

Methods and applications for assessing recursive behavior in wildlife and livestock tracking datasets

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Abstract

Recursive movements, characterized by repeated returns to previously visited locations or areas, are a fundamental component of animal movement ecology, yet they remain underutilized in ecological analyses despite their potential applications. In response, we leveraged location data from Carmen Mountain white-tailed deer (*Odocoileus virginianus carminis*) and Rocky Mountain elk (*Cervus canadensis nelsoni*) in Coahuila, Mexico, a collared peccary (*Pecari tajacu*) in southern Texas, and a cow (*Bos taurus*) in Oklahoma to demonstrate applications of recursive behavior in wildlife and livestock tracking studies. We also present an iterative moving-window framework that incorporates temporal directionality into recursion analyses. Application of this framework revealed a mobile movement strategy, characterized by frequent movements between ranges, in male yearling Carmen Mountain white-tailed deer during spring and autumn, and provided evidence that penned conspecifics may be an effective mechanism for increasing short-term post-release site fidelity in elk. Our approach also showed that a collared peccary repeatedly revisited multiple daytime bedding sites while exhibiting variable residence times, potentially reflecting a hub-and-satellite structure of bedding sites. Finally, we observed substantial seasonal variation in the spatial distribution of grazing intensity in a cow, highlighting opportunities to improve pasture management for livestock producers. Collectively, these findings demonstrate the value of recursive movement metrics for revealing ecological patterns. We encourage researchers to incorporate recursive movement analyses into broader movement ecology frameworks to improve understanding of ecological processes, including social dynamics, habitat selection, pasture utilization, dispersal, migration, and site selection for behaviors such as bedding, resting, and parturition, among other applications.

Highlights

Recursive movements are repeated returns to previously visited locations

Incorporating temporal directionality into recursion analyses improved inference

Framework revealed mobile movement strategy in Carmen Mountain white-tailed deer

Conspecific attraction facilitated temporary post-release site fidelity in elk

Residence time and return interval revealed bedding behavior in collared peccary

1. Introduction

Animals often establish semi-permanent to permanent home ranges or territories and exhibit site fidelity through repeated revisitation of, and movement among (de Guinea et al. 2021; Alavi et al. 2022), preferred resources within their ranges (Hooten et al. 2017; Ranc et al. 2022). Revisitation patterns may arise from processes such as memory, resource selection, or stochastic movement (Merkle et al. 2017; Picardi et al. 2023; Verzuh et al. 2025), and represent a fundamental concept in understanding animal

space use (Powell 2025). Memory, in particular, has been identified as a strong predictor of route or location revisitation (Merkle et al. 2019; de Guinea et al. 2021; Rheault et al. 2021), bedding site use (Fei et al. 2022; Fradin and Chamaillé-Jammes 2023), and acquisition of food resources (Weidinger 2010; Crowther et al. 2022; Wang et al. 2023; Wehr et al. 2026), and may facilitate tracking of forage recovery (Bar-David et al. 2009; English et al. 2015), ultimately conferring fitness benefits to individuals (Merkle et al. 2017).

Recursive movements are characterized by repeated returns to previously visited locations or areas and are ubiquitous across the animal kingdom (Berger-Tal and Bar-David 2015; Bracis et al. 2018). Berger-Tal and Bar-David (2015) reviewed the literature and identified three forms of recursive behavior: trapline foraging, path recursion, and predator search strategies. Trapline foraging typically describes the systematic revisitation of foraging patches by small (e.g., bees) to medium-sized animals (e.g., primates) and is generally local in spatial extent (up to a few square kilometers; Berger-Tal and Bar-David 2015). In contrast, path recursion refers to repeated revisitation of resources by medium (e.g., impala [*Aepyceros* spp.]) to large-sized animals (e.g., elephants [*Elephas* and *Loxodonta* spp.]) and typically occurs over much larger spatial scales, potentially spanning hundreds of kilometers (Berger-Tal and Bar-David 2015). Predator search strategies describe recursive movements by predators among prey patches and can occur across a wide range of spatial extents from localized areas ($< 100 \text{ m}^2$) to landscapes exceeding 10 km^2 , depending on prey distribution and hunting strategy (Berger-Tal and Bar-David 2015). Revisitation may increase in some populations during periods of resource scarcity, reflecting a relaxed functional response (Holbrook et al. 2019), or in resource-poor landscapes (Nandintsetseg et al. 2019), as animals rely on finite or dwindling resources to meet requirements (Marshal et al. 2021; Crowther et al. 2026; Stewart et al. 2026b). Increased revisitation, longer residence times (time spent in an area), and shorter intervals between visits (time between returns), either independently or in combination, may reduce the opportunity for resource recovery and potentially lead to overutilization of resources (Campbell et al. 2021).

The development of analytical tools for identifying recursive behavior in animal telemetry datasets (Lyons et al. 2013; Mahoney and Young 2017; Bracis et al. 2018; Picardi et al. 2020; Bastille-Rousseau and Wittemyer 2021; Bastille-Rousseau et al. 2024), together with the comprehensive synthesis provided by Berger-Tal and Bar-David (2015), has coincided with a marked increase in studies examining path recursion in medium- and large-bodied animals. Likewise, growing recognition that recursive behavior is an integral component of resource selection (Giotto et al. 2015; Van Moorter et al. 2016; Bakner et al. 2022; Wilson et al. 2023) has driven rapid advances in modeling approaches that incorporate recursive metrics into resource selection analyses (Youngmann et al. 2022; Bakner et al. 2023; Egan et al. 2025; Stewart et al. 2026b), providing new insights into the mechanisms underlying habitat selection. For example, Stewart et al. (2026b) demonstrated that habitat selection varied with revisitation intensity whereby several habitat covariates exhibited contrasting selection patterns across levels of revisitation. These relationships would likely have remained undetected using traditional resource selection models that do not explicitly account for recursive behavior. Beyond resource selection, recursive behavior analyses have also facilitated the identification of biologically important locations and the behaviors

associated with them, including kill sites (Anderson and Lindzey 2003; Buderman et al. 2018), reproductive sites (Marchand et al. 2021; Bowgen et al. 2022; Mirski and Anderwald 2023), haul-out sites (Brost et al. 2017), shelter sites (Smith et al. 2021), and waterholes (Wiśniewska et al. 2025; Stewart et al. 2026c).

Despite widespread recognition of the importance of recursive behavior in animal movement ecology, relatively few animal tracking studies have explicitly incorporated recursive behavior into their analyses. Consequently, repeated calls have been made to further investigate the causes, consequences, and ecological significance of recursive behavior (Bar-David et al. 2009; Riotte-Lambert et al. 2013; English et al. 2014; Berger-Tal and Bar-David 2015; Bastille-Rousseau et al. 2024; Crowther et al. 2026). In response, we initiated a research project that leveraged location data from Carmen Mountain white-tailed deer (*Odocoileus virginianus carminis*; hereafter, deer) and Rocky Mountain elk (*Cervus canadensis nelsoni*; hereafter, elk) in Coahuila, Mexico, a collared peccary (*Pecari tajacu*) in southern Texas, and a cow (*Bos taurus*) in Oklahoma. Our objectives were to demonstrate applications of recursive behavior in wildlife and livestock tracking studies and to present an iterative moving-window framework that incorporates temporal directionality into recursion analyses. Our goal was to highlight the value of explicitly identifying and integrating recursive movement patterns to improve ecological inference and to bridge the gap between methodological development and practical application.

2. Materials and methods

2.1 Recursive analysis

We used the *getRecursions* function from the *recurse* package (v. 1.4.0; Bracis et al. 2018) in R statistical software (v. 4.3.0; R Core Team 2023) to identify recursive movement behaviors from animal tracking datasets. The function quantifies recursive behavior by generating circular buffers of a user-defined radius around GPS locations and evaluating sections of the movement path that pass through each circle (Bracis et al. 2018). For each location, the function calculates the number of times an individual re-enters the buffer (revisitation), the time spent within the buffer (residence time; Bracis et al. 2018), and time between visits. Recursion metrics are calculated using movement data occurring before and after each location, ensuring that all locations have equivalent potential for revisitation events. Consequently, recursive metrics characterize recursion in space rather than directional temporal processes (Bracis et al. 2018).

We developed an algorithm that leveraged the functionality of the *getRecursions* function within an iterative moving-window framework to introduce temporal directionality into recursion analyses (Fig. 1). We calculated revisitation (deer, elk, cow) and residence time and time between visits (collared peccary) at either the subdaily (point-based) or daily temporal scales (Fig. 1). For subdaily analyses, we implemented a moving window spanning 30 days forward from each location, progressing one location at a time along the movement trajectory (Fig. 1a). Consequently, recursive metrics associated with the first location in each window incorporated only recursive behavior occurring after the observation,

thereby explicitly enforcing temporal directionality (Fig. 1a). Recursive values were extracted and stored before the algorithm advanced to the next location. We applied a similar procedure at the daily scale, except the moving window progressed forward one day at a time, instead of one location at a time, and revisitation was averaged across all locations occurring within the first day of the window (Fig. 1b). We defined the radius of buffers using the average observed step length (deer: 210 m/2 h [95% CI: 184–236]; elk: 208 m/2 h [95% CI: 181–229]; collared peccary: 144 m/h [95% CI: 132–155]; cow: 78 m/15-min [95% CI: 76–79]; Abrahms et al. 2017; Bista et al. 2022; Bejarano Alegre et al. 2024; Ulrey et al. 2026). We used a 30-day moving window for demonstration purposes; however, the temporal extent of the analysis should be selected based on the ecology of the study species and the biological processes of interest. Annotated code is provided to facilitate reproducibility and application of our approach across additional species and ecological systems (Code S1).

2.2. Applications

We applied our framework to GPS tracking data from 4 species across 3 study systems to characterize recursive behaviors and demonstrate its application under diverse ecological contexts. To further characterize recursive movement behavior and provide examples for future applications, we also conducted several complementary analyses and, in some cases, incorporated supplemental movement metrics. Collar-specific performance metrics, including fix success rates and horizontal error, are reported in Stewart et al. (2026e).

Our first case study examined GPS location data from Vectronic Aerospace Vertex Lite neck collars (Vectronic Aerospace GmbH, Berlin, Germany) collected at 2-h intervals from 2 yearling (at time of capture) male deer captured in January 2024 at El Bonito Ranch, Coahuila, Mexico (29.016830 N, 102.046978 W) and monitored from January through December 2024. We quantified revisitation rate (revisits/30 d), at a daily temporal scale, to identify seasonal patterns in exploratory behavior (Fig. 1b). The study area comprised a heterogeneous landscape with pronounced elevational gradients (1,188–2,107 m), mountain and valley systems, terrain ranging from gentle to steep slopes (0.09–70.37°), and vegetation spanning open meadows to dense forests. Deer were nonmigratory and primarily moved along valley corridors, selecting lower elevations, gentler slopes, and less rugged terrain (Lozano-Sifuentes, unpublished data). We used the *st_distance* function from the *sf* package (v. 1.0–19; Pebesma 2018; Pebesma and Bivand 2023) to calculate daily displacement (km), defined as the average straight-line (Euclidean) distance between the nearest ranch house and GPS locations. We used the *segclust* function from the *segclust2d* package (v. 0.3.3; Patin et al. 2020) to identify changes in movement behavior from revisitation rates using a joint segmentation–clustering changepoint detection framework.

Our second case study examined GPS location data from Vectronic Aerospace Vertex Lite neck collars collected at 2-h intervals from 4 elk, 2 yearlings (1 M; 1 F) and 2 adults (1 M; 1 F), monitored at Picos de Davis Ranch, Coahuila, Mexico (29.016830 N, 102.046978 W), adjacent to El Bonito Ranch along its southern boundary. Herds composed primarily of females were captured during spring after the conclusion of the breeding season and subsequently confined within a 20-ha high-fence holding pen to

mitigate predation, enhance calf survivorship, and promote fidelity to the property following release. The GPS-collared individuals were released on 20 September 2024, whereas approximately 20 adult elk and their calves remained in the holding pens for an additional year. We analyzed revisitation rate (revisits/30 d), at a daily temporal scale, using GPS location data collected during the first 250 days following release (September 2024–May 2025) to evaluate conspecific attraction, defined as the tendency of individuals to be attracted to and remain in areas occupied by conspecifics (Fig. 1b). Habitat characteristics were similar to those described for El Bonito Ranch, and elk were nonmigratory, frequently foraging within the same valley systems used by deer. We calculated daily displacement relative to the center of the holding pen. We modeled revisitation rate using generalized linear mixed-effects models (GLMMs), implemented using the *glmmTMB* function in the *glmmTMB* package (v. 1.1.10; Brooks et al. 2017). We used the *bestNormalize* function in the *bestNormalize* package (v. 1.9.1; Peterson and Cavanaugh 2020; Peterson 2021) to identify the most appropriate transformation of the displacement data (m) and apply the optimal normalization. We used the *simulateResiduals* and *testDispersion* functions in the DHARMA package (v. 0.4.7; Hartig 2024) to evaluate model diagnostics.

For our third case study, we analyzed GPS location data from Vectronic Vertex Fusion NB-IoT neck collars, collected at 1-hour intervals, from one female collared peccary tracked as part of a collaborative research effort conducted at the U.S. Fish and Wildlife Service Lower Rio Grande Valley National Wildlife Refuge complex, spanning Hidalgo, Cameron, Starr, and Willacy counties, Texas. The individual occupied the 872-ha La Joya tract in Hidalgo County (26.24186 N, 98.50806 W), which includes a partial border barrier segment along its northern boundary. We subsampled GPS location data from July 2025 to evaluate residence time (h) and time between visits (h), at a subdaily (point-based) temporal scale (Fig. 1a), at day bedding sites during the hottest period of the year. The vegetation complex was comprised of thornscrub assemblages dominated by cenizo (*Leucophyllum frutescens*), Texas ebony (*Ebenopsis ebano*), and granjeno (*Celtis pallida*; Jahrsdoerfer and Leslie 1988). Collared peccaries typically bed together in cooler microclimates, such as dense thornscrub, during daylight hours in summer and move into more open areas at night to thermoregulate (Tomassetti et al. 2026). We defined the crepuscular period as 30 min before sunrise to 2 h after sunrise and 2 h before sunset to 30 min after sunset, the day period as the interval between the morning and evening crepuscular periods, and the night period as the interval between the evening and morning crepuscular periods (Stewart et al. 2022; Stewart et al. 2026a). Using the same framework as our elk case study, we normalized residence time (h), modeled residence time using GLMMs, and evaluated model diagnostics to ensure model fit. We also used the *MeanCI* function in the DescTools package (v. 0.99.60; Signorell 2025) to generate mean residence time (h) and time between visits (h) at the most frequently used bedding site, with uncertainty estimated by resampling the data 5,000 times, and a 95% confidence interval derived from the bootstrap distribution.

For our fourth case study, we evaluated location data from Vectronic Aerospace Vertex Lite neck collars, collected at 15-minute intervals, from one domestic cow at the Oswalt Ranch (34.004040 N, 97.248353 W), a 1,821-ha property in Love County, Oklahoma, owned and operated by the Noble Research Institute (Goold 2023; Little et al. 2016). We subsampled location data to December 2017 (dormant season) and

May 2018 (growing season) to evaluate spatiotemporal shifts in intensity of revisitation. The dominant cover types were woodland/forest (49.7% of the study area), prairie/pasture (49.4%), and open water (< 1%), with minor components of barren and urban development (< 1%); 15 water sources were interspersed throughout the property (Goold 2023). We evaluated revisitation rate (revisits/30 d) at the subdaily (point-based) temporal scale prior to creating monthly intensity of revisitation rasters (Fig. 1a). We used the *rast*, *vect*, and *rasterize* functions from the *terra* package (v. 1.8–29; Hijmans 2025) to generate revisitation-intensity rasters, where each 50-m pixel represented the median revisitation value of GPS locations occurring within that spatial extent. We used a 50-m pixel for demonstration and visualization purposes; however, the spatial extent of the raster should be selected based on the ecology of the study species. We also leveraged the *cor.test* function from the *stats* package to evaluate the spatial concordance in revisitation intensity between seasons using a Spearman rank correlation and calculated mean revisitation rate (revisits/30 d) at each location.

3. Results

For the deer case study, the segmentation analysis identified 4 breakpoints in revisitation rates (revisits/30 d), resulting in 2 distinct intra-annual segments classified as State 1 (08 April–12 June, 20 July–23 October), which were defined by lower revisitation rates (hereafter, mobile state), and 3 segments classified as State 2 (remaining periods between 10 January and 30 November), which were defined by higher revisitation rates (hereafter, sedentary state; Fig. 2). Predicted revisitation rate was, on average, 1.94 times greater in a sedentary state (20.79 ± 5.17 SD) compared to the mobile state (10.69 ± 4.20 SD; Fig. 2a).

For our elk case study, revisitation rate (revisits/30 days) declined precipitously (< 20 revisits/30 d) after 65 days following release (Fig. 3a). Revisitation rate was affected by the average daily displacement (distance) from the release site ($\beta = -0.64$, $SE = 0.02$, $P < 0.001$; Fig. 3b). Predicted revisitation rate was 86.53 (95% CI: 76.34–98.08), 7.03 (95% CI: 6.52–7.57), 2.45 (95% CI: 2.20–2.72), and 1.31 (95% CI: 1.14–1.49) at 0.16, 1.00, 4.03, and 6.24 km from the release site, respectively (Fig. 3b).

For the collared peccary case study, residence time (h) was significantly higher during the daylight period ($\beta = 0.45$, $SE = 0.05$, $P < 0.001$) compared to the crepuscular ($\beta = -0.64$, $SE = 0.09$, $P < 0.001$) and night periods ($\beta = -0.84$, $SE = 0.08$, $P < 0.001$; Fig. 4a). Mean predicted residence time was 3.85 h (95% CI: 3.40–4.27) during the day, 2.29 h (95% CI: 2.03–2.51) during the crepuscular period, and 1.90 h (95% CI: 1.67–2.14) at night (Fig. 4a,b).

Residence times were highest at a single daytime bedding site located within a dense scrub thicket (Fig. 4c). The individual returned to this site during daylight hours on 42% of monitored days (13 of 31 days), with an average daytime residence time of 6.98 h (95% CI: 6.90–7.06; range: 6.10–7.93) and time between visits of 20.5 h (95% CI: 20.2–20.8; range: 18.4–23.8) (Fig. 4c).

For the cow case study, during December, the individual revisited locations 8.4 times (95% CI: 8.0–8.7; range: 1–38), on average (Fig. 5a), whereas in May, locations were revisited 6.8 times (95% CI: 6.6–7.0;

range: 1–29; Fig. 5b). Revisitation intensity exhibited a moderate negative rank correlation between December and May (Spearman's $\rho = -0.42$, $S = 173614982$, $P < 0.001$), indicating substantial seasonal restructuring of spatial use patterns (Fig. 5c).

4. Discussion

The recursion analyses presented herein demonstrated multiple applications for animal tracking data that can be used to provide greater ecological insight into animal behavior and their propensity to reuse familiar sites. Our framework enabled the calculation of revisitation, residence time, and time between visits, while explicitly preserving temporal directionality at both subdaily and daily temporal scales. The approach is reproducible, flexible, and readily adaptable to address a wide range of research questions involving recursive movement behavior. Moreover, application of this framework revealed new insights into seasonal patterns of exploratory behavior in yearling male deer, conspecific attraction among released elk, extended residency and time between visits to daytime bedding sites by a collared peccary, and spatiotemporal shifts in revisitation intensity by a cow. Pairing recursive movement metrics with complementary analyses tailored to each system yielded additional ecological insights. Collectively, these examples demonstrated that integrating recursive movement metrics into broader analytical frameworks or complementary analyses can provide a more comprehensive understanding of the ecological processes underlying animal movement (Bakner et al. 2023; Egan et al. 2025; Stewart et al. 2026b).

In our deer case study, we identified two intra-annual periods from revisitation rates that collectively represented the mobile state. These periods were characterized by reduced revisitation and increased spatial shifts (bounces) and corresponded loosely to the traditional spring (08 April–12 June) and autumn (20 July–23 October) seasons. The timing of these periods aligns closely with known seasons of dispersal in yearling male deer, which may disperse in spring due to mother–young interactions and in autumn due to male–male competition, with approximately 50–80% of males dispersing as yearlings (Long et al. 2005; McCoy et al. 2005; Long et al. 2008; Stewart et al. 2011). In addition to seasonal migration and dispersal, deer may also exhibit a mobile movement strategy in which individuals shift or “bounce” between ranges (Resop et al. 2024). When interpreted alongside the displacement metric, revisitation patterns provide additional evidence supporting the occurrence of this mobile movement strategy in Carmen Mountain white-tailed deer. This case study highlights the value of evaluating recursive behavior to identify exploratory movement behavior.

In our elk case study, revisitation was initially high (> 20 revisits/30 days) during the first 65 days following release and declined precipitously as elk used areas farther from the release site. Conspecifics were retained in the holding pen for an additional year after the release event, suggesting that the released elk exhibited strong site fidelity, likely driven by conspecific attraction (Linklater et al. 2006; Hennessy et al. 2022; Greggor et al. 2024; Stewart et al. 2026d), which was an intended outcome of the release strategy for the property. Le Gouar et al. (2012) proposed that holding conspecifics in pens on-site may enhance site fidelity of released individuals, a hypothesis that our findings appear to support.

Although further testing is warranted, these results provide additional support for the application of recursive behavior analyses and suggest that penned conspecifics may be an effective mechanism for increasing post-release site fidelity.

In our collared peccary case study, we found that residence time was, on average, 68% and 102% greater during daylight hours compared to crepuscular and nighttime periods, respectively. However, further analysis revealed that a single daytime bedding site was revisited on 42% of days, with an average residence time of approximately 7 h and a mean interval between visits of 20.5 h. This return interval highlights a spatiotemporal pattern in which the collared peccary revisited the same bedding area on an approximately 24 h cycle, a pattern also reported by Giotto et al. (2015) for Asiatic wild ass (*Equus hemionus*). Giotto et al. (2015) hypothesized that this behavior may be widespread among large herbivores, and our results provide additional support for that hypothesis. Additionally, the collared peccary revisited multiple daytime bedding sites that differed in average residence time, suggesting a hub-and-satellite structure of bedding sites (Bakner et al. 2024), a pattern also supported by preliminary analyses from a separate property (Tomassetti et al. 2026). We suggest that applying social network analysis to these recursive movement data would provide a valuable next step for investigating daytime bedding behavior (Bakner et al. 2024), potentially yielding additional insight into the organization and function of bedding-site networks.

For the cow case study, we found substantial seasonal variation in spatial patterns of grazing intensity. This result is expected, as revisitation rates are likely to increase during periods of resource scarcity, when animals concentrate their use in the remaining high-quality patches, and decrease during periods of greater resource abundance and quality, when forage is more widely distributed across the landscape (Holbrook et al. 2019; Nandintsetseg et al. 2019; Marshal et al. 2021; Crowther et al. 2026; Stewart et al. 2026b). Intensive grazing may further reduce forage availability (Campbell et al. 2021), requiring vegetation recovery before areas can be revisited (English et al. 2015). Seasonal variation in plant phenology among dominant forage species may also shift the distribution of productive grazing patches, thereby influencing patterns of animal movement and space use (Bischof et al. 2012). Consistent with these findings, Gou et al. (2020) reported that cattle redistribute grazing intensity among locations from month to month, even within the same season, to balance energetic requirements with forage availability. Given their economic importance, incorporating recursive behavior into analyses of cattle movement may provide valuable opportunities to optimize grazing pressure and improve pasture management for livestock producers.

Our findings highlight the value of explicitly identifying and integrating recursive movement patterns to improve ecological inference, which we achieved using an iterative moving-window framework. We evaluated 3 recursive metrics, revisitation, residence time, and time between visits, but additional metrics (e.g., entrance time, exit time, and others) can be incorporated to further enhance inference (Bracis et al. 2018). We encourage researchers to incorporate recursive movement analyses into broader movement ecology frameworks to improve understanding of ecological processes, including social

dynamics, habitat selection, pasture utilization (e.g., overgrazing), dispersal, migration, and site selection for behaviors such as bedding, resting, and parturition, among other applications.

5. Conclusions

Recursive movements are widely regarded as fundamental components of animal ecology (Berger-Tal and Bar-David 2015), yet their application in the published literature remains limited. We leveraged location data from 3 wildlife species and one domestic livestock species to demonstrate applications of recursive behavior analyses and present an iterative moving-window framework that incorporates temporal directionality into recursion analyses. Application of this framework revealed insights into seasonal patterns of exploratory behavior in yearling male deer, conspecific attraction in released elk, extended residency and time between visits to daytime bedding sites by a collared peccary, and spatiotemporal shifts in revisitation intensity by a cow. Furthermore, combining recursive metrics with complementary analyses provided additional ecological insight across systems (Bakner et al. 2023; Egan et al. 2025; Stewart et al. 2026b). Alongside others (Bar-David et al. 2009; Riotte-Lambert et al. 2013; English et al. 2014; Berger-Tal and Bar-David 2015; Bastille-Rousseau et al. 2024; Crowther et al. 2026), we encourage researchers to evaluate recursive movement patterns and integrate them into analytical frameworks or complementary analyses, where feasible, to improve understanding of animal ecology.

Declarations

CRedit authorship contribution statement

Dylan G. Stewart: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft. **Ivan A. Lozano-Sifuentes:** Data curation, Writing – review & editing. **Emily A. Masterton:** Data curation, Writing – review & editing. **Marcus E. Blum:** Funding acquisition, Project administration, Resources, Writing – review & editing. **E. Alejandro Lozano-Cavazos:** Funding acquisition, Project administration, Resources, Writing – review & editing. **Stephen L. Webb:** Data curation, Funding acquisition, Project administration, Resources, Writing – review & editing.

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Declaration of competing interests

The authors declare no competing interests. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Data availability statement

Annotated R code used in analyses are provided as Supplementary Information. The raw movement data used in this study are available from the Movebank online data repository (Movebank IDs: 3267722371 [Carmen Mountain white-tailed deer]; 4565667002 [Rocky Mountain elk]; 4486609508 [collared peccary]; 3000102503 [cow]).

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Figures

A) Subdaily temporal scale

B) Daily temporal scale

Moving Window

Output

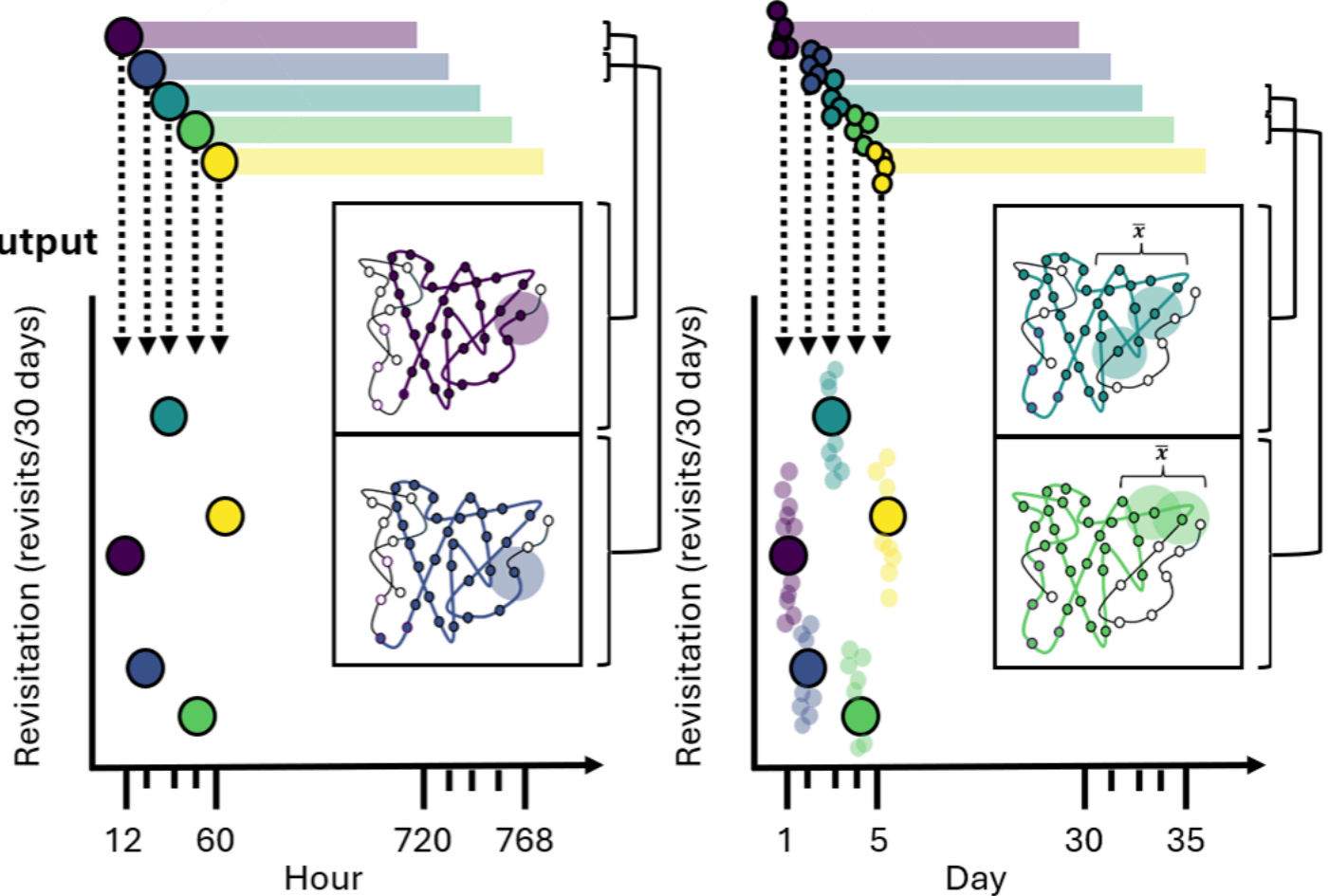


Figure 1

Workflow describing an iterative moving-window framework used to introduce temporal directionality into recursion analyses. (A) The moving window advances forward one location at a time along the movement trajectory and quantifies recursive behavior for the first location within the window (transparent colored circular buffer) using only data collected within the user-defined temporal window (colored movement path and locations). The resulting estimate is extracted for the focal location, and the algorithm continues iteratively along the trajectory (see Moving Window). Outputs can then be visualized across time (see Output). (B) The framework is modified to advance forward one day at a time, rather than one location at a time, with revisitation averaged across all locations occurring during the first day of the defined moving window.

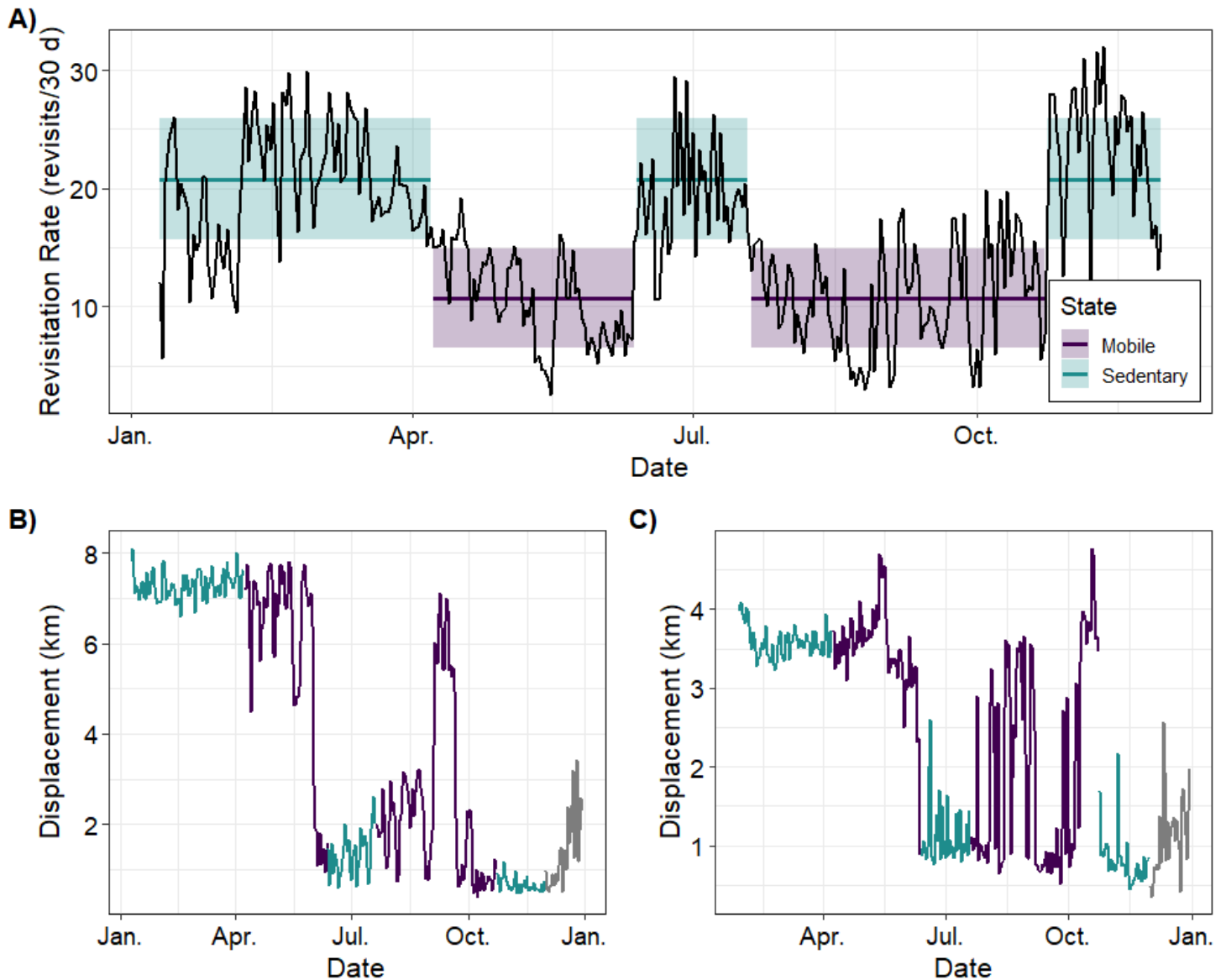


Figure 2

(A) Daily estimates of mean revisitation rate (revisits/30 d) by 2 yearling male Carmen Mountain white-tailed deer (*Odocoileus virginianus carminis*; $n = 2$) at El Bonito Ranch, Coahuila, Mexico from January through December 2024. Horizontal purple and green lines represent the estimated mean revisitation rate for the two predicted behavioral states (mobile [State 1], sedentary [State 2]), and the corresponding shaded regions represent ± 1 SD. Daily displacement (km) of (B) Deer_8 and (C) Deer_14. Continuous purple and green lines denote the mobile (State 1) and sedentary (State 2) states, respectively, across time whereas the gray line segment represents the final 30 days of monitoring, which were not assigned to a behavioral state.

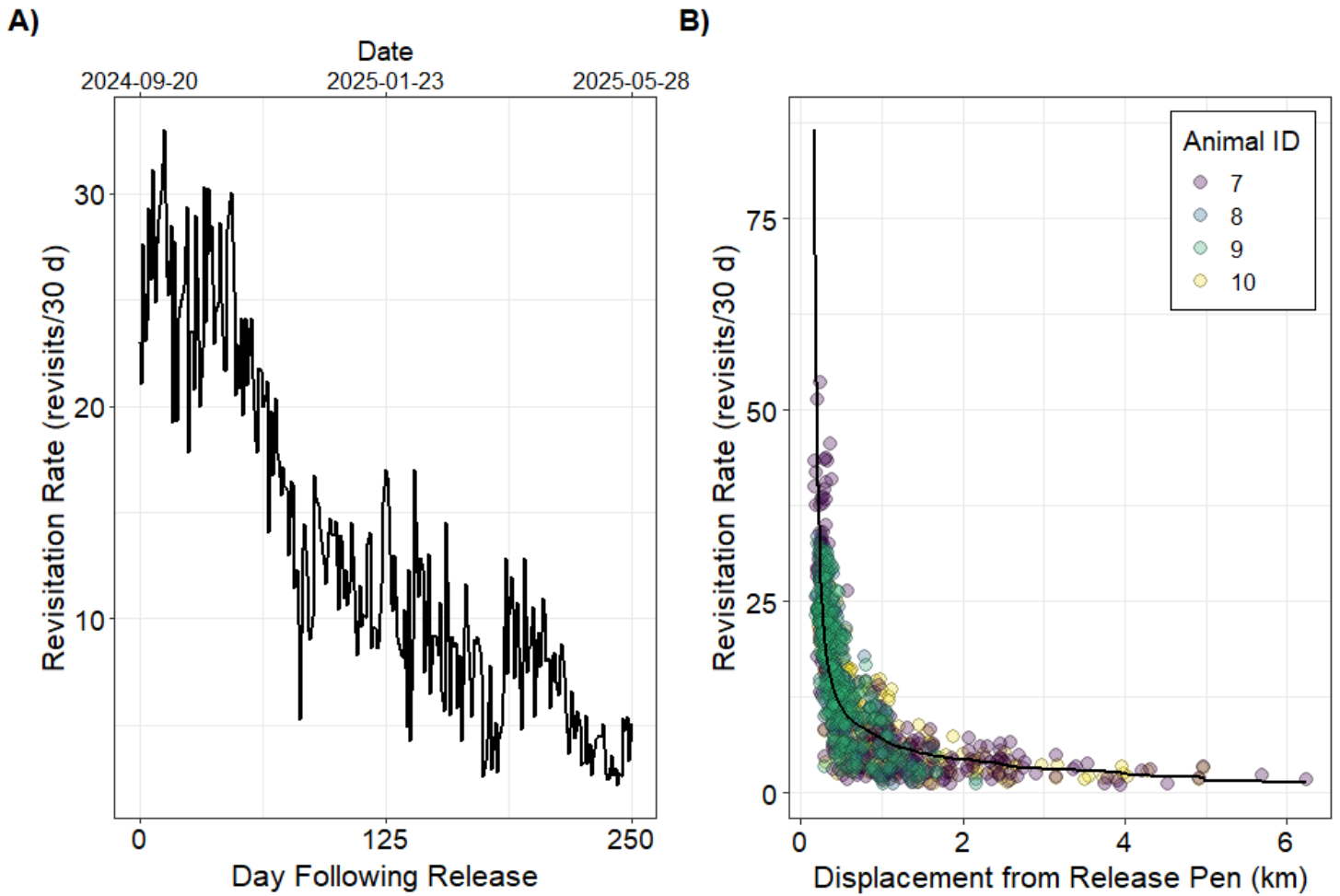


Figure 3

(A) Daily mean revisitation rate (revisits/30 d) averaged across 2 yearling (1 M; 1 F) and 2 adult (1 M; 1 F) Rocky Mountain elk (*Cervus canadensis nelsoni*) released on 20 September 2024 at Picos de Davis Ranch, Coahuila, Mexico, and monitored for 250 days following release (September 2024 to May 2025). (B) Population-level (marginal) model-predicted relationship between displacement (km) and revisitation rate. Colored points represent daily revisitation estimates for individual elk ($n = 4$). Displacement estimates were converted to kilometers for ease of interpretation.

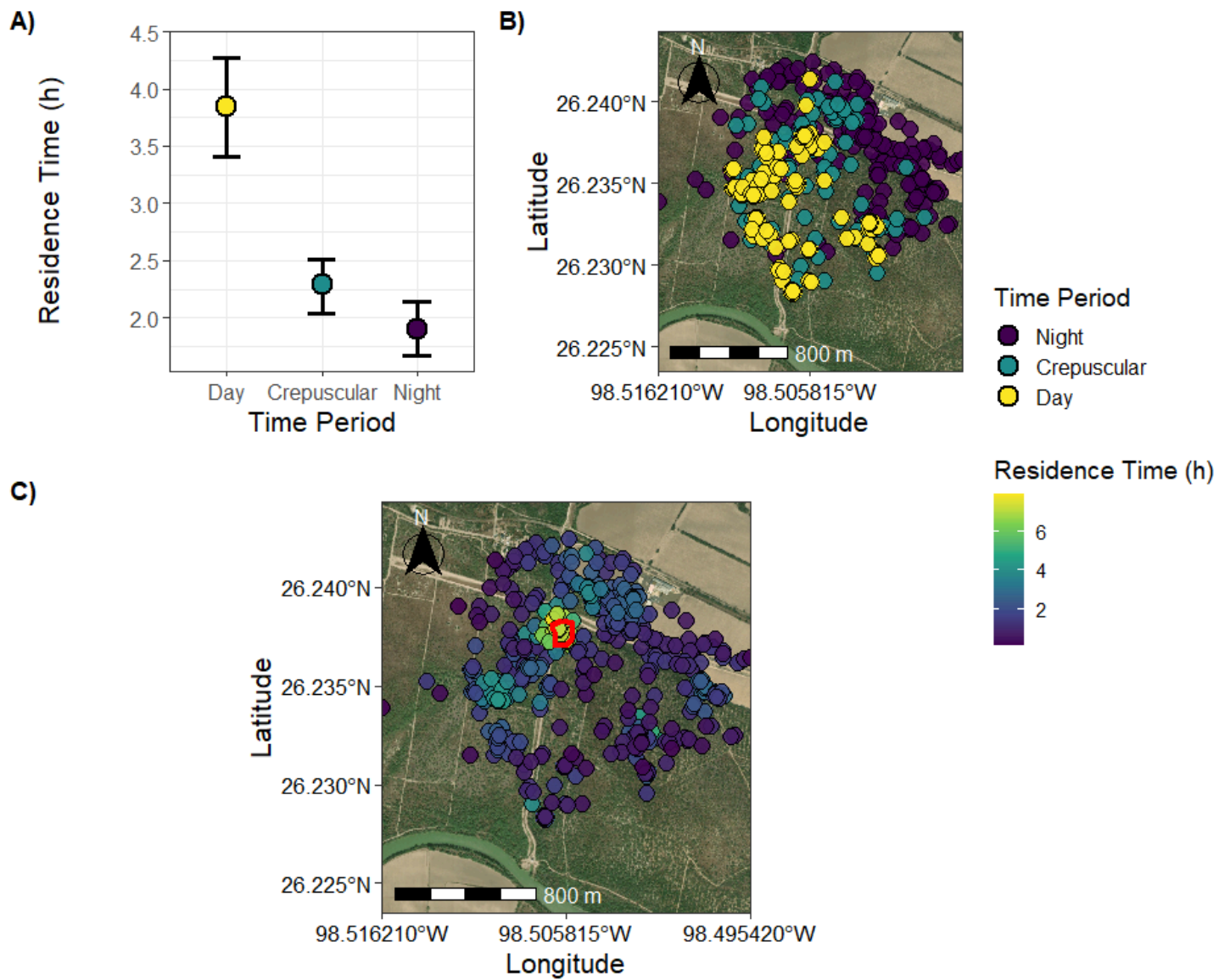


Figure 4

(A) Model-predicted residence time (h), by time period (day, crepuscular, and night), for a female collared peccary (*Pecari tajacu*) at the La Joya tract of the U.S. Fish and Wildlife Service Lower Rio Grande Valley National Wildlife Refuge complex, Hidalgo County, Texas, during July 2025. GPS locations are colored by (B) time period and (C) residency (h).

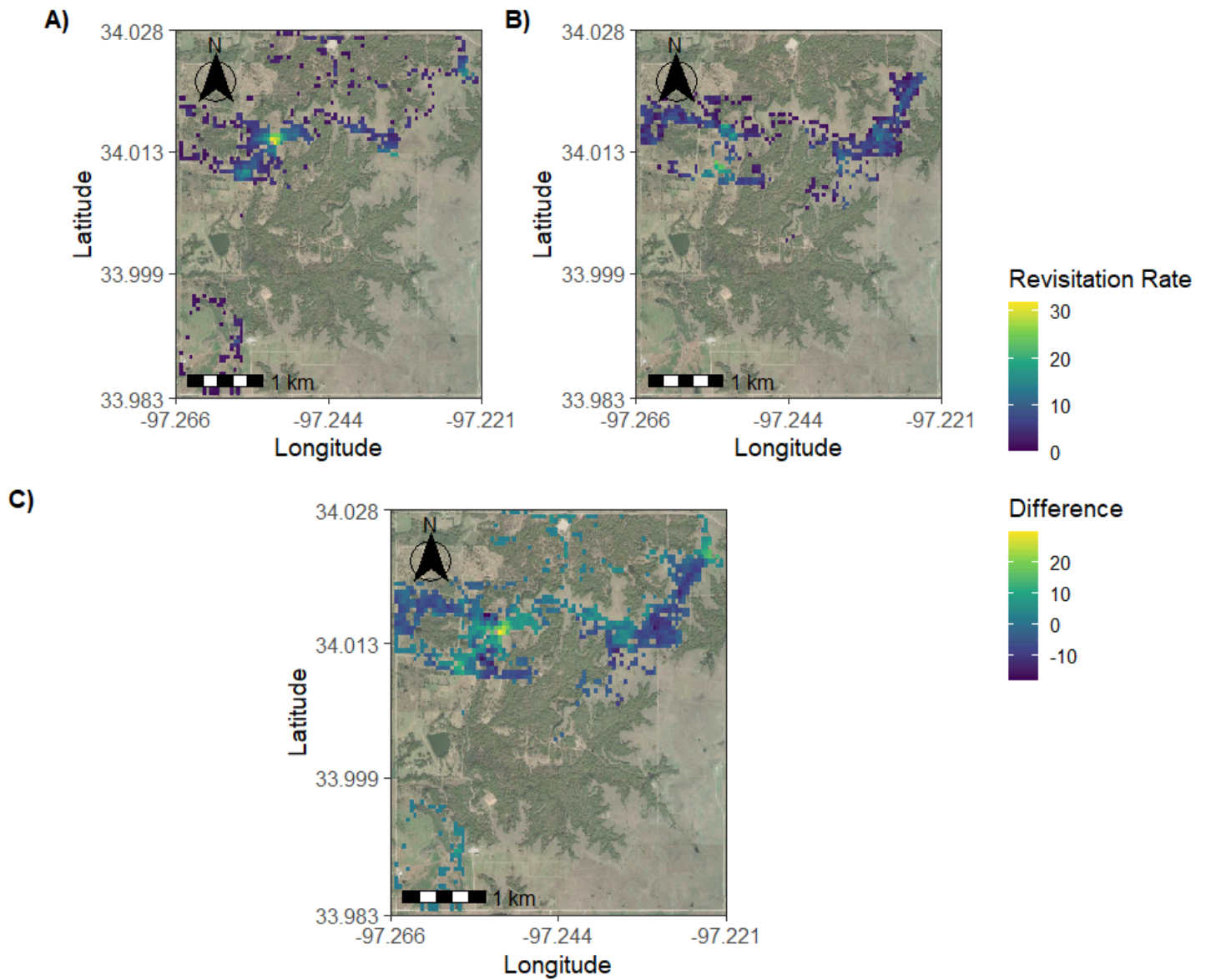


Figure 5

Revisitation-intensity rasters for one domestic cow (*Bos taurus*) at Oswalt Ranch, Love County, Oklahoma. Each 50-m pixel represents the median revisitation rate (revisits/30 d) value associated with GPS locations occurring within that pixel during (A) December 2017 (dormant season), (B) May 2018 (growing season), and (C) the difference between the December and May revisitation rasters (Dec.-May).

Supplementary Files

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