

Evaluation of Solar-Powered GPS Ear Tags and Long-Range Data Transmission for Use in Wildlife Research: Case Study of Collared Peccary (*Pecari tajacu*)

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Abstract

Background

Global Positioning System (GPS) technology has become a widely adopted tool in wildlife monitoring and research. Spatial location data can provide unique insights into animal behavior, resource selection, movement patterns, and species interactions. However, GPS data are often flawed by data loss (missing fixes due to failed GPS attempts) and horizontal error (discrepancy between recorded and true locations), which, if not accounted for, can lead to biased estimates of space use, movement, and resource selection. We evaluated solar-powered GPS ear tags (mOOvement, Brisbane, Queensland, Australia) that transmit location data using a Long Range Wide Area Network (LoRaWAN) during stationary tests at two sites in southern Texas and during deployment on collared peccaries (*Pecari tajacu*).

Results

Overall fix success during stationary testing was 58.2% at La Copita Demonstration Area and Research Ranch and 51.2% at Chaparral Wildlife Management Area (CWMA). At La Copita, fix success decreased as woody cover and distance from the LoRaWAN antenna increased in combination, whereas neither covariate influenced fix success at CWMA. Woody cover and antenna distance did not influence horizontal error at either site; average horizontal error was 21.7 m at La Copita and 26.9 m at CWMA. Battery performance also differed between sites and across woody-cover conditions, with reduced solar recharge and greater battery decline occurring under some densely vegetated conditions. Of 10 tags deployed on collared peccaries, one failed to transmit data. The remaining nine transmitted locations for 3–7 days and averaged 41.0% fix success before battery voltage declined and transmissions ceased. Peccaries frequently occupied dense woody cover, particularly during midday, likely limiting solar exposure during periods of greatest recharge potential.

Conclusions

Performance of solar-powered, LoRaWAN-enabled GPS ear tags depended on local environmental conditions and the ecology of the species carrying the device. Although these tags may provide a relatively low-cost option for wildlife telemetry, moderate fix success, positional error, and dependence on solar recharge may limit their application in densely vegetated environments or for species that regularly seek cover. Researchers should evaluate habitat conditions, species behavior, spatial-resolution requirements, and opportunities for solar recharge through pilot testing before large-scale deployment.

Background

Animal-borne global positioning systems (GPS) tracking devices are widely used tools for wildlife monitoring and research [1]. Advancements in GPS tracking technology enable the collection of location data at frequent intervals over extended periods and across a range of spatial and temporal conditions

[2,3]. Over time, improvements in device design and the available geospatial services have increased fix success rates [4] and enhanced positional accuracy [5]. Researchers commonly use GPS data to investigate resource selection, movement patterns, species interactions, and other spatiotemporal processes. Additionally, integrated technologies, such as video capabilities [6,7] and accelerometers [8], have further advanced animal tracking capabilities and expanded insights into animal spatial ecology [9].

Researchers must balance three key considerations when selecting GPS technology for a study species: device performance, potential impacts on animal welfare, and cost [10,11]. Performance metrics include missing locations (fix loss), spatial inaccuracy (horizontal [and vertical] error), and lack of precision of acquired GPS locations, all of which are inherent biases in animal tracking datasets [2,12]. If not addressed, these forms of bias in the data, and the subsequent results, may affect ecological inferences and study conclusions [13–18]. Importantly, failed fix attempts may not occur randomly because the GPS receiver may be affected by masking or shadowing [19,20], resulting from terrain, slope, and vegetation that reduces satellite visibility [2,12,18,21–24]. Additionally, landscape features can also affect the accuracy and precision of successful fixes [25,26]. Among these factors, canopy cover is frequently reported as a source of missed fixes or reduced positional accuracy because it can partially block signals between the satellites and GPS receiver [2,12]. Although canopy cover is widely recognized as a potential source of bias, its effects on GPS performance vary across studies, species, and regions, creating uncertainty about how strongly and consistently it influences GPS performance. Collectively, these biases, particularly those associated with canopy-induced shadowing, pose challenges for ecological inference and highlight the ongoing need for approaches that minimize error prior to conducting spatial analyses such as resource selection [12].

Animal welfare is also a primary consideration, with cost being a financial constraint, for researchers and wildlife professionals when selecting GPS technology for a study species. Factors such as body size, mass, morphology, behavior, and habitat use, as well as device weight and attachment methods, influence the suitability of GPS devices for different species [10,27]. Ongoing miniaturization of tracking sensors has been crucial for expanding the range of species that can be monitored while minimizing potential disruptions to their natural behaviors [1,28]. Recent advancements in solar-charging technology integrated into GPS tracking devices [29–31] have further reduced device size and weight and, in some cases, cost. These developments have expanded the feasibility of tracking smaller species and increased potential sample sizes in ecological studies.

Another approach to reducing device weight, and potentially cost, is the selection of how data are transmitted or received. Traditional GPS collars typically store location data on onboard memory, which requires physical retrieval of the device to access the data [29]. The storage hardware contributed to device weight, and the potential for data loss if collars were not recovered or were damaged [32]. Satellite-based transmission systems, such as Iridium and Globalstar, later enabled near-real-time data retrieval; however, associated transmission fees can substantially increase overall project costs [10,29]. Recent advancements in Internet-of-Things (IoT) technology have transformed livestock tracking and

monitoring by providing a low-cost alternative for transmitting location data in near real time [9,31,33,34]. Among these technologies, long-range wide area network (LoRaWAN) transmission has demonstrated reliable performance in livestock applications [35,36]. However, LoRaWAN tags and systems are typically limited to areas within range of receiving antennas, making it most effective in systems where animals (e.g., domestic livestock) remain near centralized resources, with performance often declining as distance between the tag and antenna increases [37].

Despite the potential advantages of integrating LoRaWAN data transmission with solar-powered GPS tracking technology, few studies have evaluated the effectiveness of these devices on wildlife species. Published examples are limited to species such as koalas (*Phascolarctos cinereus*) [38] and bison (*Bison bison*) [39], leaving uncertainty for wildlife professionals regarding broader applications. To address this gap, we conducted a study to evaluate the performance of mOOvement GPS ear tags (mOOvement, South Brisbane, Queensland, Australia, <https://moovement.com.au>), a solar-powered GPS tracking technology with LoRaWAN data transmission, under stationary testing and during on-animal deployment. Specifically, our objectives were to: (1) assess the influence of woody cover (%) and distance to the LoRaWAN gateway antenna (m) from the tag, and (2) evaluate the efficacy of deploying these tags on collared peccary (*Pecari tajacu*) in southern Texas.

Methods

Study area

We conducted stationary testing of mOOvement tags at La Copita Demonstration Area and Research Ranch (27.6666° N, 98.2089° W), a 1,103 ha property in Jim Wells County, Texas, owned and managed by the Department of Rangeland, Wildlife, and Fisheries Management (Texas A&M University, College Station, Texas, USA; hereafter, La Copita), and the Chaparral Wildlife Management Area (CWMA; 28.3247° N, 99.4067° W), a 6,151 ha property in Dimmit and La Salle Counties, Texas, which is owned and managed by Texas Parks and Wildlife Department (TPWD; Fig. 1). The study sites were within the South Texas Plains ecoregion, which is characterized by dense thorny shrublands and diverse plant communities [40]. The region consists of a subtropical, humid climate with annual and seasonally variable temperatures and precipitation patterns [41]. Common plants included honey mesquite (*Prosopis glandulosa*), prickly pear cactus (*Opuntia spp.*), huisache (*Vachellia farnesiana*), and various grass and forb species [42].

La Copita was composed of open grassland, savanna, and dense stands of woody shrubs [43]. Woody species included Brazilian bluewood (*Condalia hookeri*), honey mesquite, lime prickly ash (*Zanthoxylum fagara*), lotebush (*Ziziphus obtusifolia*), and Texas persimmon (*Diospyros texana*) [43,44]. The dominant grass genera included *Aristida*, *Chloris*, *Bouteloua*, *Eragrostis*, *Paspalum*, and *Tridens*. Forb richness and abundance varied seasonally, correlating strongly with precipitation patterns [43]. The terrain was relatively flat, with elevation ranging from 75 to 90 m above sea level. Cumulative precipitation was 2.2

cm during April 2024, and temperatures averaged 30.6 and 18.9 °C during the day and night, respectively [45].

The terrain at CWMA was relatively flat with gently rolling hills; elevation ranged from 74 to 130 m above sea level [46]. Common vegetation species included honey mesquite, blackbrush (*Acacia rigidula*), guajillo (*Acacia berlandieri*), cenizo (*Leucophyllum frutescens*), and various grasses and forbs [42]. Annual cumulative rainfall ranged from 50 to 80 cm across southern Texas [47]. Cumulative precipitation totaled 3.1 cm during May 2024, and temperatures averaged 35.6 and 23.9 °C during the day and night, respectively [48].

Stationary testing

We deployed a LoRaWAN off-grid model antenna (RAK7249, Shenzhen RAKwireless Technology Co., Shenzhen, China) at La Copita and CWMA, which was designed to communicate with and obtain location data from mOOvement GPS ear tags. To maximize signal strength, we installed the antenna atop a hunting blind (~8.2 m above the ground) at La Copita and on a barn peak (~10.1 m above ground level). We created a linear transect at each study site, which extended from the LoRaWAN antenna to the farthest accessible point on the property. Then, we evenly spaced sampling points along the transect at 1 location every 100 (La Copita) or every 200 m (CWMA) using the Generate Points Along a Line tool in ArcGIS Pro 3.3.1 (Esri, Redlands, CA, USA; Figure 1b, 1c). Transects were 4.5 and 7.4 km at La Copita and CWMA, respectively (Figure 1b, 1c). The maximum distances evaluated in our study were within the manufacturer's reported transmission range of up to 10 km between tags and a LoRaWAN antenna under ideal conditions. We navigated to sampling points using a Cedar CT8x2 tablet (Juniper Systems, Inc., Logan, UT, USA) and used ArcGIS Field Maps (Esri Inc., Redlands, CA, USA) to record the date, time, tag identifier, and orientation of tags at deployment.

We deployed 225 solar-powered GPS mOOvement ear tags at La Copita across 45 sampling points on 28–29 April 2024. Subsequently, we deployed 185 tags at CWMA across 37 sampling points on 10 May 2024. Each tag weighed 30–37 g and measured 45×55×10 mm. Tags were powered by energy collected by integrated solar panels and had a projected operational lifespan of five years [49,50]. Location data were transmitted from tags to antennas using LoRaWAN and subsequently relayed to a user dashboard through cellular networks. Tags were factory-programmed to record one GPS location per hour. Prior to deployment, we charged all tags in direct sunlight for ≥7 days to ensure battery voltages exceeded 4.0 V. At each sampling point, we attached 5 tags using zip ties to an 84-cm wooden stake, oriented with the solar panel facing north, south, east, west, and upward. We recorded the coordinates of the sampling points with sub-meter accuracy (3 cm) using a Trimble DA2 receiver (Trimble® Inc., Westminster, CO, USA) with Catalyst GNSS positioning service [51]. These coordinates served as reference (true) locations for the transect points [11].

On-animal testing

We captured 10 collared peccary using Jager Pro Corporal M.I.N.E. traps (JAGER PRO®, Fortson, GA, USA) baited with whole kernel corn from 28 April to 7 May 2024. Upon capture, we attached a metal animal handling chute equipped with a swinging gate and internal push board to assist with safe handling and immobilization of the peccary (Nunez et al., unpublished data). We raised the trap and chute gates to allow animals to voluntarily enter the chute. Once 1–3 individuals were inside, we dropped the chute gate and used the push board system to safely restrain individuals against one side of the chute, enabling a second researcher to administer immobilizing drugs via hand injection. We chemically immobilized individuals using intramuscular injections of one of two drug combinations: butorphanol (10 mg/mL), midazolam (5 mg/mL), and xylazine (100 mg/mL), or butorphanol (10 mg/mL), midazolam (5 mg/mL), and ketamine (100 mg/mL). We visually estimated body mass in the field to determine appropriate dosages. Administered volumes ranged from 0.5–1.2 mL for butorphanol, 0.7–2.0 mL for midazolam, 0.7–1.5 mL for xylazine, and 0.4–1.0 mL for ketamine (Thomas et al. unpublished data). Following injection, animals were observed from a safe distance until adequate immobilization was achieved for safe handling and data collection.

We recorded vital signs such as heart rate, respiratory rate, temperature, capillary refill time, and mucus membrane color at five-minute intervals during immobilization. We also recorded morphometric measurements (e.g., total body length [cm], shoulder height [cm], jaw length [cm], etc.), collected biological samples (e.g., blood, tonsil swabs, nasal swabs, etc.), and took photos of the jaws and body. We affixed a mOOvement GPS ear tag to the right ear and a uniquely numbered plastic tag in the left ear for visual identification. Following processing, we administered an intramuscular injection of flumazenil (1.0 mL at 0.1 mg/mL), naltrexone (0.5 mL at 10 mg/mL), and atipamezole (0.7 mL at 50 mg/mL) to each animal to reverse the effects of the immobilizing agents (Thomas et al. unpublished data). We monitored individuals until they recovered and were able to walk away unassisted. All capture and handling procedures were approved by the Texas A&M AgriLife Research Institutional Animal Care and Use Committee (Animal Use Protocol #2023-021A).

Data collection and preparation

We downloaded GPS location data from the QuickSight mOOvement online portal (Amazon Web Services, Seattle, WA, USA; <https://quicksight.aws.amazon.com>). Location records included tag identifier, timestamp (Coordinated Universal Time [UTC+0]), battery voltage, latitude, longitude, and other diagnostic metrics. We combined location data with the field data collected during static testing of tags, which included the sampling point identification, reference (true) coordinates, and tag orientation. We projected geographic coordinates to Universal Transverse Mercator (UTM) North American Datum 1983 (NAD83), Zone 14 N, and converted timestamps from UTC to local time (Central Daylight Time; UTC-5). We calculated the distance from each sampling point (i.e., set of 5 tags) to the LoRaWAN antenna and quantified woody cover (%) at each sample point. Specifically, we used the `st_distance` function from the `simple features (sf)` package [52] in R version 4.4.0 [53] to calculate the Euclidean distance (m) from each sampling point to the LoRaWAN antenna. We used Google Earth Engine [54] to download tree and shrub cover layers at a 30-m spatial resolution from the Rangeland Analysis Platform (RAP) [55]. We

added shrub and tree cover to create a new layer for total woody cover (%) to account for the effects of canopy cover on fix success, horizontal error, and battery voltage.

We censored tags with known deployment issues (e.g., tags dislodged and moved from the stake during testing, misrecorded identifier), duplicate records, and records with missing coordinates, a known concern with movement tags [31]. Tags that failed to transmit any GPS fixes during a full sampling day were manually retained in the dataset with a fix-success value of “0” to maintain accurate daily fix success tracking. Testing periods were defined using property-specific date ranges to ensure that only concurrent GPS fixes were retained for analysis. Testing was conducted from 30 April to 1 May at La Copita and from 11 to 12 May at CWMA. These two-day sampling windows allowed for the collection of up to 48 GPS fixes per tag, exceeding the minimum of 25 fixes suggested as sufficient for estimating variance in location error [31]. For tags fitted on peccary, we censored animal location data for 24 hours after tag deployment and then again for 24 hours prior to tag failure.

We quantified fix success (%) and horizontal error (m) to evaluate the performance of tags during stationary testing. Specifically, we calculated fix success as the total number of GPS fixes collected by each tag during the 2-day testing period and divided by the number of possible fixes (48 locations), creating a proportion, which we multiplied by 100 to convert to a percentage. We calculated the Euclidean distances (m) between each GPS fix and the reference (true) location by applying the *st_distance* function from the *sf* package in R [11].

Data analysis

We created a new variable to represent the distance from the tag to the LoRaWAN antenna whereby we applied a natural log transformation to account for a decreasing magnitude of response with increasing values for distance to the LoRaWAN antenna from the tag. Woody cover was the combination of shrub and tree cover, and was evaluated at the 30-m pixel resolution. We used generalized linear mixed models (GLMMs), implemented using the *glmmTMB* function from the *glmmTMB* package [56], to evaluate the influence of woody cover (%), distance (m) to the LoRaWAN antenna, and their interaction on fix success (0–1) and horizontal error (m). Specifically, we fit 2 fix success models and 2 horizontal error models, with separate models developed for each study site. We modeled fix success using a zero-inflated beta distribution with a logit link to account for excessive zeros. We modeled horizontal error using a Gaussian distribution and an identity link. We included the unique tag identifier as a random intercept in all models. We used the *Anova* function from the *car* package [57] to implement a Type III Wald chi-square test to assess the significance of fixed effects and interactions ($\alpha = 0.05$), and the *simulateResiduals* function from the *DHARMa* package [58] to evaluate goodness-of-fit and assess model diagnostics. We generated model-predicted marginal estimates using the *ggpredict* function from the *ggeffects* package [59].

Results

We deployed 225 tags at La Copita and 185 tags at CWMA, of which, 148 were deployed at both study sites. We censored the first sampling point ($n = 5$ tags at each study site) because the metal structures where the LoRaWAN antennas were mounted may have interfered with satellite reception of the tags. We censored 16 tags at La Copita that were moved, lost, or had a misrecorded identifier, and 2 tags at CWMA because locations were recorded in Utah, and another failed to activate. After tag censoring, 382 tags were retained for analysis, including 204 tags from La Copita and 178 tags from CWMA.

Stationary testing: fix success

Tags collected 5,701 of 9,792 possible fixes at La Copita, resulting in an overall fix success rate of 58.2%. At CWMA, tags collected 4,375 out of 8,544 potential fixes, equating to a fix success rate of 51.2%. Fix success at La Copita was affected by woody cover ($\chi^2 = 3.84$, $df = 1$, $P = 0.05$) and the interaction between distance to the antenna and woody cover ($\chi^2 = 5.69$, $df = 1$, $P = 0.02$); distance to the antenna did not influence fix success ($\chi^2 = 0.19$, $df = 1$, $P = 0.67$). Fix success decreased with increasing distance to the LoRaWAN antenna, which was compounded by increasing woody cover (Figure 2). At CWMA, fix success was not affected by distance to the antenna ($\chi^2 = 0.39$, $df = 1$, $P = 0.53$), woody cover ($\chi^2 = 0.72$, $df = 1$, $P = 0.40$), or the interaction between distance to the antenna and woody cover ($\chi^2 = 1.23$, $df = 1$, $P = 0.27$).

Stationary testing: horizontal error

Distance to the antenna ($\chi^2 = 0.22$, $df = 1$, $P = 0.69$), woody cover ($\chi^2 = 0.12$, $df = 1$, $P = 0.73$), and the interaction between distance to the antenna and woody cover ($\chi^2 = 0.16$, $df = 1$, $P = 0.69$) did not affect horizontal error of tags at La Copita. At CWMA, horizontal error also was not affected by distance to the antenna ($\chi^2 = 1.65$, $df = 1$, $P = 0.20$), woody cover ($\chi^2 = 1.59$, $df = 1$, $P = 0.21$), or the interaction between distance to the antenna and woody cover ($\chi^2 = 1.80$, $df = 1$, $P = 0.18$). Average horizontal error, averaged across tags, was 21.7 m (± 0.7 SE) at La Copita and 26.9 m (± 0.4 SE) at CWMA. Tag performance metrics across individual transect points are summarized in Table 1.

On-animal testing

One tag failed to transmit data and was excluded from analyses, resulting in a sample size of 9 tags fitted on collared peccaries. When tags were fitted on peccaries, data were transmitted for an average of 5.6 days (± 0.4 SE, range = 3–7 days). Battery voltage declined precipitously following deployment on peccary, with location transmissions starting to cease at 3.975 V (Figure 3); the last transmission of locations occurred at 3.91 V (Figure 3). When tags were functional, average fix success was 41.0% (± 6.7 SE). Despite the limited fix success and duration of tag functionality, the GPS data revealed trends in collared peccary use of woody cover throughout the day. Collared peccaries used greater woody cover during the middle of the day (1000-1800), and least from 2000-2300 hours (Figure 4).

Discussion

Solar-powered GPS ear tags may be suitable for specific animal species and under certain environmental and landscape conditions, but our static testing of tags and case study on collared peccary identified certain limitations. Woody canopy cover differentially affected fix success, likely owing to the amount of dense canopy cover at La Copita, which was much greater across the study area compared to CWMA. The denser woody cover, both vertical and horizontal structure, likely resulted in lower fix success because vegetation can interfere with satellite reception [2,21] and attenuate LoRaWAN transmissions between tags and receiving antennas through signal obstruction [60,61]. Although woody cover and distance to the LoRaWAN antenna affected fix success at La Copita, overall fix success (58.2%) was still greater at La Copita than overall fix success at CWMA (51.2%). Potential users of solar-powered tags, at least the model used herein, will need to assess whether fix success rates, similar to those observed in our study (51.2-58.2%), are sufficient to meet study objectives. Although woody cover and distance to the LoRaWAN antenna did not affect horizontal error, we still note that error was ≥ 21.7 m on average, which is greater than most traditional GPS tracking devices like neck collars [31]. Likely one of the greatest challenges of solar-powered GPS ear tags is the ability of the solar panel to charge the battery and then to maintain (or recharge) the battery efficiently. During static testing, we found that woody cover impacted battery voltage and recharge, whereby more open vegetation communities allowed the battery to maintain higher voltage and then to be recharged more fully during daylight hours (Figure 5). The loss of battery voltage was more pronounced when tags were fitted on collared peccary, a species known to use dense woody cover [62]. Battery voltage declined rapidly, with tags ceasing to function starting just 3 days after deployment. This is likely due to collared peccaries using dense cover, which we found while the tags were functional (Figure 4), especially during the middle of the day when solar radiation is greatest for battery recharge; this is also the time when temperatures are the highest, driving animals to seek shade in dense vegetation. Therefore, users of these tags, or similar ones, will need to assess habitat use and activity patterns of their target species to determine whether solar recharge of the battery is realistic and reliable.

The influence of woody cover and distance to the LoRaWAN antenna on fix success differed between study sites, suggesting that local environmental conditions may strongly influence the performance of solar-powered GPS ear tags. At La Copita, fix success decreased with increasing woody cover and distance to the LoRaWAN antenna, with the strongest reductions occurring when these factors acted in combination. This interaction suggests that, although each factor alone may moderately affect performance, their combined influence can substantially reduce fix success. In contrast, fix success at CWMA was unaffected by either covariate, indicating that these differences likely reflect site-specific effects related to variation in vegetation structure [63,64]. The interaction at La Copita was most pronounced when woody cover exceeded 45%, a condition rarely encountered at CWMA, where average cover was 36% across tag testing locations. Because woody cover exceeded this threshold across much of La Copita, and was encountered less frequently at CWMA, differences in vegetation conditions between sites may partially explain the contrasting responses observed in our models. Interestingly, other studies have reported inconsistent effects of canopy cover on fix success. Consistent with our findings at La Copita, several previous studies reported declines in fix success with increasing canopy

cover [22,65]. For instance, Stewart et al. [11] evaluated 10 animal-borne GPS devices from nine manufacturers in stationary tests across canopy closure ranging from 0–100% and found that fix success was largely unaffected by canopy cover. However, their study was conducted in the Post Oak Savannah Ecoregion in Texas, a system with heterogeneous hardwood canopies that differ from the conditions in our study. Collectively, these findings suggest that the influence of canopy cover on GPS performance depends not only on the amount of cover present but also on the structural characteristics of the vegetation, limiting the transferability of results among study systems. Additional factors, including canopy structure and composition, topography, satellite geometry, and atmospheric conditions, may also contribute to site-specific differences in performance [2,21,63,66].

An important distinction between our study and most previous evaluations of GPS performance is that a successful fix recovery for our solar-powered GPS ear tags required both acquisition of a GPS location and successful transmission of those data to a LoRaWAN antenna. Consequently, vegetation may have influenced fix success through multiple pathways, including obstruction of satellite signals and attenuation of LoRaWAN transmissions. Moore et al. [37] reported declining fix success rates with increasing distance from the LoRaWAN antenna, and other studies on LoRaWAN data transmission have reported reductions in signal strength and increased data loss in densely vegetated environments, with canopy structure, foliage density, and vegetation depth all contributing to reduced communication performance [60,61]. Therefore, the differences observed between La Copita and CWMA may reflect the pathways of how woody cover influences fix success. GPS fix acquisition likely is influenced by horizontal canopies of woody cover that interfere with reception of satellite signals to the tags, whereas communication of tags with the LoRaWAN antenna (i.e., to transmit the data) is likely affected by vertical structure of the woody vegetation.

Horizontal error was not influenced by woody cover or distance to the antenna, consistent with previous findings suggesting that canopy cover may have limited effects on locational error despite influencing fix success [13]. Although Lewis et al. [3] reported increased horizontal error under greater canopy cover, Stewart et al. [11] observed only minor canopy-related effects across several GPS devices, including mOOvement tags. Collectively, these findings suggest that environmental conditions may have a stronger influence on fix acquisition than on the horizontal error of successfully acquired locations; missing fixes usually impose greater limitations on data analysis, and require users to account for missed fixes, especially when conducting resource selection analyses [12].

Average horizontal error in our study (21.7 m at La Copita and 26.9 m at CWMA) was less than previously reported values for mOOvement tags under stationary testing conditions, which ranged from 33.3 to 41.0 m [31,37,38,49]. However, Stewart et al. [11] reported a predicted horizontal error of 19.7 m for mOOvement tags, which is similar to values observed in our study. The lower error observed in recent studies may reflect improvements in newer generations of mOOvement tags relative to earlier models. Despite these potential improvements, the horizontal error observed in our study (21.7–26.9 m) remained substantially greater than that reported for most traditional GPS collars and other animal-borne tracking devices (2–10.5 m) [11]. While suitable for many broad-scale ecological applications, the

horizontal error observed in our study may limit the usefulness of mOOvement tags for fine-scale movement, behavioral, and resource selection analyses where higher positional accuracy is required; therefore, researchers should carefully evaluate study objectives and spatial resolution requirements prior to deployment.

During stationary testing, woody canopy cover influenced battery recharge and voltage retention. Average battery voltage declined across all woody cover classes at La Copita during the 48-hour stationary test period (Figure 5). Extrapolating from observed voltage decline rates, tags at La Copita would be expected to fall below the 3.91 V transmission threshold within approximately 100 days, suggesting that available solar recharge was insufficient to offset battery consumption under our testing conditions (Table 2). In contrast, battery levels at CWMA remained relatively stable or increased slightly under low to moderate woody cover conditions (<60%). These results suggest that tags exposed to low and moderate levels of woody cover at CWMA were generally capable of maintaining sufficient charge to remain operational. Tags at CWMA in the highest woody cover class (60.1–80%) were projected to remain above the transmission threshold for approximately 320 days, substantially longer than tags exposed to comparable levels of woody cover at La Copita (45 days). The contrasting responses between study sites suggest that similar estimates of woody cover do not necessarily correspond to equivalent solar charging conditions, which may be affected by woody species, the accuracy of the remotely sensed data, and other site-specific attributes. Interestingly, Stewart et al. [11] reported only a ~0.01 V decline in battery voltage under 100% canopy cover, and this decline did not occur until days 7–9 after the start of testing. Furthermore, battery levels returned to pre-test values within one day after tags were moved back to open conditions (0% canopy cover) [11]. Although the magnitude of battery depletion differed among studies, these findings collectively indicate that solar-powered tag performance is highly sensitive to reduced sunlight availability, particularly under dense canopy cover. Consistent with our interpretation of the fix success results, discrepancies between sites and across previous studies suggest that canopy structure and composition (e.g., canopy height, density, and species composition) may influence ambient light availability and solar recharge efficiency, leading to variation in battery depletion rates and operational lifespans among regions and studies.

The influence of reduced solar recharge became more pronounced during deployments on collared peccaries, where battery voltage declined rapidly and most tags ceased transmission within 3–7 days after deployment. Further investigation indicated that collared peccaries frequently used dense woody cover throughout the day, averaging 72.9% woody cover across all hours and 85.4% during mid-day (1000–1800 CST; Figure 4), likely reducing solar radiation exposure during periods when recharge potential was greatest and contributing to rapid battery depletion and eventual tag failure [16,67,68]. The substantially shorter operational lifespan observed during on-animal deployments relative to stationary testing further suggests that collared peccary habitat use amplified the effects of limited solar recharge. Similar patterns have been reported during live-animal deployments of mOOvement tags. Stewart et al. [31] found that battery voltage for 8 of 9 tags deployed on cattle fell below the minimum transmission threshold (3.91 V) when cattle escaped direct sunlight, resulting in reduced tag performance relative to stationary testing. Together, these observations suggest that species-specific habitat selection and

behavior can strongly influence device performance, highlighting the importance of matching tracking technology to the ecology of the focal species [16,64,69]. We recommend that researchers conduct pilot studies prior to full deployment to evaluate whether a given tracking technology is compatible with the habitat use, behavior, and environmental conditions experienced by the focal species (*cf.*) [11].

Conclusion

Our evaluation of solar-powered mOOvement GPS ear tags during stationary testing and deployments on collared peccaries demonstrated that tag performance was influenced by woody cover, distance to the LoRaWAN antenna, and species-specific habitat use and behavior. Woody cover and distance to the antenna reduced fix success under certain conditions, whereas horizontal error remained relatively consistent across environmental gradients but was greater than that reported for many traditional GPS tracking devices. Battery performance emerged as the primary limitation of the technology, with reduced solar recharge under dense woody cover contributing to rapid battery depletion and shortened operational lifespan. These effects were particularly pronounced during live deployments, where collared peccary habitat selection and behavior limited opportunities for solar charging and substantially reduced tag longevity. Despite these limitations, the relatively low cost of solar-powered GPS ear tags may allow researchers to deploy larger sample sizes than would be feasible with many traditional GPS devices. Our findings suggest that these tags are best suited for medium- to large-bodied species that regularly occupy open habitats where solar recharge can occur. In contrast, species that spend much of their time in dense vegetation, such as collared peccaries, may experience substantial reductions in battery longevity and data recovery. These results highlight the importance of matching tracking technologies to both the ecological characteristics of the focal species and the environmental conditions of the study area. As GPS tracking technologies continue to advance rapidly [1,4,5], continued improvements in solar charging efficiency, battery performance, and data transmission are likely to expand the applicability of LoRaWAN-based tracking systems to a broader range of species and ecosystems.

Abbreviations

CWMA: Chaparral Wildlife Management Area

GPS: Global Positioning System

GLMM: Generalized linear mixed model

IoT: Internet of Things

LoRaWAN: Long Range Wide Area Network

NAD83: North American Datum 1983

RAP: Rangeland Analysis Platform

TPWD: Texas Parks and Wildlife Department

UTC: Coordinated Universal Time

UTM: Universal Transverse Mercator

Declarations

Ethics approval and consent to participate

All capture and handling procedures were approved by the Texas A&M AgriLife Research Institutional Animal Care and Use Committee (Animal Use Protocol #2023-021A), and under Scientific Research Permit (SPR-0923-109) by the Texas Parks and Wildlife Department.

Consent for publication

Not applicable

Availability of data and materials

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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Authors' Contributions

ET, AD, EM, and SW conceived the ideas and designed the methodology; ET, AD, and EM collected the data; ET and DS curated the data; ET, DS, and SW analyzed the data; ET prepared the visualizations and led the writing of the manuscript; ET, AD, EM, DS, JD, and SW reviewed and edited the manuscript; MB, WC, PL, JD, WG, and SW acquired funding and provided resources. All authors gave final approval for publication.

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Tables

Table 1. GPS ear-tag performance across stationary testing transects.

Property	Transect Point	Distance From Antenna (m)	Woody Cover Value (%)	Average Fix Success (%)	Range in Fix Success (%)	Average Horizontal Error (m)	Range in Horizontal Error (m)
La Copita	1	102.7	58.5	79.6	(6.2, 100)	19.2	(16.6, 21.4)
	2	163.8	72.9	95.4	(93.8, 97.9)	16.8	(14.2, 23.5)
	3	250.1	57.0	94.6	(91.7, 100)	20.7	(18.5, 26.8)
	4	339.7	49.9	97.9	(95.8, 100)	18.1	(16.1, 23.0)
	5	439.5	56.7	90.0	(58.3, 100)	37.2	(13.9, 98.0)
	6	535.8	82.6	77.1	(14.6, 97.9)	21.9	(14.3, 28.5)
	7	635.4	91.3	88.3	(72.9, 100)	22.3	(15.9, 29.8)
	8 ¹						
	9	834.3	88.8	77.9	(16.7, 97.9)	19.5	(11.8, 25.3)
	10	931.8	60.8	64.2	(8.3, 97.9)	17.8	(11.3, 27.1)
	11	1023.8	81.7	78.8	(22.9, 95.8)	33.9	(14.9, 91.6)
	12	1132.9	86.8	67.9	(12.5, 91.7)	24.1	(16.5, 33.4)
	13	1231.7	84.7	92.5	(85.4, 97.9)	22.7	(16.8, 27.2)
	14	1335.9	61.2	84.2	(58.3, 93.8)	28.0	(13.2, 62.5)
	15 ¹						
	16	1533.9	53.0	91.7	(81.2, 97.9)	18.6	(14.3, 22.5)
	17	1630.3	41.7	80.0	(14.6, 97.9)	18.5	(9.6, 24.8)

18	1735.9	42.0	69.6	(8.3, 93.8)	17.2	(13.0, 22.8)
19	1832.2	51.0	85.0	(77.1, 95.8)	27.8	(9.7, 66.6)
20	1933.2	80.2	32.5	(10.4, 62.5)	18.1	(7.8, 25.8)
21	2027.6	54.5	67.5	(12.5, 93.8)	18.3	(10.9, 22.7)
22	2129.9	56.9	89.6	(77.1, 95.8)	21.1	(15.0, 33.2)
23	2228.0	45.6	92.1	(87.5, 100)	21.9	(20.2, 23.4)
24	2331.0	29.7	78.3	(10.4, 97.9)	18.9	(8.3, 27.4)
25	2429.7	36.4	76.7	(16.7, 91.7)	21.1	(15.1, 26.4)
26	2531.4	47.9	70.0	(10.4, 91.7)	17.5	(13.9, 21.5)
27	2637.4	77.0	6.7	(0, 12.5)	31.0	(13.0, 47.1)
28	2729.9	62.8	64.6	(25, 91.7)	19.1	(10.9, 25.0)
29	2833.4	67.0	28.3	(0, 66.7)	26.3	(8.3, 54.3)
30 ²	2930.9	58.6	87.0	(70.8, 95.8)	17.3	(15.2, 20.4)
31	3028.7	60.9	73.3	(14.6, 97.9)	16.8	(10.2, 20.9)
32	3130.2	43.2	68.3	(39.6, 89.6)	16.1	(11.7, 26.0)
33	3231.0	41.8	1.7	(0, 6.2)	38.2	(8.0, 68.3)
34	3329.5	46.8	15.0	(0, 39.6)	15.6	(12.6, 18.6)
35	3429.3	66.3	21.7	(0, 60.4)	27.7	(8.8, 67.7)
36	3525.7	79.6	0.0	(0, 0)	N/A	N/A
37	3624.3	76.0	0.4	(0, 2.1)	3.6	(3.6, 3.6)
38	3734.3	83.4	11.7	(0, 31.2)	23.4	(18.2, 26.3)
39 ¹						
40	3935.5	89.1	0.0	(0, 0)	N/A	N/A

	41	4028.5	97.0	0.0	(0, 0)	N/A	N/A
	42	4125.7	87.5	32.9	(0, 85.4)	19.3	(14.3, 22.2)
	43	4233.0	73.0	31.7	(0, 70.8)	22.6	(17.6, 28.8)
	44	4355.8	59.2	28.3	(0, 64.6)	20.8	(17.5, 26.7)
CWMA	1	219.0	66.7	80.4	(12.5, 100)	16.3	(10.3, 22.9)
	2	420.3	31.7	96.2	(91.7, 100)	33.9	(9.6, 79.0)
	3	620.7	60.5	55.0	(0, 95.8)	22.7	(19.0, 30.6)
	4	814.4	56.0	57.1	(4.2, 95.8)	21.8	(14.6, 30.9)
	5	1016.2	50.9	32.9	(4.2, 97.9)	27.9	(12.7, 49.1)
	6	1213.4	22.7	42.9	(10.4, 97.9)	20.8	(12.1, 29.2)
	7	1416.7	31.1	77.9	(68.8, 93.8)	45.5	(10.3, 101)
	8	1618.0	22.7	42.9	(10.4, 83.3)	34.1	(20.3, 73.1)
	9	1821.6	49.1	90.8	(83.3, 100)	18.5	(12.7, 22.2)
	10	2017.2	50.1	44.6	(27.1, 56.2)	22.4	(15.7, 27.9)
	11	2218.8	62.2	52.9	(2.1, 97.9)	41.3	(0.5, 151.8)
	12	2415.5	16.4	43.2	(0, 93.8)	16.3	(12.5, 19.5)
	13	2617.5	34.7	25.0	(2.1, 41.7)	17.5	(8.8, 26.9)
	14 ²	2817.1	7.5	16.2	(6.2, 39.6)	22.1	(15, 34.9)
	15	3015.0	50.5	9.6	(2.1, 20.8)	11.1	(2.3, 20.2)
	16	3218.4	32.4	69.6	(12.5, 91.7)	61.6	(15.4, 187.4)
	17	3416.9	24.6	18.8	(4.2, 41.7)	49.4	(7.1, 179.2)
	18	3619.0	39.8	55.0	(0, 89.6)	19.6	(12.3, 30.9)

19	3818.0	12.2	44.2	(12.5, 95.8)	19.6	(15.2, 29.5)
20	4016.2	15.6	60.8	(14.6, 97.9)	19.1	(9.9, 24.3)
21	4218.5	9.1	78.8	(10.4, 100)	19.8	(15.3, 25.6)
22	4417.9	20.4	36.7	(8.3, 66.7)	24.1	(17.7, 34.6)
23	4618.8	24.7	52.1	(4.2, 91.7)	11.9	(5.7, 19.2)
24	4816.7	8.7	94.2	(83.3, 100)	29.4	(13.3, 70.6)
25	5016.7	21.9	83.3	(72.9, 91.7)	22.6	(13.7, 38)
26	5218.1	31.2	39.2	(10.4, 89.6)	19.7	(13.2, 29.2)
27	5413.0	19.3	39.2	(10.4, 81.2)	31.5	(11.6, 62.9)
28	5620.6	25.0	30.8	(12.5, 79.2)	18.3	(9.1, 27.6)
29	5816.8	18.5	52.9	(0, 91.7)	17.2	(10.1, 23.4)
30	6017.1	24.7	55.4	(8.3, 91.7)	22.6	(12.5, 40)
31	6214.6	22.9	81.2	(25, 100)	21.4	(15, 31.2)
32	6418.1	7.3	22.9	(0, 58.3)	15.2	(9.8, 17.9)
33 ²	6618.5	28.1	16.1	(0, 45.8)	6.9	(3.8, 12.9)
34	6818.1	20.5	17.9	(0, 62.5)	20.9	(14.3, 23.9)
35	7018.6	23.0	56.2	(0, 93.8)	21.0	(17.1, 25.3)
36	7153.1	17.6	61.7	(6.2, 97.9)	21.2	(12.2, 36.9)

¹5 solar-powered GPS ear tags censored from analysis (see Methods)

²1 solar-powered GPS ear tag censored from analysis (see Methods)

Summary of solar-powered GPS ear tags (mOOvement, South Brisbane, Queensland, Australia)
performance at transect points along stationary testing transects at La Copita Demonstration Area and
Research Ranch (La Copita), in Jim Wells County, Texas, USA, and Chaparral Wildlife Management Area

(CWMA), in Dimmit and La Salle Counties, Texas, USA, April–May 2024. Variables include distance from the LoRaWAN antenna (m), woody cover (%) within a 30-m pixel, average fix success (%), range in fix success (%), average horizontal error (m), and range in horizontal error (m).

Table 2. Battery performance of solar-powered GPS ear tags across woody cover classes.

Property	Woody Cover	Average Start	Average End Battery	Slope	Predicted Failure
	(%)	Battery	(V ± SE)	(V/hr. ± SE)	(Days ± SE)
		(V ± SE)			
La Copita	20-40	4.101 ± 0.0051	4.096 ± 0.0042	-1.04E-04 ± 1.38E-04	76.3 ± 2.1
	40-60	4.090 ± 0.0038	4.086 ± 0.0038	-7.60E-05 ± 1.13E-04	98.4 ± 2.1
	60-80	4.075 ± 0.0050	4.067 ± 0.0061	-1.52E-04 ± 1.64E-04	45.3 ± 1.4
	80-100	4.061 ± 0.0070	4.046 ± 0.0095	-3.20E-04 ± 1.64E-04	19.7 ± 0.9
CWMA	0-20	4.093 ± 0.0029	4.098 ± 0.0029	9.47E-05 ± 8.56E-05	NA
	20-40	4.082 ± 0.0024	4.089 ± 0.0025	1.62E-04 ± 7.32E-05	NA
	40-60	4.079 ± 0.0044	4.083 ± 0.0055	1.01E-04 ± 1.47E-04	NA
	60-80	4.088 ± 0.0036	4.087 ± 0.0077	-2.31E-05 ± 1.76E-04	320.0 ± 6.6

Summary of battery performance metrics and predicted failure durations of solar-powered GPS ear tags (mOOvement, South Brisbane, Queensland, Australia) across woody cover classes at La Copita Demonstration Area and Research Ranch (La Copita), Jim Wells County, Texas, USA, and Chaparral Wildlife Management Area (CWMA), Dimmit and La Salle counties, Texas, USA, April–May 2024. Variables include woody cover class (%), average starting battery level (V), average ending battery level (V), battery voltage change rate (slope), and predicted failure duration (days).

Figures

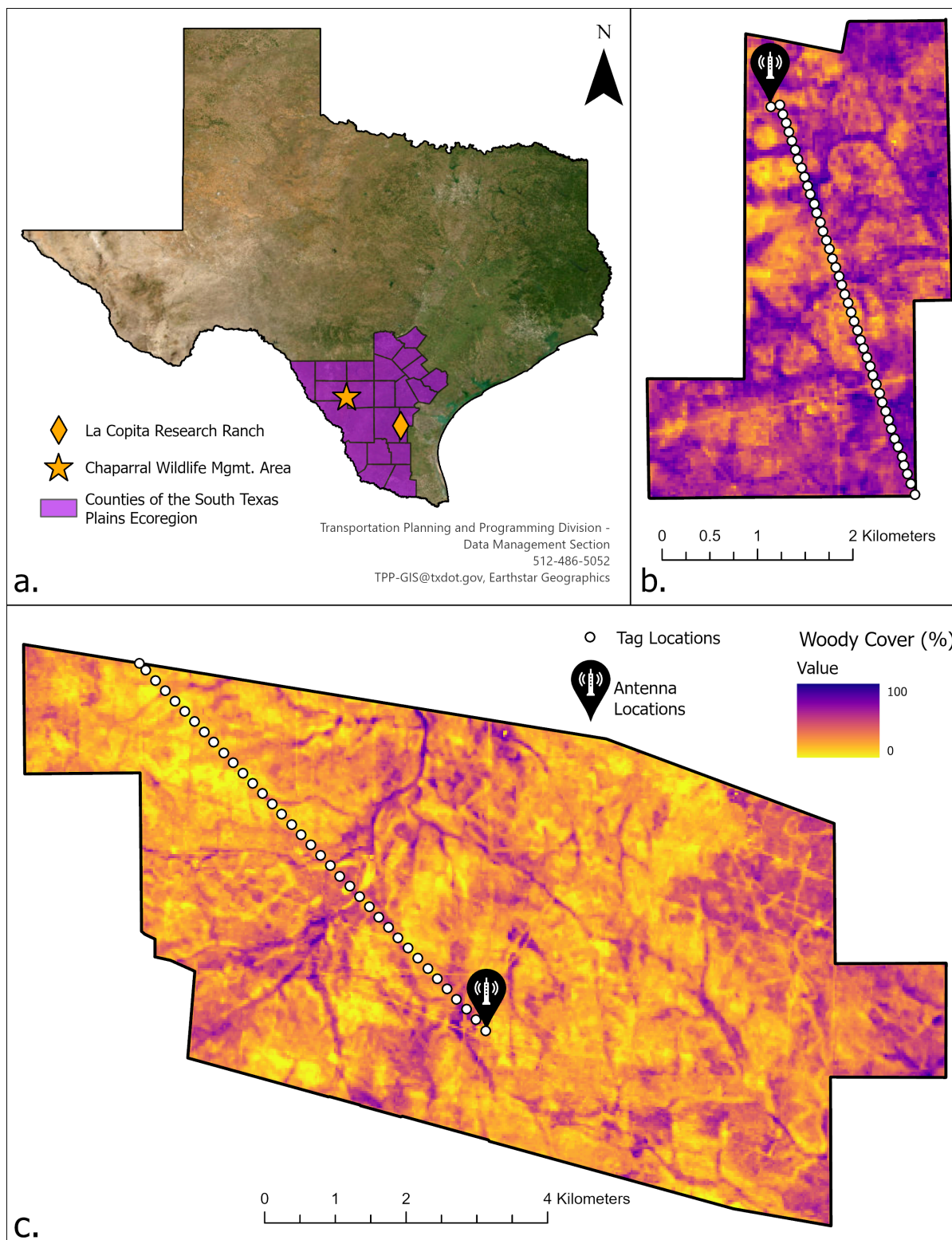


Figure 1

Overview of study sites in southern Texas.

(a) Texas counties are represented in black and counties within the South Texas Plains Ecoregion are represented in purple. The geographical location of La Copita Research and Demonstration Ranch is represented with a star, and the Chaparral Wildlife Management Area (CWMA) is represented with a

diamond. (b) La Copita in Jim Wells County and (c) CWMA in Dimmit and La Salle counties are shown with woody cover (%), LoRaWAN antenna locations, and GPS tag testing sites along transects. Woody cover is the combination of shrub and tree cover for each 30-m pixel obtained from the Rangeland Analysis Platform for 2024.

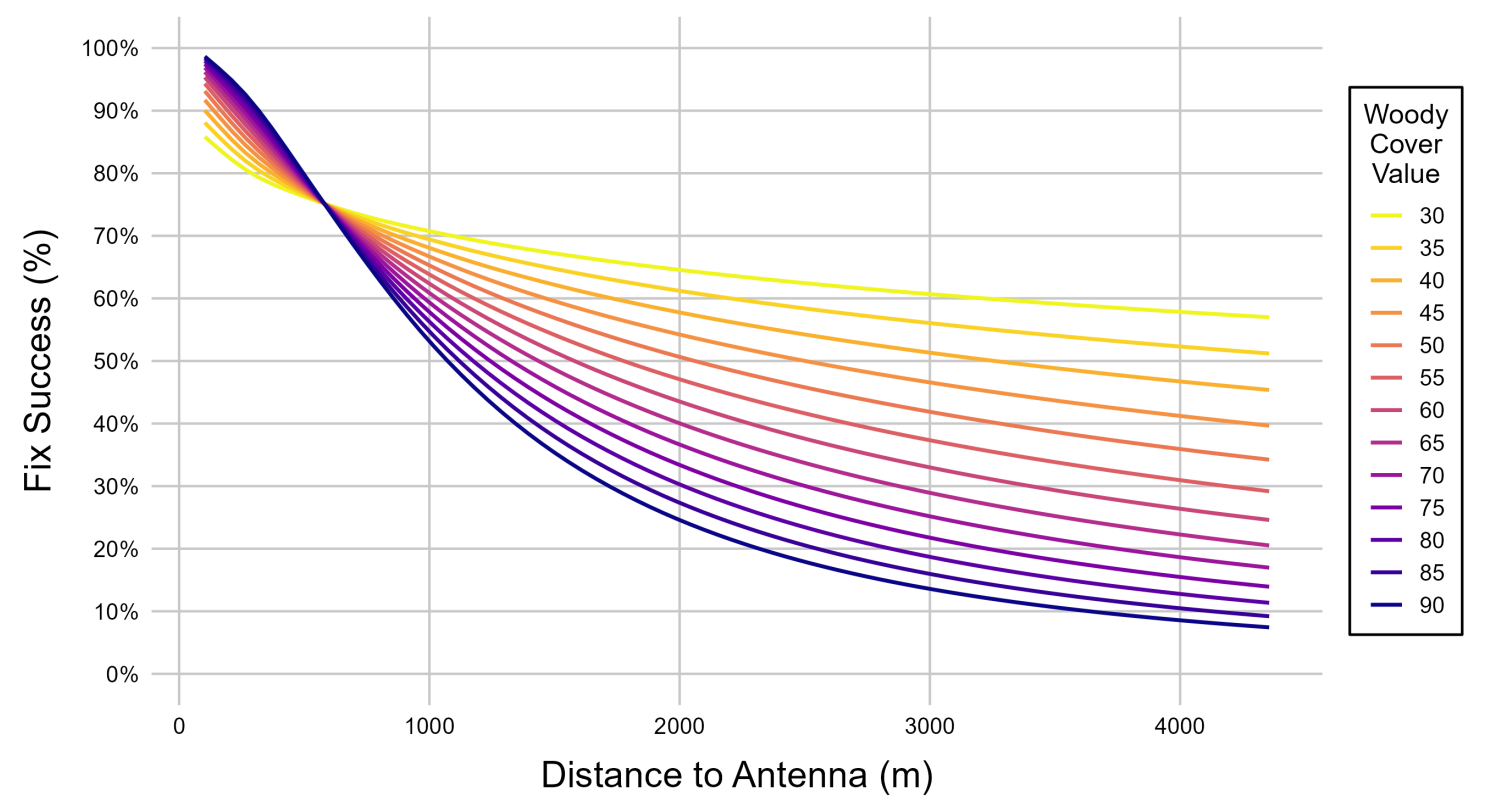


Figure 2

Fix success in relation to woody cover and antenna distance.

Fix success (%) of solar-powered GPS ear tags (mOOvement, South Brisbane, Queensland, Australia) as a function of woody canopy cover (%) and distance (m) from the long-range wireless antenna station during static testing at La Copita (Jim Wells County) during April 2024. There was an interaction between woody cover and distance to the antenna on fix success, whereby fix success declined with increasing distances between the tag and antenna station, which was amplified by increasing woody cover (i.e., woody cover further reduced fix success).

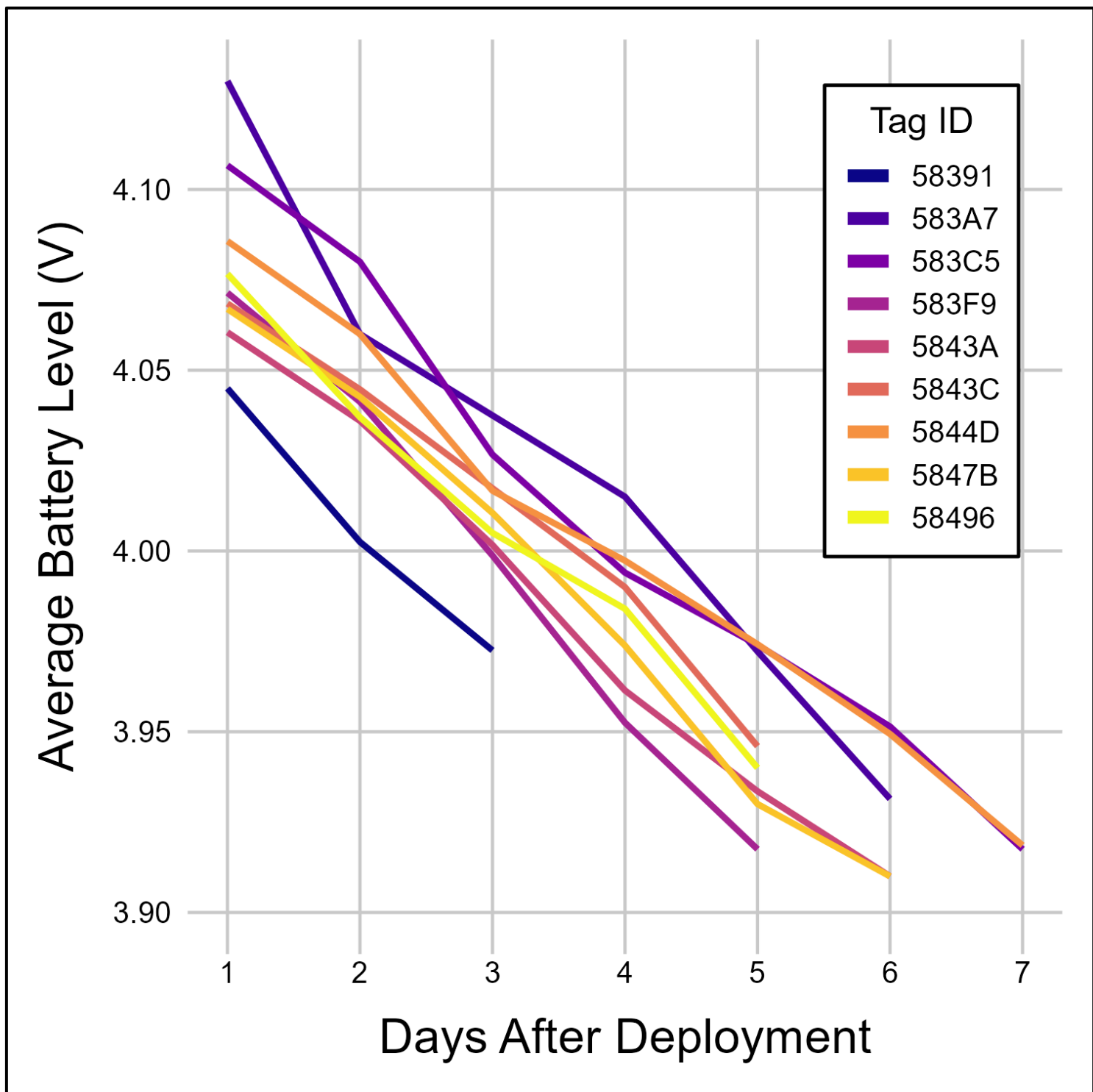


Figure 3

Battery voltage during deployment on collared peccaries.

Average battery voltage (V) of solar-powered GPS ear tags (mOOvement, South Brisbane, Queensland, Australia) after deployment on collared peccary (*Pecari tajacu*; $n = 9$) in Jim Wells County, Texas from 29 April to 14 May 2024.

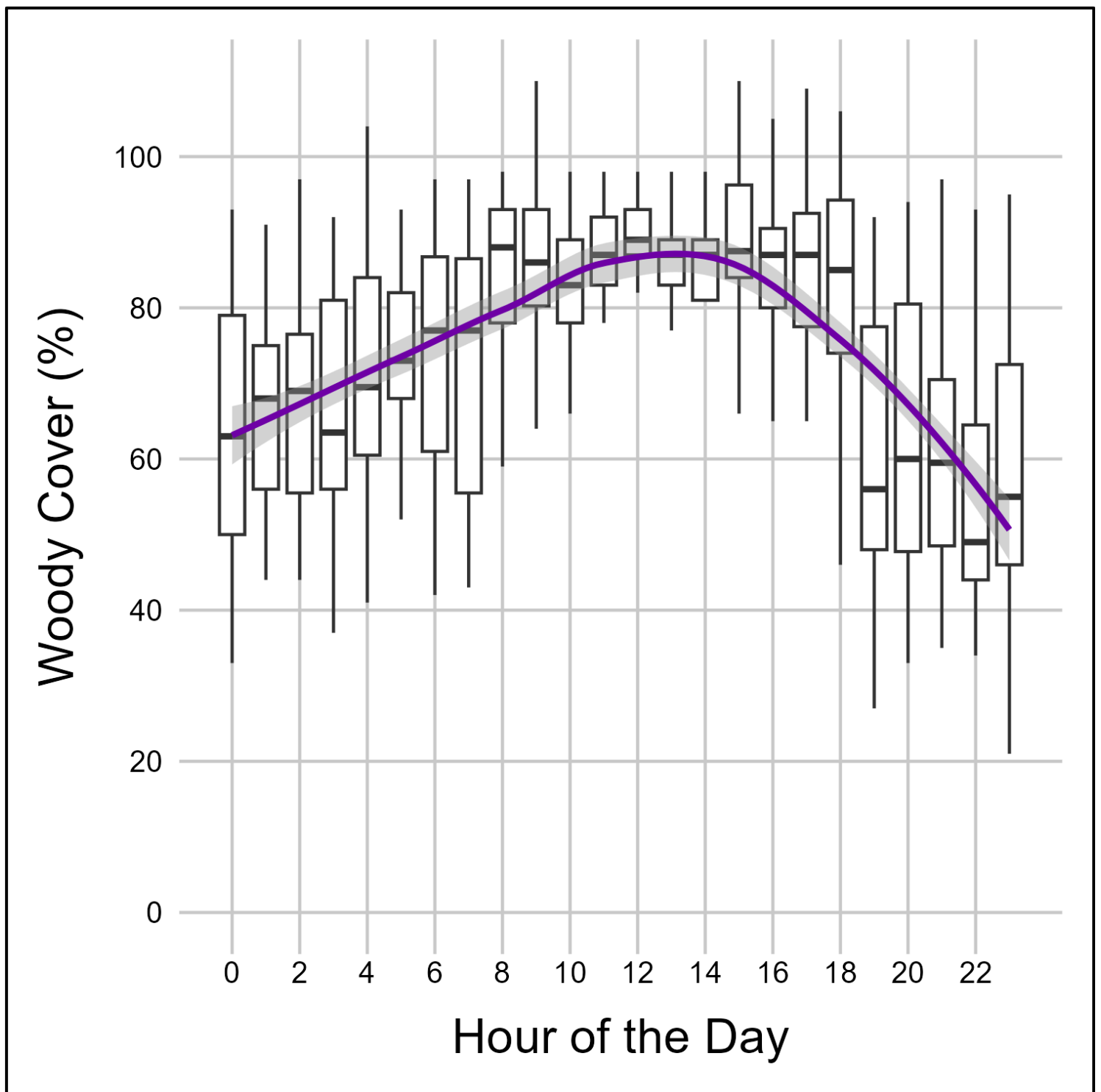


Figure 4

Hourly woody cover used by collared peccaries.

Box plots showing the use of woody canopy cover (%) in relation to time of day (hour) by collared peccary (*Pecari tajacu*; $n = 9$) in Jim Wells County, Texas from 29 April to 14 May 2024. The smoothed purple line indicates average use of woody cover (%) by hour; the gray shaded area represents the 95% confidence interval.

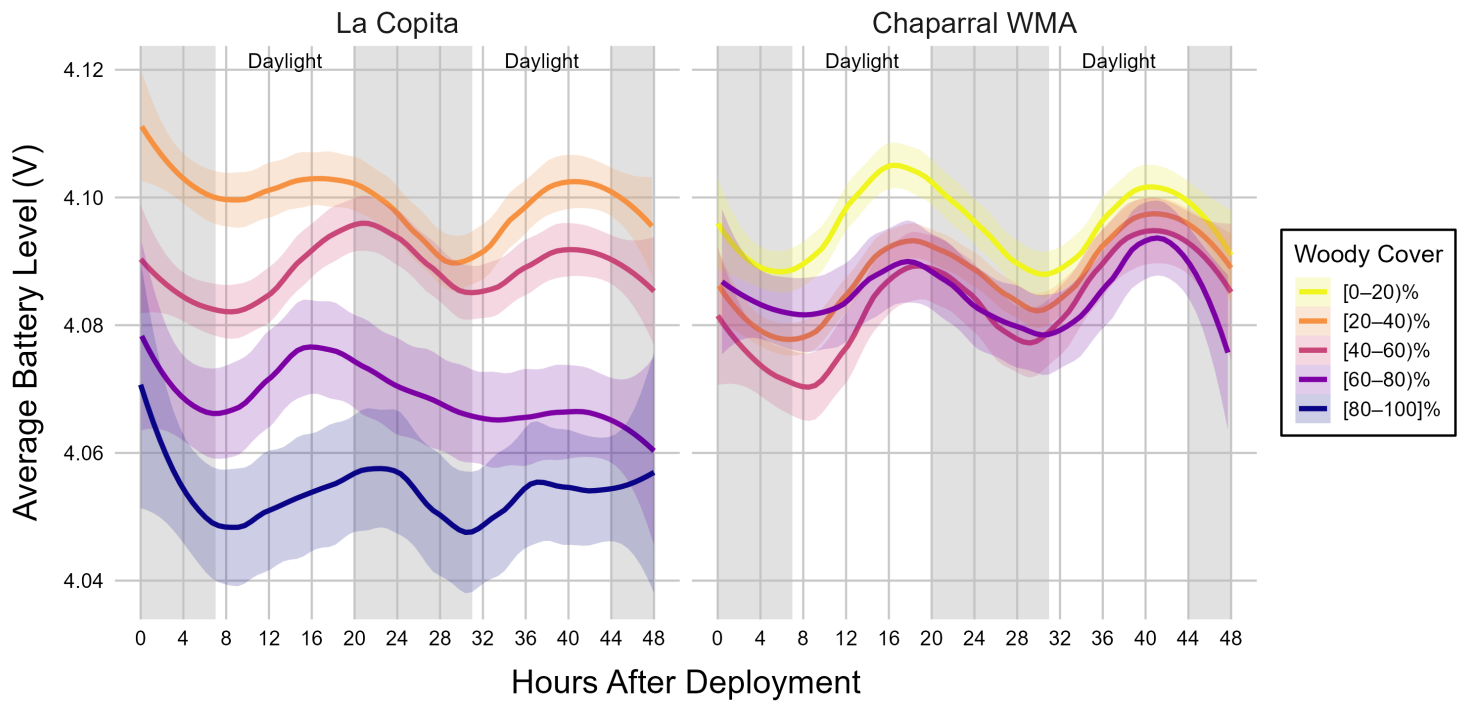


Figure 5

Battery performance during stationary testing across woody cover classes.

Average battery voltage (V) of solar-powered GPS ear tags (m00vement, South Brisbane, Queensland, Australia) after deployment (hours) and as affected by woody canopy cover (%). Tags were deployed as part of static testing on two study sites (La Copita Demonstration and Research Ranch and Chaparral Wildlife Management Area) in southern Texas (*cf.* Figure 1). Colored lines represent the average battery level (V) for 5 groups of woody canopy cover (%) in 20% intervals. The shaded ribbons represent ± 1 SE, and daylight hours are shown with white, vertical backgrounds and nighttime hours with gray, vertical backgrounds.