Moore *et al. Animal Biotelemetry* (2023) 11:35
https://doi.org/10.1186/s40317-023-00347-w

Animal Biotelemetry

CASE REPORT **Open Access**

A case report assessing the utility of a low-cost tracking GPS device for monitoring terrestrial mammal movements

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Abstract

Background Accurate data on animal movements can highlight behavioural and ecological issues, such as territorial interactions, barriers to migration patterns, including compromised movement corridors, or avoidance of deteriorating habitats, and disease transmission, thus helping in conservation decision making. This study examines the utility of mOOvement global positioning system (GPS) tags, a low-cost cattle ear tag tracking device to monitor movements of terrestrial mammal populations in South Australia.

Results Stationary tags ($n = 40$) were used to test horizontal accuracy with a median location error of 33.26 m ($IQR = 16.9–59.4$), and maximum recorded error of 410 m. The locational accuracy was weakly influenced by the horizontal dilution of precision (HDOP), a measure of satellite availability and geometry, and overhead canopy cover. Numerous tags produced infrequent and inconsistent readings, median of 12 records per day ($IQR = 6–12$), correlating negatively with the tag's distance from the centrally located LoRa antenna; however, some tags recorded fewer than one position per day.

Conclusions We propose that the primary cause of mOOvement tag inadequacy is the use of only the GPS satellite constellation (USA, 1978), which does not provide adequate coverage in either satellite number or geometry in the sky at the − 35° latitude to calculate accurate positions regularly over 24 h, unlike the multiple constellations available in the global navigation satellite system (GNSS). We conclude that GPS tags are unsuitable for studies requiring high locational accuracy or identification of an individual's social interactions, where the GPS constellation has a limited number of satellites available during prolonged periods. They can, however, be used to provide estimates of home range size or track large scale daily movements of animals in more equatorially located regions.

Keywords Animal movements, GNSS, GPS, Satellite tracking, Home ranges, South Australia, Case report

Background

Identifying how individuals within populations use habitat can provide insight into their survival and fitness [1]. Movement patterns are indicative of foraging and social strategies [2], and many species maintain and defend a territory to secure resources [3]. Monitoring can also provide insights into interactions between individuals, including disease transmission opportunities [4, 5], dispersal patterns [6], interactions with urban or industrial expansion [7–9], and effects of climate change [10–13]. These landscape-level threats can indirectly impact population density in remnant habitat and predispose individuals to stress-related illness, and intraspecific territorial conflicts [14–17].

The selection of optimal tracking equipment for animal movement monitoring must be guided by body size

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and behaviour of the study animal, its preferred habitat and accessibility, and ultimately, the ecological research question [18]. Prior to the availability of satellite technology, animal movements were determined using radio tracking VHF collars, requiring a high level of personnel input to collect data locations using a receiver and radiotelemetry antenna [19–21]. VHF radiotelemetry location accuracy depends on researcher expertise, terrain, and triangulation calculations [22], Gilsdorf et al. [23] reporting mean location errors of the magnitude 128 m ($SD=91.3$ m, range 0–408 m). This technique also typically produced fewer animal locations, missing many of the fine spatiotemporal scale locations offered by the global position system (GPS)/global navigation satellite system (GNSS) units currently available [24, 25]. In the wider ecologist field, there is an assumption that 'GPS' tags are all equal; however, the use of the term GPS as an overarching descriptor for tags using satellite tracking technology has led to ubiquitous assumptions about the quality of data available from such tags [26]. In addition to the GPS constellation of 30 satellites, GNSS tags also use the 24 GLONASS (Globalnaya Navigazionnaya Sputnikovaya Sistema) satellites (Russia, 1993), Galileo's 26 satellites (European Commission, 2016), and the 45 BeiDou satellites (China, 2020). These additional satellites provide more geometrically optimal positions for location multilateration calculations, thus producing more frequent and accurate records than just GPS enabled tags [27, 28]. The 7 satellites of the Indian regional Navigation Satellite System (IRNSS) and Japan's Quazi-Zenith Satellite System (QZSS) add further location accuracy in their respective latitudes for GNSS capable technology.

This pilot study assesses the utility of GPS constellation only tags for the purpose of monitoring koalas' social interactions and home range areas in a native bushland environment in South Australia. The mOOvement tags (hereafter GPS tags) record locations which are transmitted from the tags via radio waves to a low power, long-range antenna (LoRa), and uploaded to an internet portal for analysis. Previous studies using GPS movement trackers on koalas have calculated horizontal errors in static tags of between 32 m in low level vegetation and 86 m in plantations [29, 30], and animal tracking data collected using these tags required filtering to remove likely spurious records of unlikely sequential movements in space or direction [31]. Several studies previously investigated the effects of varying quantities of overhead cover [32, 33], orientation of the tag [34], topography [35, 36], and the number of satellites visible [32] on fix success rate and horizontal accuracy of small GPS tags for animal monitoring. The inaccuracies and missing location fix data produced by such tags can compound errors in calculation of home range areas, overlook potential interactions, or exclude more subtle diurnal and seasonal changes in behaviours. Since koalas can live in high densities, more than 7 per hectare in South Australia's Tasmanian blue gum (*Eucalyptus globulus*) plantations (pers. obs.), and are sometimes found within the same tree, identifying potential close contacts and territory overlaps, requires regular, high frequency (30 min fixes) position records with at least 3–5 m accuracy. We investigated the frequency, a function of both the tag's ability to calculate a location from the available satellites, and its transmission from tag to antenna dependent on unobstructed line of sight. We also examined the quality of data collected by deploying fixed location test tags in different canopy cover classes and orientations around the study site, and at varying distances from the LoRa antenna. This will establish if the tags produce sufficiently frequent and regular positional records as animals move further from the centrally located LoRa antenna or into areas of higher density tree cover. We also assessed the GPS tags' accuracy to determine whether using them on animals with small total daily movements will provide information with adequate detail to monitor behavioural interactions.

Methods

Study site

The study was conducted between September 2021 and March 2022, on private land approximately 3 km west of Parndana on Kangaroo Island, South Australia (137.2233825°E, 35.7767122°S) (Fig. 1a). Daylight hours average between 10 and 14.5 h (winter–summer, respectively). The study area comprised 105 ha of eucalypt woodland and areas of scattered trees and paddocks on neighbouring farm property (Fig. 1b).

Stationary GPS tag testing protocol

MOOvement GPS tags (mOOvement, South Brisbane, Queensland, Aus, https://moovement.com.au), (Fig. 1c), have been used on koalas in Queensland by Richardson et al. [37]. These lightweight, solar-powered (30 g) tags, created as ear-tags for cattle tracking, are economical ($79), and transmit location data through a LoRa wireless area network antenna to an internet portal in almost real-time, allowing users to find individuals in the field quickly using a smartphone application interface. Solar panels on the tag power the transmission of locations to the LoRa antenna location, within a stated range of up to 10 km in flat, open terrain. Data provided by the mOOvement portal included a fix accuracy value, described as equivalent to the horizontal dilution of precision (HDOP) value quoted for GNSS units, although on a different numerical scale to the accepted standard range (Fix accuracy range 0–50) [38]. HDOP is a measure of the horizontal location accuracy using the satellites' geometrical locations [39].

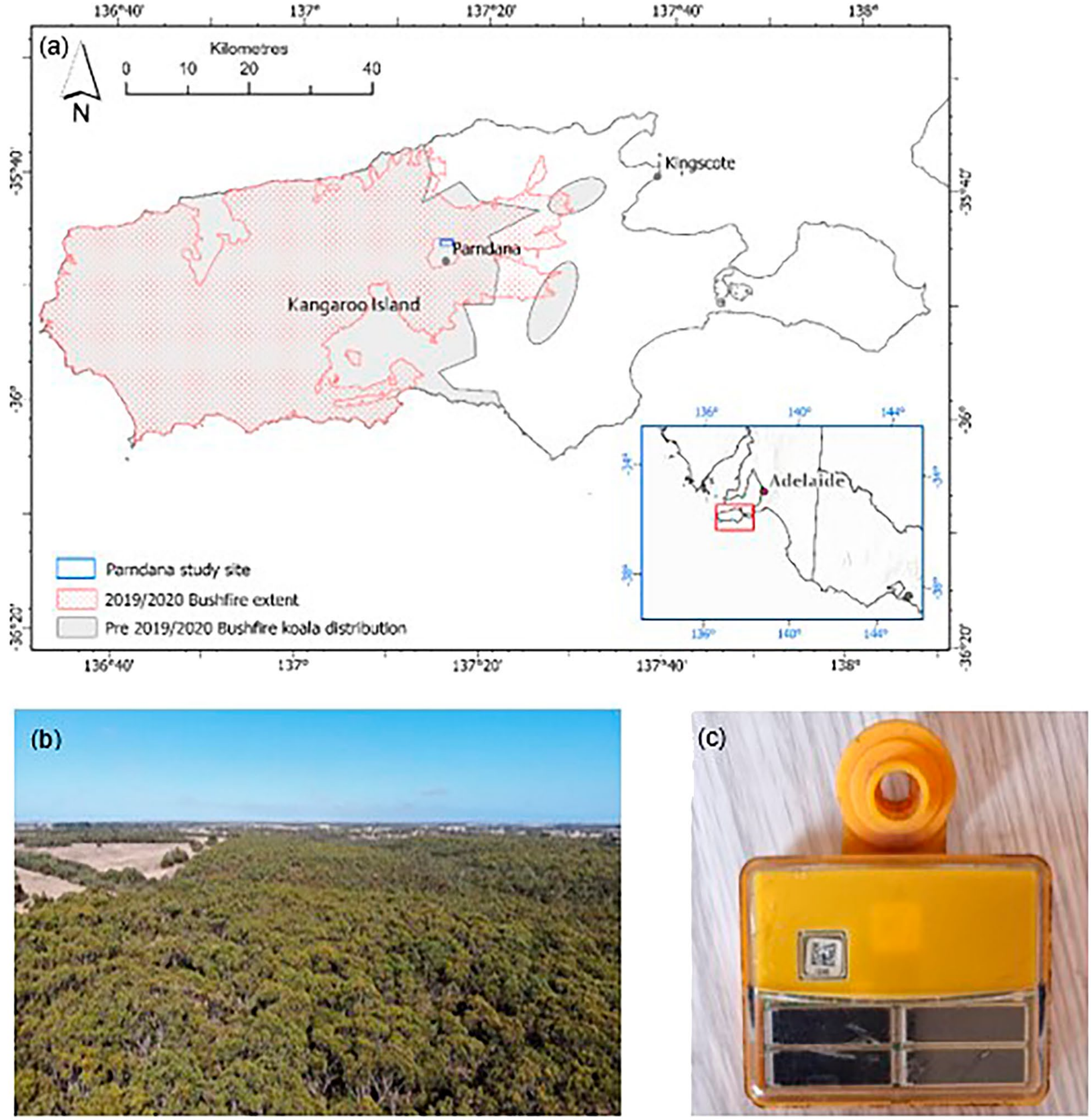

Fig. 1 **a** Location map of study site on Kangaroo Island South Australia, **b** drone image of vegetation cover looking west towards the LoRa antenna, **c** MOOvement tag (Claire Moore)

Large HDOPs (greater than 1) imply greater locational errors are likely; thus, this scaled value of estimated error is used to determine the reliability of a positional record.

Forty GPS tags were set out in pairs and fixed in place facing north, one in vertical and one in horizontal orientation at each location. Each test site position was recorded using a Trimble R10 Real Time Kinematic GNSS unit (horizontal accuracy 1 cm). Five replicates were deployed at four different categories of tag location: including open paddock, under a single tree, on the edge of woodland, and under woodland canopy. The stationary tags were set to record locations every 30 min to replicate data collection for the fine-scale movements of animals. Distance of tag from the LoRa antenna was varied to assess the potential influence of tag proximity on the number of location records and the horizontal accuracy of location.

Data, including latitude/longitude, battery level, and fix accuracy were downloaded as a csv file from the mOOvement portal for analysis. ArcGIS Pro vers. 2.9.2 [40] was used to calculate the distance of each tag from the LoRa antenna, and the horizontal error between the recorded location of the GPS tag and its true coordinate position. Trimble GNSS planning software [41] catalogued the number of GPS, and the total complement of GNSS satellites (GPS, GLONASS, Galileo, and BeiDou) constellations visible in the sky at the study site at the start of January 2022). The average number of GPS satellites visible per hour during January 2022 was 8.8 (IQR 6–11), whereas GNSS satellites averaged 44.8, (IQR 37–51). When calculating locations, a minimum of 4 satellites is required to produce a 3D location, incorporating latitude and longitude, but also elevation. To improve this accuracy, many GNSS units now calculate locations from different sets of visible satellites almost simultaneously and create an 'average' final reported record [42].

Statistical analysis

All statistical analyses were completed in R (version 4.2.1, [43]).

Number of records per tag

We modelled the number of records per tag per day using generalised linear mixed models with a Poisson distribution in *lme4* [44]. We tested for the effects of tag battery level, tag location, tag orientation, and distance of tag from antenna on the number of location records received. We fitted tag ID as a random effect to account for repeated measures. We started with a full model, including all main effects and an interaction term between tag location and tag orientation. Effects were tested by likelihood ratio tests of nested models, where each term was sequentially dropped from the model and tested against a model with the focal term included. The fixed effect coefficient estimates from the final model values were inverse log-transformed to obtain actual count effects in the final model.

Horizontal accuracy

We used linear mixed effect models to test for the effects of tag location and reported fix accuracy on the observed horizontal error using the package *nlme* [45]. We log-transformed horizontal error to account for the effects of a strongly right-skewed distribution on model fit. We also found that fitting fix accuracy as a predictor variable generated heteroscedasticity in the residuals, which we accounted for by fitting an exponential weights function. Once we had an appropriate model specification, we proceeded to test each fixed effect by comparing nested models via likelihood ratio tests.

Simulating lower-bounds for home range estimates using mOOvement tags

Satellite tags are often used to estimate the size (area) of home ranges of animals. We expected that there would be some degree of horizontal error in the location records of the mOOvement tags and as a consequence, there would be some lower-bound for the home range of animals that can be estimated using this particular technology. In other words, the mOOvement tag system will only be useful for estimating the home ranges of animals that have a home range area larger than some minimum size beyond the measurement error of the tags. Our aim was to determine what the minimum size of home range to statistically differentiate from the 'home range' that was a result of measurement error of the mOOvement tags. We took a simulation approach to estimating the threshold of detectable home range size. First, we estimated the 95% 'home range' of stationary test tags using AdeHabitatHR [46]. We used the default bivariate normal fixed kernel, and the reference bandwidth, *href,* as the smoothing parameter for each tag [47].

We then used simulations to estimate the threshold size of home ranges that can be distinguished from home ranges generated purely by measurement error. We considered the home ranges of the stationary test tags to be the null distribution against which to compare a set of simulated home ranges of varying mean and standard deviation. The null home range distribution had an estimated mean of 3.77 ha and standard deviation of 1.55 ha. We generated a set of 1000 simulated home ranges (area, in hectares) by sampling from a random normal distribution with a mean varied between 3.67 and 4.77 and a standard deviation of 1.55 (equal with null model, as estimated from the stationary tags). We then ran a series of t tests for differences between a mean of a sample of simulated home ranges and the mean of the null distribution of home ranges. We ran the simulation twice using arbitrary sample sizes of $n=10$ and $n=50$, respectively, which is on a similar scale of sample size for animal biotelemetric studies. For each iteration, we calculated a t statistic for a test of the difference between the means of the simulated and null distributions. The outcome was a data set of pair values of mean home range and t. We then fitted to these data to a linear regression of t as a function of home range means and plotted the predicted equation, which allowed us to identify the value of X (i.e., home range area), where the regression line transected the critical t value (~ 1.68 for a one-side t test with degrees of freedom between 30 and 120).

Results

We found that both the number of records collected, and the horizontal errors of the locations recorded, were both important determinants of tag quality and viability for our research purposes.

1.1. Number of records per tag

Thirty percent of the tags did not record a reading on each of the 183 days of the trial, with 5 tags recording zero locations and an additional 3 tags recording on fewer than 25% of the days deployed. Individual tag performance, i.e., number of records per day/expected records of 12 per day, ranged from 0% to 97%, with 48% of the 40 tags averaging at least 10 records per day. Of the 5 tags that recorded no readings, 4 were in pairs, 1.21 and 1.3 km from the antenna, respectively, with an elevation of 143, and 9 m lower than the antenna height.

The tags closest to the LoRa antenna consistently collected the most location records, with a median count per day of 12, and an interquartile range of 9–12. The most influential fixed effect was distance of the tag from the antenna (Fig. 2). Residuals were slightly under-dispersed (ratio 0.665) for this model. The model fixed effect intercept, after log transformation, was 12.9 records; the predicted number of records that tags beside the antenna would collect per day. More distant tags collected 60% fewer records with each kilometer away from the LoRa antenna. Tags furthest away, approximately 2.6 km, recorded only 27% of the number of locations of tags placed within 100 m of the antenna (Fig. 2).

Battery level, site class and orientation had no significant influence on the number of records sent by the stationary tags. The random effect variance was 1.2 suggesting that there was some difference in individual tag performance, but it was weakly related to distance from the LoRa antenna.

2.2. Horizontal errors

Fix accuracy values, analogous to the more commonly used HDOP parameter, should positively correlate with the margin of measured horizontal error for each tag; however, only a very weak positive relationship was found, Fig. 3.

The distribution of fix accuracy values showed a left skew (median 42, IQR 31–47), associated with a high degree of estimated error from the satellite geometry used to calculate the tags' location.

Horizontal errors for the test tags had a right skew (median 33.3 m, IQR 17–59.4), with a maximum error of 409.7 measured, requiring a log transformation prior to the linear mixed modelling.

The final model showed a significant but weak positive correlation ($\chi^2 = 3988.1$, df = 1, $P < 0.0001$) between measured horizontal error and fix accuracy. On average for every unit increase in fix accuracy, there was an increase in 1.12 m horizontal error produced ($se = 1.02$, $t = 54.1$, $P < 0.0001$); however, with R^2 of 0.07, this relationship is unlikely to be useful in a predictive model. The correlation with site class was weakly positive ($se = 1.00$, $t = 1.85$, $P < 0.07$), with tags in edge locations having

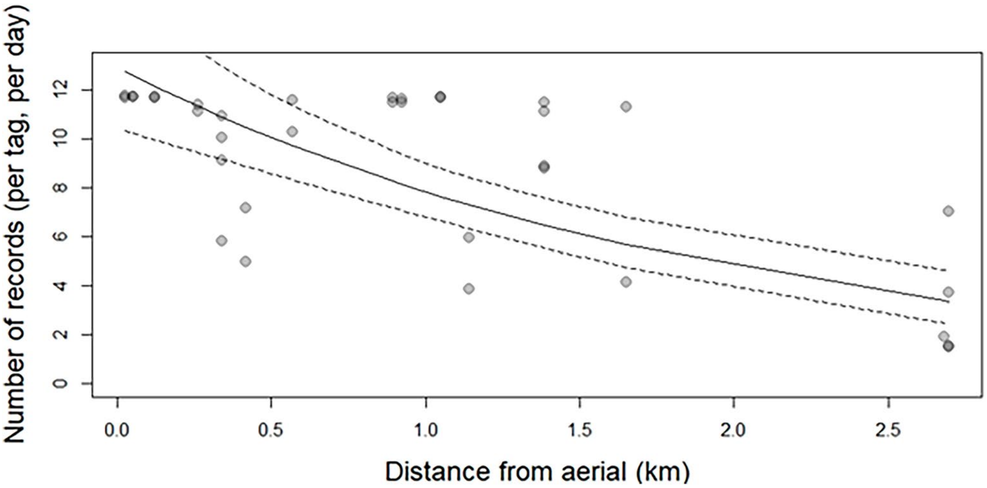

Fig. 2 Generalised linear mixed effects model demonstrating a negative relationship between the distance of the stationary tag from the LoRa antenna site and number of records per tag per day, with 95% confidence intervals as dashed lines. Points at the same distance along the x axis were paired tags of horizontal and vertical orientation, but orientation had no significant effect on the number of records received

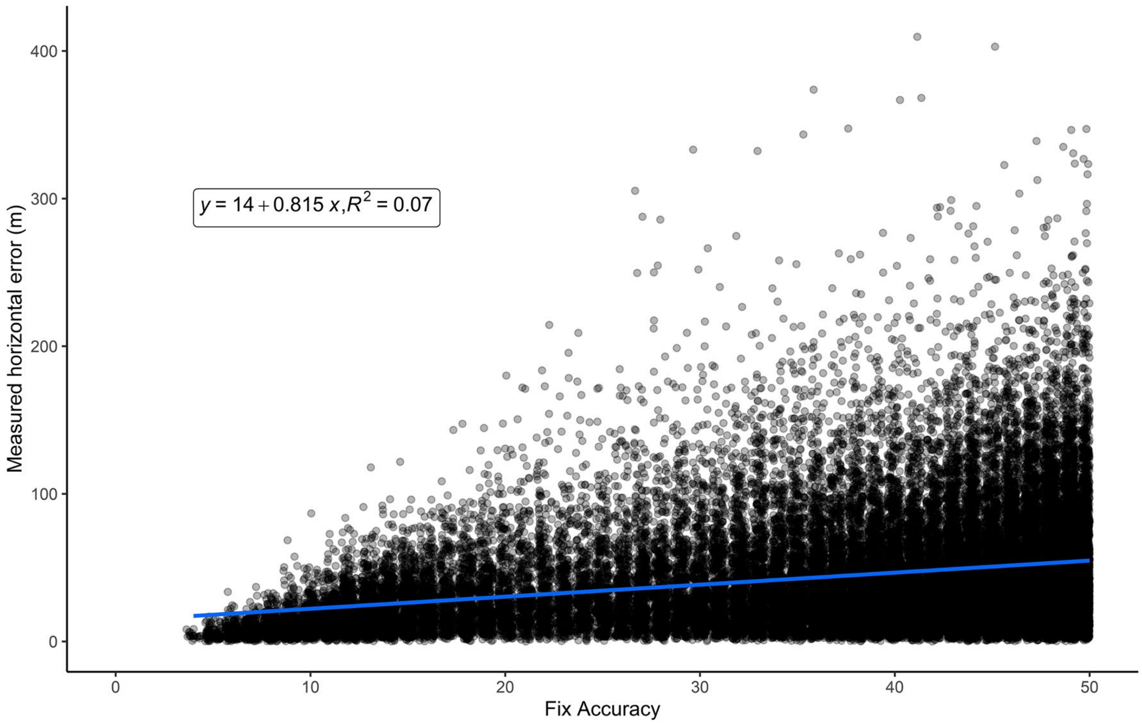

Fig. 3 Scatterplot showing weak correlation between fix accuracy (equivalent to estimated degree of horizontal accuracy for the location record from the number of satellites available and their geometry) and the actual measured horizontal error for each reading

an increase in horizontal error of an additional 1 m over those in the open sky locations for every unit increase in fix-accuracy, but overall the effect on error between site classes was insignificant.

Satellite visibility and horizontal dilution of precision values

The mean HDOP values for the GPS-only satellite constellation was higher than that obtained for GNSS constellations visible during a sample time period at the study location ($t = 22.21$, df $= 7$, $P < 0.05$), meaning that location accuracy is greater when utilising the more than 30 additional satellites available across the GNSS constellation.

Home ranges of stationary tags and simulated home ranges

The home range areas of the stationary tags had a right skewed distribution with a median 95% home range of 3.61 ha, $sd = 1.55$ ha.

The simulation analysis, Fig. 4, revealed that for larger sample sizes of tagged animals ($n = 50$), home range areas under 4.29 ha would likely indicate over-estimated actual home ranges using the GPS tags ($t = 1.68$, df $= 30$). With a smaller sample size of 10 subjects, the minimum calculated area which would provide credible analysis would be 4.62 ha.

Discussion

The stationary test tag analysis established that the GPS only mOOvement tags were unable to achieve the locational accuracy and record frequency required for the investigation of individual relatively low mobility animals' daily movements and social encounters at this location. The number of tag locations recorded is negatively correlated with distance of the tag to the LoRa antenna, implying that the signal strength of transmitted records from the tag to the antenna attenuates with distance sufficiently to prevent a location being received. The LoRa network's reception of transmitted tag locations was adversely impacted by interference from local power lines transecting the site, and physical obstructions in the line of sight, such as trees and topographic elevation differences between the test tags and the antenna. Variability within stationary tag pairs suggested that distance from the antenna alone was not responsible for tag record numbers but was likely the result of difference in reliability of the individual tags, since tag battery level and orientation did not affect record number. Since the number of satellites available to the tags was also highly variable at this site, occasions when the visible satellite

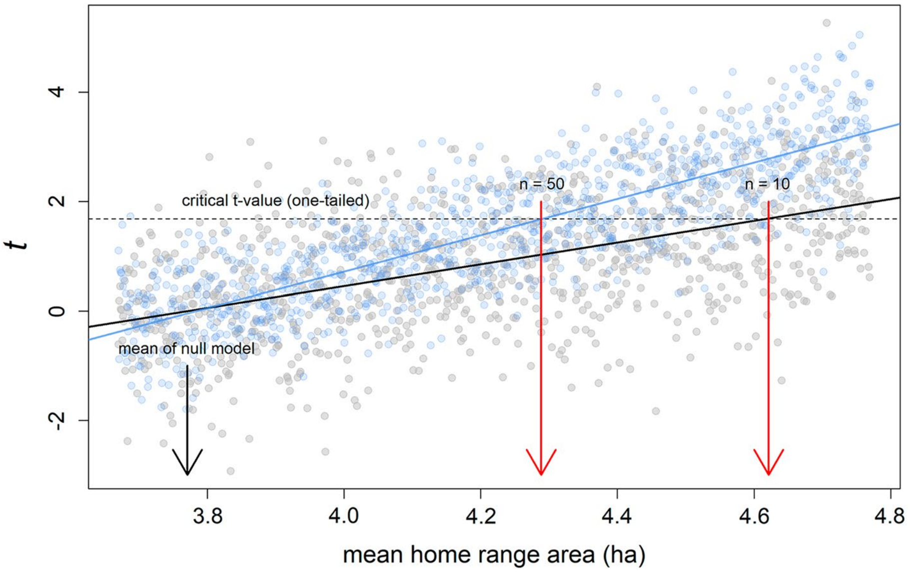

Fig. 4 Output of simulations used to determine the home ranges sizes that can be statistically distinguished from the null home range of stationary GPS tags. The plotted data represent the results of a series of *t* tests of differences between the means of simulated home ranges and the mean of the null distribution of home ranges. The null distribution had an estimated mean of 3.77 ha and standard of 1.555 ha. We generated a set of 1000 simulated home ranges by drawing a random sample from a normal distribution with the mean varied from 3.67 to 4.77 and a standard deviation of 1.555 (equal with null model, as estimated from the stationary tags). We ran the simulation twice using realistic sample sizes ($n = 10$ and $n = 50$, shown in grey and blue dots, respectively) for ecological studies of animal movement. Solid lines show linear regression of t as a function of home range means (black line for $n = 10$ and blue line for $n = 50$). The red arrows indicate the home range area at the point, where predicted mean t transects the critical *t* value (~ 1.68 for a one-side *t* test with degrees of freedom between 30 and 120)

number was below the threshold required to calculate a location when the tag was active may have coincided, resulting in a missed record for that time. The irregularity of daily recorded locations results in gaps in movement data if deployed on animals in uneven terrain or dense vegetation cover. The addition of more LoRa antennas in a network around the study site would help mitigate these issues but greatly increase costs.

In terms of horizontal accuracy, the average error was 41.2 m, (median 33.3 m), which may be too high to make the tags suitable to monitor species with small daily movements. For example, in certain locations, where habitat resources are plentiful, high population densities can occur with koalas only showing movement between 3 and 4 trees for months at a time. A home range encompassing 4 trees within a 60 m radius could appear to be up to 100 m or more in radius if using mOOvement tags and show considerable overlap with surrounding koalas in similarly falsely calculated home ranges. Inferences on how this population co-existed and moved around each other would produce erroneous insights on their mating and territorial actions.

Fix accuracy values correlated weakly with the measured horizontal error, likely due to the underlying algorithm used by the mOOvement tag software, since HDOP is calculated using well-recognised and calibrated equations [39]. Surprisingly, the site class, representing increasing canopy coverage over the tag, had a weak negative influence on accuracy, suggesting that these tags can provide equally useful data for both arboreal or native bush woodland inhabitants and animals living in clear sky open paddocks, despite the signal attenuating effects expected in woodland areas [49]. This may be because the canopy cover of the woodland at the study site was irregular in both height and leaf cover due to over-browsing by the resident koalas and drought weather conditions causing leaf fall [50].

The study provides evidence that the mOOvement GPS tags failed to produce sufficiently accurate locations for tracking animals. Despite placing tags in pairs facing northwards, and replicating height and orientation, the topography of the study area and the vegetation land cover caused inherent variation between tags at each location. In addition, overhead canopy cover was difficult to completely duplicate between sites, and since koalas tend to spend a proportion of their time high within a tree canopy, the tag's position at only 1.5 m above ground level does not reflect the true function if used on free ranging koalas. These factors thus have adversely influenced line of sight to the central LoRa antenna, and visible horizon for the stationary tags. However, koalas would not always be in the 'perfect' position, nor at the optimal time to produce the most advantageous GPS location, and thus this method was considered the best compromise to assess the GPS tags' accuracy in the variety of conditions.

For research into the territorial interactions between individuals, the large home ranges calculated for the stationary test tags (mean 3.77 ha) exceeded the estimated home ranges of several small marsupial species previously studied [16, 51]. This implies that for animals with small daily movements, less than 80 m (diameter of a stationary tag home range), and a territory less than 6.88 ha, the tags would be unable to provide any accurate information regarding activities, or exact location should the animals require observation or recapturing. For those animals with larger territories, the degree of error may be outweighed by knowledge of the larger scale movements measurable, and, as suggested by both Acácio et al. [48] and Lonergan et al. [52], an increased frequency of location fix would greatly improve the accuracy and precision of the movement record. This would also improve home range calculations by including data of the irregular forays of animals outside their normal core areas [53]. Unfortunately, while this has obvious benefits for animal tracking accuracy, it would require a greater power supply to transmit the larger number of records calculated; a potential problem for solar-powered tags fitted to arboreal or den-living, nocturnal species.

Despite our models' findings, probably the most influential factor on the GPS tags' record frequency and accuracy, is the use of the GPS satellite constellation, since GNSS tags currently deployed in the nearby study site produce mean horizontal errors of 5.53 m (*s.e.* = 0.1) (data available on request, Moore, 2023) [27, 32, 36]. For the GPS tags, the number of satellites recommended to calculate an "accurate" location at the study site are available for an average of only 15.5 h per day,, [54, 55], whereas GNSS tags have between 37 and 53 satellites visible within the horizon at any time during the day, guaranteeing more locational records opportunities. This increased number also ensures that multilateration calculations and averaging of locations using multiple different groups of visible satellites, each with different geometry, improve both accuracy and precision of the computed position [35, 39, 54].

This study highlights the limitations of the most basic GPS tag technology. The infrequency and irregularity of location records received by the LoRa antenna, and their calculated large horizontal error range, make the detailed analysis of animal movements and contacts impossible. In terms of their applicability to wildlife tracking, post-processing filtering algorithms which remove obvious erroneous locations based on movement rate or sudden changes in direction from an otherwise obvious trail, could make these tags suitable for animals with larger hourly movements, such as ungulates or carnivores. However, the frequency of data collection, and requirement for additional LoRa antennas for these more actively ranging species could quickly surpass some of the original cost-saving gains. When using satellite tracking tags for wildlife research, the expense of the associated technology is often an overarching factor in brand choice. For scientists without knowledge of the realistic achievable accuracy of the units on offer, selection is based on either the company's reputation or others' recommendation, not necessarily what unit will provide the location accuracy they require. The additional cost associated with creating GNSS capable chipsets, and their associated increased battery power needs, may result in poor choices and unreliable data. Thus, despite the relatively low-cost, solar power, and remote data uploads, the value of these tags for many scientific purposes is low. The inclusion of improved satellite positioning technology or GNSS satellite constellations when retrieving locational data would be needed to obtain accurate results.

When selecting tracking tags for animal movement monitoring, researchers should ensure that their choice is suitable for the detail and scale required for their study. Many commercial tracking tags are still identified as GPS, when in fact they may utilise the GNSS network constellations which provide adequate coverage, both number and distribution across the horizon, over the study area, and, thus, provide the higher level of accuracy. A discussion with the tracker technology company prior to investment is essential to ensure that the purchased equipment will fulfill the demands of the research question.

Abbreviations

ACT	Australian capital territory
Df	Degrees of freedom
GNSS	Global navigation satellite system
GPS	Global positioning system
HDOP	Horizontal dilution of precision
IQR	Inter quartile range
KoRV	Koala retrovirus
LoRa	Low power long range

Acknowledgements

The authors would like to acknowledge the Kangaroo Island Wildlife Park for the use of their premises and conservation area, where this research was carried out. The team of Honours students; Connor Mulligan, Eden Worthey and Jess Lynch, and Flinders associates Mike Doane and Bronte Hodgson provided assistance in finding and capturing the koala subjects.

Author contributions

CM, JB, MB and KBdS conceived the ideas and designed methodology; CM, JB and MB collected the data; CM, JB and MB analysed the data; CM led the writing of the manuscript. CM and KBdS acquired funding resources, all authors contributed critically to the drafts and gave final approval for publicatio*n*.

Funding
Funding was provided by the Holsworth Wildlife Research Endowment, The Field Naturalists Society of South Australia, the Nature Foundation, and the Kangaroo Island Koala Rescue Centre.

Availability of data and materials
The data set supporting the conclusions of this article is available on request to the corresponding author.

Declarations

Ethics approval and consent to participate
All work with the koalas was carried out under the animal ethics approval was provided by the Flinders University Animal Welfare Committee, AEC_BIOL4222, and the Scientific Research permit from the Department for Environment and Water (U27069).

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no financial or non-financial competing interests.

Received: 17 April 2023 Accepted: 12 September 2023

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