Animal Biotelemetry

CASE REPORT

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Case report: Long-term GPS tracking throughout the breeding and non-breeding seasons of the streaked shearwater *Calonectris leucomelas*

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Abstract

The collection of wildlife tracking information throughout a species' entire life cycle is important for comprehensive ecological elucidation and the establishment of practical protected areas. Although streaked shearwater (SS) is a seabird species for which biologging techniques are highly developed, there have been no reports of successful global positioning system (GPS) tracking during the early breeding and non-breeding seasons, when recapture is difficult. In this study, we succeeded in long-term GPS tracking, obtaining highly accurate tracking data during the non-breeding season from November to March and the early breeding season from April to July. We discuss the relationship between prey distribution and the marine environment to understand the species' foraging habitat preferences. In September 2018, we attached GPS tags to birds breeding on Toshima, in the Izu Islands, and recaptured two birds in August 2020 and 2022. The tags worked for 277 and 549 days and fixed 23,510 and 37,233 positions, respectively. During the early breeding season, the foraging area had low sea surface temperatures (SST) and high chlorophyll-*a* (Chl-*a*) concentrations and moved northward as the season progressed. During the non-breeding season, one bird wintered in the South China Sea and the other off northern New Guinea. In the South China Sea, SS preferred sea areas with an average SST of 26 °C and high Chl-*a* concentrations (> 0.8mg/m^3), whereas off northern New Guinea, SS preferred an area with an average SST of 29 °C. The foraging area used during the early breeding season depended on the optimal water temperature zone for their primary prey—Japanese Anchovy. The foraging areas used during the non-breeding season matched the optimal water temperature zones of the main fish distributed in each sea area. The GPS tracking data obtained in this study, while not a statistically sufficient sample size, are valuable and provide new insights into the environmental preferences of SS during early breeding and non-breeding seasons; life stages for which little information is available.

Keywords Chlorophyll-*a*, Foraging area, GPS tracking, Marine environment, Marine productivity, Migration, Procellariiformes, Seabirds, Sea surface temperature

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Introduction

The recent development and widespread use of biologging technology has enabled researchers to record the behavior of wild animals [1]. The highly accurate locations and vital records from biologging are used not only to understand the behavioral ecology of target species, but also to protect endangered species and for designating protected zones [2]. However, biologging studies often depend on the ease of capturing animals during particular periods of their life cycle [3]. For example, seabird surveys assume that recapture will most frequently occur during the breeding season when they are committed to their nests [3]. The breeding season is a period that is most important for conservation and adaptive evolution; however, it is also a period for which there is insufficient information to ensure the survival and reproduction of a species, population, or individual [4, 5]. The biologging information accumulated so far covers only part of the life cycle of the target species. Ideally, the collection of tracking information throughout a species' entire life cycle would be more useful for comprehensive ecological elucidation and effective protected area designation.

Streaked Shearwater (SS) *Calonectris leucomelas* is a member of the family Procellariidae which breeds in burrows on islands in East Asia from May to October [6, 7], and migrates to winter in the South China Sea and around the island of New Guinea [8]. This species is now listed as "near-threatened" by IUCN, considering that several breeding grounds are believed to have been lost, mainly on islands where humans have introduced Japanese Weasel *Mustela itatsi* and domestic cat *Felis catus.* Mikurajima, once supported the largest population, but it has been severely impacted by introduced predators [9]. Furthermore, the rapid development of offshore wind power generation around Japan [10] may cause habitat loss and barrier effects for this species, which spends much of its life cycle in coastal areas [11].

SS is one of the best-studied species using biologging, providing location tracking data, recording bird's-eye view images, and monitoring metabolic status and neural activity [1, 12–14]. Location tracking has been particularly active at major Japanese colonies such as on Mikurajima, Awashima, and Sanganjima [8, 15, 16]. In the late-breeding season (August to November), when birds can be recaptured, they are tracked with global positioning system (GPS) loggers. While foraging, birds either make short trips (short-distance and short-period flights) to the sea around the colony when feeding chicks, or long trips (long-distance and long-period flights) to use productive areas to the north, with lower sea surface temperatures (SST) and higher chlorophyll-a (Chl-*a*) concentrations to restore their own nutritional status [7, 17].

In the early breeding season (April to July), and in the non-breeding season, light level geolocation (GLS) is used when it is difficult to recapture birds [22]. Although GLS has a positional error of about 100 km, long-term tracking is possible. In the late breeding season, when parent birds can be handled with low risk of them abandoning their chicks, gastric contents have revealed that their primary prey consists of Japanese Anchovy *Engraulis japonicus* [16, 18]. Using highly productive marine areas is a common foraging strategy for species in the genus *Calonectris* and has important implications for reproductive success [19–21]. In the non-breeding season [8], using GLS, found that SS overwinter in the South China Sea, also off northern New Guinea, and in the Arafura Sea.

Long-term GPS tracking during consecutive life cycle phases is rarely successful in seabirds [23, 24]. In particular, there have been no studies of species that breed in burrows because backpack GPS devices may be easily damaged when entering or leaving their narrow burrows. This is true for SS, for which highly accurate GPS-based location information is not yet available during the non-breeding and early breeding seasons. In this context, we have succeeded in long-term GPS tracking of SS, albeit with a limited sample size of two birds. In this case report of those two birds, we provide highly accurate location information on their movements and utilization distributions (UD) during the non-breeding and early breeding seasons. The relationship between UD and environmental data (including SST and Chl-*a* as indicators of ocean productivity and prey availability), is described to characterize foraging environments. Furthermore, by considering whether each foraging environment is consistent with potential prey habitat, we aim to better understand ocean use throughout the species' life cycle.

Methods

Animal capture, GPS logger attachment, and data collection

The survey site, Toshima (34.5130°N, 139.2763°E), is located in the Pacific Ocean off the coast of Japan, 70 km north of Mikurajima. The island supports the largest breeding population of SS. This volcanic island has a circumference of 8 km, an area of 4 km^2, and a maximum elevation of 508 m. The entire island is covered with Japanese Camellia *Camellia japonica* plantations. The SS colony that we studied is located in the southern part of the island at an elevation of 240 m. We captured seven birds in September 2018, and after sexing them based on their vocalizations [25], we attached a solar-battery Gipsy Remote (Technosmart Europe srl.; fix interval every 15 min) with a Teflon harness (total weight of 13 g) to each bird. They were then promptly released into their burrows. The weight of each tag corresponds to 2.4% of the average weight of this species on Toshima and is lighter than the tags used for long-term tracking of Lesser Black-backed Gull *Larus fuscus* [23]. The two individuals successfully GPS-tracked in this study were both male (SS 2205 weighed 540 g and SS 2206 weighed 640 g); they were both recaptured in August 2020 and 2022. Although the GPS loggers were broken, tracking data were recovered using TechnoSmart (The GPS tracking data is available in Supplementary Information 1).

Our experiment complied with protocols reviewed by the Institutional Animal Care and Use Committee and was approved by the President of Niigata University (Permit Number: SA00736). The capture of SS was permitted by the Tokyo Metropolitan Government.

Data analysis

We mapped the location data as flight trajectories using ArcGIS Pro. Kernel densities were calculated for each month using R ver. 4.3.0 [26] and R package “adehabitatHR” [27] to determine UD during the early breeding (April–July) and non-breeding (when birds were away from Toshima) seasons, and to identify high-frequency areas (50% Kernel UD). The non-breeding seasons of SS 2205 and 2206 were from November 2018 to February 2019, and January and February 2019, and from December 2019 to March 2020.

In the seas around the Japanese breeding areas of SS, SST fluctuate greatly seasonally due to their mid-latitude location and the confluence of cold and warm currents. In particular, the SST near Toshima rises from approximately 18 to 25 °C from April to July (early breeding season). By overlaying the marine environment and UD for each month, we investigated the seasonal changes in foraging behavior around the Toshima colony. In the non-breeding season, we calculated mean SST and Chl-*a* concentrations within the UD and tracked environmental changes in the sea area where they stayed. The marine environmental information is monthly SST and Chl-*a* concentration (0.1-degree resolution, Aqua-MODIS) obtained from NASA Earth Observations (freely available at https://neo.gsfc.nasa.gov/).

Results

The GPS tag for SS 2205 was active for 277 days (15 September 2018 to 19 June 2019) and provided 23,510 fixed coordinates, while the GPS tag for SS 2206 was active for 549 days (from 10 September 2018 to 12 March 2020) and provided 37,233 fixed coordinates. During the breeding season, both birds remained in coastal Japanese waters close to their colony, and during the non-breeding season SS 2205 visited the South China Sea while SS 2206 visited the sea off northern New Guinea (Fig. 1). SS 2206 visited the same wintering area twice from 2018 to 2020 (Fig. 1).

We overlaid UD with SST and Chl-*a* concentrations for each month of the early breeding season (Fig. 2). UD tended to shift northward with seasonal progression. UD for April through June were in the 10–20 °C SST zone and in the 15–25 °C SST zone for July. Particularly, in May, concentrated UD were observed in coastal areas with a gradient in SST and spotty high densities of Chl-*a* (Fig. 2).

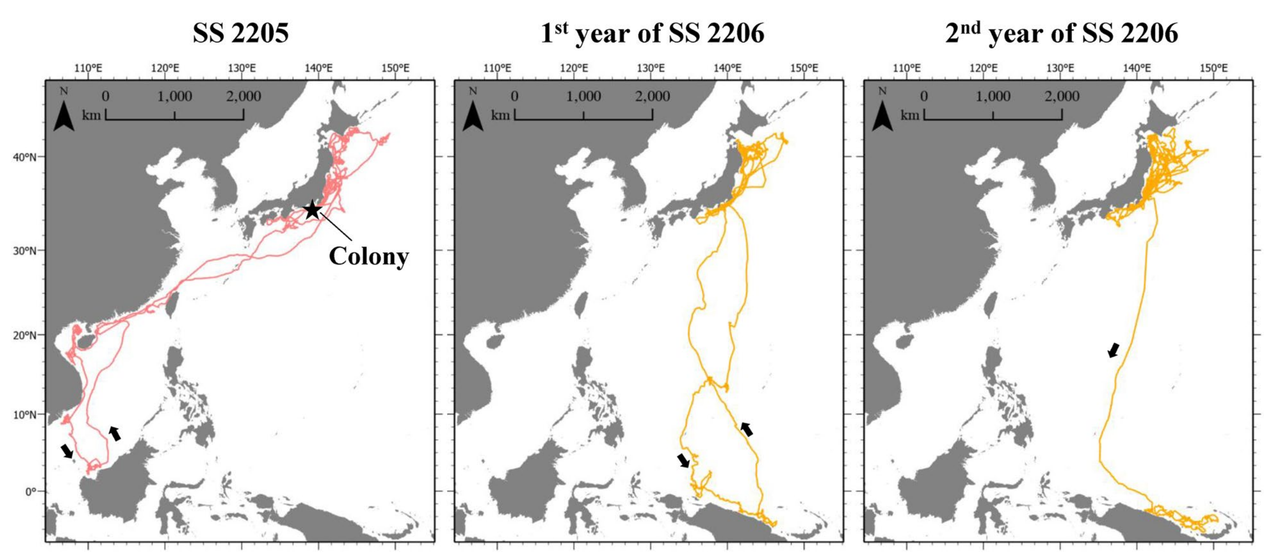

Fig. 1 Flight trajectories by long-term GPS tracking. Two GPS-tagged birds were recaptured after 277 and 549 days. Flight trajectories are shown for each bird and year. The year separates the arrival time at the breeding site from the overwintering site. Arrows indicate the direction of migration

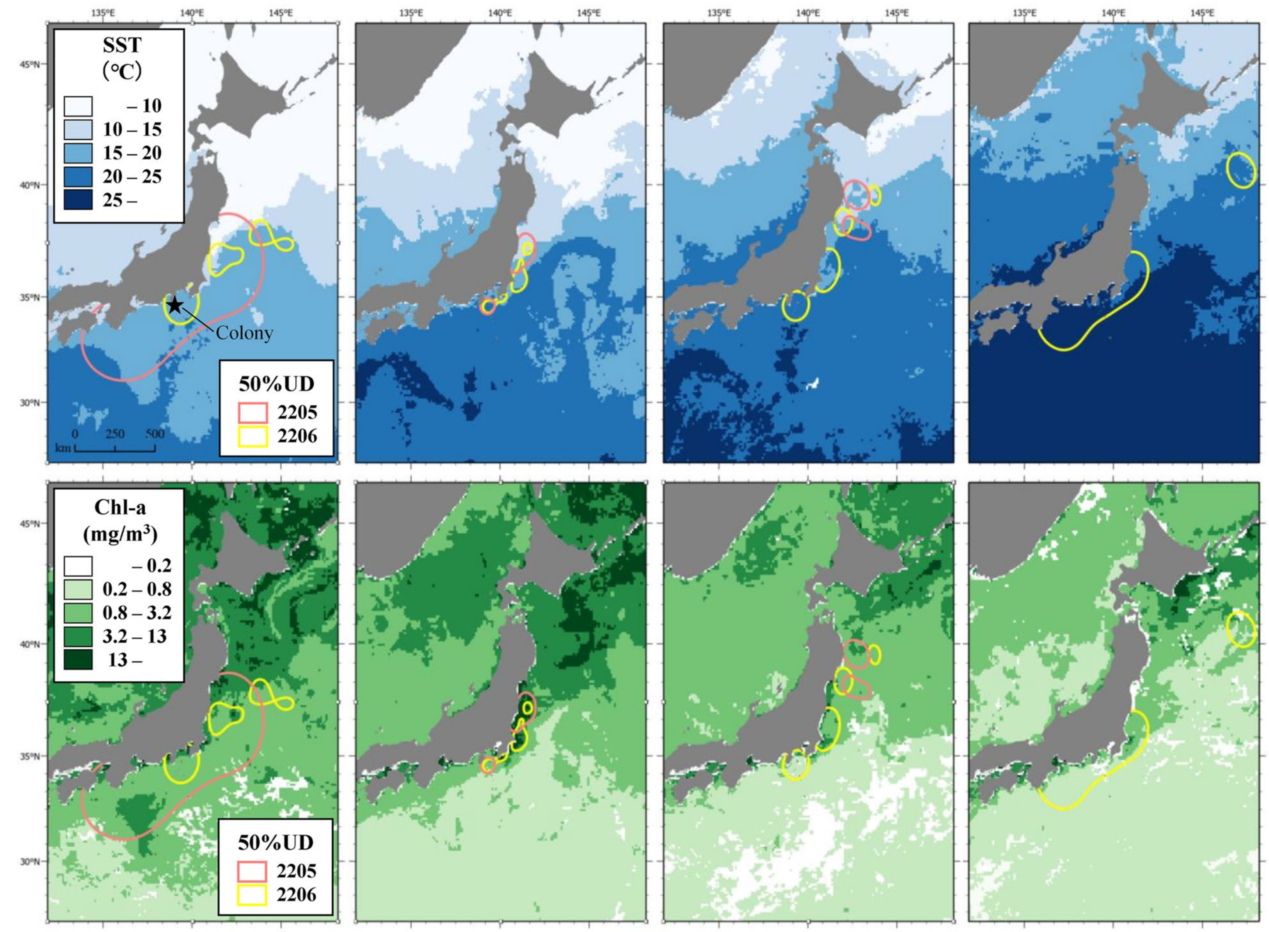

Fig. 2 Seasonal pattern of utilization distribution and marine environment in the early breeding season. The 50% kernel utilization distribution (50% UD) was estimated for each month from April to July and overlaid on sea surface temperature (SST) and chlorophyll-a (Chl-*a*) concentration layers, which in marine environments are indicative of primary productivity

We also showed monthly UD in the overwintering areas (Fig. 3). In the South China Sea, the wintering area of SS 2205, UD shifted southward as the season progressed. In the sea off northern New Guinea, which was used for overwintering by SS 2206, the UD pattern varied from year to year, with the 2018–2019 wintering sites located further west than in 2019–2020 (Fig. 3).

In the South China Sea, SS 2205 used sea areas with SST ranging from 25.5 to 26.4 °C from November to January; in February it used a much warmer area of 27.9 °C SST (Table 1). The timing of the use of each area by SS 2205 coincided with when Chl-*a* concentrations in each area were highest (Table 2).

In the sea off northern New Guinea, SS 2206 used areas ranging from 28.9 to 29.6 °C SST during two winters (Table 1). There was no preference for areas with higher concentrations of Chl-*a* throughout the season (Table 2).

Discussion

This study of streaked shearwater is the first to report UD based on GPS tracking during the non-breeding and early breeding seasons. A previous study inferred the northward shift of the foraging area in the early breeding season from the GLS tracking of birds from Mikurajima [22], an inferred shift which is now directly supported by our GPS tracking study. Variations in foraging areas are likely to be related to the distribution of Japanese Anchovy as prey [28]. Japanese Anchovy prefer waters with high primary productivity, and with SST around 20 °C for reproduction [29, 30]. Adult fish 10 cm and longer (age 1–2 years) migrate to waters between 35° and 43° N from May to November; this is consistent with SS UD from May to July in this study and the distribution of foraging areas from August to November, during the late breeding season [31]. Thus, the seasonal progression of UD strongly suggests that Japanese Anchovy is

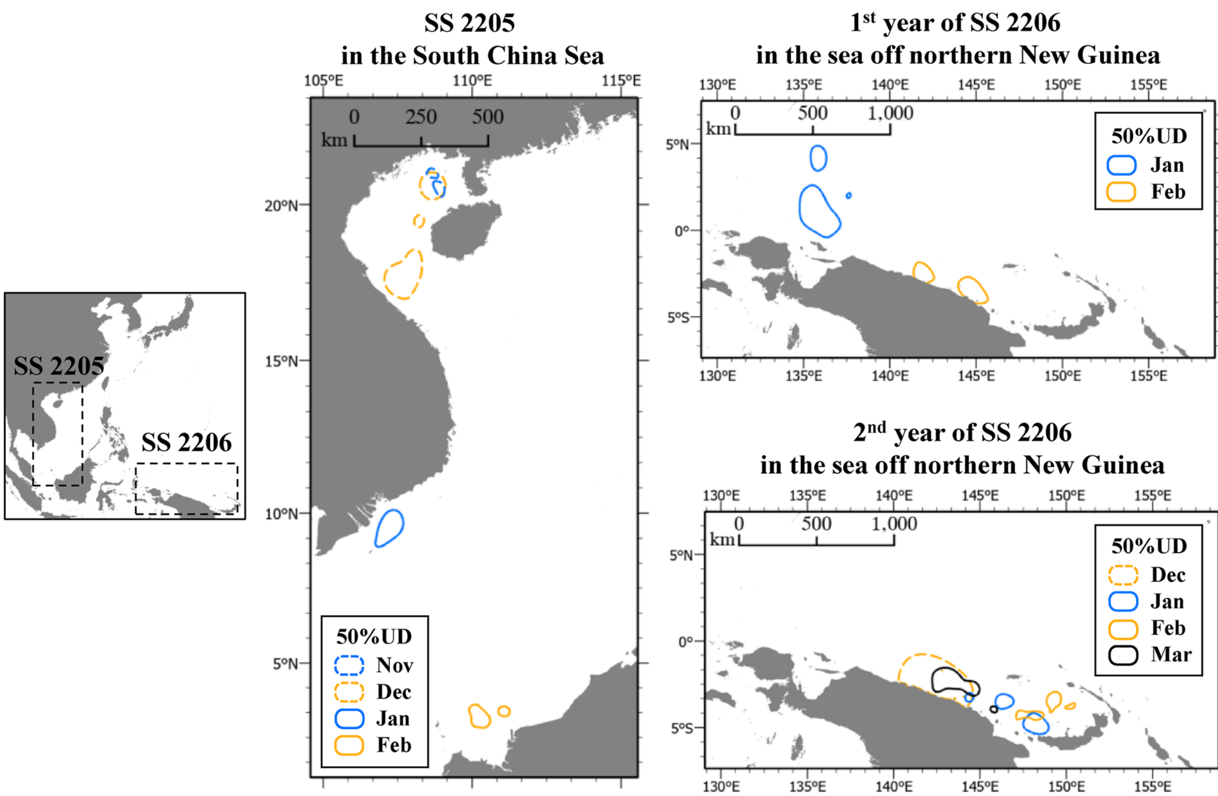

Fig. 3 Seasonal pattern of utilization distribution in the non-breeding season. The 50% kernel utilization distribution (50% UD) was estimated each year at each wintering site (SS 2205 in the South China Sea and SS 2206 in the sea off northern New Guinea)

Table 1 Sea surface temperatures in the utilization distribution (UD) area for each month during the non-breeding season

UD in each month	SST (°C) in each month				
	Nov	Dec	Jan	Feb	Mar
SS 2205					
Nov	**26.4**	23.4	20.2	22.4	–
Dec	27.3	**25.5**	23.5	24.1	–
Jan	27.8	27.4	**26**	26.3	–
Feb	29.8	30.3	28.1	**27.9**	–
SS 2206 1st year					–
Jan	–	–	**29.1**	29.3	–
Feb	–	–	28.8	**28.9**	–
SS 2206 2nd year					
Dec	–	**29.6**	29	30	29.9
Jan	–	30.7	**29**	28.9	30
Feb	–	30.6	29.4	**29.2**	30.1
Mar	–	29.6	29.1	30.2	**29.6**

To investigate the relationship between changes in the marine environment and bird migration, we calculated the mean sea surface temperature (SST) for each month in each monthly 50% kernel UD area. Values indicated in bold font give SST during the timing of use by SS

Table 2 Chlorophyll-a concentration in the utilization distribution (UD) area for each month during the non-breeding season

UD in each month	Chl-*a* (mg/m^3) in each month				
	Nov	Dec	Jan	Feb	Mar
SS 2205					
Nov	**2.17**	1.98	0.4	0.47	–
Dec	0.62	**0.87**	0.73	0.48	–
Jan	0.94	0.61	**1.07**	0.54	–
Feb	0.22	0.2	1.09	**1.14**	–
SS 2206 1st year					–
Jan	–	–	**0.12**	0.15	–
Feb	–	–	0.74	**0.87**	–
SS 2206 2nd year					
Dec	–	**0.24**	0.39	0.28	0.21
Jan	–	0.17	**0.26**	0.29	0.23
Feb	–	0.11	0.23	**0.25**	0.24
Mar	–	0.18	0.36	0.24	**0.21**

To investigate the relationship between changes in the marine environment and bird migration, we calculated the mean chlorophyll-a concentration (Chl-*a*) for each month in each monthly 50% kernel UD area. Values indicated in bold font give Chl-a during the timing of use by SS an essential prey species for SS throughout the breeding season.

Little is known about the prey species of SS during the non-breeding season, although it is inferred that they eat surface-dwelling fishes [8]. Seasonal shifts in UD have been observed in the South China Sea, associated with the southward fishing activity observed in satellite imagery [32]. The Japanese Scad *Decapterus maruadsi*, one of the major fishery targets in the South China Sea, avoids SST above 28 °C in the autumn, and prefers SST of 26 °C in the spring [33]. This environmental preference tends to be related to the UD shift pattern in this study (Table 1). Therefore, given the patterns of SS behavior observed during the breeding season, its foraging behavior during the non-breeding season may depend on the migratory patterns of surface-dwelling fish. In addition, Ochi et al. [34] indicated that SS around their breeding sites prey on discarded fish; therefore, behavior patterns in their wintering areas may involve following fishing vessels.

The sea off northern New Guinea is used for foraging during the non-breeding season despite its high SST and low Chl-*a*. This sea area is known to be one of the world's leading habitats for Skipjack Tuna *Katsuwonus pelamis* [35]. Ashida et al. [36] have shown that juvenile tuna exhibit higher growth rates at high SST of approximately 30°C. High marine productivity in tropical regions does not necessarily contribute to higher growth rates of small plankton-feeding fish (such as for example Neon Damselfish *Pomacentrus coelestis*) [37]. SS 2206's preferred foraging area, characterized by high SST and low Chl-*a* concentrations, is consistent with it being suitable habitat for potential prey growth. Foraging behavior associated with the habits of tuna and small fish in tropical areas has been observed in the related Wedge-tailed Shearwater *Ardenna pacifica* [38]. The suitable habitat of potential prey fishes according to sea area, is an essential clue to understanding UD patterns of shearwaters in overwintering areas.

The inferred environmental preferences between SS UD and prey migration in the non-breeding and early breeding seasons offer new insights. They help us to understand the mechanism of habitat selection throughout the species' life cycle. However, more research involving tracking and identifying prey species is needed to provide more reliable ecological information and to identify hotspot areas for protection. Long-term GPS tracking is rare in seabirds, with only a few examples of studies to date [23, 24]. In addition, the scarcity of data based on the difficulty of recapturing animals due to the ecology of the target species is not likely to be easily solved by the development of electronic technology for GPS tracking. We anticipate that even limited data, such as those provided by our case study, will accumulate as further case reports and web archives are published facilitating future analyses based on sufficient samples to be statistically reliable.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40317-024-00397-8.

Additional file 1.

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Author contributions
T.K., M.Y., and T.Se. designed the study; S.M., K.H., and M.Y. provided technical assistance on survey methodology. T.K., T.Sa., H.M. collected the data; T.K. analysed the data; T.K. and T.Se. led the writing of the manuscript. All authors contributed critically to the drafts and gave final approval for publication.

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Data availability
The data obtained in this study is provided within a supplementary information file.

Declarations

Competing interests
The authors declare no competing interests.

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