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The Potential Role of High-Resolution Telemetry in Supporting Spatial Management of Forest-Wildlife Interactions

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Abstract

The research analysed the space-use and habitat-preference characteristics of red deer (*Cervus elaphus*) in the Sopron Mountains, Hungary, utilising high-resolution Global Positioning System (GPS) telemetry data and two distinct land-cover databases. Hourly location data from 10 individuals were processed using the minimum convex polygon (MCP) and kernel home range (KHR) methods. Additionally, a relative stability index (RSI) was developed to describe seasonal shifts in area use. Significant sexual dimorphism was identified in the extent of annual home ranges: the mean space use of stags (3381 ha) significantly exceeded that of hinds (1391 ha). Geomatical analyses highlighted the seasonality of space use: the smallest extent was recorded in June, and shifts in home ranges within a single year were significant, while the winter period exhibited the least seasonal variation. Regarding habitat selection, significant seasonality was observed in hinds, reflecting temporal changes in resource availability, whereas this pattern was not observed in stags. The study concluded that the applied methods are appropriate for gathering baseline information; however, integrating high-precision databases is essential for accurate modelling of deer–forest interactions.

Keywords: red deer; habitat use; land cover data; GPS collar; Jacobs' selectivity index

1. Introduction

Large herbivores are key drivers of forest ecosystem dynamics, governing both vegetation structure and composition [1]. Their foraging and movement patterns shape biodiversity; nevertheless, the population growth witnessed in recent decades has introduced substantial economic challenges. A primary concern in sustainable forest management is maintaining equilibrium between wildlife and vegetation [2]. Browsing pressure from increased populations may limit, or in extreme cases, entirely prevent forest regeneration, whilst selective browsing further modifies species composition. Consequently, these impacts are not merely ecological but represent a critical economic factor, as browsing degrades timber quality and significantly raises the reforestation costs [3]. Damage mitigation, such as fencing construction, imposes additional financial strain on managers and contributes to habitat fragmentation, which in turn, indirectly influences population densities [4]. Managing these forest–wildlife interactions has therefore become a complex undertaking that requires rigorous, evidence-based data collection. Conventional

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approaches, such as strip transects, winter track counts, or pellet group counts, frequently yield unreliable data regarding species distribution or behaviour, often due to inadequate survey design or improper implementation [5]. Such indirect observations, along with earlier low-resolution VHF (Very High Frequency) telemetry, lack the precision needed to describe fine-scale spatial use, habitat preferences, and diel activity patterns. Due to their limited spatial resolution, these datasets often remain static and fail to capture wildlife's dynamic responses to environmental shifts [6].

In recent decades, advancements in geographic information systems (GISs) and modern remote sensing have facilitated the growth of movement ecology, enabling a more thorough investigation of human–wildlife interactions, particularly the ruminant–forest relationship [7]. High-resolution remote sensing data, such as LiDAR or satellite-based databases (e.g., CORINE, Landsat), enable the detailed mapping of habitat structure across extensive areas [8]. These geomatic layers are now indispensable for understanding spatial distribution and complex movement patterns, as they provide an objective basis for analysis. Through integrated data analysis, researchers obtain more precise insights into environmental responses, thereby directly informing the development of scientifically grounded decision-support systems [9]. GPS (Global Positioning System) telemetry enables the continuous, high-resolution tracking of individuals, significantly exceeding the capabilities of earlier methods such as visual observations of colour-coded or numbered tags and VHF radio telemetry [6]. The technology provides fine-scale spatial and temporal data, facilitating the analysis of behavioural processes and movement patterns that were previously inaccessible or difficult to characterise [10]. The precision of fine-scale GPS datasets has significantly advanced movement ecology, enabling more reliable home-range estimations, movement activity analyses, habitat-suitability modelling, and the detailed identification of individual responses to environmental variables [11].

High-resolution telemetry provides animal movement data at near-continuous rates with detailed spatial and temporal resolution. This technology is not merely a static positioning tool but a method capable of recording precise temporal metrics, such as residence time within specific areas (duration) or revisitation frequency [12]. Such data density allows for the fine-scale differentiation of behaviours—for instance, distinguishing between resting and foraging—revealing exactly when and for how long an individual utilises resources within a given habitat [13]. The resulting spatiotemporal information is well-suited for informing site-specific management decisions [14]. However, fine-scale GPS fixes are raw spatiotemporal coordinates in isolation; their ecological significance is derived from their integration with heterogeneous environmental databases [15], such as land cover (CORINE [16]), terrain (DTM [17]), and vegetation structure (LiDAR [18]) layers. The key to the geomatic approach lies in consolidating data from disparate sources onto a common spatial platform (GIS), which enables the identification of relationships between movement patterns and environmental variables [19]. The use of GNSS (Global Navigation Satellite System) technology in closed forest stands and rugged terrain poses significant technical challenges, as canopy shading and steep slopes can induce multipath effects [20]. To ensure the reliability of geomatic analyses, it is critical to control for positioning errors, for example, by filtering data based on HDOP (horizontal dilution of precision) values [21]. Integrating GPS points recorded in the global WGS84 system with databases held in local projections requires precise transformation to maintain geometric fidelity. This positional accuracy is a prerequisite for 'point-in-polygon' analyses, ensuring that each localisation is correctly assigned to the actual land cover type [22]. Furthermore, the temporal resolution of telemetric sampling dictates the detail of the movement trajectory, where addressing statistical autocorrelation is essential for unbiased modelling. In spatial modelling, synthesising

polygon-based (e.g., CORINE) and continuous raster-type environmental variables remains a complex interoperability challenge [23].

Red deer (*Cervus elaphus*) is among Europe's most widespread large herbivores, with populations growing significantly over recent decades [24]. Through its foraging strategy and habitat selection, it influences the vegetation composition and woody plant succession described above. These characteristics render it an appropriate model species for investigating forest–herbivore interactions by examining fine-scale spatial use [25]. Central to this is determining the home range, which delineates the area where an individual conducts activities essential to survival, such as foraging and reproduction [26]. One of the longest-established methods for quantifying home ranges is the minimum convex polygon (MCP), which defines the area of use by connecting the outermost recorded positions [27]. While the MCP effectively represents the total extent of the area traversed, it is often criticised for overestimating the actual space requirements, as it incorporates outliers and occasional movements, thereby including unused areas within the home range [28]. In contrast, kernel home range (KHR) methods provide a probabilistic estimate of area use based on the spatial density of GPS fixes [29]. The 90% KHR (KHR90), widely used in red deer research, enables a more refined delineation of the home range, allowing uncertainties arising during trajectory analysis to be managed with a specific smoothing parameter [30]. These two methods have been widely used in red deer studies around Europe in the last decades [31–38]. Conventional KHR approaches assume statistical independence between successive locations, an assumption that may be violated during modern, high-frequency tracking [39]. To address temporal autocorrelation, frameworks and methodologies such as autocorrelated kernel density estimation (AKDE) have been developed and are increasingly utilised in movement ecology [40]. Evaluating high-resolution telemetry data by applying multiple methods in parallel provides a robust basis for data interpretation [28]. Habitat availability and preference are fundamental to the formation of the home range. During habitat use, individuals decide how to utilise available resources through a series of innate and learned behavioural responses. High availability of a specific habitat type within the home range does not necessarily imply high usage or preference [41]. To evaluate a habitat type as a genuine driver, selectivity indices—such as Jacobs' index [42]—are employed, which quantify conscious selection or avoidance by comparing use with availability. Combined, high-resolution telemetry and preference indices facilitate a deeper understanding of the species' behaviour [43].

The study proceeds from the premise that investigating high-resolution telemetry datasets can reveal the potential of precision spatial data to support forest–wildlife management more effectively than traditional, generalised systems. The fine-scale spatial and temporal information revealed by telemetry permits the identification of critical habitat types, providing a baseline to support long-term forest planning and wildlife management schemes. Our objective was to robustly estimate red deer home ranges in the Sopron Mountains and characterise temporal shifts using high-resolution GPS data while evaluating the performance and consistency of traditional estimation methods. Furthermore, we analysed preferences across static land-cover and forestry databases, with a particular focus on young forest stands in relation to diel dynamics. This is presented within a methodological framework that evaluates the supportive role of integrated baseline data while critically highlighting their inherent spatiotemporal limitations, thereby establishing a foundational stepping stone for future predictive modelling.

2. Materials and Methods

2.1. Study Area

The research was conducted in the Sopron Mountains, situated in the northwestern region of Hungary (Figure 1), as part of the eastern foothills of the Alps (elevation ranging from 250 to 550 m a.s.l.) [44]. Steep valleys and undulating plateaus characterise the area's geomorphology. Approximately 85% of the land cover consists of closed-canopy forests—predominantly oak (*Quercus* spp.), beech (*Fagus sylvatica*), and conifers—which are sharply demarcated from the surrounding agricultural and urbanised landscapes [31]. A defining feature of the study site is its immediate proximity to the city of Sopron. The designation of peri-urban forest sections as park forests, coupled with an extensive network of marked hiking trails, results in significant anthropogenic pressure. From a wildlife management perspective, the area is intensively managed. The two most dominant large ungulate species are red deer and wild boar (*Sus scrofa*), with roe deer (*Capreolus capreolus*) also present. Population control for these species is conducted in accordance with statutory hunting seasons through both individual stalking and organised driven hunts.

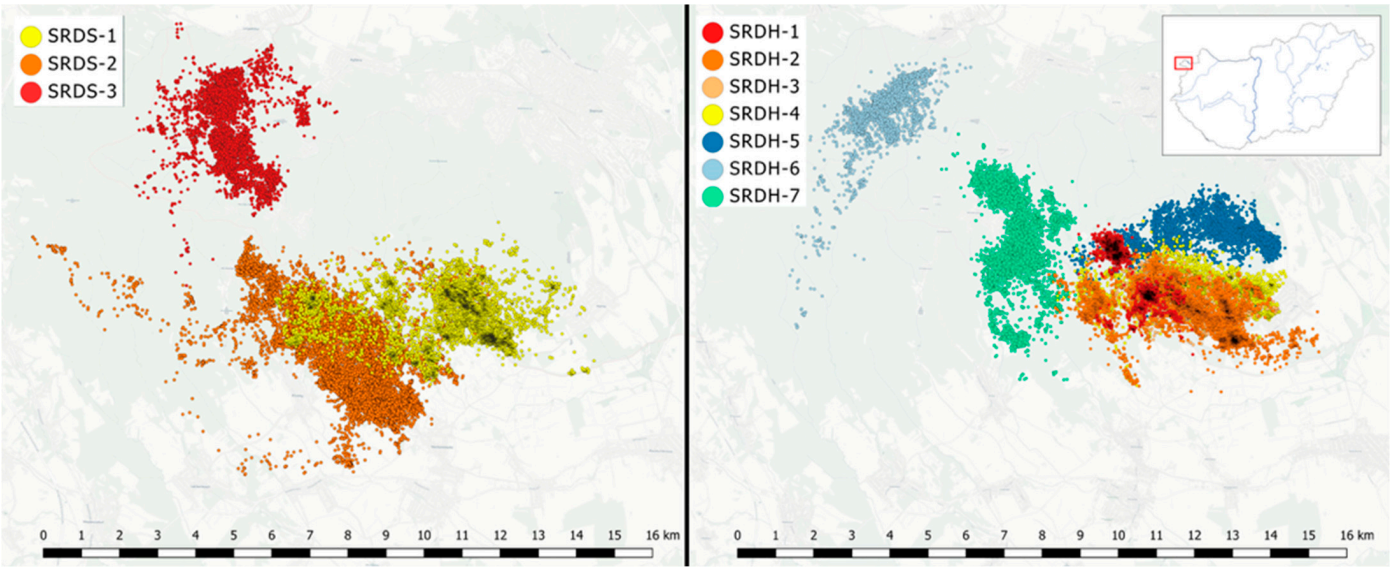

Figure 1. Map of the study area (Sopron Mountains); the left part of the picture represents the telemetry locations of collared and tracked hinds, while the right part of the picture represents the locations of collared and tracked stags. Background map: ©CARTO, Data: ©OpenStreetMap contributors.

2.2. Capture and Marking Protocols

The capture and handling procedures employed during the marking process complied with relevant international animal welfare guidelines and national legislation (Act LV of 1996; FVM Decree 79/2004. (V. 4.)). Capture operations were conducted during the winter period using horizontal drop nets deployed at established feeding stations [45]. Manual activation of the netting system ensured high selectivity, targeting only adult individuals of both sexes. Upon capture, individuals were immediately subjected to chemical immobilisation and injected with a uniform intramuscular dose of 150 g/kg body weight of 10 mg/mL Cepesedan® (CP-Pharma Handels GmbH, Burgdorf, Germany) [32]. To mitigate capture-induced stress, blindfolds were applied throughout the procedure. Respiratory rates were continuously monitored throughout the immobilisation [46]. To minimise handling time, all sampling and marking protocols were completed within 15 min [47]. Following marking, all animals were released in situ at the capture site. A total

of 10 individuals (7 adult hinds and 3 young stags, 3–5 year olds) were marked during the study (Figure 1; Table 1).

Table 1. Tracking data of collared individuals.

Identifier	Sex/Age Group	Monitoring Period	Number of Monitored Days	Number of Filtered Fixes Used in Data Processing	Mean Daily Number of Fixes (Mean ± SE)
SRDH-1	Middle-aged hind	01-03-2005–28-02-2006	357	7609	21.31 ± 0.09
SRDH-2	Middle-aged hind	01-03-2005–28-02-2006	365	7752	21.24 ± 0.08
SRDH-3	Middle-aged hind	01-03-2005–31-08-2005	184	3960	21.52 ± 0.1
SRDH-4	Middle-aged hind	01-03-2006–28-02-2007	365	8574	23.57 ± 0.06
SRDH-5	Middle-aged hind	01-06-2007–29-05-2008	364	8614	23.66 ± 0.05
SRDH-6	Middle-aged hind	01-03-2010–30-07-2010	152	3468	22.82 ± 0.17
SRDH-7	Middle-aged hind	01-03-2008–28-02-2009	365	8554	23.44 ± 0.08
SRDS-1	Young stag	01-03-2005–28-02-2006	365	7503	20.56 ± 0.13
SRDS-2	Young stag	01-06-2008–31-05-2009	365	8398	23.01 ± 0.07
SRDS-3	Young stag	01-03-2010–18-02-2011	355	8017	22.58 ± 0.1

2.3. Collaring and Telemetry

The captured individuals were fitted with Followit Tellus (Followit AB, Lindesberg, Sweden) GPS collars. In all instances, the device's total mass remained below 3% of the individual's estimated body mass [48]. The collars were programmed with a 1-h fix interval, providing a high-resolution dataset suitable for fine-scale movement analysis [49]. The units were equipped with integrated mortality sensors. Throughout the study period, monitoring was conducted via VHF telemetry; in addition to field observations, data were periodically checked and downloaded using an RX900 (Followit AB, Lindesberg, Sweden) receiver unit. The final dataset used for analysis was retrieved after the collars were physically recovered. To adhere to animal welfare standards and ensure reliable equipment retrieval, each collar featured a timed drop-off mechanism [36] that released the device no later than 15 months post-deployment.

2.4. Data Processing

Data retrieval and conversion were performed using the Tellus Project Manager v.1.09 (TPM) software (Followit AB, Lindesberg, Sweden). The raw GPS database was subjected to a multi-stage filtering protocol to eliminate technical errors and biologically implausible movements [50]. The precision of spatial analyses was controlled using quality metrics, whereby only coordinates with a PDOP (position dilution of precision) value below 10 were retained [51]. Based on prior stationary tests conducted under a closed canopy during the vegetation period, the mean positional error of the employed technology ranged from 5 to 12 m, consistent with international accuracy standards for large-mammal telemetry studies [52]. During outlier management, positions were excluded if the velocity between two successive points exceeded 15,000 m/h. The filtered dataset underwent a final visual inspection to manually remove anomalies not identified by the software, such as 'spikes' (unrealistic, abrupt changes in direction) [53]. To account for potential behavioural biases induced by capture and marking stress [54], data from the first 15 days post-capture were excluded from the analysis. Transformation of GPS coordinates, spatial data visualisation, and database management were executed using TopoLynx-topXmap v3.19.1.20 (TopoLynx Kft., Kőszeg, Hungary). Home range sizes were calculated using the Animal Movement Analyst Extension for ArcView 3.2. ESRI (Environmental Systems Research Institute, Redlands, CA, USA) [55]. To ensure spatial consistency, all coordinates were projected into the Hungarian Uniform National Projection (EOV/EPSG:23700). The light-grey geographic

background on figures was provided by the CartoDB Positron basemap (Map data © OpenStreetMap contributors, styled by CARTO under CC BY license).

2.5. Data Analysis

Following data validation, a cumulative dataset encompassing 107 months in total and 72,449 validated positions was incorporated into the analyses. Relative to the expected fixes, the average data loss per individual was 5.95%, and the average proportion of locations excluded from the study was 1.48% per individual. Data analysis was conducted on the period and number of positions for all individuals, as shown in Table 1. To justify the chosen sampling density, preliminary subsampling/rarefaction analyses were performed. During these tests, the sampling frequency ranged from 24 locations per day to 1 location every two weeks [56]. Reducing the number of positions down to 4 fixes per day resulted in only minimal changes in the home-range estimates. Although sparser sampling would have been sufficient for delineating home ranges, we opted to retain the hourly dataset because it provides the necessary resolution to analyse fine-scale spatial dynamics, accurately determine habitat use, and assess habitat preference characteristics. To evaluate the extent and spatial dynamics of home ranges, two complementary methods were employed. The minimum convex polygon (MCP) method [27] was used to delineate annual (requiring at least 12 months of tracking), seasonal (Spring: March–May; Summer: June–August; Autumn: September–November; Winter: December–February), and monthly home ranges. For monthly assessments, only complete calendar months were included, and the MCP method was used exclusively to maintain robustness against lower sample sizes. Additionally, the kernel home range (KHR) estimator was applied [57]; a larger isopleth (KHR90) was used to define general space use, while a smaller isopleth (KHR60) was utilised to identify core areas [58].

To quantify the spatial shift of home ranges, a relative stability index (RSI) was introduced. This index was defined as the ratio of the total home range (MCP) calculated for a given period (annual or seasonal) to the arithmetic mean of the monthly home ranges (MCP) within that same period. The index serves as a proxy for site fidelity and spatial dynamics. Values approaching 1 indicate stable space use and high overlap between successive monthly home ranges; increasing values signify greater spatial segregation at the monthly level, reflecting a shift in the home range within the season and a reduction in overlap.

Habitat use was quantified by determining the relative frequency of locations within various land cover categories [38]. Habitat selection was measured using the Jacobs' index [59], which assesses the asymmetry between habitat use and availability, $D = (r - p)/(r + p - 2rp)$, where 'r' is the proportion of habitat use; 'p' is the proportion of habitat available to red deer; D varies from −1 to +1, where −1 to 0 indicates negative preference, and 0 to +1 indicates positive preference for the habitat [60]. Availability was defined based on the habitat composition within each individual's annual MCP [38]. In addition to broad-scale landscape use, we specifically monitored red deer presence in 0–15-year-old forest stands, which are critical for browsing damage. These stands were classified into three age classes: regeneration (1–5 years), thicket (5–10 years), and pole stage (10–15 years). A total of 17,080 GPS positions recorded across 120 forest compartments were analysed. The frequency of use for these areas was analysed at hourly scales, with particular emphasis on diel (day/night) patterns.

2.6. Land Cover Databases

To characterise the habitat features of the study area, we integrated two spatial datasets with differing resolutions. For the identification of broad-scale land cover categories, the

CORINE Land Cover (CLC) database [61] was utilised, derived from ortho-corrected SPOT-4 and IRS LISS III satellite imagery [62]. This database, at a scale of 1:100,000, provided reliable and standardised information on land cover characteristics, with a minimum mapping unit of 25 hectares for areal elements and a width of 100 metres for linear features [42]. During data processing, categories were aggregated to the first hierarchical level. This approach facilitated the differentiation of primary landscape components, which are dominant in the study area, including arable land, vineyards, grasslands, broad-leaved forests, coniferous forests, mixed forests, transitional woodland-shrub, and other land cover types [63]. This classification framework, which incorporated habitat-type pooling, was adopted to mitigate data scarcity and reduce excessive sensitivity in preference-index calculations, particularly given that certain subclasses had low spatial coverage. Although this approach may inherently reduce ecological resolution and mask fine-scale variations, it remains appropriate for fulfilling objectives aligned with broader-scale analyses. For the fine-scale analysis of forested areas based on stand age, data were extracted from the official National Forest Database (forestry management plans).

2.7. Statistical Analyses

Statistical analyses were performed using PAST 5.3 software [64]. Data normality was assessed for each dataset using the Shapiro–Wilk test; based on the results, non-parametric tests were applied. Movement ecology data are presented as mean ± standard deviation ($\bar{x} \pm$ S.D.) and median with interquartile range (M_{dn} [Q1–Q3]). Comparisons between sexes were conducted using the Mann–Whitney U test, with exact permutation *p*-values reported due to the small sample size. Stochastic dominance and group separation were quantified using the Vargha–Delaney 'A' effect size. Differences among three or more groups (seasonal and monthly datasets) were analysed using the Kruskal–Wallis test, followed by Dunn's post hoc test for pairwise comparisons. Habitat use frequencies were analysed using the χ^2-test (or Fisher's exact test). For all statistical tests, the significance level was set at $p < 0.05$.

3. Results

3.1. Annual Home Range Dynamics

The annual home ranges of the collared individuals were calculated using three distinct methods as described in Section 2, with results disaggregated by sex. Based on the minimum convex polygon (MCP) method, hinds utilised an average area of 1391 ± 492 ha (M_{dn} = 1435.9, [980.3–1781.32]), whereas this value was substantially higher for stags, averaging 3381 ± 1641 ha (M_{dn} = 2651.2 [2232.9–5261.7]). A statistically significant difference was observed between hinds and stags (U = 0, $p = 0.036$), which is further corroborated by the Vargha–Delaney effect size (A = 0), indicating a substantial disparity. In the analysis of home ranges using the KHR90 method, hinds exhibited an average annual home range of 88 ± 36 ha (M_{dn} = 101.7 [53.3–117.9]), while stags averaged 261 ± 69 ha (M_{dn} = 245.1, [202.8–338.1]). The difference between the sexes was significant (U = 0, $p = 0.036$), supported by the Vargha–Delaney effect size (A = 0). Based on the KHR60 core area estimates, hinds utilised 14 ± 6 ha (M_{dn} = 12.81, [8.97–20.1]), while stags occupied 33 ± 15 ha (M_{dn} = 30.6, [20.6–50.3]). In this case, the Mann–Whitney U test did not indicate a statistically significant difference (U = 1, $p = 0.071$). However, the Vargha–Delaney effect size (A = 0.067) suggests a notable difference in the distribution between the two groups.

3.2. Seasonal Home Range Dynamics

According to the MCP data, the summer period was characterised by the smallest home range sizes for both sexes (Table 2). When examining the effect of seasons, the

Kruskal–Wallis test showed no statistical significance for any parameter (MCP, KHR90, KHR60) in either sex ($p > 0.05$). However, a statistical trend was observed in hinds for both MCP (H = 7.01; $p = 0.072$) and KHR90 (H = 7.14; $p = 0.068$) values. Dunn's post hoc test for hinds indicated that summer home ranges significantly differed from those in spring (MCP: $p = 0.049$; KHR90: $p = 0.034$; KHR60: $p = 0.034$) and winter (MCP: $p = 0.014$; KHR90: $p = 0.017$). In contrast, seasonal parameters for stags were more stable, showing neither significant shifts nor clear trends across any of the examined periods ($p > 0.24$) (Figure 2).

Table 2. Seasonal home range patterns of the studied individuals ($\bar{x} \pm SD$).

		MCP (ha)	KHR90 (ha)	KHR60 (ha)
Hinds	Spring	896 ± 501	133 ± 113	27 ± 20
	Summer	418 ± 250	35 ± 22	8 ± 4
	Autumn	817 ± 264	104 ± 67	20 ± 9
	Winter	1003 ± 454	161 ± 100	24 ± 14
Stags	Spring	2018 ± 1789	274 ± 247	37 ± 40
	Summer	1313 ± 627	134 ± 119	21 ± 20
	Autumn	2761 ± 1328	265 ± 113	51 ± 13
	Winter	1617 ± 460	374 ± 261	84 ± 65

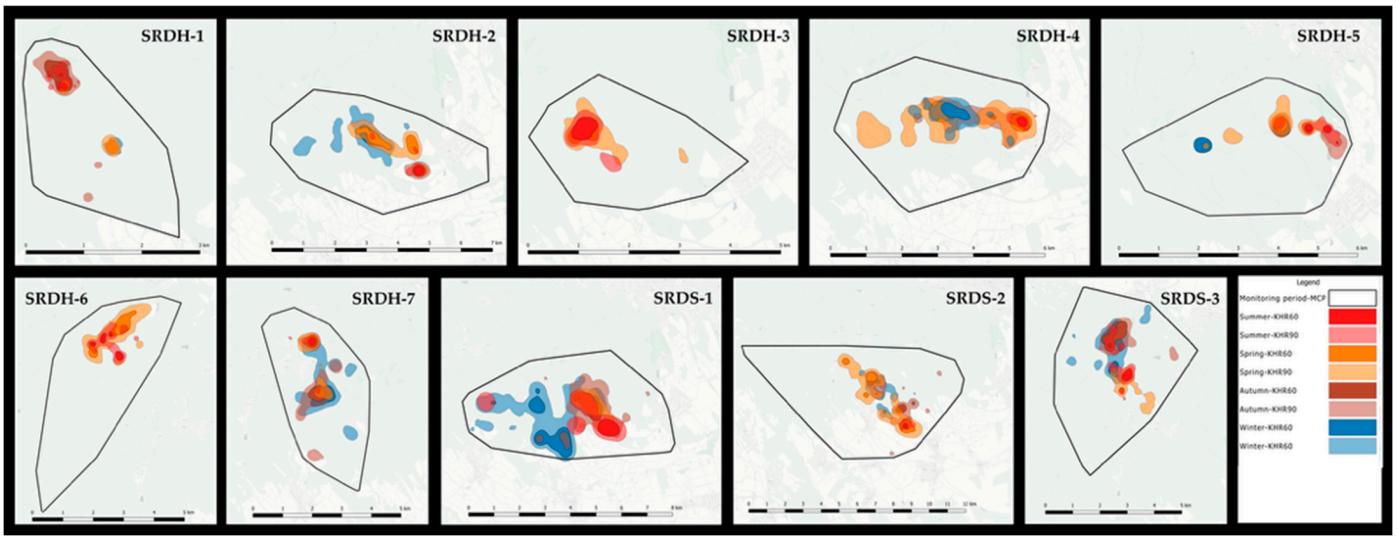

Figure 2. Maps of collared animals with MCPs of monitoring periods and seasonal KHRs. Background map: ©CARTO, Data: ©OpenStreetMap contributors.

Monthly home-range dynamics varied between sexes, and seasonal fluctuations were also present within each sex. For both sexes, the smallest home ranges were recorded in June (hinds: 229 ± 137 ha [M_{dn}: 288.5, 153–482.3]; stags: 539 ± 336 ha [M_{dn}: 690.3, 337.3–1042.6]). In the case of hinds, home range size showed a continuous increase until March, peaking at 752 ± 517.7 ha (M_{dn}: 854 [356.4–1194.5]), followed by a drastic contraction in April and May. For stags, home ranges increased from June onwards, reaching a maximum in September (1466 ± 1466 ha [M_{dn}: 909.28, 360.6–3129.84]). From October to March, the stag dataset exhibited a fluctuating trend: a reduction in October, followed by an increase in November, a subsequent decrease through January, another increase in March, and finally a decrease in April and May (Figure 3).

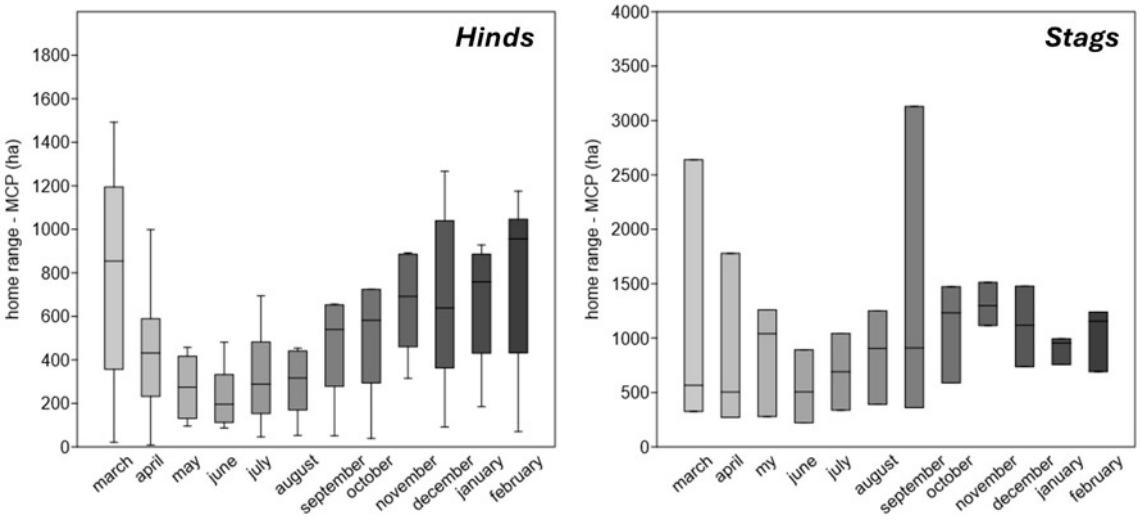

Figure 3. Monthly home range patterns of the studied individuals. Boxes represent the interquartile range (Q1–Q3), the line indicates the median, and whiskers show the non-outlier minimum and maximum values.

Statistical analyses further confirmed the divergent trends between the two sexes. For hinds, the Kruskal–Wallis test demonstrated significant monthly fluctuations ($H = 22.37$; $p = 0.022$). Dunn's post hoc test indicated that these differences were primarily driven by the late spring and early summer period: values for May and June differed significantly from those of the winter and early spring months, specifically November, December, January, and February ($p < 0.05$). The most pronounced disparities were observed between June and February ($p = 0.004$), as well as June and November ($p = 0.014$). In contrast, the Kruskal–Wallis test indicated no significant seasonality for stags ($H = 8.24$; $p = 0.69$).

Due to the small sample size, sexes were pooled into a single dataset for the investigation of spatial shifts. For the annual study period, the relative stability index (RSI) was 2.98 ± 0.59 ($M_{dn} = 2.71$ [2.62–3.79]). Comparison of seasonal ratios via the Kruskal–Wallis test revealed significant differences between medians ($H = 8.359$; $p = 0.039$). Post hoc evaluation using Dunn's test showed that the greatest spatial shift occurred in spring (1.92 ± 0.31), whereas the lowest values were recorded in winter (1.44 ± 0.34). A statistically significant difference was confirmed between spring and winter ($p = 0.0069$). The disparity between spring and summer proved to be borderline significant ($p = 0.051$), while no significant differences were detectable for other pairwise seasonal comparisons ($p > 0.01$) (Figure 4).

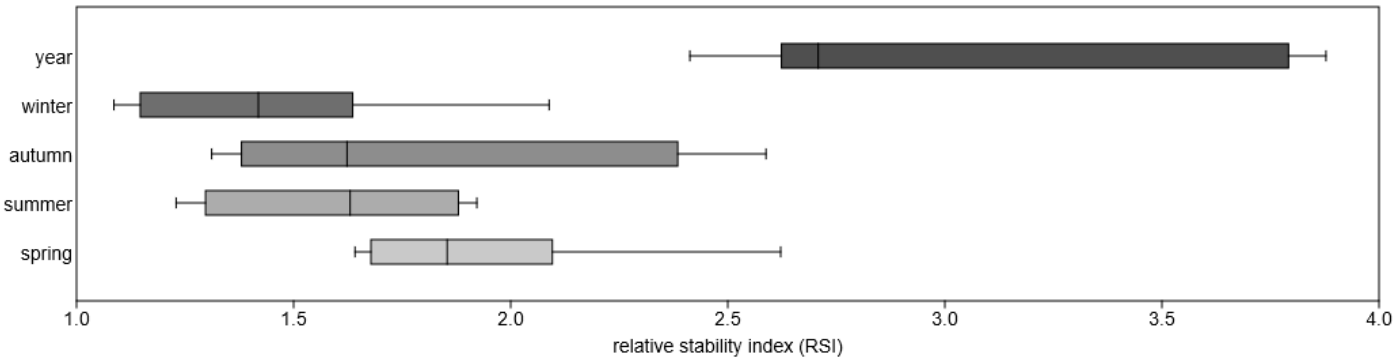

Figure 4. Annual and seasonal patterns of the relative stability index (RSI). Boxes represent the interquartile range (Q1–Q3), the line indicates the median, and whiskers show the non-outlier minimum and maximum values.

3.3. Habitat Use and Preferences

Analysis of annual habitat-use characteristics revealed significant differences in habitat use and preferences between stags and hinds. The most significant divergence occurred in the utilisation of arable land: stags used these areas with an occurrence frequency of 11%, whereas this proportion was merely 3% for hinds (χ^2, $p = 0.048$). According to the Jacobs' index, however, no positive preference towards agricultural areas could be identified for either sex. In contrast, the use of grasslands was more pronounced among hinds (14%), while the presence of stags in this habitat type remained minimal (1%; χ^2, $p = 0.001$); hinds exhibited a distinct preference for grasslands. The utilisation of vineyards was low (hinds: 3%, stags: 1%), the difference between the sexes did not prove significant ($p = 0.25$), and no positive preference was observed. Forest areas played a dominant role for both sexes, although the intensity of use differed (hinds: 61%, stags: 77%). A more detailed breakdown shows that stags utilised road-leaved forests at nearly twice the rate of hinds (61% vs. 31%; χ^2, $p < 0.001$), and a clear preference was confirmed in their case (D = 0.248).

An inverse trend was observed for mixed forests: the utilisation rate for hinds (27%) exceeded that of stags (15%), but this was not found to be significant ($p = 0.055$). Hinds exhibited a preference for this habitat type (D = 0.168). The use of coniferous forests was low for both sexes (2.8% and 0.2%), without a significant difference or preference ($p = 0.497$). Transitional woodland-shrub areas were utilised at 18% by hinds and 9% by stags. Although the difference between sexes was not significant ($p = 0.096$), the Jacobs' index indicated a strong preference for this habitat category for both hinds (D = 0.579) and stags (D = 0.545) (Figure 5).

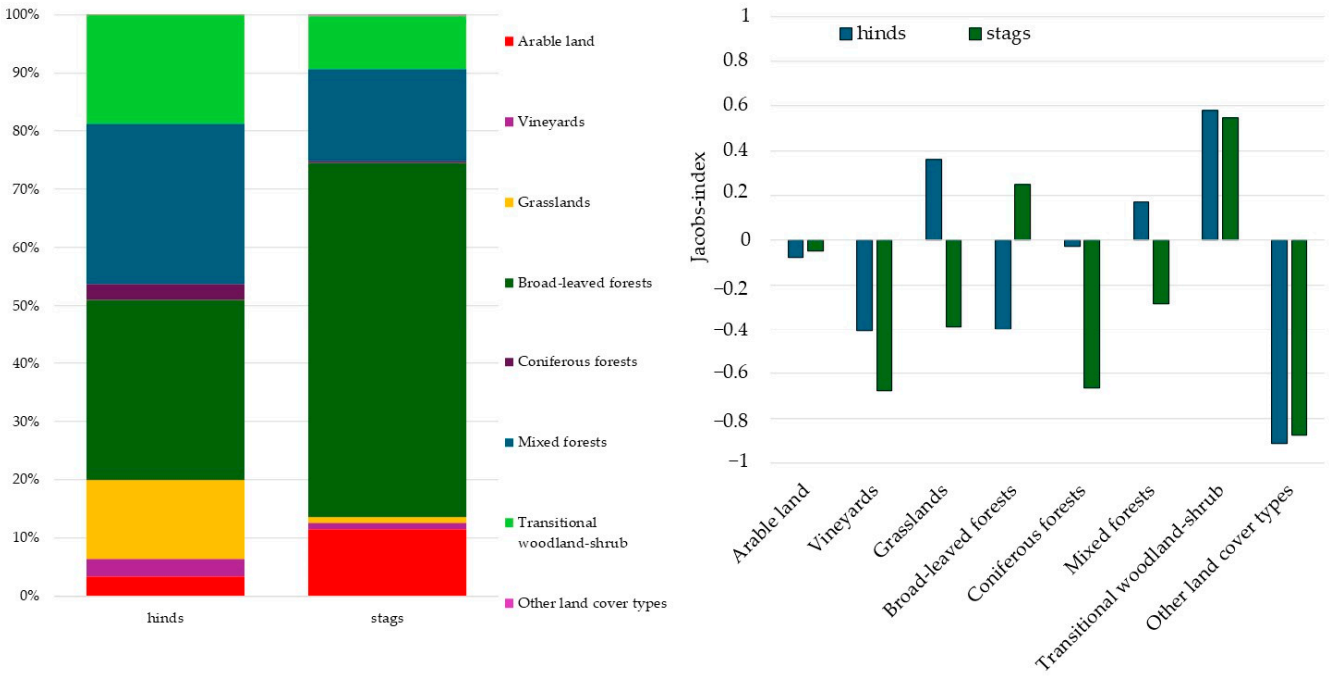

Figure 5. Annual characteristics of habitat use and habitat preference of the studied individuals based on the CORINE Land Cover map.

The monthly utilisation and preference of habitat types exhibited distinct seasonality, although patterns diverged between the sexes (Figure 6). In the case of hinds, the use of open habitats (agricultural fields and grasslands) closely followed the vegetative cycle; intensive utilisation exceeding 30% was observed from June to September. Positive preference was recorded for grasslands from May to November, and for arable land in June and throughout the autumn period (September–November). Vineyards were visited from May

to December, with prominent (9.5–7.7%) and preferred utilisation occurring in September and October (September: D = 0.18). The importance of forest habitats—particularly mixed stands, which were preferred from August to April—increased outside the vegetation period, as did the preferred use of coniferous forests, which exceeded 5% during winter (December–March). Transitional shrublands played a decisive role between April and July (>20%) and were a preferred habitat throughout the year (D > 0.2). In contrast, seasonal boundaries were less clearly defined in the stags' monthly habitat use; however, the role of arable land remained significant year-round, with monthly utilisation exceeding 5% and peaking in January–February and September–October. While stags avoided vineyards throughout the year, their use of broad-leaved forests reached approximately 75% between May and July, accompanied by a prominent preference (D > 0.4). Although the utilisation of coniferous stands only became measurable in October, transitional shrublands proved to be a favoured habitat nearly year-round, despite lower utilisation rates compared to those observed in hinds.

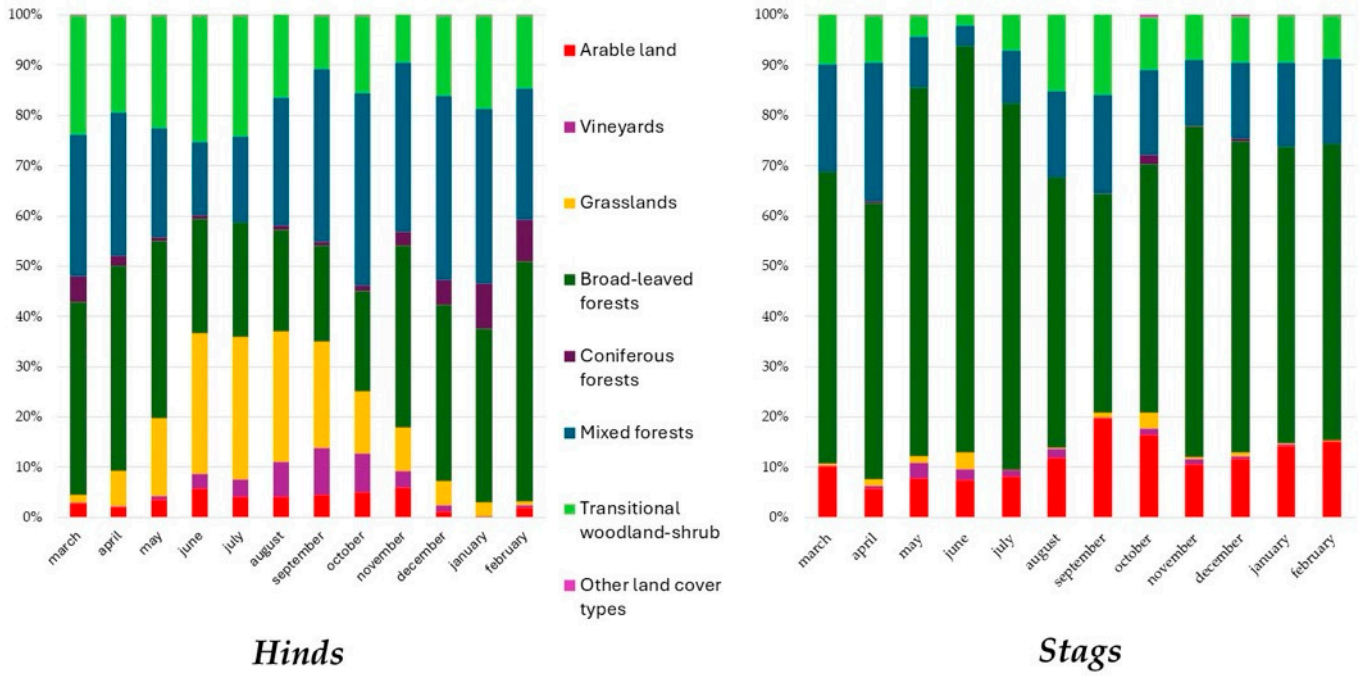

Figure 6. Monthly characteristics of habitat use of the studied individuals based on the CORINE Land Cover map.

Regarding the utilisation of forest regeneration areas and young stands, it can be observed that within the 1–15-year age group, the collared individuals utilised 5–10-year-old thickets in an outstandingly high proportion (72%), followed by 10–15-year-old pole-stage stands (21%) and 1–5-year-old regeneration areas (7%). Chi-square tests confirmed significant differences across all comparisons ($p < 0.001$). Seasonal dynamics within each category exhibited substantial variability (χ^2): in the regeneration stage, the summer period differed significantly from both winter ($p < 0.001$) and autumn ($p < 0.001$). For young stands, both spring and summer were distinct from the autumn and winter periods ($p < 0.05$), while for pole-stage stands, winter showed a significant difference compared to spring ($p = 0.009$) and summer ($p < 0.001$) utilisation. The analysis of hourly position distribution highlighted disparities in diurnal dynamics: whereas regeneration areas were characterised by low daytime and high nocturnal presence, young stands and pole-stage stands exhibited the opposite trend, with predominantly daytime use. The difference between diurnal and nocturnal frequencies proved significant for the regeneration–young stand ($p < 0.001$) and regeneration–pole stage ($p < 0.001$) comparisons; however, no verifiable difference was

found between the diurnal patterns of the young stand and pole-stage categories ($p = 0.598$) (Figure 7).

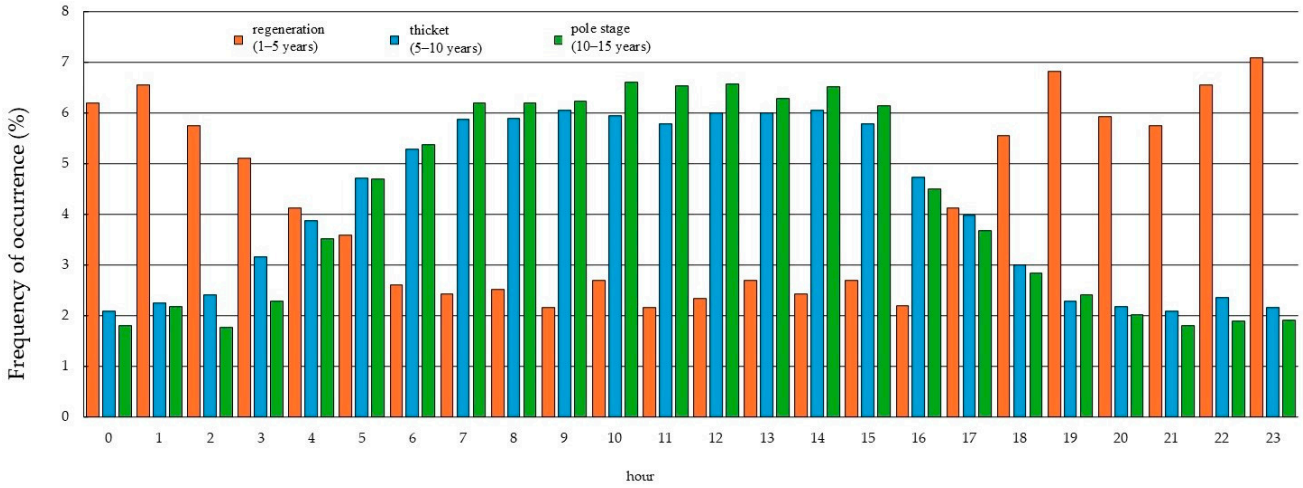

Figure 7. Diel dynamics of young forest stand utilisation, based on forest management maps.

4. Discussion

Analysis of the annual and seasonal home ranges of the investigated red deer population revealed significant differences in spatial utilisation between stags and hinds. The sensitivity of the specific home range estimation methods employed may influence these patterns. Based on the results, stags utilise significantly larger areas on average (MCP: 3381 ± 1641 ha) than hinds (1391 ± 492 ha). This trend is consistent with other European studies, in which the greater body mass of stags and their extensive searching behaviour during the breeding season explain their expanded spatial activity [34,53]. Furthermore, although not directly tested in the present study, disturbance factors may also influence periodic surges in spatial activity [65]. Ultimately, these temporal movements can significantly affect home-range extent, depending on the methodology applied, and this effect relies on a causal mechanism that remains to be verified for our specific dataset.

The three methods applied in this study (MCP, KHR90, KHR60) illustrate animal spatial utilisation from different perspectives. While the minimum convex polygon (MCP) is suitable for delineating the total potentially traversed area, the kernel home range (KHR90 and KHR60) methods identify core areas that are actively utilised [33,66]. The MCP method is notably more sensitive to the aforementioned large-scale periodic movements. For stags, the KHR90 values exceeded those of hinds (88 ha), indicating that stags not only utilise peripheral areas, but also their internal core areas with higher spatial variation. It is important to note that advanced geomatic procedures, such as autocorrelated kernel density estimation (AKDE), may provide a more precise representation by accounting for spatial correlations between hourly GPS positions, thereby avoiding the over- or underestimation inherent in traditional KHR methods [34,53,54]. The seasonality of home ranges reached its minimum for both sexes in June (hinds: 229 ha, stags: 539 ha), which may be linked to the abundance of forage; consequently, biomass quantities derived from various remote sensing data (e.g., Sentinel-2 based NDVI) can be utilised to support these assumptions [67,68]. Furthermore, the early summer reduction in area observed in hinds may be associated with decreased mobility during the calving season [34], whereas in stags, antler growth may influence activity levels [69].

As previously described, the MCP method is sensitive to large-scale displacements; however, the relative stability index (RSI) employed in this study demonstrated that when analysed through temporal partitioning, it is effective for estimating spatial shifts. Its appli-

cation enabled the characterisation of seasonal differences, with the lowest inter-monthly spatial variability recorded during winter (1.44). This phenomenon may be attributed to the synergistic effects of environmental factors (e.g., snow cover) and anthropogenic influences, such as supplemental feeding [35].

Regarding habitat use, CORINE Land Cover proved highly effective for monitoring seasonal variation, as evidenced by significant differences between the two sexes. In the case of hinds, this is clearly attributable to changes in forage availability, most notably the utilisation of vineyards in autumn and coniferous forests in winter. The application of the Jacobs' index facilitated the quantification of habitat selection by relating availability to utilisation, confirming that hinds exhibit a positive preference for grasslands. This preference coincided with the onset of the growing season, when these habitats provide high-quality forage [41,68]. Notably, transitional woodland-shrub areas exhibited prominent Jacobs' index values (hinds: D = 0.579; stags: D = 0.545), indicating a strong preference by both sexes. These ecotones exert a significant influence on red deer habitat use, a magnitude that can be substantiated using remote sensing models (e.g., LiDAR). Such horizontal structures simultaneously provide thermal and security cover against disturbance and abundant understory vegetation for foraging [8,49].

The dominant utilisation of 5–10-year-old young stands (72%) further corroborates that these areas serve as refuges where animals prioritise security. In these habitats, individuals select cover-providing environments over more open yet riskier areas [14,49]. In contrast, during nocturnal active periods, low-height forest regenerations were utilised, which are consequently highly susceptible to browsing damage [5]. However, young forest stands may introduce biases into geomatic analyses. In dense stands, such as the 10–15-year-old thickets utilised by individuals 21% of the time, GPS fix success rates often decrease due to canopy closure, potentially leading to the underestimation of home ranges [6,52]. Nevertheless, the hourly fix rate used in this research provided sufficiently fine resolution to identify daily peaks in habitat use, consistent with the bimodal activity patterns described in the literature [70].

In light of the study's limitations and future perspectives, it is important to acknowledge that our analysis of habitat use relied primarily on static land-cover and forest-stand characteristics. Although these variables are relevant and reliably available to forest managers, they do not incorporate topographic features, microhabitat resource availability, or the potential impacts of anthropogenic disturbance. It is well-known that terrain ruggedness, slope gradient, aspect, and proximity to hiking trails or roads significantly influence red deer behaviour and their efforts to optimise energy expenditure. Consequently, the distinct preference for certain habitat types may partially reflect unmodelled topographic advantages, such as thermal cover provided by steep valleys, or the avoidance of human activity along hiking trails. Habitat preference may also be shaped by actual forage availability associated with specific fix locations, which broad-scale land-cover databases likewise cannot represent. In addition to environmental covariates, the technical constraints of satellite telemetry in dense forests must be considered. While the mean positional error of the employed technology is assumed to have a negligible impact on large-scale databases such as CORINE, it can lead to minor misclassifications in fine-scale forest management maps. This potential displacement may result in minor habitat assignment errors, particularly along the borders of adjacent forest compartments (edge effects). Nonetheless, because the home ranges of the monitored individuals encompass these preferred forest compartments, the overarching ecological patterns remain robust. Future analyses should implement model-based frameworks, such as resource selection functions (RSFs), which simultaneously integrate high-resolution digital elevation models and dynamic remote

sensing products (e.g., NDVI) to decouple the structural effects of forest stands from terrain configuration and anthropogenic pressure.

Furthermore, we acknowledge that high-frequency GPS telemetry data used for home-range estimation exhibit temporal autocorrelation, which can lead to an underestimation of home-range size when employing traditional kernel density estimation (KDE) methods. To assess the impact of this issue, we conducted a preliminary sensitivity analysis, as described in Section 2. The subsampling resulted in only limited changes in the home-range estimates. However, data reduction would have led to the loss of fine-scale spatial movement information. Therefore, we opted to retain the hourly dataset. Despite this, we intentionally retained the standard KDE approach without applying temporal subsampling in our final analyses. This decision was further justified by two factors. First, it ensures direct comparability with prior baseline studies. Second, given that the tracking protocol and sampling frequency were uniform across all individuals, the effect of autocorrelation is systematic. Consequently, although the absolute area estimates may be conservative compared to modern methods that account for autocorrelation (e.g., AKDE), relative comparisons of home range sizes between sexes and seasons remain robust and internally valid for identifying overarching behavioural patterns.

5. Conclusions

This research highlights that the integrated application of high-resolution GPS telemetry and various geographic information system (GIS) databases—such as CORINE Land Cover—is effective for developing macro-level, baseline spatial use models and supporting decision-support systems. The employed methodology enabled the robust delineation of home ranges and the quantification of preferences across diverse habitat types. Simultaneously, the investigation identified methodological challenges inherent in exploring the complex interrelationships within forest–wildlife interactions. The shading effects caused by closed canopy cover and topographical features pose significant technical challenges, as they may reduce GPS fix success rates and positional accuracy, potentially leading to the underestimation of home ranges and spatial activity.

Based on these findings, the continued use of traditional methods, such as the minimum convex polygon (MCP), is recommended, at least as supplementary information. Although the MCP is prone to overestimating spatial requirements, its application remains essential for ensuring comparability with historical research spanning several decades. Our experience suggests that while static, categorised land cover databases (e.g., CORINE) are valuable for broad-scale assessments, they may be inherently limited in describing environmental impacts that change rapidly over time. Furthermore, their reliability is significantly influenced by their spatial resolution. Consequently, to refine these models, the supplementary use of the normalised difference vegetation index (NDVI) or other remote sensing databases capable of periodically estimating vegetation cycles is strongly advised. In future, combining these dynamic, time-varying data with topographic features and human-induced factors will be essential to overcome the fundamental limitations of the static habitat models used in this study.

For fine-resolution wildlife damage modelling, data from forest management plans may prove particularly suitable. These databases can illustrate seasonal shifts in both the quantity and quality of forage, which directly influence the spatial dynamics of the animals. Land cover data alone are insufficient for validating complex ecological hypotheses. Individual behavioural traits and biological cycles—such as calving, calf-rearing, or, in the case of stags, antler development and the rut—significantly influence positioning and activity within the home range. As these individual factors often overshadow habitat

characteristics, a thorough understanding of the biological context is indispensable for robust modelling.

In terms of practical application, the true value of high-resolution telemetry in spatial management lies in its capacity to highlight species-specific behavioural traits that, when integrated with readily available and easily manageable mapping databases, can directly support management decisions. By revealing sex-specific spatial segregation and distinct temporal shifts in habitat use, these data enable managers to implement precise spatial zoning and optimise the timing of silvicultural operations to mitigate forest–wildlife conflicts. Ultimately, integrating high-resolution tracking with local forest planning can ensure that wildlife management and forestry objectives are effectively balanced through data-driven, adaptive decision-making.

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