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Research article

Monitoring the effects of ovariectomy on seasonal movement behavior in suburban female white-tailed deer using internet of things-enabled devices

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Abundant deer populations often cause conflicts in suburban communities, yet traditional population reduction methods, such as controlled hunting, can be challenging to implement. Fertility control, specifically through ovariectomy, can limit reproduction and reduce populations in certain settings, but its effect on movement behavior remains poorly understood. Concerns persist that hormonal changes may affect movement behavior, potentially leading to increased physiological demands and influencing deer–vehicle collision (DVC) risks. We evaluated the effects of ovariectomy-induced anestrus on seasonal movement behavior in female white-tailed deer *Odocoileus virginianus* using internet of things (IoT) biologging devices connected via a low-power wide-area network (LPWAN). From 17 January 2023 to 1 June 2024, we collected telemetry data from ovariectomized (treated) and control (untreated) female deer in South Euclid, Ohio, USA, and quantified seasonal movement patterns using 7-day home-range size, daily diffusion, and daily excursivity estimated through continuous-time movement models. Of the three metrics, only diffusion differed significantly between groups. Untreated females exhibited seasonal increases in all three metrics leading up to and during the breeding season (late July to November) and reduced movement around parturition (late May). Treated females did not exhibit strong seasonal behaviors. Although our sample size was small, our findings suggest that ovariectomy removes hormonal triggers without leading to otherwise unusual movement behavior or increasing excursive behavior. Biologging devices using LPWAN-enabled IoT for data transmission proved to be a low-cost, low-power, lightweight alternative to traditional devices that transmit data using satellite or cellular technology, though data transmission was irregular. We conclude that ovariectomy is a safe management tool for controlling abundant deer populations; however, further research is needed

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to more precisely quantify the effects of ovariectomy and explore the potential and limitations of IoT-based biologging for wildlife research.

Keywords: deer management, fertility control, GPS, IoT devices, *Odocoileus* spp., population management

Introduction

Managing abundant deer populations is a significant concern in suburban and urban areas globally (Nugent et al. 2011, Krausman et al. 2014, Curtis 2020). Expanding deer populations contribute to increased deer–vehicle collisions (DVCs; Bissonette et al. 2008, DeNicola and Williams 2008), garden and residential landscape damage (Waller and Alverson 1997, DeNicola et al. 2000), and the spread of tick-borne diseases (Kuehn 2013, Telford 2017). Traditional deer management strategies rely on controlled and recreational hunting (Boulanger et al. 2014, Curtis 2020), but fertility control has gained interest as a potential management alternative in suburban settings where hunting is often restricted or impractical (Fagerstone et al. 2006).

Fertility control methods, including surgical sterilization and immunocontraceptive vaccines, have been studied for their ability to limit reproduction (Matschke 1977, Warren and Warnell 2000, Boulanger et al. 2012, Massei and Cowan 2014, DeNicola and DeNicola 2021). However, little is known about how these interventions influence movement behavior, which is critical in assessing their management implications (Gray and Cameron 2010). Hormonally driven changes in space use can influence energy expenditure, social behavior, and human–wildlife interactions such as DVCs (Beier and McCullough 1990, Bertrand et al. 1996, Hothorn et al. 2015, Stickles et al. 2015). Female white-tailed deer *Odocoileus virginianus* (hereafter, deer) often exhibit distinct movement shifts associated with reproduction, including increased mobility before breeding and parturition, followed by reduced movement post-parturition (Bertrand et al. 1996, D'Angelo et al. 2005, Kolodzinski et al. 2010, Debeffe et al. 2014, Sullivan et al. 2017, Wright et al. 2021). Methods such as ovariectomy and GnRH immunocontraceptive vaccines, which eliminate estrous cycling and subsequently parturition, may disrupt these movement cycles, potentially leading to changes in seasonal movement patterns.

Recent advances in wildlife tracking enable cost-effective, lightweight, low-power, long-term movement data transmission using biologging devices that leverage the internet of things (IoT; Antoine-Santoni et al. 2018, Wild et al. 2023). Traditional biologgers typically rely on satellite or cellular networks for data transmission, which require large battery units and incur high equipment and data transmission costs, factors that can limit their use in budget-constrained research (Tomkiewicz et al. 2010). In contrast, IoT-enabled devices, such as those used in this study, can transmit data via low-power wide-area networks (LPWANs), providing a cost-effective alternative (Antoine-Santoni et al. 2018, Wild et al. 2023). These devices can connect to existing LPWAN infrastructure, where available, or operate through user-installed base stations linked to commercial cellular networks (Wild et al. 2023). Additionally, they support GPS-less geo-location using Wi-Fi networks (Wild et al. 2023).

Beginning in January 2022, the city of South Euclid, Ohio, USA, adopted an integrated deer management strategy that combined professional sharpshooting with surgical sterilization via ovariectomy to manage an abundant deer population in a densely developed suburban environment (Boulanger and Ellingwood 2024). In this free-range treatment–control study, we used IoT-enabled biologging devices connected via a LPWAN to evaluate seasonal movement patterns in ovariectomized and untreated female deer. To understand the effects of ovariectomy-induced anestrus, we tracked individuals from January 2023 to June 2024 and quantified movement behavior across reproductive seasons.

We assessed three key movement metrics: 1) 7-day home-range (HR) size, which quantifies the spatial extent of an animal's local movements; 2) daily diffusion rate, which reflects movement variability and range exploration; and 3) daily excursivity, the tendency for an individual to move outside core-use areas. We hypothesized that ovariectomized females, lacking hormonal cues from estrus and parturition, would exhibit a lower degree of seasonality in their movement patterns. In contrast, untreated females would expand their movement leading up to the breeding season and reduce movement following parturition. We expected peak breeding season to occur annually between 3 and 16 November, and peak parturition to occur between 18 May and 7 June (Nixon 1971). Our study offers new insights into how ovariectomy-induced anestrus influences seasonal movement patterns in female deer and demonstrates the application and limitations of IoT-based biologging as a scalable and low-cost tool for wildlife monitoring.

Material and methods

Study site

The city of South Euclid (41°31'19"N, 81°31'40"W, Fig. 1) is a suburban community in Cuyahoga County, Ohio, USA, located in the northeastern part of the state (Boulanger and Ellingwood 2024). The topography is relatively flat, with a shallow forested ravine at the northern end of the city. At the time of the study, the community spanned approximately 12.2 km^2 and consisted of residential neighborhoods, small commercial areas, and interspersed green spaces, including parks, riparian corridors and privately owned wooded areas. Despite being heavily developed (2019 census: 1768 people km^{-2} in

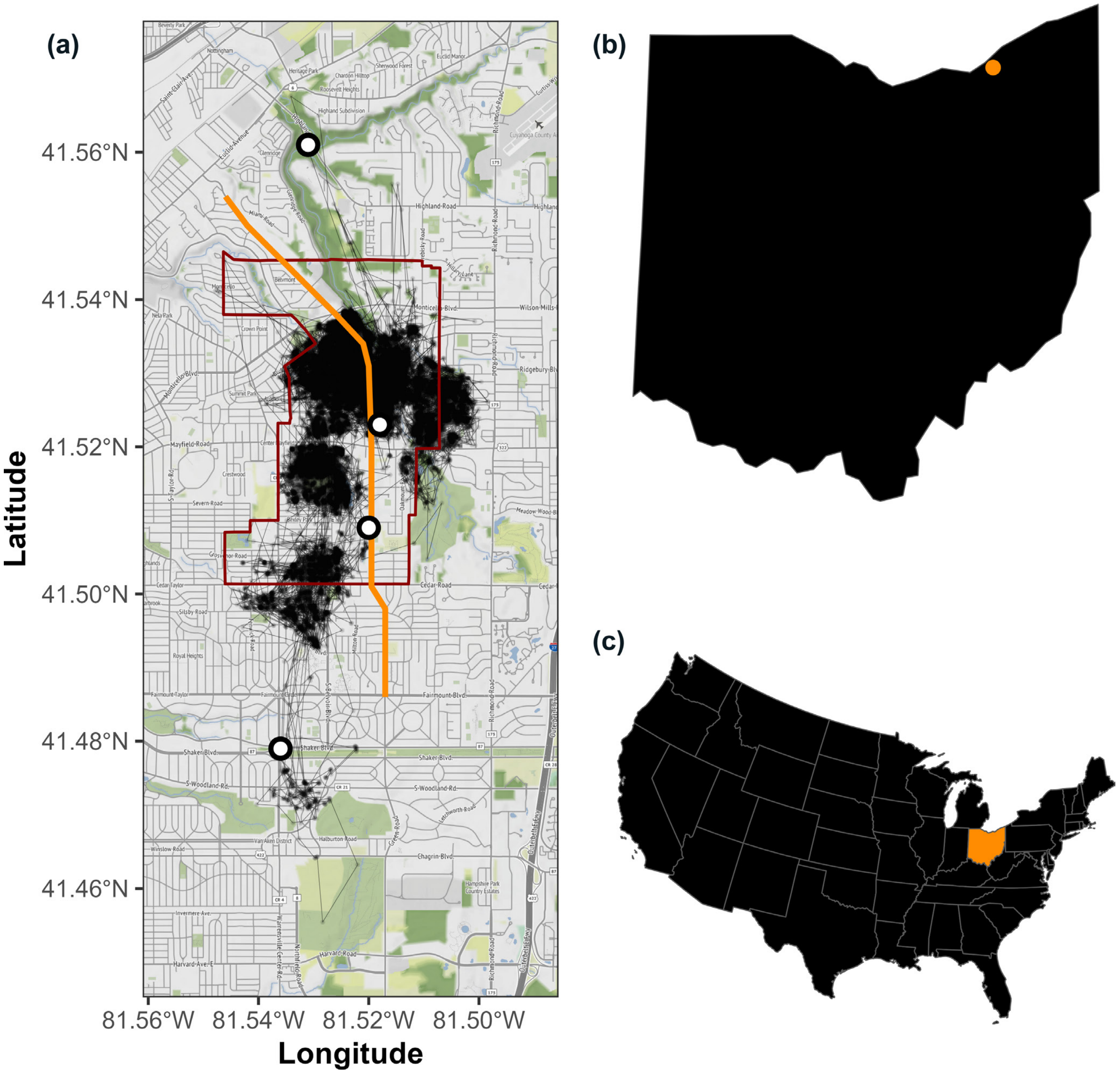

Figure 1. Location of the study area and visualization of white-tailed deer movement data in South Euclid, Ohio, USA. (a) Black points indicate deer telemetry locations (after data cleaning) and are overlaid on a street-level basemap of the study area, South Euclid, Ohio (red boundary). The four white circles indicate the fixed positions of the base stations used for data collection and transmission. Under typical suburban or semi-open conditions, each base station has an effective range of approximately 1–20 km, depending on line-of-sight conditions, environmental obstructions (e.g. buildings, vegetation), and antenna height (Wild et al. 2023). The orange line represents South Green Road. Deer captured west of this road underwent surgical sterilization (treatment group), while those captured to the east remained untreated (control group). Targeted removal of white-tailed deer via professional sharpshooting was conducted on both public and private properties within open spaces throughout the city during two periods: 15–23 February 2023 and 24 October–17 December 2024. (b) Location of South Euclid (orange point) within the state of Ohio. (c) Location of Ohio (orange fill) within the continental United States. Map (a) uses spherical coordinates (EPSG:4326), while maps (b) and (c) use the Universal Transverse Mercator (UTM) projection, Zone 17N. Basemap tiles were sourced from Stadia Maps, Stamen Design, OpenMapTiles, and OpenStreetMap contributors.

9071 households), the distribution of green spaces provides a suitable habitat for deer. South Euclid is bordered by similarly developed communities with connectivity via riparian and green space corridors.

The region has a humid continental climate with four distinct seasons, including cold, snowy winters and warm, humid summers (99 cm average annual precipitation, including 173 cm average annual snowfall). The forested areas are characteristic of the eastern deciduous forest biome, dominated by oak *Quercus* spp., maple *Acer* spp., American beech *Fagus grandifolia* and hickory *Carya* spp.

Recreational hunting is not permitted within the community. During the study, no non-human predators were present that could appreciably limit deer populations. The city has experienced an increase in deer-related conflicts, including rising DVC rates, landscape damage, and concerns regarding the transmission of tick-borne diseases (Boulanger and Ellingwood 2024). In January 2022, the local deer population was estimated at 36 deer km^{-2}, highlighting the need for alternative management strategies (Boulanger and Ellingwood 2024). Targeted removal of deer via professional sharpshooting was conducted in accessible open spaces on both public and private properties within the city (indicated by the red boundary in Fig. 1a) where permission had been granted. Removal occurred during two periods: 15–23 February 2023 and 24 October–17 December 2024. All deer within the city, including those used in this study, were potentially subject to these activities.

Animal capture and handling

Between January 2023 and January 2024, we immobilized adult female deer using projectors with 2 ml transmitter darts (Pneu-Dart Inc.; Kilpatrick et al. 1997). Each dart administered 1.5 ml BAM (butorphanol 0.65 mg kg^{-1}, azaperone 0.22 mg kg^{-1}, medetomidine 0.26 mg kg^{-1}; Wildlife Pharmaceuticals, Inc.) combined with 0.5 ml of 200 mg ml^{-1} ketamine. We approached deer by vehicle on public and private roadways and properties where permission had been granted. Working in coordination with local law enforcement, we used radio telemetry to locate each immobilized deer 15 min post-dart deployment.

We captured and fitted 20 adult female deer with IoT-enabled biologging devices (Sensolus Tracker – SNT3 Compact track 1010; Wild et al. 2023) mounted on nylon collars. These lightweight devices (95 g) were selected for their low power consumption, extended battery life (~ 18–24 months), and affordability (USD95 per unit, plus USD20 for the collar). In additional to GPS fixes, the devices were set to obtained geo-localized fixes via Wi-Fi when available, enhancing spatial coverage (Wild et al. 2023). Devices were programmed to record a location (fix) every 1 h while the animal was in motion and every 6 h regardless of movement status. If an animal remained stationary for more than 5 min, a stop fix was recorded. If the animal resumed continuous movement for at least 1 min, a start fix was logged. These start and stop events were location fixes and were marked with movement status.

The decision to use this sampling regime was based on a tradeoff between battery conservation and the temporal resolution required to estimate three movement metrics: HR size, diffusion rate and excursivity. These metrics operate at timescales greater than 4 h. Prior research in deer using similar sampling rates (DeNicola et al. 2025a) has demonstrated their suitability for evaluating spatial responses to fertility control. Additionally, Fleming et al. (2014) provide a formal framework that demonstrates HR size and exploratory behavior (i.e. diffusion) can be accurately estimated even with moderate fix rates, so long as autocorrelation is accounted for. All individuals were fitted with numbered ear tags for individual identification.

Telemetry data were transmitted via four micro base stations connected to the internet via cellular data (SMBS T4 Micro Base Station, Sigfox; 110 V powered; USD539/unit; data cost: USD20/month; Fig. 1a). The stations were strategically deployed at elevated locations (3–8 m) in collaboration with the manufacturer to ensure the best possible coverage, given the sites made available by the community. In suburban and semi-open environments, these base stations typically achieve an effective range of 1–20 km, although this can vary with terrain, vegetation, and structural interference (Wild et al. 2023). Optimal coverage is achieved when they are installed at elevated, unobstructed locations, whereas signal degradation is more likely in low-lying areas or densely built urban settings (Wild et al. 2023).

Deer captured east of South Green Road were assigned to the control group (n = 10), while those captured west of the road were assigned to the treatment group (n = 10). This boundary was selected due to permit restrictions governing the larger management study, but both groups could move freely across this road. No fawns or yearlings (individuals younger than two years old) were included to better mimic the expected age class in a high-treatment ovariectomy program, where adult females would dominate if reproduction ceased. While approximate ages were recorded using methods described by Severinghaus (1949), all individuals were classified as adult females since the live aging of deer is inherently imprecise.

Control females were released after collaring, whereas treatment females were transported to a public property where surgical ovariectomy was performed following the protocol described by DeNicola and DeNicola (2021). Following the procedure, all animals were returned to their original capture location, selecting release sites with minimal human disturbance to facilitate post-handling recovery. We administered atipamezole (50 mg IM) and naltrexone (25 mg IM) as reversal agents and monitored each deer during recovery.

Data collection continued until battery depletion, mortality, or the individual left the base station coverage area. Collars remained affixed to animals. All procedures were conducted under the Ohio Department of Natural Resources Scientific Collection Permit (no. SC210047).

Data processing and analysis

We downloaded telemetry data collected by the base stations from the manufacturer's website (www.sensolus.com) and transferred it to MoveBank (study ID: 2689852069; 100 374 locations). After downloading the data, we censored the first five days of data following capture (Dechen Quinn et al. 2012). We then identified and removed 162 outlier fixes (0.16% of data) using visual inspection of telemetry data and diagnostic plots of minimum speed (based on straight-line displacement between locations), deviation from the median location, turning angle, and time intervals between locations (procedure available in DeNicola et al. 2025c).

Our objective was to compare seasonal trends in movement behavior between treatment and control females over time. We estimated movement behaviors using continuous-time stochastic movement models, following the workflow outlined by Calabrese et al. (2016) for the 'ctmm' package (ver. 1.2.0) in R ver. 4.4.0 (www.r-project.org), to account for data gaps in movement data and irregular telemetry intervals while addressing inherent autocorrelation. Using a moving-window approach, we analyzed three key movement metrics:

1) 7-day HR size – the estimated area used by an individual within the 7-day window, which we estimated using the 95th percentile of the autocorrelated kernel density estimate (AKDE; Alston et al. 2022, Silva et al. 2022);
2) daily diffusion rate – a measure of mean squared displacement per day that reflects the rate at which an individual explores space over time (Fleming et al. 2016, DeNicola et al. 2025a); and
3) daily excursivity – a metric based on AKDE quantiles that indicates whether an individual is remaining in core-use areas (low excursivity) or venturing into peripheral areas (high excursivity) and provides insight into exploratory behavior.

We modeled the telemetry data for each animal (Supporting information) using a moving-window approach with 7-day windows and 3-day shifts (Smith et al. 2023, DeNicola et al. 2025a). Adjacent windows thus had 4-day overlaps: days one to seven (1–7) would constitute the first window while days 4–10 would correspond to the second window, so both windows included days four, five, six and seven. Given that deer generally cross their range multiple times per day (DeNicola et al. 2025a), we chose the window's duration to be sufficiently long to capture multiple range crossings and produce robust estimates of HR size and diffusion rates (Fleming and Calabrese 2017, Fleming et al. 2018, 2019). On the other hand, we chose the windows to be short enough to provide insights into behavioral changes that occurred over days to weeks (e.g. proestrus/estrus, breeding, pre-parturition, parturition, post-parturition; Nixon 1971, Ozoga and Verme 1975). The four-day temporal overlap between adjacent windows allowed estimates to change smoothly over time. We did not base the window size on the number of observed locations since estimates of HR size and diffusion rate depend on the number of temporally independent observations rather than the total number of observations (Noonan et al. 2018, Silva et al. 2022).

For each window with at least five locations, we fit a continuous-time movement model and AKDE. The AKDE provided an estimate of an animal's 95% home range during the given window. We fit movement models using the *ctmm::ctmm.select()* function, which considers the data's sampling frequency and degree of temporal autocorrelation when selecting among models to estimate an animal's average diffusion (km^2 day^{-1}) and speed (km day^{-1}) during the window (Calabrese et al. 2016). Due to the coarse and irregular sampling of the location data, we were unable to estimate the animals' speed in 76.3% of the windows with HR estimates (i.e. at least five locations), so we did not assess the effects of the treatment on the animals' daily distance traveled. Since the mean sampling time was coarser than the animals' mean directional persistence (i.e. the amount of time the deer walked with a consistent direction and speed), estimates of speed would tend to underestimate the true distance traveled (Noonan et al. 2019, DeNicola et al. 2025a). However, diffusion, a measure of the animals' exploratory behavior, is tightly correlated speed and less sensitive to sampling frequency (DeNicola et al. 2025a). Accurate estimates of HR size do not require sufficiently fine sampling since they depend on an animal's locations but not its movement paths. Instead, unmodeled autocorrelation in telemetry data (i.e. the presence of clear movement paths) is a considerable source of bias in HR estimation (Noonan et al. 2018, Silva et al. 2022).

To estimate excursivity, we first used each animal's entire telemetry dataset to estimate its AKDE throughout the entire tracking period. We then extracted the quantile corresponding to each telemetry location and calculated each animal's daily mean AKDE quantile. A value near 0 indicated that the individual remained in high-use areas, whereas a value near 1 indicated that the individual spent more time in 'peripheral' areas and engaged in more excursive behavior (Fig. 2). Since excursivity did not depend on the 7-day models, we were able to produce estimates of daily excursivity even for 7-day windows with fewer than five locations.

To quantify the seasonal changes in movement behavior, we fitted three hierarchical generalized additive models (HGAMs; Pedersen et al. 2019) using the 'mgcv' package ver. 1.9-1 (Wood 2017) for R. GAMs allow one to model complex nonlinear relationships using flexible, nonlinear, and smooth relationships that are informed by the data rather than by relationships determined a priori by the analyst (Simpson 2018). HGAMs leverage the hierarchical structure of multi-individual datasets to estimate group-level trends while accounting for differences in sample size and variance across individuals.

The HGAMs for the 7-day HR size and daily diffusion used a gamma family of distributions with a log link function, whereas the HGAM for daily excursivity used a beta distribution with a logit link function. Each model had the form:

$$g(\mu_i) \sim f_C(\mathrm{doy}) + \sim f_D(\mathrm{doy})\delta + \sim f_i(\mathrm{doy}),$$

where μ_i is the mean for deer i, g( ) is the model-specific link function, $f_C(\mathrm{doy})$ is the smooth trend over day of year for the control group, $f_D(\mathrm{doy})$ is the difference between the treatment and control group, and δ is a dummy variable that is 0 for control deer and 1 for treated deer, such that the seasonal trend for the treatment group is $f_T(\mathrm{doy}) = f_C(\mathrm{doy}) + f_D(\mathrm{doy})$ (section 7.2.5 of Wood 2017). Finally, $f_i(\mathrm{doy})$ is the individual-level deviation from the group-level estimate. Parameterizing the model in terms of the difference between groups via

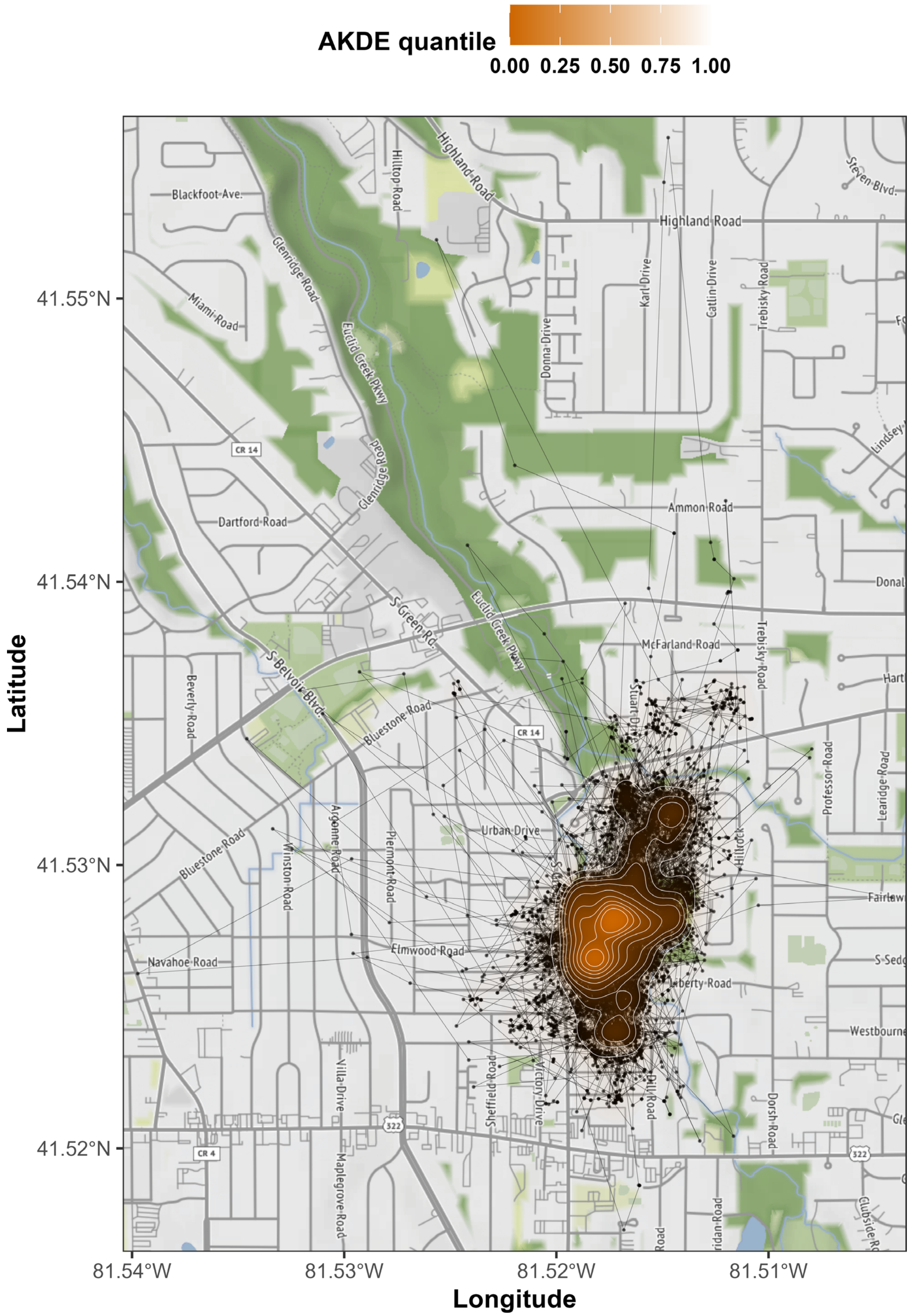

Figure 2. Telemetry data (black dots) and autocorrelated kernel density estimate (AKDE) for female white-tailed deer (individual C_100) in South Euclid, Ohio, USA. Orange shading represents the AKDE cumulative density function, with brighter colors indicating higher-use areas. Contours represent the AKDE quantiles at 0.1 intervals from 0.1 to 0.9. Excursive behavior was quantified using the AKDE quantile averaged across each day's observed locations. Values closer to 0 indicate the deer remained within core-use areas, while values closer to 1 reflect use of peripheral areas and increased excursions. The basemap was sourced from Stadia Maps, Stamen Design, OpenMapTiles, and OpenStreetMap contributors.

the f_D(doy) term allowed us to produce a single p-value for the difference between groups, akin to performing a single F-test for the difference between the groups' intercept and smooth terms at the same time. We optimized smoothness selection using fast restricted maximum likelihood (fREML; Wood 2017, pp. 83 and 262).

To test whether sampling intensity differed between the groups, we fitted a fourth HGAM with the same terms to model the number of daily telemetry fixes each animal had from the deployment of the collar until the day of the last fix (including days with no fixes).

Results

Between 17 January 2023 and 18 January 2024, we handled 20 adult female deer (10 treatment; 10 control; Supporting information). Two telemetry devices failed to transmit data when the individuals left the area (control animals: C_101, C_103) and were excluded from the analysis. One control individual was observed in the area but was omitted due to having only 16 recorded locations (C_201). Data collection concluded on 1 June 2024 and collars remained on the individuals. Additionally, the southernmost base station (Fig. 1a) was offline between ~ 15 March and 1 July 2023, resulting in reduced data transmission for some individuals. We recorded a DVC and a cull in each group, resulting in a total of four mortalities during the study period (Supporting information).

Data quality and movement behavior estimates

After cleaning the data from 17 individuals (10 treatment, 7 control), the final dataset included 100 358 telemetry fixes, with 162 outliers removed (0.16%). The median GPS fix sampling interval was 47 min (Supporting information). Across individuals, the median fix intervals ranged from 33.0 to 64.5 min.

The number of daily fixes varied significantly across time in the control group ($p = 0.0002$), and the seasonal change in daily fixes was significantly different between groups ($p = 0.0064$; Supporting information). Daily fixes declined from 25 February to 1 July 2023, likely due to the base station outage. Since fewer fixes were collected when deer were stationary, variability in data collection may also be influenced by increased sedentary behavior, device/base station failure, or individuals moving beyond the base station coverage area. We were unable to determine the cause of this variability with sufficient certainty.

Our sample included windows from ten treatment and seven control individuals (Fig. 3).

- Five individuals had devices that transmitted data for a limited duration. Three of these individuals (C_106, C_107, T_159) were subsequently observed outside the study area in neighboring communities, while one was observed in the study area (T_160), and one was not observed (C_200).
- Six individuals (C_108, T_152, T_153, T_158, T_163, T_166) had sporadic coverage during the monitoring period. Two mortalities occurred in the group, shortening the monitoring period for these individuals (C_108, T_158).
- The remaining six individuals had regular coverage (C_100, C_102, C_161, T_151, T_155, T_169). One mortality occurred among the group, shortening the monitoring period for this individual (T_169).

Of the 692 7-day windows from seven control animals, we were able to analyze data from: 90.8% windows for HR size, 88.7% for diffusion, and 92.1% for excursivity. For the 1082 7-day windows from 10 treatment animals, the analyzable proportions were lower: 64.5% windows for HR size, 64.3% for diffusion, and 67.9% for excursivity (Supporting information). Note that the percentage of windows with estimates of excursivity is higher than those with HR estimates because we included estimates of excursivity from windows with one to four observations, which were excluded for HR estimation. The effective sample size was above 3 for the great majority of windows for both HR size (1288 out of 1342; 96.0%) and diffusion (1310 out of 1342; 97.6%), which indicated that the 7-day moving window was sufficiently large to obtain robust estimates of both HR size and diffusion (Calabrese et al. 2016, Fleming and Calabrese 2017; Supporting information).

One treated deer (T_169) exhibited movement patterns associated with short-term commuting behavior in ungulates. Commuting behavior is defined as regular, repeated travel between two spatially distinct used areas without establishing a stable central range (Cagnacci et al. 2016, Gurarie et al. 2017). This lack of range residency within approximately 16 windows, relative to the 7-day window size, resulted in 15 unreliable and inflated HR estimates that were 10 times larger than the group mean, and a single outlier diffusion estimate 6 times greater than the group mean (Supporting information). Visual inspection confirmed that this individual made at least eight discrete round-trip movements between two non-contiguous locations. Because (AKDE-based) HR estimation assumes range residency (Silva et al. 2022), these movement bouts spuriously inflated spatial use estimates by including travel corridors. Accordingly, we excluded these windows from further analysis. We observed one additional HR window with commuting behavior in individual T_158, which we similarly excluded from HR calculations (Supporting information).

Seasonal movement trends

All HGAMs exhibited reasonably good fits, though residual histograms showed slightly heavy tails (Supporting information). The models explained 74.3% of the deviance in 7-day HR size, 58.4% of the deviance in daily diffusion, and 31.1% of the deviance in daily excursivity.

Overall, both groups had similar HR sizes, diffusion, and excursivity (Fig. 4). Control deer followed seasonal physiological cycles ($p < 2 \times 10^{-16}$ for all three metrics),

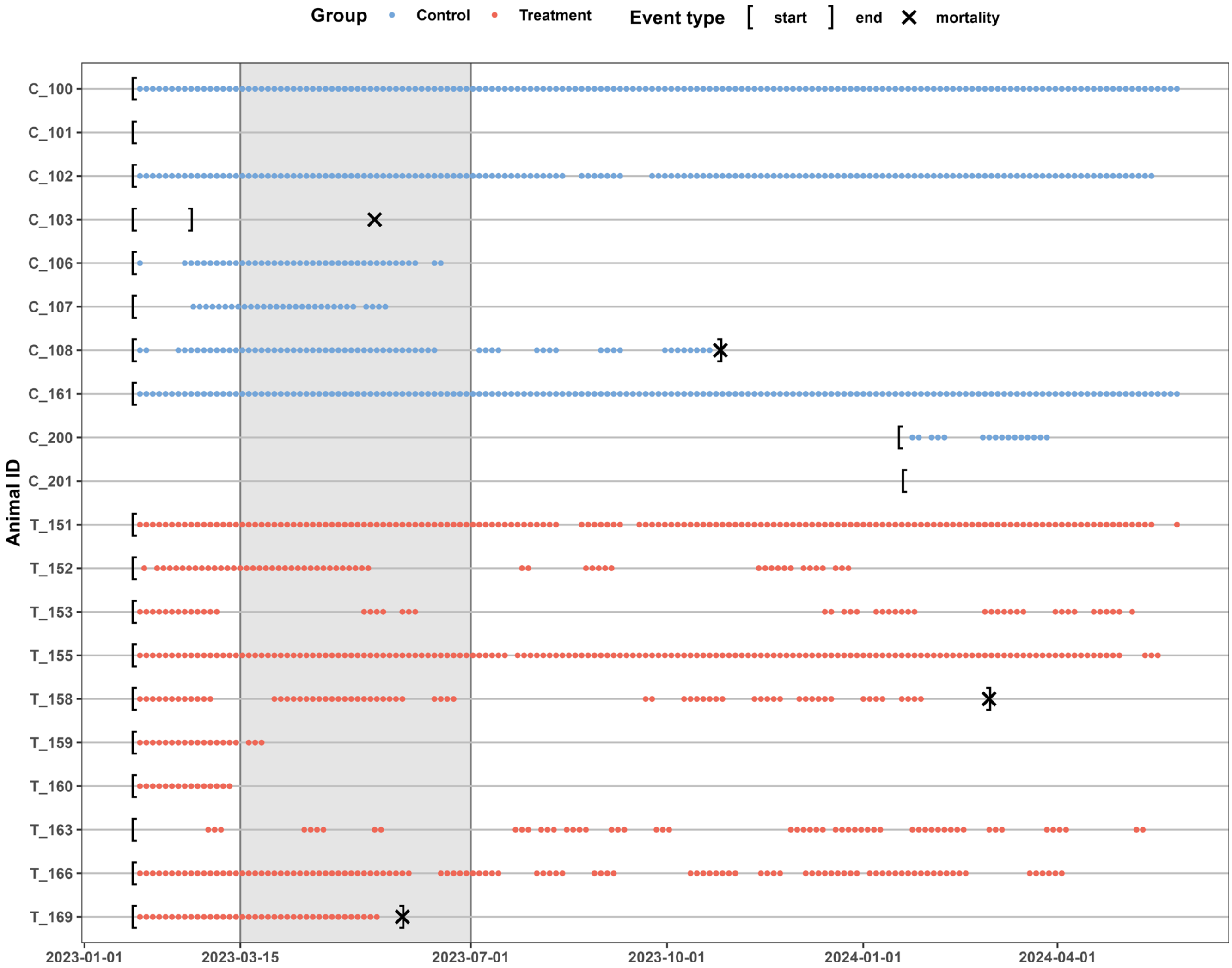

Figure 3. Sampling events from biologging devices for the control (C) and treatment (T) white-tailed deer in South Euclid, Ohio, USA. Each dot represents the center of a 7-day window with at least five fixes. The gray band represents the period when the southernmost base station was offline, from 15 March to 1 July 2023.

increasing movement leading into the breeding season (late July–November) and reducing movement during and after parturition (April–June; Fig. 4). In contrast, treated deer showed little or no common seasonal behavior for any of the metrics. Overall, differences between groups, averaged across day of year, were small (HR size: 0.1 km^2; diffusion: -0.03 km^2 day^{-1}; excursivity: 0.004), and only diffusion differed significantly between groups (Fig. 4; $\alpha = 0.05$; HR size: $p = 0.102$; diffusion: $p = 0.0007$; excursivity: $p = 0.101$).

Discussion

Our findings indicate that ovariectomized deer had, overall, similar HR sizes, diffusion, and excursive behavior to control deer. However, based on visual trends of the metrics (Fig. 4), control females exhibited expected seasonal shifts associated with reproductive cycles, whereas treated deer maintained relatively stable movement patterns year-round. The increase in control females' HR size, diffusion, and excursivity during the pre-breeding and breeding seasons is consistent with an increase in fawn mobility that occurs in late summer (Webb et al. 2010, Holland et al. 2024) as well as mate-searching behaviors that are typical of late fall and winter (D'Angelo et al. 2005, Kolodzinski et al. 2010, Sullivan et al. 2017). During parturition (May–June), control females exhibited an expected contraction in movement as they selected fawning sites and engaged in maternal care (D'Angelo et al. 2005, Webb et al. 2010, Wright et al. 2021). In contrast, the estimated mean of all three metrics increased for treated females during the same period. Thus, although the differences between groups were not always significant, the lack of change in HR size, diffusion, and excursivity for treated deer between seasons provides some evidence that eliminating estrous cycling may not only remove the hormonal cues that drive reproductive-linked shifts in movement

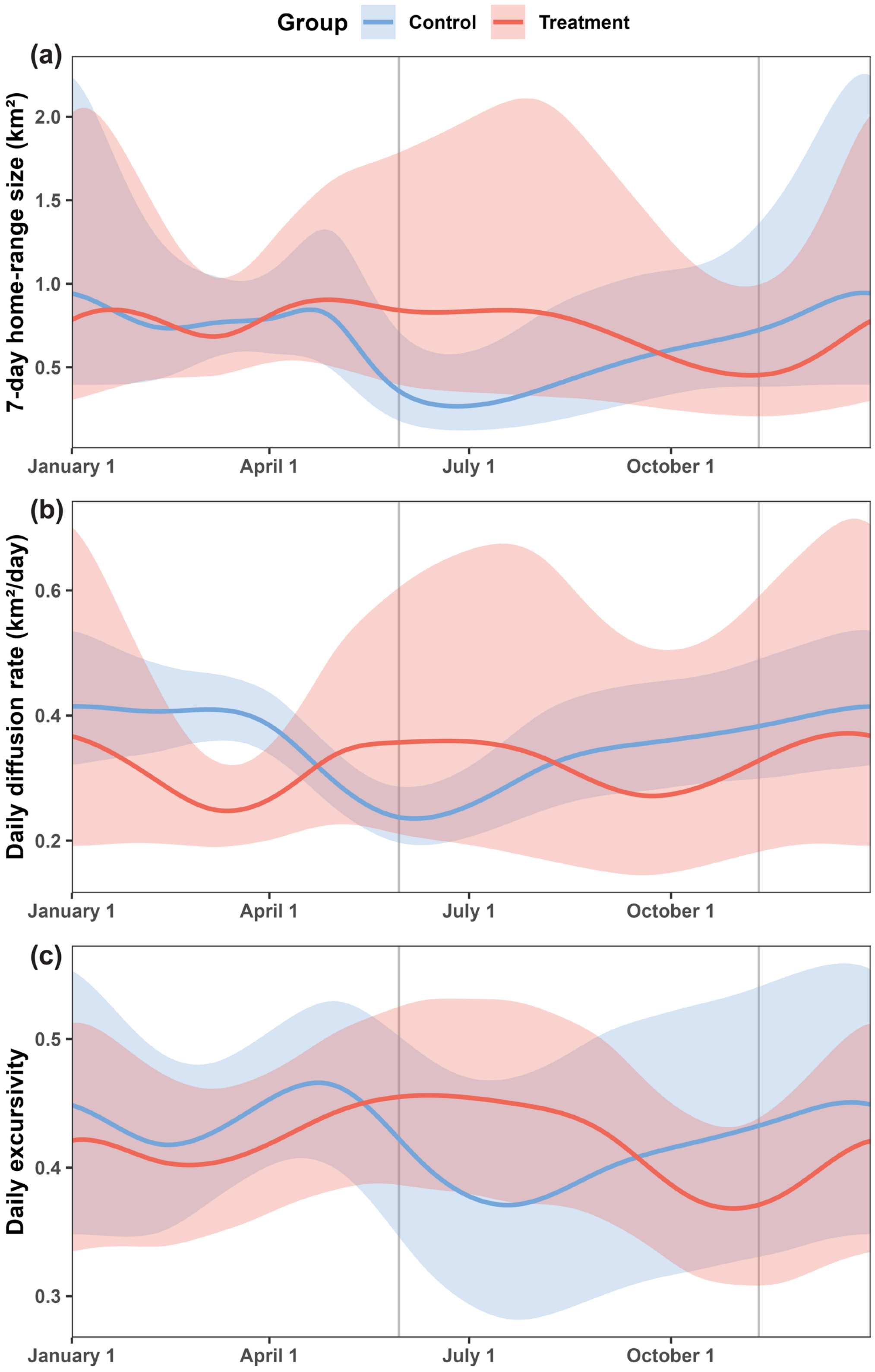

Figure 4. Seasonal trends in movement behavior of treated and control female white-tailed deer in South Euclid, Ohio, USA. Group-level seasonal patterns in (a) 7-day home-range size (km^2), (b) daily diffusion rate ($km^2\ day^{-1}$), and (c) daily excursivity for ovariectomized (treatment; red) and untreated (control; blue) adult female white-tailed deer. Curves represent the estimated group-level trends from hierarchical generalized additive models (HGAMs), with shaded ribbons indicating 95% Bayesian credible intervals (under the assumption of Gaussian coefficient estimates). Vertical gray lines denote estimated biological milestones for Ohio deer populations: peak parturition (~ 30 May) and peak breeding (~ 10 November) based on Nixon (1971). Telemetry data were collected from 17 January 2023 to 1 June 2024. After data cleaning and exclusion of individuals with insufficient data, final sample sizes included 10 treated females and 7 control females.

behavior but may also allow other drivers of movement to have greater effects on movement behavior (Nathan et al. 2008). Still, the negligible differences in overall mean HR size, diffusion, and excursivity suggest that ovariectomy does not introduce any concerning differences in space use or movement behavior (e.g. increases in HR size or exploratory behavior) or energetic expenditure. While treated deer had, on average, slightly greater HR size, diffusion, and excursivity than post-parturition control deer, the minimal differences are unlikely to result in increased energetic costs. Particularly since ovariectomized deer do not undergo gestation, parturition, or lactation, all of which would have higher metabolic demands than the routine movement seen during this period (Hewitt 2011).

Three factors contributed to the large uncertainty in the estimated difference between groups: 1) the small number of individuals per group, 2) the irregular data sampling, and 3) the variability in the estimated trends of treated individuals. The estimates for treated deer were thus most uncertain during late spring and summer, when data were relatively scarce and individual estimates were most variable. Additionally, the uncertainty in the behavior of the treated group was likely exacerbated by the lack of synchronous behavior among treated deer. Future studies should leverage a larger sample size and more consistent sampling frequencies to estimate the potential differences between groups with greater precision and, if possible, identify the main drivers of movement behavior in the absence of hormonal cues.

The removal of fawning for treated deer would likely cause an overall decline in both spring and fall DVCs. Spring collisions often coincide with behavioral displacement during parturition, and fall collisions are driven by breeding behavior and yearling male dispersal (Marcoux et al. 2005, Ramakrishnan et al. 2005). While we found no evidence of differences in DVC-related mortality among groups, we acknowledge that our sample size was small. Future studies should investigate movement with larger sample sizes and more reliable biologging devices.

Device performance and data limitations

A key limitation of our study was gaps in our data due to the reliance on biologging devices that required base station coverage for data transmission. While the Sigfox IoT network has coverage in 70+ countries, there was no coverage in the USA at the time of this study (https://sigfox.com/coverage/). To collect data, we needed to deploy and maintain micro-base stations that required power and cellular-based connectivity. While this system provided a cost-effective alternative to traditional data transmission modes, such as cellular or satellite, it introduced challenges related to data completeness, as failed and irregular transmission resulted in gaps between fixes. The commuting behaviors of some deer exacerbated irregularities; however, there is no evidence suggesting that the treatment affected their commuting behavior. Instead, the behaviors we observed likely represent natural variation in behavior, especially since the movement behavior was similar across groups.

Additionally, the Sensolus Track 1010 devices were configured with a target GPS sensor accuracy of 25 m, meaning that 50% of location fixes are expected to fall within a 25-m radius of the true position. While this level of accuracy is lower than that claimed for GPS sensors used for traditional collars, it is generally sufficient for estimating broad-scale movement metrics such as HR size, diffusion rate and daily excursivity. These metrics are robust to small-scale location uncertainty, especially when analyzed using continuous-time movement models that explicitly account for spatiotemporal autocorrelation (Calabrese et al. 2016, Fleming et al. 2018, Silva et al. 2022). Thus, while Sensolus devices with these settings were not suitable for estimating fine-scale habitat selection, step-level path analysis, or movement trajectories and speed (Noonan et al. 2018), they were well-suited to evaluating seasonal and population-level patterns in space use under constraints of cost, collar weight, and deployment duration. To improve the reliability of IoT-enabled biologging, future deployments may benefit from additional base station coverage, manual data retrieval efforts (e.g. using drones or vehicles to collect data), or integration with complementary tracking technologies such as VHF for real-time detection, as well as higher accuracy GPS settings. While the system proved useful in this setting, researchers should consider the limitations when applying similar methods in broader landscapes with more extensive animal movements, such as migrations or a lack of range residency. It was not possible to evaluate the performance of Wi-Fi geo-location in providing locations, which is an advantage of IoT-enabled biologging.

Our choice of statistical models was particularly valuable in addressing data limitations. HGAMs enabled us to estimate seasonal trends across multiple individuals and over two years while accounting for variations in data frequency and also allowing the estimated behaviors to vary smoothly over time (Marra and Wood 2012, Wood 2017, Simpson 2018, Pedersen et al. 2019). Continuous-time movement models allowed us to model movement behavior while accounting for location error, avoiding the limitations of discrete-time modeling, including irregular sampling (Calabrese et al. 2016). Thus, although the small sample size and irregular data collection resulted in relatively uncertain estimated differences between groups, our findings appear to be informative and representative of the effects of ovariectomy on female deer. Still, we suggest that future studies aim for larger sample sizes as well as finer and more regular sampling.

Management implications and future research directions

The efficacy of fertility control in limiting deer population growth over time has been well studied (Gray and Cameron 2010, Boulanger et al. 2012, DeNicola and DeNicola 2021), but potential behavioral side effects have received less attention. Our findings suggest that ovariectomy does not induce changes in movement behavior that compromise the health or alter the spatial ecology of treated individuals. However, due to our small sample size, it is not possible to credibly conclude whether the treatment affects the incidence of DVCs.

Monitoring both treated and untreated animals with consistent data quality is essential, but it is logistically and financially challenging, especially in communities that are reluctant to fund the capture and monitoring of untreated control animals. In future studies, further attention should also be given to how landscape features, health status, and social interactions shape movement behavior, as these factors likely become central drivers of movement in the absence of hormonal and reproductive cues, particularly in an aging population (Nathan et al. 2008). As conflicts with abundant deer populations continue to increase in suburban landscapes worldwide, evaluation of alternative management strategies should remain a priority.

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Author contributions

Vickie DeNicola: Conceptualization (lead); Data curation (equal); Formal analysis (equal); Funding acquisition (equal); Investigation (lead); Methodology (equal); Project administration (equal); Resources (equal); Software (supporting); Validation (equal); Visualization (supporting); Writing – original draft (lead); Writing – review and editing (lead). **Stefano Mezzini**: Data curation (equal); Formal analysis (equal); Methodology (equal); Software (lead); Validation (equal); Visualization (lead); Writing – original draft (supporting); Writing – review and editing (supporting). **Francesca Cagnacci**: Conceptualization (supporting); Formal analysis (equal); Funding acquisition (equal); Methodology (supporting); Project administration (equal); Resources (equal); Supervision (lead); Validation (equal); Writing – original draft (supporting); Writing – review and editing (supporting).

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Data availability statement

Data are available from the Dryad Digital Repository: https://doi.org/10.5061/dryad.h70rxwdxb (DeNicola et al. 2025c).

Supporting information

The Supporting information associated with this article is available with the online version.

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