*Notornis, 2025, Vol. 72: 97–105, https://doi.org/10.63172/410134zowhso*
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# GPS tracker trial on kea (*Nestor notabilis*) at Aoraki/Mount Cook National Park

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**Abstract:** Understanding the drivers for the seasonal movements of kea at landscape scales is critical to their conservation. Recent developments and increasing use of Global Positioning System (GPS) trackers prompted a small-scale trial on kea (*Nestor notabilis*) in Aoraki/Mount Cook National Park during October 2021 to February 2022. We attached a solar charged Druid Debut Lego™ tracker to four birds: two nesting females, a juvenile male and a recently fledged male. One tracker, with a raised solar panel, transmitted data by 3G cell phone network and the others sent data by 2G GSM cell phone network. The two trackers with raised solar panels collected and transmitted substantially more data than the flush-mounted solar panels. Location data was mapped, and elevation, distances travelled, 24-hour movement patterns and activity behaviour were analysed. The limitations of these GPS trackers are discussed, and recommendations are made for future use of GPS trackers on kea where topographic shading, power consumption, satellite reception, and data transmission are likely to remain significant challenges.

Greene, T.C.; Krouse, S.; Goodman, T.; Williams, E.M. 2025. GPS tracker trial on kea (*Nestor notabilis*) at Aoraki/Mount Cook National Park. *Notornis 72(2)*: 97–105, https://doi.org/10.63172/410134zowhso

**Keywords:** telemetry, cell networks, solar charging, mobility, home-range, behaviour

## INTRODUCTION

The conservation of mobile species, such as kea (*Nestor notabilis*) requires an understanding of their distribution and movement patterns throughout the year (Williams 2021). Their often remote, rugged and inaccessible location, coupled with large home range, low density and cryptic nature, makes estimating their population size difficult. Consequently, kea studies have tended to focus on short term behaviour and local movement patterns (Weston *et al*. 2023).

Local kea movement has been studied via VHF (very high frequency) radio telemetry (Kemp *et al*. 2022; van Klink & Crowell 2015), mark-resight of colour banded birds (Bond & Diamond 1992; Diamond & Bond 1999; Jarett & Wilson 1999) and Global Positioning System (GPS) trackers (Kennedy *et al*. 2015; Latham *et al*. 2015). Limitations of these methods include irregular and infrequent collection of location data (radio telemetry), dependence on often chance encounters (mark-resight), or requirement to recapture birds (GPS data loggers). All methods are constrained by data collection and transmission as determined by battery life. This is particularly problematic for kea that habitually frequent remote back-country areas, where observations of individuals and recaptures are difficult.

Recent developments of GPS trackers for wildlife have provided researchers with an opportunity to collect finer-scale data on bird movements over longer periods

*Received 25 January 2024; accepted 27 March 2025*
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of time (López-López 2016; Van Der Kolk *et al*. 2022; Iverson *et al*. 2023). GPS trackers can collect environmental, accelerometer, altitudinal, and location data and can be deployed with smaller batteries supported by solar panels. The type of data and frequency with which it is collected can be programmed by users before tag deployment and, if necessary, altered following deployment using appropriate data transmission networks. There are four main methods of GPS data transmission: 1) physical retrieval and download of archival tags (Kennedy *et al*. 2015); 2) remotely via proprietary receiver (often referred to as 'gateways', 'nodes' or 'hubs') (Mainwaring *et al*. 2002); 3) automated download via satellite (e.g. ARGOS, Iridium) (Yeap 2022); and 4) automated download via cell phone networks (Yeap 2022).

Determinants for the successful deployment of GPS trackers include topography, remoteness, climate, bird movement patterns and habitat use, bird behaviour, vegetation density, canopy cover, and the flexibility of the chosen method for data download. Kea pose a particular challenge as they frequently inhabit some of the most inhospitable terrain in New Zealand from which to collect movement data.

To test GPS tracker performance for kea, we carried

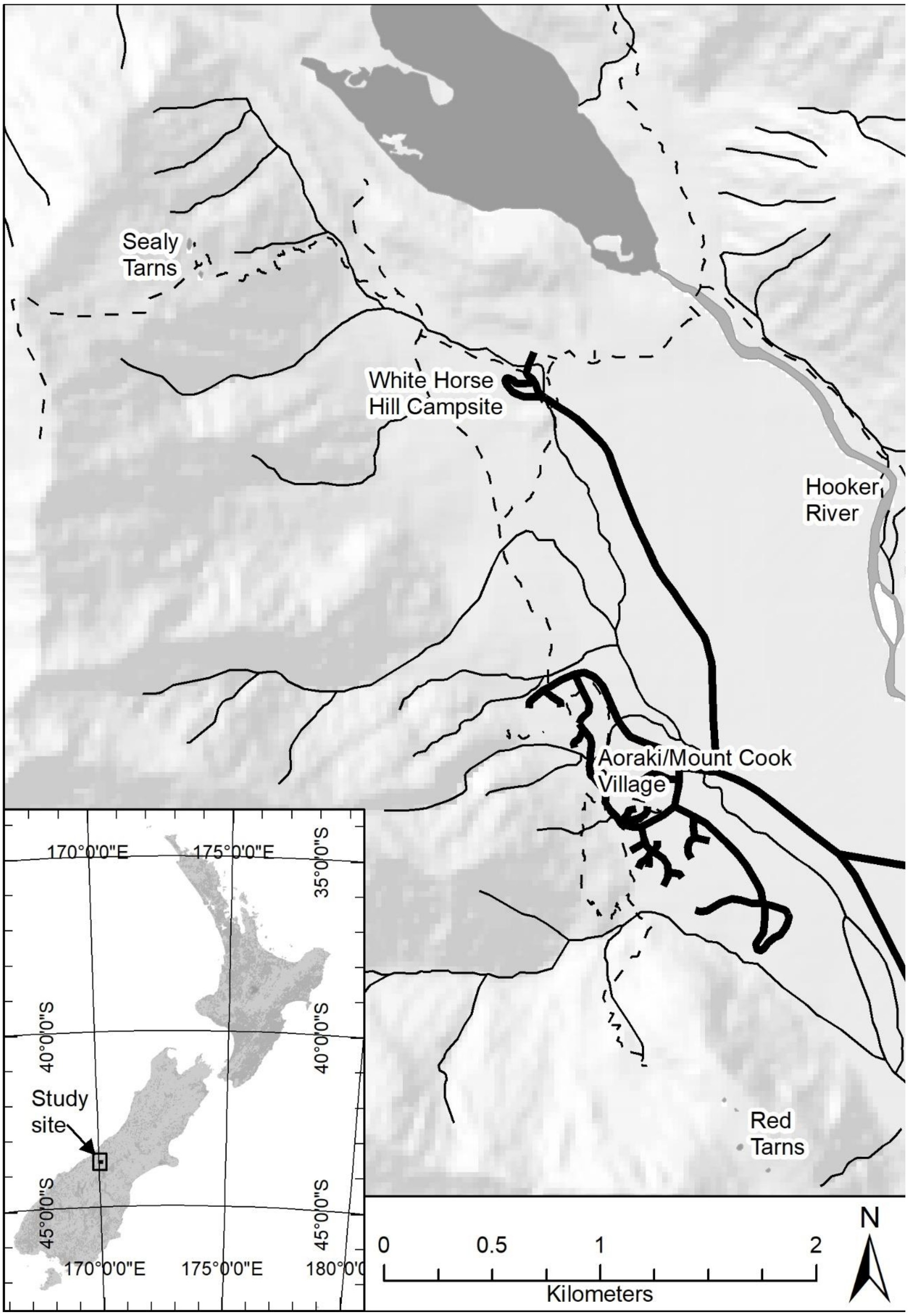


**Figure 1.** Location of study area and kea capture sites at Aoraki Mt Cook National Park

out a small-scale trial of Druid Debut Lego™ GPS trackers on four kea at Aoraki/Mount Cook National Park, in the Southern Alps of the South Island. As cell phone network coverage was greater to the east than to the west of the Southern Alps and kea were more readily accessible, we based our study within <5 km of Aoraki Mount Cook village. We assessed the performance of the GPS trackers on kea by examining the physical robustness of tags and comparing data collection and transmission of two solar panel configurations: one that sits flush and one that is elevated above the body of the device. Raising the panel was expected to increase tag performance by increasing the energy gain/power levels of the device. Results from this study will be used to inform future use of GPS trackers on kea (and other species of similar size) so that the accurate assessment of population trends, impact of management actions, and kea mobility can be better explored.

**Figure 2.** Images of Druid Debut Lego™ GPS trackers with a flush (left) and raised (right) solar panels on kea.

## METHODS

### Study site

Aoraki/Mount Cook National Park (42.93°S, 171.56°E) is in the Southern Alps, New Zealand (Fig. 1). The landscape is characterised by deeply incised glacial valleys, high alpine peaks, and steep scree slopes, ranging from 300 m to 1,720 m above 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 2022).

### Kea

Kea (*Nestor notabilis)* are large, olive-green parrots, with scarlet underwings (males 900-1100 g and females 700-900 g); they are endemic to New Zealand with a conservation status of Nationally Endangered (Robertson *et al.* 2021). Found throughout much of the South Island, kea are most common within montane forests, adjacent alpine zones, and the lowland forests of South Westland.

Four kea: two nesting females, a juvenile male, and a fledgling male were caught and fitted with Druid Debut Lego™ GPS trackers during October 2021 to February 2022 at Aoraki/Mount Cook National Park (Fig. 1). Work was undertaken as part of routine nest monitoring checks by the Department of Conservation. Birds were only handled by highly capable operators with extensive previous kea handling experience. All birds were captured, weighed, measured (bill length, tarsus, wing chord), banded, and tagged with GPS trackers immediately following capture. Birds were then given a quick health check before being released as quickly as possible.

### GPS tracker units

The Druid Debut Lego™ GPS trackers are lightweight (18.7 g, which is ~2% of kea bodyweight), have a working temperature range of between -20°C and ~60°C, a solar panel for maintaining charge, and are capable of storing 380,000 data records (460 days of regular use). The internal batteries have high capacity for their size (210 mAh) and are capable of recording 700 or more GPS fixes without any solar charge.

GPS trackers were attached using a standard 'backpack' type harness with an integrated linen weak link (Karl & Clout 1987). Trackers #5037 and #4944 had solar panels flush with the top of the main unit. Trackers #4789 and #5208 had solar panels elevated above the main body of the device (Fig. 2). These elevated units also had 6 solar cells compared to the 4 cells found on the flush mounted units and as such had a 50% increase in available solar charging area. Tracker #5208 was programmed to transmit and collect data using the 3G cellular network. The other three trackers (#4789, #4944, #5037) were programmed to use the 2G GSM cellular network, which had greater coverage (https://one.nz/network/coverage/) but lower data transmission rates (Table 1). Two of the trackers (#4789 and #5037) were deployed in late October 2021 on nesting adult female kea at Sealy Tarns and near White Horse Hill Campground. The other two trackers (#4944 and #5208) were deployed on a juvenile and a fledgling male at Red Tarns in February 2022.

All trackers were programmed to collect GPS locations at one-hour intervals. Trackers also had 'Inflight boost' mode enabled so that sampling increased to one fix per 20 seconds provided the bird was moving at a speed ≥5 m/s, and the tag's battery threshold was ≥3.92 V (Druid default settings). The tracker then returns to its normal sampling rate (of once per hour) if the voltage fell below 3.92 V or the speed became lower than 2 m/s. Three other default dynamic boost modes were also enabled which essentially increased data collection and transmission intervals as voltage dropped (steps at 4.1 V, 4.02 V, and 3.97 V). Trackers recorded Overall Dynamic Body Acceleration (ODBA), which is a measure of activity derived from triaxial accelerometers (Wilson *et al*. 2006). This information can be used to interpret activity levels and speed. Trackers were also programmed to search for the 2G and 3G GSM networks every 12 hours. If the trackers were successful (i.e. within range of the local network), any movement and tracker diagnostic data on the tracker were automatically uploaded to the Druid data servers and accessible to us via their website or mobile phone app. All environmental and

**Table 1.**

| Kea | Tracker ID | Date attached | Last record | Days operative | Number of fixes | Network | Solar panel |
|---|---|---|---|---|---|---|---|
| Nesting female | #4789 | 21 Oct 2021 | 19 Aug 2022 | 303 | 1731 | 2G | Raised |
| Nesting female | #5037 | 20 Oct 2021 | 24 Sep 2021 | 4 | 76 | 2G | Flush |
| Juvenile male | #4944 | 23 Feb 2022 | 02 Mar 2022 | 7 | 149 | 2G | Flush |
| Fledgling male | #5208 | 23 Feb 2022 | 23 Jun 2022 | 120 | 693 | 3G | Raised |

tag sensors embedded within the trackers were enabled (e.g. temperature, light, acceleration) and were a customisation of default Druid settings (i.e. ODBA collection rate was increased and data transmission interval decreased). Transmission of data stopped when battery voltage fell below 3.72 V, and collection of GPS and environmental/OBDA data ceased when battery voltage reached 3.67 V and 3.65 V respectively.

## RESULTS

### Collection and transmission of data from kea

All trackers collected and transmitted GPS location data; however, performance was erratic (Table 1). The total number of satellite fixes logged for each individual ranged from 76 to 1731. The flush-mounted solar panel trackers (#4944, #5037) only operated for 4 and 7 days, while the elevated solar panel trackers operated for 120 days (#5208) and 303 days (#4789) respectively.

There were insufficient data from the fledgling male kea (#5208) to determine any movement patterns. The low number of fixes for the juvenile male kea (#4944) only recorded short-term movement. The raised solar panel tracker #4789 on the 2G network collected and transmitted more than twice the number of locations than raised solar panel tracker #5208 on the 3G network over the same number of days. Tracker #4789 also reawakened itself to transmit data some 6 months after it was assumed to have failed on 17 Feb 2022. It continued to record for at least a further 2-3 months.

Outliers were only occasionally recorded. For example, although the kea carrying tag #5037 recorded a single location almost 9 km from its usual range within a 2-hour period, there was no evidence from the GPS data that this was an inaccurate result.

### #4789 Nesting adult female

This nesting female was caught on 21 Oct 2021 near White Horse Hill Campground (Fig. 3A). The raised solar panel recorded and transmitted data over the 2G network for 303 days. Most movements were concentrated within a relatively small area around her capture site at her nest on White Horse Hill and the track leading to Sealy Tarns (Fig. 3A). Her movements were bounded by the northern end of the Sealy Range south to Black Birch Stream, with a secondary area of activity on the slopes immediately east of the southern end of Mueller Lake. Her longest flights were 8 km south into the head of the Dobson River and a 5 km north-east to the west facing slopes above Hooker Lake. She also made visits to the White Horse Hill Campground and the back door of The Hermitage.

### #5037 Nesting adult female

This nesting female was caught on 20 Oct 2021 on the slopes below Sealy Tarns (Fig. 3B). The flush solar panel tracker #5037 only collected and transmitted data over the 2G network for 4 days. Most movements were near her nest site. Her movements were bounded by the very northern end of the Sealy Range. Her longest flight was 8.9 km north-west across the Southern Alps to the Sierra Range/Lucy Walker Pass region.

### #4944 Juvenile male

A juvenile male was caught on 23 Feb 2022 at Red Tarns (Fig. 3C). The flush mounted solar panel tracker connected to the 2G network but only operated for 7 days. Most of this bird's movements were to the north-facing slopes adjacent to the Red Tarns below Mount Sebastopol and near the head of Birch Hill Stream below Mt. Cran. Its longest flights were 5 km north to the end of the Sealy Range and 10 km south

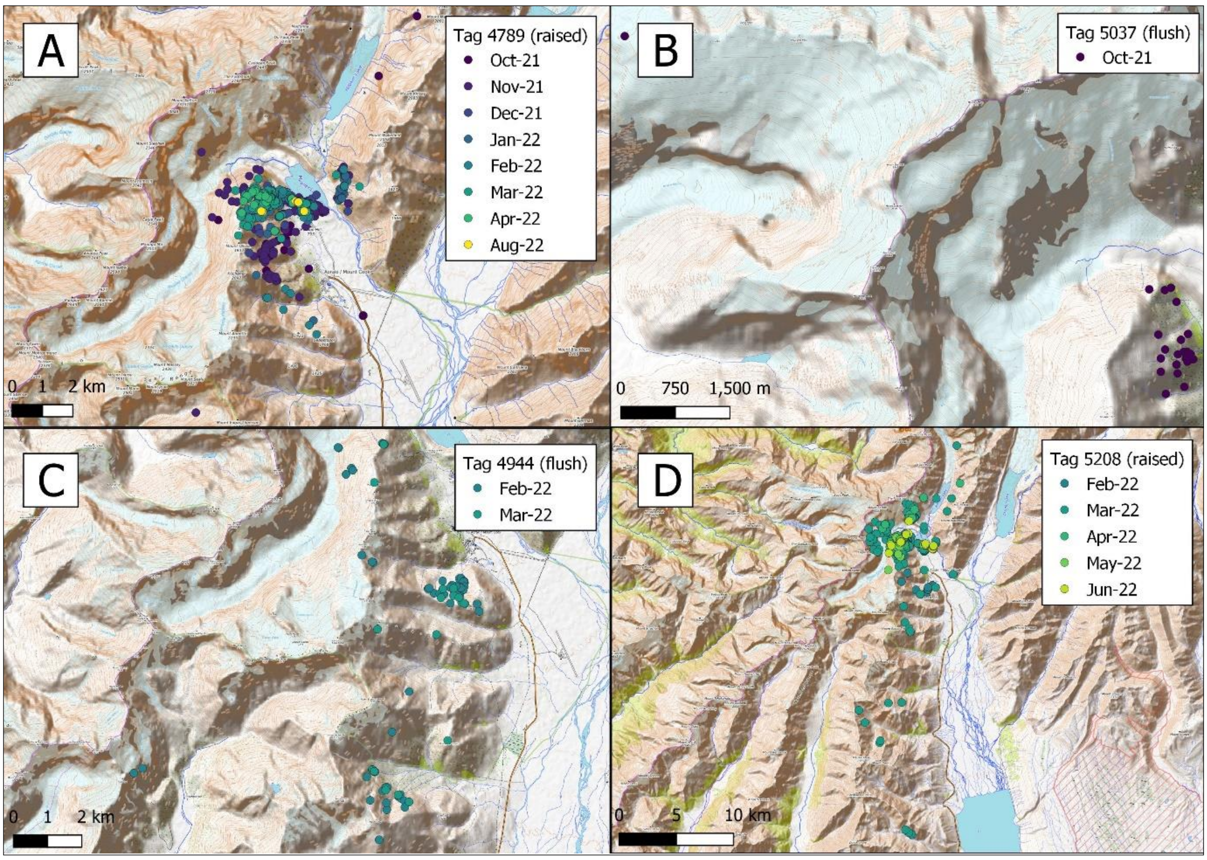


**Figure 3.** Location data for four kea tagged with GPS trackers (two with trackers that had raised solar panels and two with trackers that had flush solar panels). Kea were caught and tagged in Aoraki/Mount Cook National Park, Aotearoa/New Zealand, between October 2021 and February 2022.

**Table 2.**

| Kea | Tracker ID | Period | Min distance (m)* | Mean distance (m) | Max distance (m) |
|---|---|---|---|---|---|
| Nesting female | #4789 | Day | 53.25 | 5708.21 | 18236.4 |
| | #4789 | Night | 2.2 | 911.38 | 7455.76 |
| Nesting female | #5037 | Day | 158 | 5866.21 | 11767.04 |
| | #5037 | Night | 11.14 | 46.22 | 129.61 |
| Juvenile male | #4944 | Day | 2557.21 | 10121.41 | 16799.99 |
| | #4944 | Night | 77.74 | 2943.02 | 11399.52 |
| Fledgling male | #5208 | Day | 16.64 | 4729.68 | 28567.36 |
| | #5208 | Night | 0 | 1728.52 | 14414.58 |

*Tests by Druid suggest that >85% of GPS fixes obtained by their tags have a horizontal error within 5 m from the centre position indicated.

**Table 3.**

| Kea | Tracker ID | No. of fixes | Mean elevation above ground (m) | Max elevation above ground (m) | 100% MCP ($km^2$) |
|---|---|---|---|---|---|
| Nesting female | #4789 | 1415 | 6.7 | 1974.6 | 54.4 |
| Nesting female | #5037 | 76 | 0.6 | 41.2 | 5.9 |
| Juvenile male | #4944 | 149 | 6.6 | 199.3 | 67.0 |
| Fledgling male | #5208 | 693 | 4.6 | 680.7 | 179.4 |

to the Faith Col/Hourglass Glacier area in the Naumann Range, west of the Dobson River.

**#5208 Fledgling male**

A fledgling male from a nest in the vicinity of the Sealy Tarns was caught on 23 Feb 2022 at Red Tarns (Fig. 3D). The raised solar panel tracker transmitted data over the 3G cellular network for 3–4 months. Most of this bird's movements were near the Sefton Bivvy and above the Frind and Mueller Glaciers. His longest flights were 9 km north up the Hooker Glacier, and ~26 km south along the Sealy Range, as far as the south-facing slopes above Whale Stream.

**Movement patterns and nest activity**

All four kea frequently moved several kilometres and occasionally moved longer distances. The shortest mean distance travelled was 46 m at night (nesting female #5037) and the largest was 10 km during the day (juvenile male #4944) (Table 2). During a 24-hour period, ODBA measurements suggested that nesting female #4284 and fledgling male #5208 were active between 05:00 and 21:00 hrs. There were two periods of activity before and after a rest during the middle of the day. The nesting adult female was more active during the warmer month of February (06:00–21:00 hrs) compared to the cooler month of June (06:00–18:00 hrs). Between 21 and 24 Oct 2021, the nesting female #5037 seldom moved more than 1 km from her nest, apart from a short 7–8 km flight. Between 1 Nov 2021 and 7 Aug 2022, the second nesting female #4789 frequently moved about 2 km from her nest site, with occasional movements of 4–7.5 km. There were at least 6 distinct breaks in her data stream, perhaps when she spent a long time inactive in her nest. Between the end of November 2021 and the beginning of December 2021 she no longer returned to her nest site but remained within about 2 km of its location.

All kea tended to remain relatively close to the ground (Table 3). The maximum elevation reached by the adult female #4289 and fledgling male #5208 was 1,974 m and 680 m, respectively.

**Home range**

Naïve estimates of home range using 100% minimum convex polygons (MCP) suggest that range sizes are highly variable between individual birds and seemed somewhat independent of the number of locations recorded (Table 3). The nesting female #4789 had a home range of 5,440 ha, while the fledgling male #5208 had a home range about three times larger (17,940 ha), despite having fewer than half the number of fixes. The juvenile male #4944 had a home range of 6,700 ha. The nesting female #5037 had a very small home range, which was a function of the lack of data.

**Operational parameters of GPS trackers**

All kea trackers rapidly lost voltage (Fig. 4A) within the first fortnight. Adequate operational voltage levels were never reached by the flush mounted solar trackers, or were unable to be sustained at the 'boost' level (3.92 V) for raised solar panel trackers. Voltage gain and loss as well as transmitter failure was directly correlated with the low light intensities (Fig. 4B) recorded by the trackers.

A minimum of four satellites are needed to record an accurate spatial location, and the median number of satellites detected by the kea trackers was low (4–5), with the mean time required to fix a location being 62 seconds (Fig. 5A; 4). The average GPS time consumption (or 'search time') for failed tracker fixes for kea was 131 seconds and all kea trackers had a high number of fix failures (total across all four birds = 544; Fig. 5B). For the fixes that failed (i.e. their lat/long was 200), satellite search time was high, i.e. 84 took approximately 20 seconds before giving up, while the remaining 151 took approximately 151 seconds (Fig. 6).

## DISCUSSION

GPS tags present significant opportunities for improving both the frequency and spatial accuracy of location data for mobile species at considerably greater resolution than more traditional technologies. Despite the small sample in this pilot study, much useful data were collected, particularly concerning the operational limitations of the tags deployed

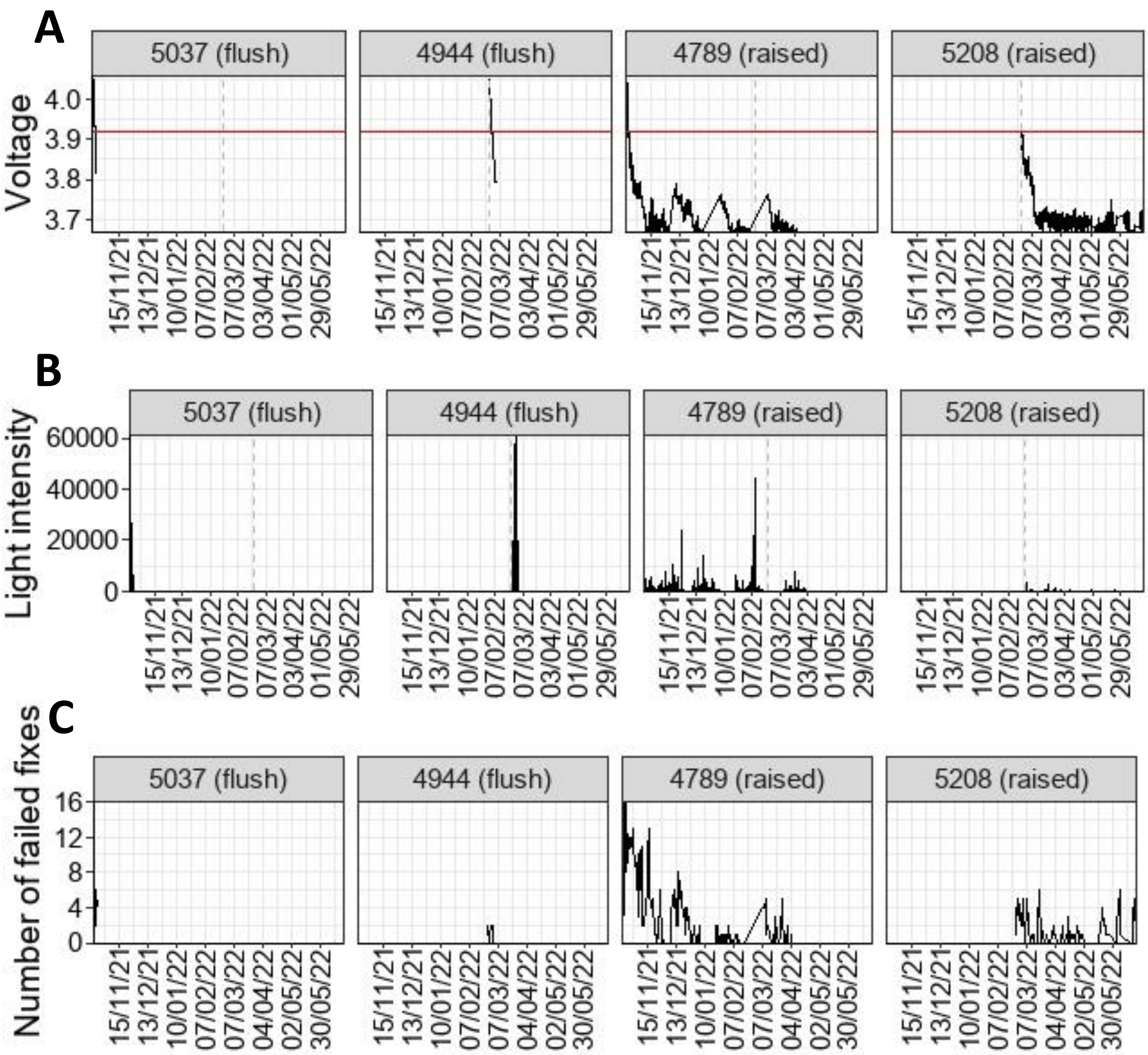


**Figure 4.** Performance of four Lego tags (two with raised solar panels and two with flush solar panels) deployed on four kea in Aoraki/Mount Cook National Park, Aotearoa/New Zealand, between October 2021 and February 2022. Graphs show: A) rapid declines in voltage (V) over time (s), with the red line showing the threshold the tags would need to exceed to trigger 'inflight boost' mode; B) rapid declines in light intensity (Lx) over time (s); and C) change in number of failed fixes over time (s).

in this mountainous environment and the rapid long-distance movements displayed by kea, which would be difficult to capture using other technologies.

All trackers collected and transmitted GPS location data. However, performance was impacted by low light intensity and difficulties receiving sufficient GPS signals when tall mountains were present, which frequently shaded the solar panels and blocked obtaining satellite fixes. This led to increased connection attempts, which in turn, resulted in battery voltages being run down prematurely.

The two trackers with raised (and larger) solar panels collected and transmitted substantially more data compared to the two trackers with flush-mounted solar panels, likely because the solar panels were covered less frequently by the surrounding feathers. Of the raised solar panel trackers, the one connected to the 2G GSM cellular network (#4789) transmitted substantially more data than the one connected to the 3G network (#5208). This may be because the coverage extended by a 2G tower is further (up to 10 km), compared with a 3G tower (that can only extend up to 3 km). The length of time (over 9 months) this tracker operated suggests that the tracker units themselves are robust to both kea interference and environmental extremes. In comparison, the two flush mounted solar panel trackers (#5037 and #4944) operated for less than a week. As tracker voltage levels declined rapidly immediately after they were deployed, we consider it likely that direct shading of the solar panels, either by preened feathers or time spent in deep shade (e.g. nests, topographic shading, or extended overcast skies) caused tracker failure; however, as we did not resight birds, this could not be confirmed. It is also likely that power failure was exacerbated by inadequate cell phone and GPS signal reception resulting in an increased duration of attempts to communicate with cellular networks or GPS satellites. There is also the possibility that both birds simply removed the trackers or that the embedded software or hardware failed.

GPS trackers can re-establish communication after considerable periods in low power hibernation, if their batteries recharge sufficiently, and they can provide some data from periods they were 'offline' (What are the working voltage thresholds for DEBUT devices? | Help Center; viewed 26 Feb 2025). For example, although fixes from

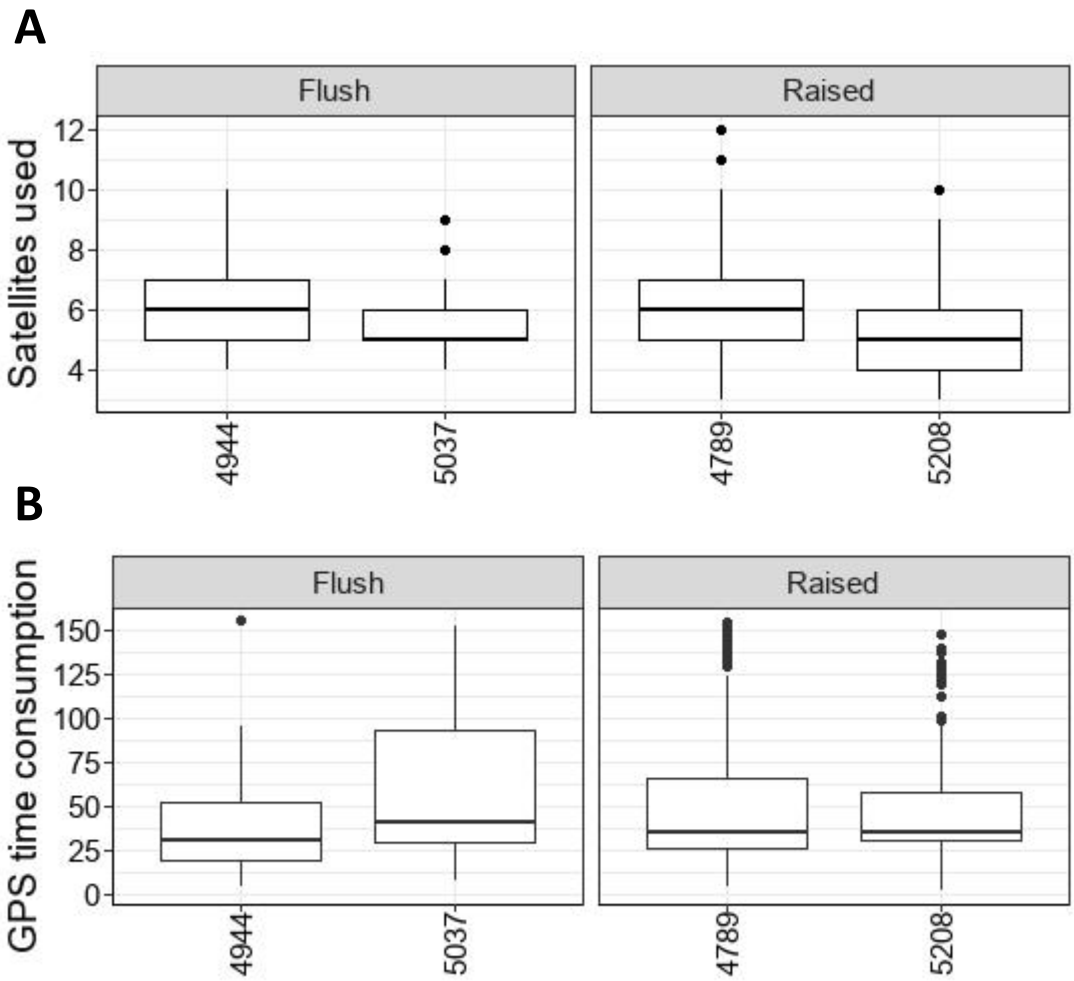


**Figure 5.** Box plots showing: A) the number of satellites used to achieve resultant fixes; and B) amount of time (s) it took to achieve the resultant fix. Data are from four Lego tags (two with flush solar panels and two with raised solar panels) deployed on four kea in Aoraki/Mount Cook National Park, Aotearoa/New Zealand, between October 2021 and February 2022.

GPS trackers on the Eurasian oystercatcher (*Haematopus ostralegus)* in the Netherlands revealed frequent large gaps in data during winter months, data were able to be recovered when tagged birds were located for 'manual' download or when trackers were retrieved from dead birds (Van Der Kolk *et al.* 2022). The kea wearing tracker #4789 did not transmit data for about 6 months, but once light intensity and voltage subsequently increased, it resumed operation for at least another 3 months. We therefore recommend that any attempt to recapture and remove trackers from live birds (e.g. for birds #4789 and #5208) be carried out at least a year after their last communication. Attempts should, however, be regularly made (monthly) to observe all tagged birds to confirm the tracker status (presence/absence) and/or condition of the trackers, as well as the bird's welfare.

The amount of power needed to achieve a GPS fix was significantly higher for kea than that for other species fitted with similar trackers being tracked by the authors (i.e. Australasian bittern *Botaurus poiciloptilus* and South Island pied oystercatcher *Haematopus finschi*; authors' unpubl. data). This is despite us using the same tracker type and settings on both kea and bittern. Fix failure rates (544 failed fixes) were high in our kea study, as was the GPS consumption time (i.e. 84.6% of failed fixes took the maximum amount of time to try to find a fix). Yet for the South Island pied oystercatcher data, where tag performance appeared to be better, only 11.2% of failed fixes took the maximum amount of time to try to find a fix (14 tags; 905 failed fixes, where 804 took approximately 20 seconds and 101 took approximately 151 seconds). For our bittern data, 100% of failed fixes took the maximum amount of time to try to find a fix (2 tags; 14 failed fixes, all 14 took approximately 154 seconds), but total fix failure rates were low (only 14 failed fixes in total), which was why tag batteries seemed better able to recover. This suggests that for kea it is the two factors (GPS consumption time and fix failure rate) that caused the higher power usage observed. The steep terrain inhabited by kea in the Southern Alps, likely exacerbated these factors by blocking a higher proportion of available satellite signals, compared to the open habitats where Australasian bittern and South Island pied oystercatchers were being tracked.

Other factors may have also contributed. Bittern trackers had a longer battery life but had an identical search time to kea trackers. Differences in tag performance may have been attributable to the markedly different environments they inhabit, as well as improved cell phone coverage and reception in Australasian bittern habitats, and differences in species' behaviour. In general, bitterns inhabit dense vegetation but are known to walk along reed bed edges as they forage for prey in the water. During these occasions, bitterns may prefer to forage with the sun on their backs as this casts a shadow across their line of sight, making it easier to see and catch their prey. Direct sun on the tracker would greatly extend the operational life of solar powered GPS trackers.

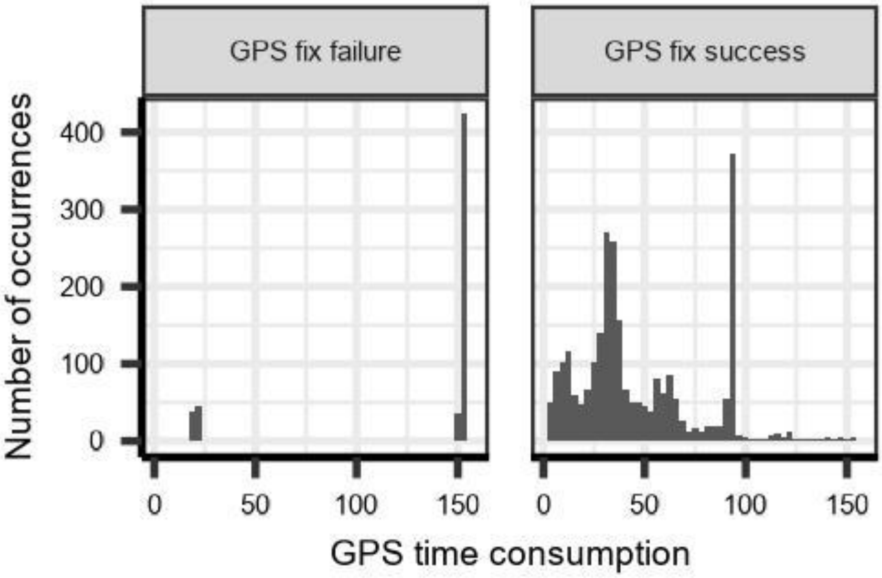


**Figure 6.** Graph showing the number of seconds a tracker took to look for a satellite in an attempt to gain a fix. Data are from four Lego tags (two with flush solar panels and two with raised solar panels) deployed on four kea in Aoraki/Mount Cook National Park, Aotearoa/New Zealand, between October 2021 to February 2022.

The power requirements and expense of GPS trackers are generally greater than that for VHF tags. This makes it essential that objectives for GPS tracker studies are well defined, that there is a clear understanding of the advantages and disadvantages of the technology, and rational expectations of the scale of likely data collection prior to deployment. Elevation of solar panels above the tag enclosure (within reason) to avoid obstruction by feathers seems to be a key requirement for deployment on kea. Although the use of solar panels to supplement power supply and therefore significantly extend tag life is seductive, in some cases it might be more useful to consider either, a) increasing the number of solar cells used on the panel (to increase solar charging capacity), or b) using a larger battery without solar panels to provide a more stable and continuous data collection and transmission platform (albeit over shorter time frames).

Deployment of GPS trackers (with or without solar panels) on wildlife in less-than-optimal environments is likely to remain problematic. Limited opportunities for solar charging such as changes in behaviour (e.g. females nesting in dark cavities for prolonged periods), environmental limitations (e.g. topographic shading and poor weather), difficulties receiving sufficient GPS satellite signals in all locations, and the subsequent transmission of data all need to be considered, especially if the rate of failures is likely to be high.

Selection of GPS tracker model and the choice of available settings before and during deployment also need to be carefully considered. The greater the frequency data are collected and transmitted, the greater the drain on the battery. If the number of satellite fixes are likely to be low and search time high, there will be a trade-off between the time taken to secure a fix, the frequency of fixes and the probable success of subsequent attempts. With hindsight, reducing the GPS and OBDA data collection rates (to 12 hours and 30 min respectively), neutralising the default dynamic boost modes (especially modes 2 and 3), and increasing the voltage threshold for dynamic boost mode 1 to >4.1 V would significantly increase both the data collection and transmission intervals and reduce power demands.

Less predictable is the power required to send data through cell phone networks, particularly when the networks are sparse, as many attempts may fail to connect. The facility to control 'connection' time and the use of alternative data transmission networks (e.g. Ultra High Frequency (UHF), Bluetooth, LoRA) should be investigated. Additionally, the use of the 'Boost' function that automatically increases data collection and transmission (depending on battery condition and movement state, i.e. 'dynamic sampling') to set the rate of fix collection may also contribute to slower battery recovery rates. As such, it is important to carefully consider the voltage thresholds for turning on settings that result in extra sampling, like the Boost feature.

Erratic data collection and transmission often makes describing and measuring a species' behaviours problematic. If behavioural (e.g., accelerometer) data is considered a sufficiently important objective in addition to the core work of logging location data, the algorithms that are available to carry out on-board tracker processing of trained behaviour classes should be enabled (i.e. Yu *et al*. 2022). Onboard algorithm use will significantly reduce the data transmission load and battery drain, thereby extending battery life. However, only certain tag types have such a capacity, and training the algorithms to recognise an individual's behaviours accurately requires considerable observational data, which can be problematic or impossible to obtain, particularly for cryptic, secretive, or remotely located species.

Further efforts to improve battery life and tracker capability may be a relatively simple matter of discarding solar recharging in favour of installing a larger battery. Optimal data download mechanisms other than cell phone networks such as 'local' UHF nodes/hubs and/or ARGOS enabled trackers, along with optimised software settings, would also reduce power demands. Depending on the location at which trackers are to be deployed, such changes are likely to markedly prolong the operational life of the GPS trackers and should be explored.

To date, most GPS tracker studies of small birds (<500 g) have been undertaken on shorebirds, songbirds, and raptors (e.g. Iverson *et al*. 2023), that typically occupy open habitats with little shade. Species that spend considerable time beneath vegetation canopies, particularly where there are significant topographic and technological barriers to signal propagation, will continue to be challenging. However, continued advances in GPS tracker technology data transmission such as LoRA and 'direct-to-cell' (DTC) cellular networks are likely to provide further opportunities for development and improvement.

With increased sample sizes and using trackers that are better optimised for power, GPS, and data transmission, significant further data capture and analysis could be undertaken, particularly in relation to home-range and network analysis for individuals and groups of kea. The combination of GPS and accelerometer, for example, provides the means to calculate and merge information on time budgets, foraging strategies and efficiency, resource use, and energy expenditure (Shamoun-Baranes *et al*. 2012).

Notwithstanding the issues raised above, despite the small number of kea tracked in this study, and the high cost of GPS trackers, valuable data were captured, particularly in relation to accurate 3D positioning and long-distance movements, which would be difficult to collect using other technologies.

## ACKNOWLEDGEMENTS

We thank Kerry Weston for assistance with attaching the GPS trackers on the kea, encouragement to publish, and comments on an earlier draft of the manuscript. We also thank Derek Brown for producing the map of the study location. The manuscript was greatly improved by comments by Brenda Greene and from two anonymous referees. This work was approved by the Department of Conservation's Animal Ethics Committee as meeting the criteria outlined in Section 5(3) of the Animal Welfare Act, 1999 (DOC-7867288).

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