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Source: The Auk, 132(2) : 389-396

Published By: American Ornithological Society

URL: https://doi.org/10.1642/AUK-14-196.1

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The Auk
Ornithological Advances
www.aou.org

Volume 132, 2015, pp. 389–396
DOI: 10.1642/AUK-14-196.1

RESEARCH ARTICLE

GPS telemetry for parrots: A case study with the Kea (*Nestor notabilis*)

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Submitted August 28, 2014; Accepted December 5, 2014; Published February 18, 2015

ABSTRACT
Parrots are one of the most complex avian lineages worldwide, yet little is known about their patterns of movement and space use. Such information is vital for understanding the social development and structure of members of this long-lived order, as well as for the establishment of effective conservation and management actions for the many threatened or endangered species. While global positioning system (GPS) telemetry has been employed successfully on a broad range of birds, to date no studies have been published in which this technology has been used on any psittaciform species, most probably due to concerns held by researchers regarding the high cost of GPS units or the perceived ability of members of this order to remove or damage tracking gear. Here, we evaluate the feasibility and performance of animal-borne GPS telemetry as a means of tracking parrots. First, we encased inexpensive (<US$70) archival GPS dataloggers (~19 g) in bite-proof housing, and then we evaluated the effects of the devices on the study animals and their operational performance during field trials ($n = 14$) on wild-caught Kea (*Nestor notabilis*), a large (~1 kg) parrot endemic to the Southern Alps of New Zealand. We observed no apparent adverse effects of the loggers on the behavior and condition of the Kea and no damage to the devices that impaired their function, and found that the operational performance of the loggers was similar to that reported for devices deployed on other birds and animals. Our study demonstrates that GPS telemetry can be a highly effective method for characterizing the movement patterns of free-ranging parrots.

Keywords: GPS telemetry, parrots, dataloggers, movement, Kea, *Nestor notabilis*

Estudio de factibilidad del uso de telemetría GPS para loros: Un caso de estudio con *Nestor notabilis*

RESUMEN
Los loros son uno de los linajes de aves sociales más complejos del mundo, y sin embargo poco se sabe sobre sus patrones de movimiento y uso del espacio. Esta información es vital para entender el desarrollo social y la estructura de los miembros de este orden de larga vida, así como para el desarrollo de acciones efectivas de conservación y manejo para muchas de las especies amenazadas o en peligro. Mientras que la telemetría con sistemas de posicionamiento global (GPS por sus siglas en inglés) ha sido usada con éxito en una amplia gama de aves, no hay estudios publicados donde se haya usado esta tecnología con ninguna especie de Psitaciforme, probablemente debido al alto costo de las unidades GPS o a la habilidad potencial de los miembros de este orden para sacarse o dañar los equipos de rastreo. Aquí evaluamos la factibilidad de uso y el rendimiento de la telemetría GPS desde el nacimiento de los animales, como un medio para seguir a los loros. Primero, revestimos un registrador de datos de GPS (~19 g) barato (<$70 USD) en un envase a prueba de mordidas y luego evaluamos los efectos de estos equipos en los animales de estudio y su rendimiento operativo en las pruebas de campo ($n = 14$) en individuos cautivos de *Nestor notabilis* – un loro grande (~1kg) endémico de los Alpes del Sur de Nueva Zelandia. No observamos efectos adversos de los registradores en el comportamiento y en la condición de *N. notabilis*, tampoco hubo daño a los equipos que impidiera su funcionamiento, y encontramos que el rendimiento operativo de los registradores fue similar al de otros equipos colocados en otras aves y animales. Nuestro estudio demuestra que la telemetría GPS puede ser un método muy efectivo para caracterizar los patrones de movimiento de los loros silvestres.

Palabras clave: loros, movimiento, *Nestor notabilis,* registradores de datos, telemetría GPS

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INTRODUCTION

Parrots are one of the most distinctive, speciose, and socially complex avian lineages worldwide, yet they also are one of the most threatened groups of birds, with 171 of the 398 recognized extant species being classified as near-threatened to critically endangered (IUCN 2014). Major threats include the degradation, destruction, and fragmentation of critical habitats (Snyder et al. 2000), as well as the illegal trade in wild-caught birds (Weston and Memon 2009). Conversely, in some areas parrots are considered to be major environmental pests because of the damage that they cause to crops and human property (Bomford and Sinclair 2002). Moreover, a number of parrot species that have been introduced outside of their original geographic ranges carry infectious diseases and/or are able to outcompete, displace, or pose other risks to indigenous wildlife (Clavero et al. 2009). Despite the importance of understanding the social development of parrots, as well as the critical need for development of effective conservation and management strategies, little is known about the movement and space-use patterns of parrots (Herrod et al. 2013). Such information is required to identify essential habitats, describe foraging and/or migratory pathways, characterize responses to human perturbation of natural ecosystems, and locate potential 'hotspots' of human–wildlife conflict that necessitate monitoring or protection.

Currently, one of the most effective means of characterizing the movement patterns of free-ranging birds is satellite telemetry based on the global positioning system (GPS). GPS telemetry has many advantages over other animal-tracking methods such as direct observation, VHF or UHF radio-telemetry, ARGOS satellite telemetry, light-based geolocation, and RFID sensor networks. Such benefits include its typically high spatial accuracy (Hansen and Riggs 2008), capability of determining location at high sampling frequencies (>1 Hz for some devices), ability to record and store large numbers of observations (e.g., >100,000 fixes), scope to precisely register when location estimates are made, capacity to remotely collect bias-free position information in the absence of human observers (Hebblewhite and Haydon 2010), and ability to continuously track the movements of wide-ranging animals for prolonged periods, even in climatic and topographic conditions that are highly unsuitable for field staff (Arthur and Schwartz 1999).

GPS telemetry has great potential to increase knowledge of the movement and spatial ecology of parrots; however, to date no studies have been published in which this method has been employed (Herrod et al. 2013). Most probably this is because of concerns held by researchers that the strong crushing beaks, acute manual dexterity, and high intelligence (Pepperberg 2006) of psittaciforms may limit the durability and retention of animal-borne GPS receivers (Herrod et al. 2013, Le Souef et al. 2013). Moreover, parrots may become more wary of humans following capture (Beissinger and Snyder 1992), increasing the difficulty of recovering archival tracking devices.

Here, we assess the feasibility of tracking parrots using GPS telemetry in field trials on wild-caught Kea (*Nestor notabilis*; Figure 1), an endangered montane parrot endemic to the South Island of New Zealand. Our aims were to evaluate: (1) the effects of the GPS loggers on the behavior and physical condition of the study subjects; (2) the extent of the damage caused to the tracking gear; (3) the loggers' operational performance; and (4) the quality of the resulting data. Our study is the first reported use of animal-borne GPS telemetry for parrots; as such, it offers crucial insights into the application of this tracking technology for the study of the ecology, behavior, conservation, and management of this large and diverse group of birds.

METHODS

Study Species

The Kea is a large, omnivorous parrot (family Strigopidae) found mostly in high-altitude southern beech (Nothofagaceae) forest, subalpine shrublands, and high-alpine basins and ridges in the South Island of New Zealand. The species is moderately sexually dimorphic, with males (900–1,100 g) weighing ~20% more than females (700–900 g) and having longer (12–14%) upper mandibles (Higgins 1999). Recently, Kea were classified as 'Nationally Endangered' by the New Zealand Department of Conservation (Robertson et al. 2013); currently, the IUCN classification is 'Vulnerable' (IUCN 2014). In some areas, populations appear to be in decline due to predation by or competition with introduced mammals, and, to an unknown extent, direct or indirect conflicts with humans (Elliot and Kemp 2004, Gartrell and Reid 2007).

Study Area

Our study was undertaken at Arthur's Pass National Park (42.93°S, 171.56°E) in the Southern Alps, near Mounts Rolleston, Temple, and Cassidy (Figure 2). Topographic features at the study site include deeply incised glacial valleys, high alpine peaks, and steep scree slopes; elevations range from 300 m to 1,720 m above mean sea level. The study area has a mean annual rainfall of >4 m, and mean monthly air temperatures range from a low of –2°C in July to a high of 18°C in February (CliFlo 2014).

Tracking Devices

The GPS loggers evaluated in this study comprised a commercially available 20-channel receiver (Mobile Action Technology, Xindian District, New Taipei City, Taiwan) with integrated data storage and passive ceramic aerial,

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FIGURE 1. Kea (*Nestor notabilis*), an endangered montane parrot endemic to the South Island of New Zealand. Photo by Todd Dennis

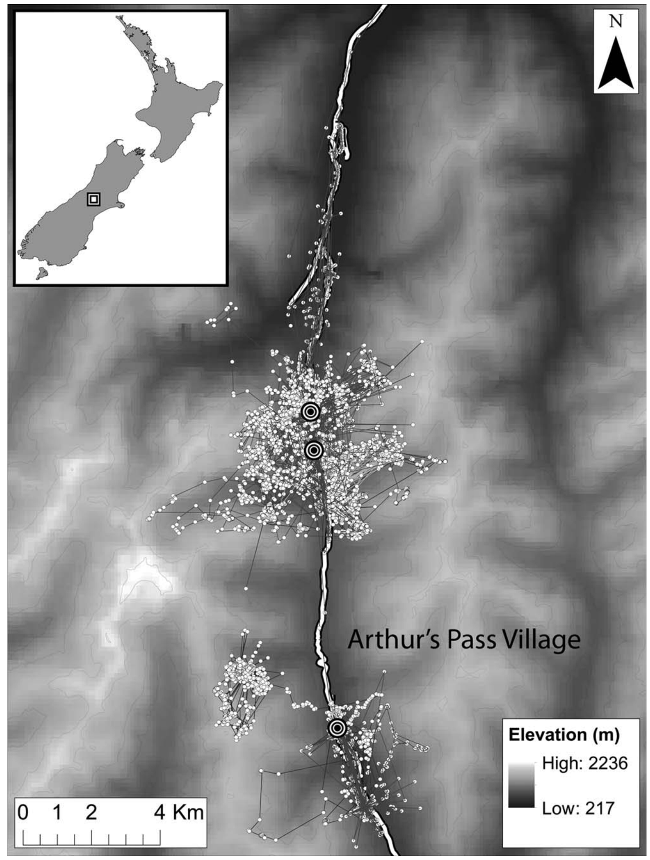

FIGURE 2. Study area in Arthur's Pass National Park, New Zealand, showing GPS fixes from all study birds linked sequentially by medium-gray lines. Light-gray lines indicate elevation contours at 300-m intervals. The heavy white line in the center of the figure represents a major road, and ringed circles denote the three capture locations.

powered by a 380 mAh 3.7 V lithium-polymer rechargeable battery. Loggers were made weather- and bite-proof by removing the receivers from their original plastic housing and sealing them in two layers of ~0.9 mm polyolefin heat-shrink wrap (RNF-100-1; Raychem, Menlo Park and Redwood City, California, USA). Plastic tubes (6 mm and 4 mm external and internal diameters, respectively) for attachment of harnesses were fixed to the loggers with superglue before a third layer of shrink wrap was added and sealed. Completed devices weighed ~19 g and were ~60 mm × 27 mm × 12 mm (Figure 3). The GPS loggers were configured to continuously record position fixes over a 24-hr period at a nominal sampling interval of 1 fix every 3 min; such a sampling regimen permitted collection of sufficient data with which to describe the birds' daily patterns of movement and behavior in detail. The GPS microprocessors used in our study could be programmed by the user to record locations at intervals ranging from 1 fix per 1 s to 1 fix every 2 hr; operational periods of the devices will vary accordingly.

Capture, Handling, and Evaluation of Performance

GPS dataloggers were deployed on 14 adult male Kea intermittently between September 3, 2012, and January 8, 2014. Birds were deemed to be suitable candidates for the study only after they had been observed at the field site at least 3 times during the week prior to attempts to tag them. Individuals were captured using a leg noose mounted on a 1-m pole, noose lines (see Bub 2012), or a net gun that used a 0.32-calibre blank pistol cartridge to propel a 4-m weighted net over the target. GPS loggers were attached to the birds (generally in <15 min) between the wings and above the center of gravity using backpack harnesses (2 g) constructed of 2-mm nylon cord that incorporated a cotton weak link positioned over the keel (as described in Karl and Clout 1987). Following deployment of the loggers, birds were released at their capture locations and observed for up to 1 hr to assess how they responded to handling and carrying the tracking devices. Weights of the GPS devices and harnesses ranged from 1.9% to 2.6% of the study birds' body masses (810–1,079 g).

The GPS loggers were retrieved by recapturing the birds (using the methods described above) after a minimum of 7 field-trial days—the approximate operational life of the batteries at the scheduled sampling interval. The time required to recapture individual Kea once they were resighted following termination of the trial varied between 1 hr and 5 days. Upon recovery of the loggers, study

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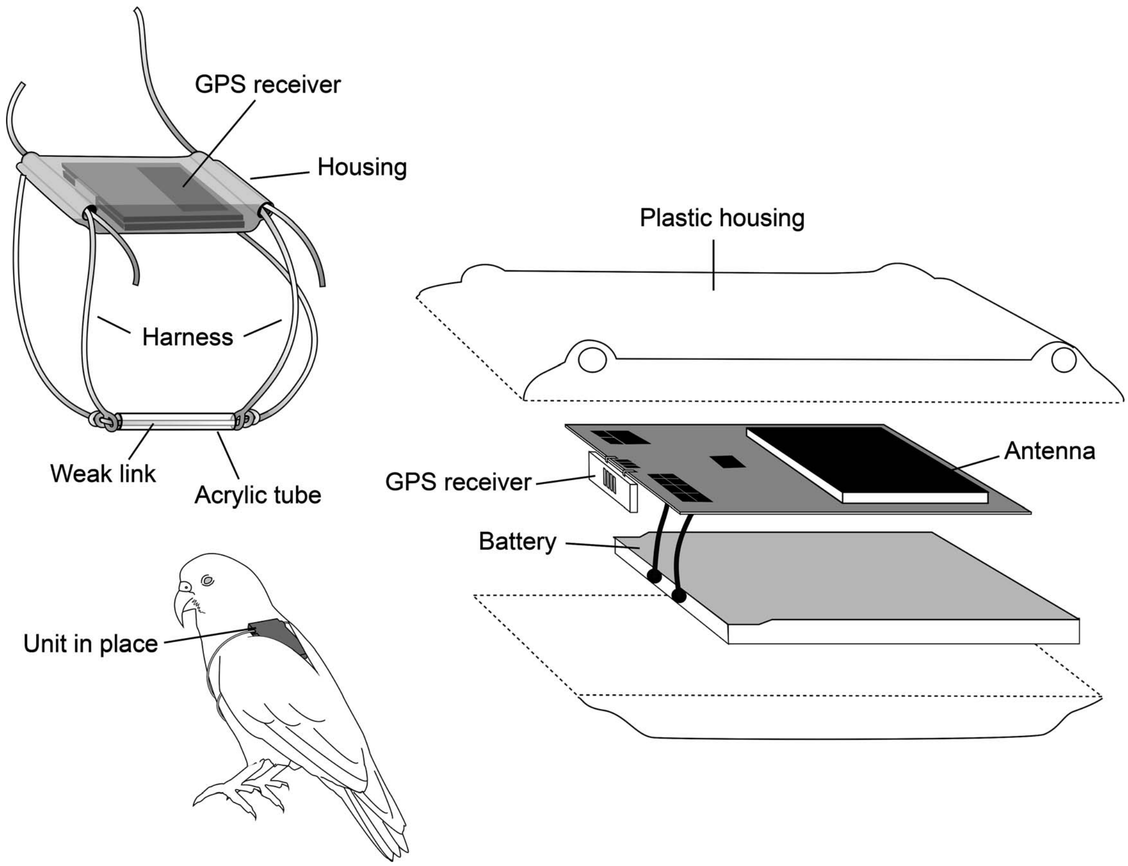

FIGURE 3. Schematic diagram of a GPS datalogger and harness used to track the movements of adult Kea (*Nestor notabilis*) in Arthur's Pass National Park, New Zealand, September 2012–December 2013.

animals were inspected for loss of body condition and damage to feathers and skin where the device and harness had been attached. Data recorded in the on-board memory of the loggers were then downloaded to a laptop computer for subsequent analysis.

Field performance of the GPS loggers was assessed primarily though consideration of fix success rate (FSR: the proportion of scheduled GPS observations that were actually obtained), as the accuracy of the GPS receivers is high compared with other tracking methods and is well documented, and the operational lifetime of devices is strongly dependent on battery size and sampling interval, which will vary according to study species and research objectives (Rempel and Rodgers 1997). Unless otherwise stated, statistical values are reported as means ± standard deviations (SD).

RESULTS

Effects on Study Animals

Immediately after release, and occasionally during deployments, we observed all of the study birds resting, walking, and flying while carrying the GPS loggers, and saw no obvious indications of distress, impaired movement, or change in normal patterns of behavior. Periods for which the loggers were carried by individual birds ranged from 6 to 270 days (median = 11 days); the maximum deployment period was an extreme case in which the individual disappeared from the study area for a prolonged time before it eventually returned and the tracking device was recovered. At the time of recapture, none of the Kea exhibited signs of substantial wear or damage to feathers or skin where the GPS loggers had been fitted; in most cases, the loggers and harnesses had been well preened into the body feathers. Visual inspections showed that all birds had healthy amounts of muscle mass around the keel and none exhibited noticeable loss of body condition.

Retrieval and Damage Assessment of GPS Loggers and Harnesses

Twelve of the 14 GPS units were eventually recovered, all of which had sustained only minor damage to the outer layer of heat-shrink wrap (particularly at the ends), most probably because of attempts by the birds to remove the devices. Of the 12 recovered devices, 2 were removed by the Kea within the first hour following deployment—these

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TABLE 1. Performance characteristics of archival GPS dataloggers recovered from 10 wild adult kea following field trials at Arthur's Pass National Park, New Zealand. 'FSR' refers to fix success rate, the ratio of the number of location estimates actually recorded to the number expected during the observed operational periods given the nominal sampling interval. '*' denotes a logger that collected more position fixes than was expected, due a probable malfunction of the internal clock, therefore it was excluded from the calculation of mean FSR.

ID	Date deployed	Observational period (hr)	Number of fixes	FSR
V-1694	September 3, 2012	148.3	2,302	77.6
V-0755	September 4, 2012	118.7	1,384	58.3
V-0303	September 5, 2012	147.9	2,090	70.7
V-1021	November 11, 2012	165.3	2,306	69.7
V-0026	November 27, 2012	177.0	3,622	102.0*
V-0669	November 27, 2012	173.6	2,632	75.8
V-0754	January 10, 2013	184.1	3,112	84.5
V-2353	November 10, 2013	186.0	2,996	80.5
V-0601	November 27, 2013	174.9	2,452	70.1
V-0032	December 11, 2013	145.1	2,195	75.6
Mean ± SD		162.1 ± 21.5	2,509 ± 622	73.7 ± 7.6

units were operating normally, but due to their short deployment periods they were excluded from further analysis. One of the two birds from which the GPS logger was not recovered was seen several times after deployment, but proved too difficult to recapture; the second was never observed again. Small amounts of moisture had condensed in the outer layers of the shrink wrap in 5 of the 14 loggers; however, when recovered, all of these units were in working order and had successfully recorded locations. Eight of the harnesses appeared to have been chewed, but the damage was superficial and did not weaken the integrity of the attachment.

Performance of GPS loggers

Operational periods of the GPS loggers during the field trials ranged from 118.7 to 186.0 hr, and the number of position fixes recorded by the devices varied between 1,384 and 3,622 ($n = 10$; Table 1). Fix success rates ranged between 58% and 102% (mean = 74% ± 8%). The higher-than-expected FSR of 102% recorded for one logger was most likely due to water damage to the internal clock, which was evident when the device was recovered; therefore, this logger was excluded from the calculation of FSR. Removal of gaps (3 or more successive fixes between sunset and sunrise) in the time series of GPS observations, when presumably the Kea were roosting in rock cavities or other areas where fixes could not be obtained, increased the mean FSR to 84% ± 9%. The median locational error of one logger ($n = 400$ observations) at a fixed location under open sky was 5.7 m.

Data recorded by the GPS logger of one Kea are shown in Figure 4. From variation in patterns of movement, distinct bouts of flight (location 1 [L1] in the figure), walking (L2), and area-restricted behaviors suggestive of foraging or rest (L3) can be identified. Probable night-roost areas (L4, L5, and L6) can be inferred through consideration of the timing of prolonged periods of stasis. During 4 of the 6 days of the field trial, this Kea repeatedly visited a popular scenic lookout ('Death's Corner'; L7), mostly during the middle of the day, where it was observed begging for food from tourists and 'playing' with motor vehicles. From the GPS data it was possible to accurately quantify how long the bird remained at the site (~2 hr per day), where it regularly interacted with humans. One location (L8) was visited daily, perhaps because it was a favored foraging area, but more probably because the bird was provisioning a nest. Periods of stasis and active movement can be easily differentiated, and during day 6 there was a brief bout of flight over a distance of >1 km beginning well after midnight (L9), which is somewhat unusual for a Kea because the species is considered to be strongly diurnal (Diamond and Bond 1998).

DISCUSSION

We assessed whether GPS telemetry is a viable means of tracking the movement patterns of wild, free-ranging Kea. Three main results emerged from our field trials: (1) the retention rate of GPS loggers attached by backpack harnesses was sufficiently high (6–270 days) to justify confidence in obtaining acceptable results in future studies; (2) the datalogger housing was robust enough to endure water and bite damage such that operation was not impaired; and (3) the inexpensive and simple-to-construct loggers that we evaluated in our study performed similarly to comparable devices deployed on other animal species.

During the field trials, most of the Kea initially would chew on or attempt to remove the harnesses and loggers, but when later resighted the devices appeared to be well preened into the body feathers, reducing the likelihood of snagging on vegetation or other materials. Similarly to Le Soeuf et al. (2013), who investigated the effects of attachment methods of tracking devices on several species of captive Black Cockatoos (*Calyptorhynchus* spp.), we

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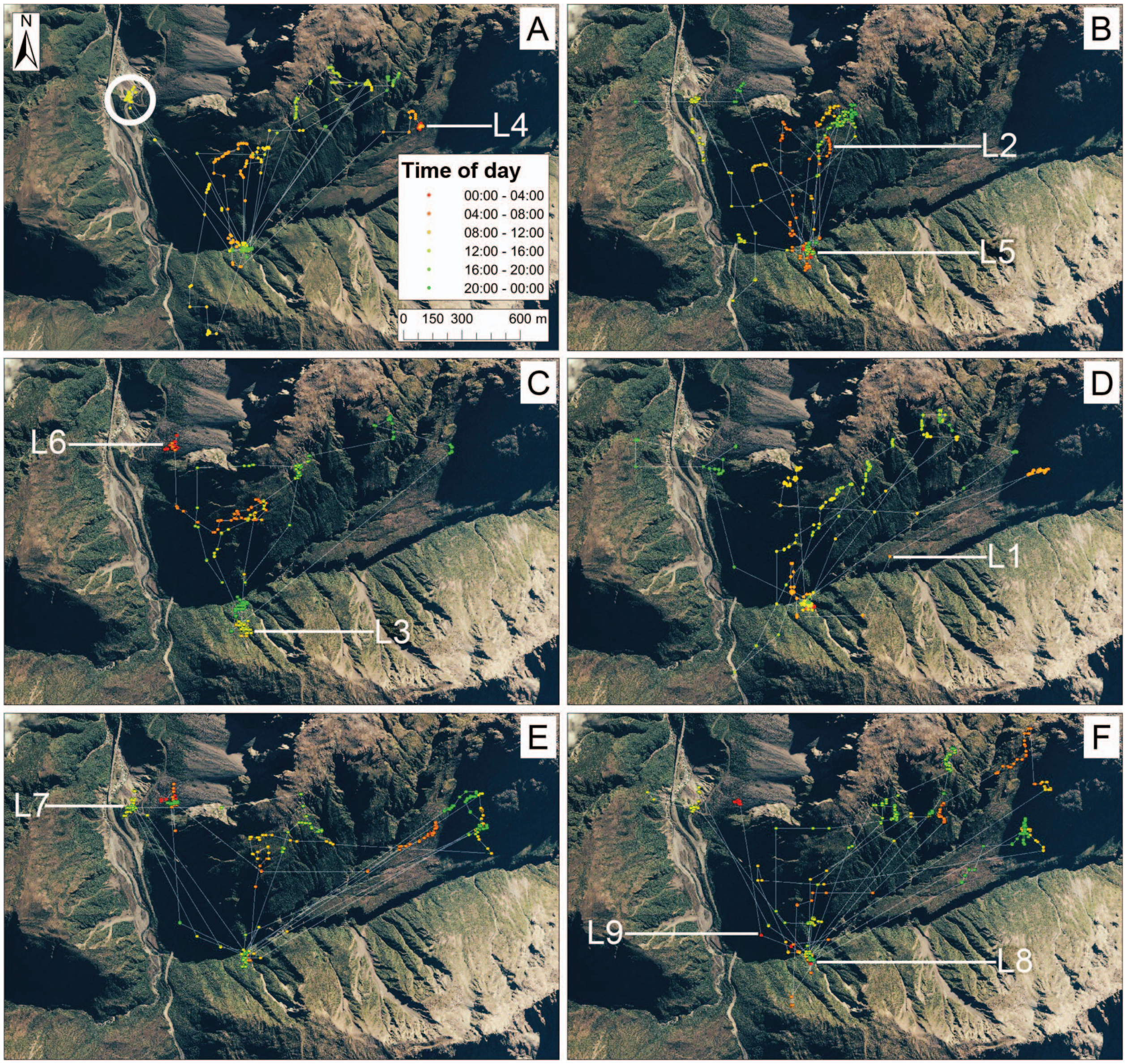

FIGURE 4. Consecutive daily GPS locations of an adult male Kea (*Nestor notabilis*) in Arthur's Pass National Park, New Zealand, November 28–December 3, 2012. The letters in the upper right-hand corners represent the sequence of days over which the data were collected (i.e. (**A**) = day 1, (**B**) = day 2, etc.). Colored points indicate individual location estimates differentiated by time of day (nominal sampling interval = 3 min) and light-gray lines link sequential observations. The white circle in (**A**) denotes the capture location. Numbered locations refer to comments in the main text.

observed no damage to skin or feathers where the tracking devices were fitted to the Kea. Finally, we noted no discernable differences in flight behavior during the field trials between tagged and untagged birds, which we attribute to the comparatively low proportional weight (1.9–2.6%) and cross-sectional area of the loggers (~3.2 cm^2, only around half of which protruded above the body feathers).

Two of the Kea removed their dataloggers during the field trials; in both cases this occurred within 1 hr of deployment, suggestive of a 'critical period' after which the probability of loss is reduced. Direct observations of these two study birds during the field trials and inspection of the discarded loggers indicated that both Kea had chewed through the weak links on the harnesses to remove the devices. Careful redesign of the weak links so that they are inaccessible to the birds and use of stronger materials may mitigate this problem. The external housing of the GPS units proved to be sufficiently durable to successfully dissipate the bite forces of the Kea, most likely because it

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was difficult for birds to tightly grasp the housing's rounded and smooth surface. Species-specific differences in bite strength should be contemplated when evaluating the potential of GPS telemetry for other psittaciforms, especially for large species. For such species, a number of other materials are available from which to construct external housings that may be suitable, including carbon fiber, epoxy–microballoon composites, and various vacuum-molded plastics.

The marked variation in FSR among the individual GPS loggers (ranging between 58% and 85%, excluding the one unit that malfunctioned) may have been due to a number of factors, including: the amount of 'available sky,' which depends on the composition and density of local vegetation and topography; and individual differences in patterns of activity and behavior, which can affect the orientation and, therefore, the reception probability of GPS antennae (Frair et al. 2010, Mattisson et al. 2010). Inspection of the movement trajectories of the study Kea in geographic information system (GIS) software revealed that large gaps in the time series of GPS locations occurred mostly at night, during assumed rest periods. Kea commonly roost in natural rock crevices, but also in hollow logs, tree cavities, and among the roots of trees (McCaskill 1954, Jackson 1963, Temple 1996). Acquisition of GPS position fixes in such places is often unsuccessful, as dense wood, earth, and rock occlude reception of satellite signals (Cain et al. 2005, Bourgoin et al. 2009). Nevertheless, the FSRs of the loggers in our study compare favorably with those of other field deployments of GPS receivers. Cain et al. (2005), who reviewed 35 published studies using GPS devices to track a variety of animal species, reported a mean FSR of 69%, marginally below the 74% observed in our study.

The operational performance of the GPS loggers that we evaluated compares well to that of other tracking technologies. The large volume (~2,500 fixes; 367 ± 55 per bird per day) of data collected during our field trials (at a cost of ~2 cents per fix, excluding labor) would be difficult to replicate with methods other than GPS telemetry. A review of 20 studies that used radio-telemetry to track 11 different parrot species showed that almost half employed radio-telemetry simply to relocate animals, primarily for quantification of mortality rates (e.g., Meyers et al. 1996, Collazo et al. 2003, White et al. 2005). These studies collected far less data per unit time than is possible with GPS telemetry, and also incurred higher logistical costs because of the increased need for involvement of field staff. For example, one radio-tracking study of Ground Parrots (*Pezoporus wallicus*) in Australia obtained only 28–70 fixes per bird over a period equivalent to our trial duration of ~7 days (McFarland 1991).

Although the dataloggers that we developed and evaluated in this study performed well, a number of technological innovations will greatly extend the applicability of GPS telemetry for the study of parrots. Among the most important developments is the ongoing reduction in the size of GPS receivers; 1-g devices are now commercially available, so species weighing as little as 30 g are large enough to be tracked. A second innovation is the increasing access to radio technologies that enable two-way communication with tracking units. Such technology permits the remote downloading of data, precluding the need to recapture tagged animals (Thomas et al. 2011), and allows researchers to define geographic areas within which alerts can be communicated via SMS text or email when study animals enter or exit ('geofencing'; Wall et al. 2014), as well as enabling remote reconfiguration of the sampling regimen of tracking devices. Advances in the efficiency of batteries and photovoltaic cells will greatly increase the operational lifetimes of tracking devices (Tarascon 2010, Jung et al. 2011). Remote drop-off harnesses, especially those operated by user command, will aid in the recovery of archival data and tracking devices from birds that may be difficult to recapture. Collectively, these technologies herald a new era in which GPS telemetry will be able to provide information about the movement and space-use patterns of free-ranging parrots (and other birds) that is critical for the establishment of effective conservation and management strategies.

ACKNOWLEDGMENTS

The authors would like to thank Meng Yang, Britney McKelvey, and Craig Simpkins for their invaluable help with field work. We also thank Megan Friesen, Jingjing Zhang, Chrissie Painting, and Hendrik Schultz for comments on earlier drafts.

Ethics statement. All animal capture and handling protocols were approved by the New Zealand Department of Conservation Animal Ethics Committee (AEC/11/2012/250 and AEC/11/2013/258).

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