heat source was found at a higher temperature than the ground and vegetation, the drone approached and identified whether the object was a deer. If it was a deer, we moved the UAV above it and captured photographs to record its coordinates. Location coordinates were required to determine the distribution of the deer herd in another study; therefore, the locations of the herd, not of individual deer, were recorded. Videos were always captured during the flight. The assistant recorded the observation time and deer numbers in real time during the flights and

assisted with battery changes. Deer numbers were later confirmed by checking videos recorded in the laboratories.

Witczuk et al. (2018) reported that animals are difficult to detect via UAV in coniferous forests with closed canopies. Several evergreen coniferous forests exist in the study area, and observations within these forests were difficult. Sentries drove the deer out of these forests before the beginning of the survey and stationed them until the end of the survey to prevent them from entering again. There were four evergreen conifer forests with one sentry present in each forest (Fig. 1). Six participants were required for the drone survey: one pilot, one assistant, and four sentries. The survey effort was calculated based on the duration of the survey, defined as the time from leaving the research base on the island to returning, and the number of personnel involved. The survey effort was compared with the drive counts conducted on the island over several years.

In 2021, the survey was discontinued because the UAV was uncontrollable due to high winds and crash landings on trees during the survey. Therefore, data from 2021 were excluded from the analysis.

Statistical analysis for UAV effectiveness

We compared the number of sika deer detected by TIR camera on the UAV with population estimates derived from harvest-based estimation (HBE). The HBE estimates the population size under hunting pressure by analyzing how the abundance index responds to the number of animals harvested (Iijima 2020). In the study area, deer have been culled as part of an eradication program for several years and their abundance indices have been monitored using drive counts and camera traps. Abundance of deer on Nakanoshima Island was estimated from FY2013 to 2024 using a state-space model:

$$\mathrm{NA_t}=\mathrm{NB_t}\text{-}\mathrm{C_t}$$

$$\mathrm{NB_{t+1}}=\mathrm{NA_t}\times\mathrm{G}$$

where NB_t and NA_t are latent variables representing deer abundance before and after culling in fiscal year t, respectively. C_t is the number of culled deer (observed data), and G is the apparent growth rate. We utilized culling data from the eradication program spanning FY2013 to 2023. A left-truncated normal distribution with a mean of 0 and precision of 0.01 was used as the prior distribution for the apparent growth rate G and initial population size NB_{2013}. Based on the peak calving season in Hokkaido occurring in June (Suzuki et al. 1996) and intensive culling from summer onwards, we assumed the deer population increases at the start of the fiscal year, reaching a maximum (NB_t) in summer, and decreases to a minimum (NA_t) following culling.

The observation process model of the HBE used abundance indices obtained from drive counts and camera traps. The observation process for the drive counts was modelled as follows:

$$\mathrm{DC_t}\sim\mathrm{Poisson}\left(\mu\mathrm{DC_t}\right)$$

$$\log\left(\mu \mathrm{DC}_{\mathrm{t}}\right) \sim \mathrm{Normal}\left(\log\left(\mathrm{B} \times \mathrm{NA}_{\mathrm{t}}\right), \tau \mathrm{DC}\right)$$

where, DC_t is the number of individuals detected in fiscal year t via drive counts and follows a Poisson distribution with an expected value of μDC_t. To account for potential oversights or duplications, we assumed the logarithm of the μDC_t follows a normal distribution with a mean defined by the product of the NA_t and a conversion factor, B. A left-truncated normal distribution with a mean of 0 and precision of 0.01 was used as the prior distribution for B. The τDC can be expressed as $1/\sigma^2$, and uniform distribution from 0 to 100 was used as the prior values for σ. In the drive count at the study area, boat observers counted the number of deer driven to the lakeshore by 10–30 people (Igota et al. 2024). As the drive count was conducted during winter, when forest visibility was clear owing to fallen leaves and snow, we related it to the abundance after culling. Drive-count data from FY2013 to 2023 were used, excluding 2022 due to the impacts of COVID-19.

The observation process for camera traps is as follows:

$$\mathrm{CT}_{\mathrm{i,j,t}} \sim \mathrm{NegativeBinomial}\left(\mathrm{p}_{\mathrm{i,t}}, \mathrm{r}_{\mathrm{i}} \times \mathrm{EFT}_{\mathrm{i,j,t}}\right)$$

$$\mathrm{p}_{\mathrm{i,t}} = \mathrm{r}_{\mathrm{i}} / \left(\mathrm{r}_{\mathrm{i}} + \mathrm{eCT}_{\mathrm{i,t}}\right)$$

$$\mathrm{eCT}_{\mathrm{i,t}} = \mathrm{b0}_{\mathrm{i}} \times \mathrm{NB}_{\mathrm{t}}{}^{\mathrm{b1}_{\mathrm{i}}}$$

where $CT_{i,j,t}$ and $EFT_{i,j,t}$ indicate the number of deer detected and the number of camera operating days at location j during survey i in fiscal year t, respectively. $p_{i,t}$ represents the probability parameter, and r_i denotes the size parameter for the negative binomial distribution. A left-truncated normal distribution with a mean of 0 and precision of 0.01 was used as the prior distribution for r_i. We conducted two camera trap surveys: the first at 20 locations from FY2013 to 2020, and the second at 28 locations from FY2019 to 2023. As the cameras in these two surveys were installed at different locations, they were incorporated into the model separately. We used camera data obtained in August and September, when the deer population peaked, and assumed that the expected number of deer detected by camera traps ($eCT_{i,t}$) follows a power-law relationship with NB_t. A normal distribution with a mean of 0 and precision of 0.01 was used as the prior distribution for $b0_i$ and $b1_i$.

Posterior distribution of each parameter was estimated using Markov chain Monte Carlo (MCMC) simulations. These simulations were performed in JAGS ver. 4.3.1 (www.mcmc-jags.sourceforge.net), executed via the R ver. 4.1.2 (www.r-project.org) using the RunJags package (Denwood 2016). We ran three parallel MCMC chains for 250,000 iterations following a burn-in period of 250,000 iterations for each chain, with thinning every 50th sample. The model convergence was examined using the potential scale reduction factor (PSRF; Gelman and Rubin 1992) to verify the absence of divergent transitions. Convergence is approximately reached if the PSRF is close to one. As mentioned above, the UAV survey was conducted between January and April; therefore, it may be assumed that this roughly corresponds to the after-culling population (NA_t) in the HBE. Therefore, we evaluated the relationship between the

number of deer counted in the UAV surveys and the median estimated population size derived from the HBE using Pearson's correlation coefficient.

RESULTS

Observation of drones

Sika deer were identified during both early morning and night surveys (Fig. 2). High-temperatures signatures also indicated deer tracks and bedding sites (Fig. 3). Although crows and other birds also exhibited high thermal signatures, they were distinguishable from deer based on their distinct morphological shapes and the fact that deer tend to have higher relative head temperatures. A summary of the deer counts is presented in Table 1.

Table 1
Survey dates, total flight time, total effort, and the number of deer detected by thermal infrared camera using UAVs on Nakanoshima Island in Lake Toya, Hokkaido, Japan.

Year	Date	Total flight time	Total effort[b]	Deer group detected	Deer ind. detected
2019	14–15 Jan.	3h24m	58.0h	69	136
2020	11–12 Jan.	3h17m	53.0h	33	85
2021[a]	24, 26 Apr.	1h35m	-	19	54
2022	25, 27 Mar.	3h45m	57.0h	15	41
2023	23–24 Apr.	2h55m	48.0h	33	76
2024	25–26 Apr.	2h57m	40.5h	26	73

[a] Suspension of survey because of UAV accident during flight

[b] Calculated using the time bound for the survey, from leaving the research base until returning, and the number of people required

Survey effort

Regarding survey effort, the average flight time was 3 h and 15 min, with a total annual effort for UAV surveys calculated at 51.3 person-hours (51 h 18 min). In contrast, the drive-count survey required 35 participants—including two boat operators, three observers, and 30 beaters—and took 7 h to complete. Consequently, the total drive-count effort was 245 person-hours.

Comparison with HBE estimation

Population size estimated by the HBE decreases by 64.8% over the period from 2019 to 2024 (Fig. 4), showing a positive correlation with UAV results (R = 0.67).

DISCUSSION

The positive correlation between UAV-based population estimates and HBE estimates suggests that UAV surveys effectively monitor sika deer population dynamics. Notably, UAV survey effort required only 20% of the effort of drive counts. Furthermore, drive-count personnel must traverse snow-covered mountainous terrain and are at a risk of slipping or being lost. However, UAV surveys can be conducted with only a small number of people, and safety is easier to implement. Therefore, UAV surveys are suitable as a population monitoring method with minimal effort that can be implemented in the long term. The correlation coefficient between the population estimates by UAV and HBE was 0.67. The UAV observations were underestimated in 2020 and 2022, outside the credible interval of the model. In this study, the UAV survey was conducted on two separate days. Some of the radio-collared deer moved between the four flight areas used in this study, although the study period differed between 2009 and 2010 (Takeda 2011). Thus, the deer may have moved between the flight areas during the daytime, and the underestimations in these two years may have been due to some deer being overlooked. Although the present results allowed for the monitoring of population decline, by completing the survey within a short period, specifically within a single day, it was possible to obtain more accurate estimates, as sika deer are less likely to move between flight areas. Populations will continue to decline owing to ongoing culling efforts aimed at eradicating deer populations, and UAV surveys are expected to be an effective method for monitoring population trends.

The optimal timing for TIR camera observations is reported to be around sunset (Beaver et al. 2020) and from midnight to immediately after sunrise (Ito et al. 2020, 2023). A high thermal contrast between the target animals and the surrounding environment facilitates detection. Surveys were conducted at night (starting 2 h after sunset) or in the early morning (up to 1 h after sunrise), both of which allowed deer detection. In the subarctic study area, winter and spring temperatures remain low. Owing to low daytime temperatures, the temperature rise in the surrounding environment after sunrise was likely slow, and the temperature drop after sunset was rapid. In such situations, UAV surveys can be carried out successfully if conducted outside of peak daytime hours. It is also important to schedule observations in accordance with the activity patterns of the target animals (Witczuk et al. 2018). To ensure detectability, surveys should avoid periods when animals are likely to rest or utilize densely vegetated habitats. The deer in the study area exhibit crepuscular activity patterns (Ikeda et al. 2019). Our surveys were conducted at night, when it was outside the crepuscular activity of the deer in the study area. However, as long as the ground surface was visible, such as in a leafless forest, deer could be detected even if they were inactive. Deer activity should not be considered in such situations.

Ground-based surveys, such as driving and road counts, sometimes affect deer behavior. Thus, the location of the deer does not necessarily match its activity range. However, the disturbance of UAV surveys of animals can be reduced if the drone is not close to the animals. Larsen et al. (2023) reported that disturbances to ground mammals were minimal when the UAV flight height was 55–120 m above the ground. Similar heights were observed in the current study, and few deer moved or ran away during the observation period, indicating low disturbance. Therefore, the locations where the deer were observed were considered representative of their typical activity range, and this spatial information was valuable for identifying suitable culling sites. As deer eradication programs progress, the effort required to capture a single deer increase (Masters et al. 2018). The inability to detect deer at low densities is a primary factor in eradication failure. In other words, a high probability of detecting deer at low densities results in successful eradication. Camera trap surveys are also an effective method for identifying remaining deer populations (Masters et al. 2018), but no information is available outside the camera point. Therefore, numerous cameras were required to cover the entire culling area. UAVs are useful for obtaining the location of deer over a wide area and could be an effective method for deer detection, leading to increased capture efficiency. Furthermore, during the velvet season, it is possible to distinguish between males and females using UAV observations (Ito et al. 2022), which enables sex-selective culling, such as preferentially capturing females.

The results of this study indicate that UAV surveys equipped with TIR cameras provide a highly reliable and cost-efficient method for long-term wildlife monitoring compared to traditional surveys and are likely applicable to similar environments beyond our study area. More reliable population size estimates can be obtained if the survey is completed within a short period. The use of UAVs capable of long wide-range flights and/or multiple pieces of equipment makes this possible. The study area is a closed population and the accuracy of each counting method is expected to improve, dating back to the eradication of deer in the future.

DECLARATIONS

Authors contribution:

All authors contributed to the study conception and design. Material preparation and data collection were performed by Takehiko Ito, Takuma Watanabe, and Hiromasa Igota. Data analysis was performed by Takashi Ikeda and Daishi Higashide. The first draft of the manuscript was written by Yukiko Matsuura, and all authors commented on previous versions of the manuscript. All authors read and approved of the final manuscript.

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COMPETING INTEREST & FUNDING STATEMENTS

There are non-financial interests that are directly or indirectly related to the work submitted for publication. The UAV surveys were conducted as part of a commissioned deer management project by the Ministry of the Environment in 2019 and 2020, and funded by Toyako Town from 2021 to 2024. The authors declare no conflict of interest.

DATA AVAILABILITY STATMENT

The datasets generated during and/or analyzed during the current study are not publicly available due to the ongoing population control program conducted in collaboration with local stakeholders, and the consequently associated restrictions on data sharing. The data are available from the corresponding author upon reasonable request, subject to approval by the relevant stakeholders.

ETHICS DECLARATION:

not applicable

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Figures

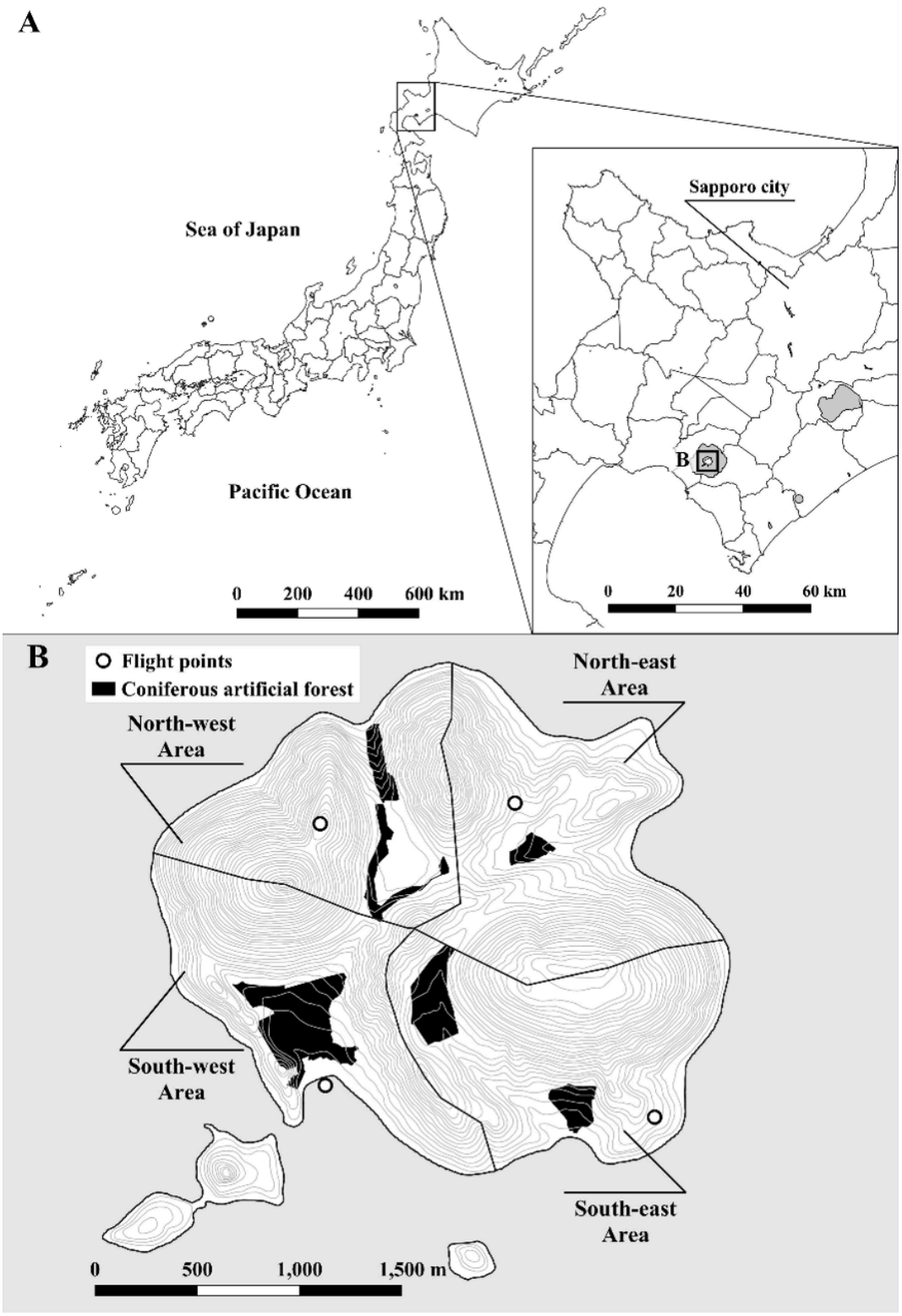


Figure 1

The study area, Nakanoshima Island, located in Lake Toya, Hokkaido, Japan (A). The island was divided into four flight areas (B). Open circles indicate landing points within each area.

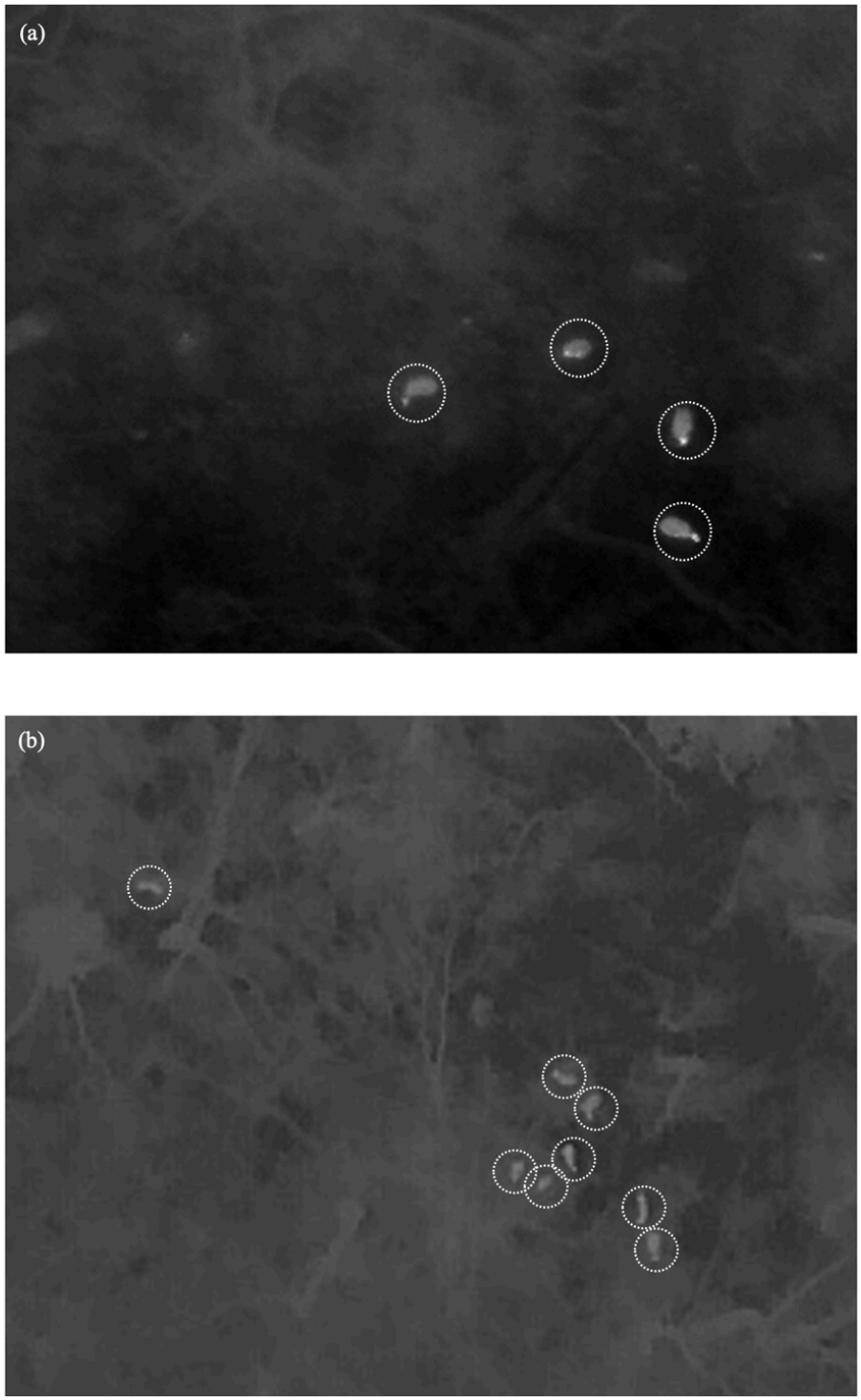


Figure 2

TIR images of sika deer observations in leafless deciduous broadleaf forest using UAVs in the morning (a) and at night (b) on Nakanoshima Island in Lake Toya, Hokkaido, Japan. Deer are visible within dashed circles.

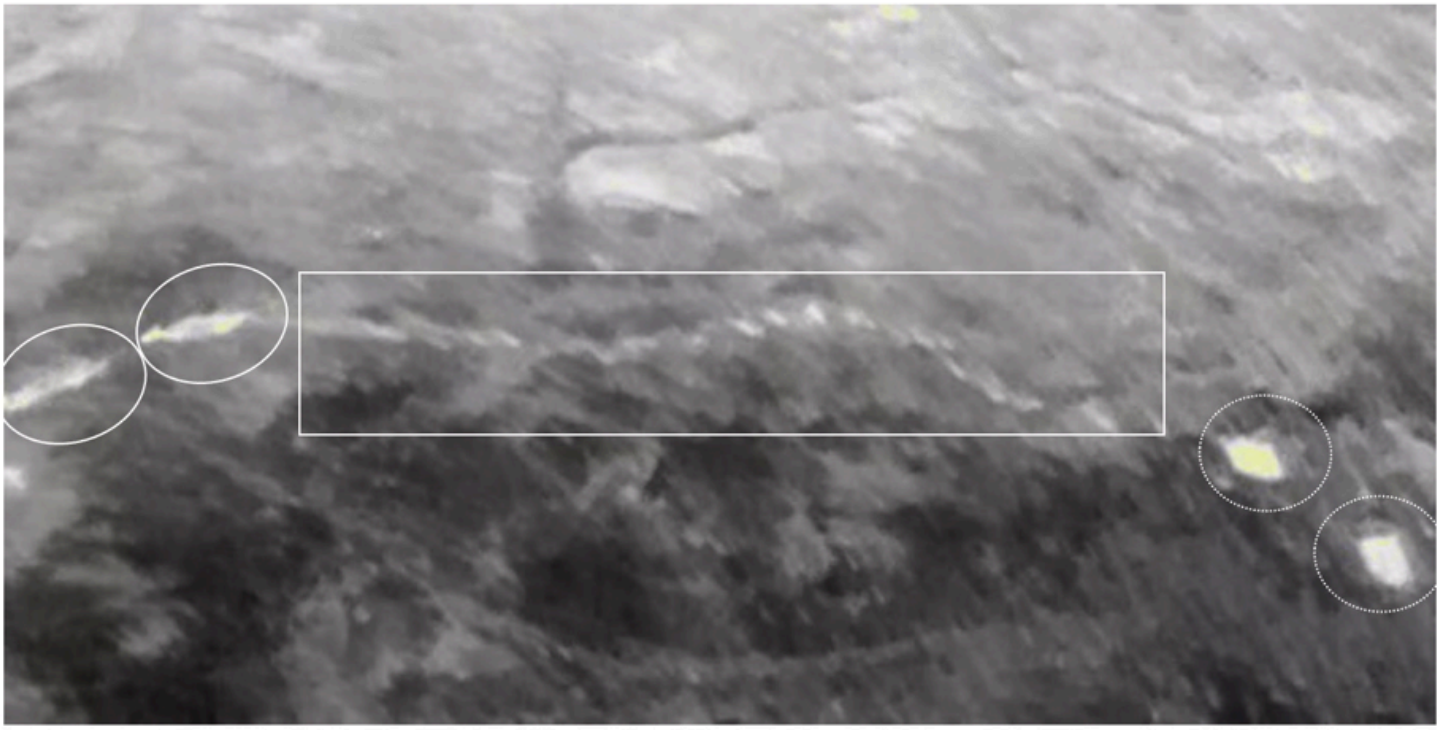


Figure 3

Sitting marks and footprints of sika deer also showed high temperatures via a UAV equipped with a TIR camera on Nakanoshima Island in Lake Toya, Hokkaido, Japan. Solid circles show sika deer, dashed circles show sitting marks, and solid square shows footprints

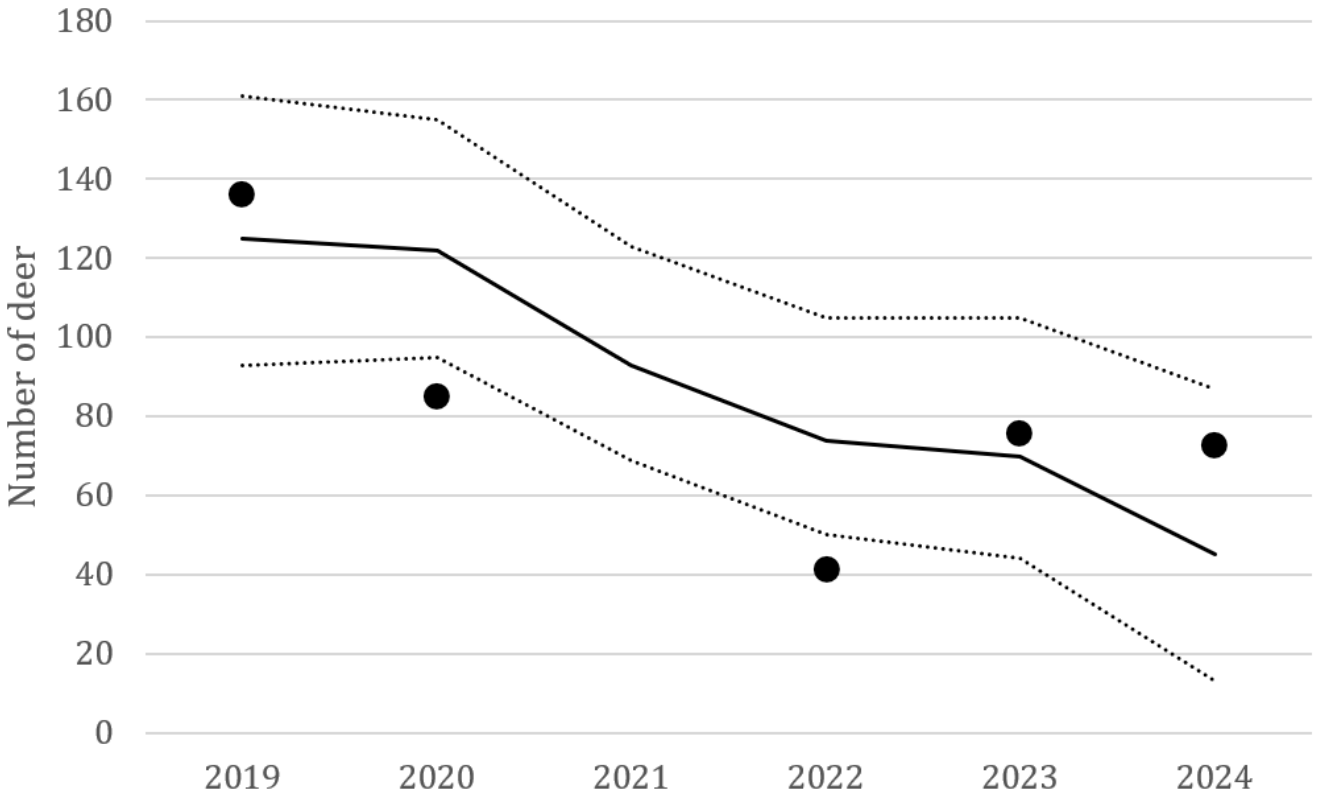


Figure 4

The number of sika deer estimated by harvest-based estimation (solid line represents median, dashed lines represent the range) and the deer detected by drone with thermal infrared camera (circles) on Nakanoshima Island in Lake Toya, Hokkaido, Japan from 2019 to 2024.