



Improved monitoring of hares (*Lepus* spp.) using thermal imaging combined with distance sampling

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Abstract

Technical innovations are transforming our ability to estimate population size and status. Hares (*Lepus* spp.) are cryptic species, often nocturnal or semi-nocturnal, and thus they may be challenging to monitor. Here, we assess the combination of distance sampling with thermal imaging to improve the population monitoring of hares. Three study areas in central Sweden were selected based on presumed hare occurrence across agricultural, mixed, and forested habitats. Each area was surveyed five times from November 2022 to February 2023, during daylight along a total of four 1-km transects using thermal imaging binoculars with regular 360° scans. Detected hares were approached for visual species identification and to obtain more precise estimates of the lay. Over the 15 survey days, 29 hares were detected, with 79% through thermal imaging. Only European brown hares (*Lepus europaeus*) were observed, with 55% found in forested habitats where detection would have been challenging without thermal imaging. Detection distances reached up to 315 m in open terrain and density estimates derived from distance sampling ranged from 0 to 8.1 hares/km² among the study areas. Our study demonstrated the potential for using thermal imaging to enhance detection probability in daylight and thus improving population estimates for wildlife management. In addition, the method enables e-DNA sampling from lays and the opportunity to identify habitat preferences and behaviours of cryptic species like hares.

Keywords Monitoring · Management · Conservation · *Lepus europaeus*

Introduction

The application of thermal imaging (TI) has increased in wildlife surveys (Cilulko et al. 2013), including studies on hares, *Lepus* spp (Karp 2020; Voigt and Siebert 2020; Sliwinski et al. 2021). Thermal imaging cameras detect emitted heat, enabling effective observation even when visual detection is hindered by camouflage or lack of light (Havens and Sharp 2016). Even so, more examples and evaluations

of the application of TI to problems in wildlife management are needed to more fully explore its field applicability.

Many hare populations in Europe have experienced significant declines in recent decades due to intensive agricultural practices (Hackländer and Schai-Braun 2018), increased predation pressure (Schmidt et al. 2004), climate change (Acevedo et al. 2012; Rödel and Dekker 2012), diseases (Mörner 1999; Wibbelt and Frölich 2005) and interspecific interactions (Thulin 2003). There is growing concern regarding their population status and the necessity for effective conservation measures, highlighting the need for reliable monitoring tools to track population trends and facilitate sustainable management efforts.

Traditionally, in Europe, harvest data have served as the primary tool for monitoring hare populations (Apollonio et al. 2010; Putman et al. 2011). Additional methods include nighttime spotlight inventories, pellet counts and snow-tracking (e.g. Litvaitis et al. 1985; Smith and Nydegger 1985; Novaro et al. 1992; Lindén 1996). Whereas, in Canada, snowshoe hare (*Lepus americanus*) population abundance and trends are monitored using

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various methods, including capture-mark-recapture (Majchrzak et al. 2022; Oli et al. 2026), pellet counts (Strong and Jung 2012; Krebs et al. 2023), and camera traps (Villette et al. 2017; Kenney et al. 2024). However, use of harvest data in Europe have been criticised for inaccuracies and limited ability to reliably reflect true population trends (Ranta et al. 2008; Imperio et al. 2010; Eriksen et al. 2018). For some species of hares, thermal imaging has proven more efficient than spotlight counts (Focardi et al. 2001; Bedson et al. 2021); for example, Focardi et al. (2001) demonstrated that spotlight counts significantly underestimated European brown hare (*Lepus europaeus*) populations compared to thermal imaging, a finding corroborated by Sliwinski et al. (2021). Bedson et al. (2021) conclude that daytime surveys of mountain hares (*Lepus timidus*) underestimate number compared to nighttime thermal imaging. However, neither Bedson et al. (2021) or Focardi et al. (2001) used thermal imaging for daytime detection of hares in their lays using distance sampling (Buckland 2001).

In this pilot study, we present and evaluate the efficiency of combining thermal imaging with distance sampling to detect hares during daylight hours, thereby enhancing simultaneous opportunities for visual species identification, population density estimation and habitat preference analyses.

Materials and methods

Survey area

The experimental area was confined to a semiboreal region of south-central Sweden, just south of the bio-geographical north, 'limes norrlandicus' (Sernander 1901), that marks sharp differences in snow cover, vegetation and soil composition. Three study sites were selected, the Grimsö site, predominantly forested, the Lisjö study site, characterized by a mix of fields and forests, and the Fiholm study site, dominated by open agricultural fields with scattered forest patches. In each site we placed a quadrat comprising four 1-km transects (Fig. 1). In this region, both the endangered, native mountain hare and the non-native European brown hare co-occur. The study sites were thus selected in areas where both species were expected to occur, at unknown densities, while the exact placement of the transects along the quadrates were randomly selected.

Distance sampling

Surveys were conducted during the daytime to detect hares in their lays, and during the cold season from

November 2022 until February 2023 to maximise thermal contrast between hares and their colder surroundings. Each site was surveyed five times, with at least one week between surveys to ensure event independence and minimize disturbance. Consecutive study areas were surveyed within 1–2 days. Surveys were not conducted during adverse weather conditions, such as fog, rain, snowfall, or high humidity, which could reduce detection probability (Allison and Destefano 2006; Cilulko et al. 2013; Havens and Sharp 2016). Surveys were conducted by walking each transect, which were mapped using ArcMap 10.8.1 (ESRI Inc., Redlands, CA, USA) and uploaded to a GPSMAP® 64s (Garmin Ltd., Olathe, KS, USA) hand unit for field navigation. All GPS routes were stored at the hand unit and later uploaded to a computer server. The four first complete surveys (all sites) were conducted by Carolin Berndt and the final (fifth) survey by Carl-Gustaf Thulin.

During the surveys, 360° scans were conducted at regular intervals adapted to the terrain (e.g., 10–50 m depending on if the terrain consisted of shrubbery, dense forest, open forest or open fields) using a Pulsar Merger LRF XP50 (Yukon Advanced Optics Worldwide, Vilnius, Lithuania) thermal imaging binocular with an integrated laser rangefinder. Each detection of a hare was recorded, noting whether the animal was stationary in its lay or exhibiting movement. Observations of hares detected without thermal aid were also documented, including individuals flushed from their lay because of observer proximity. For flushed or moving hares, the distance measurement was referenced to the original lay location (see below); in cases where the precise lay could not be identified, the most likely pre-disturbance location was estimated to maintain spatial consistency. This procedure minimized positional uncertainty for subsequent analyses of detection probability and disturbance effects.

The locations of the observer and the hare's lay (or the original undisturbed position) were recorded using a Garmin handheld GPS unit. Detection distance was defined as the straight-line distance between the observer and the hare's actual or estimated undisturbed location at the moment of initial detection, prior to any disturbance caused by the observer. GPS coordinates of hare positions were subsequently used to calculate perpendicular distance to the transect line based on this original, undisturbed reference point. To minimize false positives, all thermal detections suspected to be hares were approached for in situ verification. Lays were typically identifiable as areas of flattened vegetation, and in some cases as distinct depressions (Fig. 2). When using the thermal binocular, it was possible to find the lay through a clearly visible latent heat signature.

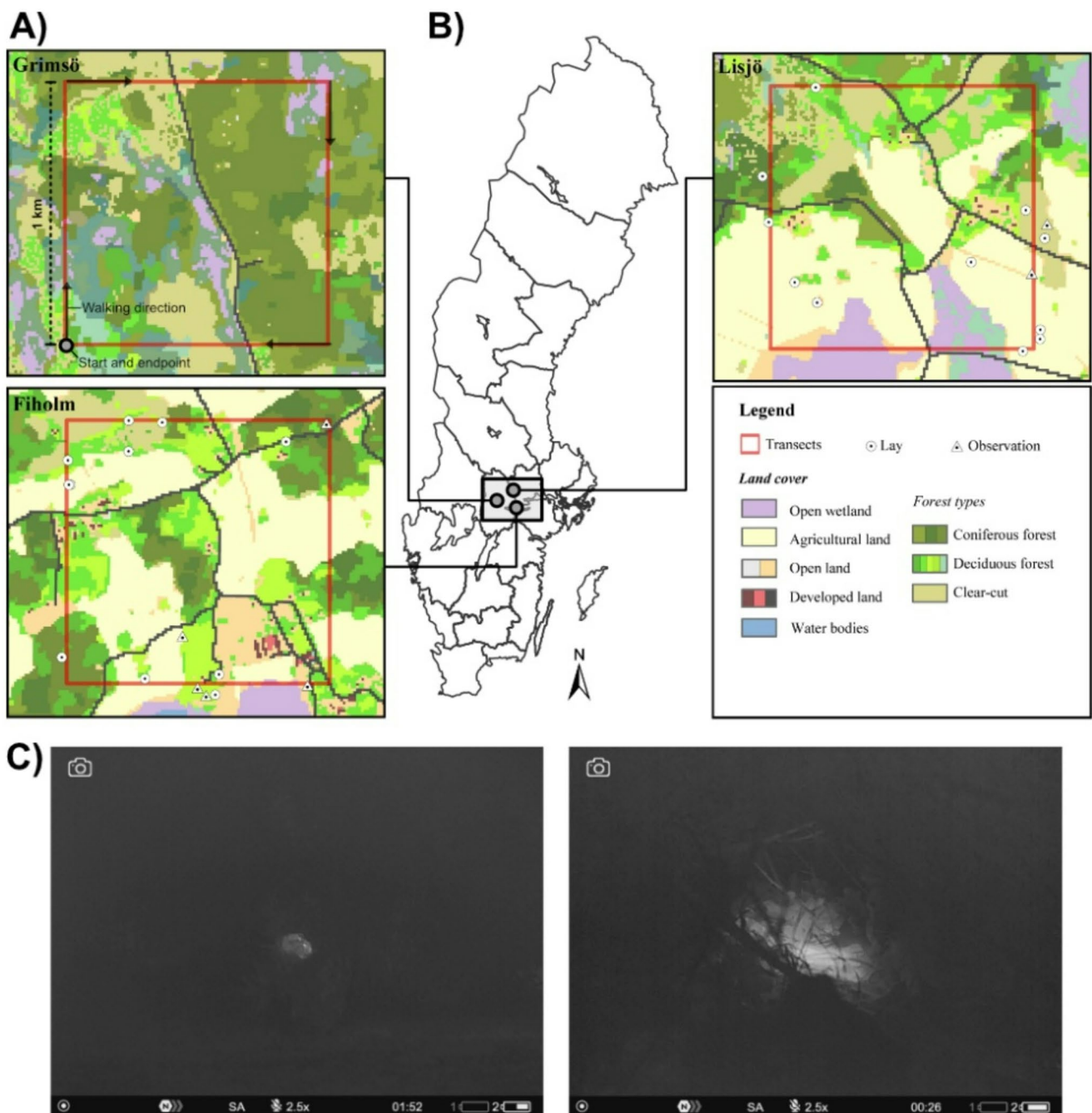


Fig. 1 (A) The land cover maps over the three study sites Lisjö, Grimsö and Fiholm including the survey transects along the sides of a square in red, and the observations and detected lays (see legend). (B) the

location of the study sites in south-central Sweden. (C) Example pictures of a detected hare with thermal imaging (C left) and the thermal signature of a lay without a hare (C right)

Data analysis

To assess if hares used habitats in proportion to habitat availability we compared the distribution of hare observations across habitat types with the corresponding habitat availability in each study area. Land cover data were derived Swedish National Land Cover Database (NMD) (Sw. “Nationella Marktäckedata”) (Naturvårdsverket 2023)

with a 10 × 10-meter resolution. Habitat classes were consolidated into six categories; coniferous forest, deciduous forest, clear-cuts, agricultural land, open land, and artificial land (e.g. anthropogenic areas such as farmyards, farm buildings, private residences and roads; Fig. 1). Water bodies were excluded from the analysis. Observed hare counts were based on all detections, regardless of detection method. For each study area, we calculated the proportion of each



Fig. 2 Photos of four different lays

habitat type within 200 m on both sides of the transects using a GIS (ArcMap 10.8.1), representing habitat availability. We selected a 200 m threshold based on the empirical distribution of detection distances. Although the maximum recorded detection distance was 315 m, this occurred only once and under exceptionally open terrain conditions. The overall distribution was strongly right-skewed, with only 5 of 29 detections (<17%) occurring further than 150 m from a transect. Truncating the analysis at 200 m therefore captures most detections while excluding rare long-range observations that are unlikely to be representative of typical survey conditions. This approach reduces the influence of outliers on distance-based metrics and aligns with recommended practices for defining biologically realistic detection ranges in transect sampling.

To assess whether hare observations differed from habitat availability, we conducted a chi-squared goodness-of-fit test. Expected hare observations were calculated by multiplying the total number of observed hares by the proportional availability of each habitat type. Since some expected counts were <5, we used a Monte Carlo simulation with 10,000 replicates to improve the accuracy of the p-value estimation and ensure the validity of the chi-squared approximation. We assessed whether detection distance varied among

habitat types using a Kruskal-Wallis rank sum test. All calculations were performed in R version 4.4.2.

For distance sampling, detection probability was modelled using Distance 7.5 software 5 (Thomas et al. 2010). We used repeated surveys along the same transects to maximize sample size; that is, to increase the number of transects with at least one detection and thereby improve precision in density estimates. The increased sampling effort was accounted for analytically by multiplying transect length by the number of visits, so that each transect was treated as 5 km rather than 1 km, following standard procedures in distance sampling when target densities are low. Detection functions were evaluated using Akaike's Information Criterion (AIC) and diagnostic plots, and the best-fitting detection function was a half-normal simple polynomial with a right truncation at 150 m, to reduce the influence of infrequent long-distance detections.

Results

A total of 60 km of transects were monitored (four 1-km transects per survey quadrat walked five times each) across the three study plots. An average of 3.46 h was spent for each survey on each of the survey plots (46 ± 22 min for each 1-km transect). The total time spent surveying all survey plots was 55 h.

In Fiholm, a total of 16 hares were detected during the five surveys, followed by 13 in Lisjö and no hares in Grimsö (Fig. 1). Thus, a total of 29 hares were detected of which 23 (79%) was detected with thermal binoculars (19 in lay, four moving) and six (21%) were flushed out of their lay while walking the transect or observed moving (three hares respectively). Most hares were detected in their lays, 19 with and three without thermal binoculars (22 observations, 76%), whereas we observed seven (24%) hares for which no lay could be found (Table 1). One pellet was found in a lay (Lisjö study area).

During the first three surveys weeks (15 Nov 2022 to 18 Nov 2022; 29 Nov 2022 to 1 Dec 2022; 2 Jan 2023 to 05

Table 1 Differentiation of detected hares based on detection type. Lay=Hare detected in a lay, Obs=Observation of a hare without finding a lay, TI=Detected with thermal imaging binoculars; Visual=Detected with eyes (without thermal imaging binoculars)

Area	Fiholm	Lisjö	Grimsö	Sum
Type of observation				
Lay – TI	9	10	0	19
Lay – Visual	2	1	0	3
Obs – TI	4	0	0	4
Obs – Visual	1	2	0	3
Sum	16	13	0	29

Jan 2023), a total of 23 hares were observed (7.6 hares on average), whereas only six in the last two (16 Jan 2023 to 18 Jan 2024; 13 Feb 2023 to 16 Feb 2023; 3 hares on average; Table 2). We observed on average 3.2 hares per survey event in Fiholm, 2.6 hares in Lisj6, and 0 hares at Grims6. Thus, we walked 1.25 km between hare detections at Fiholm, and 1.5 km at Lisj6 respectively. Only brown hares were detected.

There were no significant differences in detection distances between habitats ($\chi^2=5.83$, $df=4$, $p=0.212$). Thermal binocular detection distances ranged from 12 to 315 m, with a median detection distance of 54 m, a mean of 90 m, and a standard deviation (SD) of 87 m. In contrast, hares detected without thermal binoculars had a median detection distance of 12 m, a mean of 47 m, and a SD deviation of 80 m. The average perpendicular distance from the hare to the transect was 51 ± 69 m, with the maximum recorded distance being 273 m. Flushing distances were recorded for 26 out of 29 observations, ranging from <1 to 112 m.

The detection distance between the observer and hares varied, ranging from 1 to 315 m, with the majority (55%) of observations occurring within 50 m (Fig. 3). The mean detection distance across all habitats was $81 \text{ m} \pm 86 \text{ m}$ (median=46 m; $n=29$). Detections decreased with increasing distance but varied depending on habitat type. In open habitats, such as agricultural areas (mean=114 m) and open lands (mean=102 m), hares were detected at longer distances, with the maximum detection recorded at 315 m. In contrast, detection distances were closer in forested environments (coniferous forest: mean=29 m, deciduous forest: mean=87 m, clear-cut: mean=33 m). The average detection distance in coniferous forests (29 ± 30 m) was lower than in deciduous forests (87 ± 102 m), reflecting the reduced visibility and thermal contrast in denser habitats. The perpendicular distance varied between 1 and 273 m. The distance sampling estimates of hare densities differed between the study sites and was highest in Fiholm (8.1 hares/km²; 95% CI=2.8–23.3). In Lisj6 the estimated density was 6.4 hares per km² (95% CI=2.6–15.8). The pooled estimate, including both areas, was 7.2 hares/km² (95% CI=3.9–13.4).

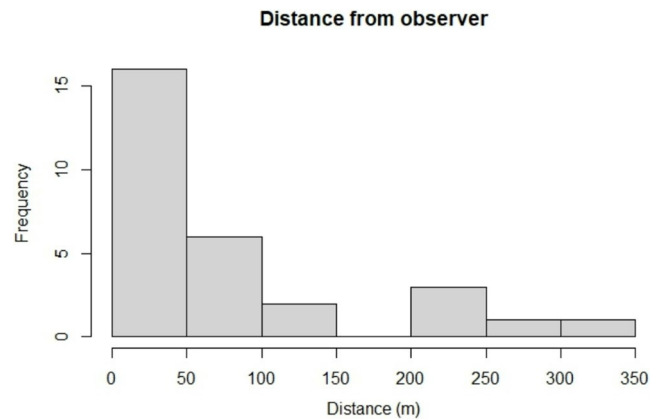


Fig. 3 Histogram of number of detections for each distance interval (straight distance from observer to hare when first detected) ($N=29$)

Grims6 area was not included in the analysis since no hares were detected.

The flushing distance varied between 0 and 112 m and in 22 out of 26 recorded flushing distances was below 20 m, with an outlier of 112 m of a hare that was detected sitting and approached in an open field.

Discussion

Our data demonstrate that the number of hares observed in their lays during daytime with thermal binoculars increased five-fold, thus increasing detection probability and accuracy of population size estimates using distance sampling methodologies. Hares are cryptic species, behaviourally and functionally evolved to avoid predation from terrestrial and aerial predators (Lindstr6m et al. 1986). However, with thermal binoculars we were able to find hares in different land cover types, including forests and densely vegetated clearcuts, and at more than 300 m distance in open, vegetated fields. Although the 95% confidence intervals in this pilot study were quite high, and thus provide uncertainty in actual densities, we believe that this method is a good approach for an integrated monitoring of hares particularly

Table 2 Overview of detected hare lays and observed hares in the three different study areas for the different survey weeks (Week 1: 15 Nov 2022 to 18 Nov 2022, Week 2: 29 Nov 2022 to 1 Dec 2022, Week 3: 2 Jan 2023 to 05 Jan 2023, Week 4: 16 Jan 2023 to 18 Jan 2024, Week 5: 13 Feb 2023 to 16 Feb 2023)

Survey week	Fiholm		Lisj6		Grims6		Sum
	in lay	observed	in lay	observed	in lay	observed	
1	2	1	4	0	0	0	7
2	4	1	4	0	0	0	9
3	5	0	0	2	0	0	7
4	0	1	2	0	0	0	3
5	0	2	1	0	0	0	3
Sum	11	5	11	2	0	0	29
	16		13		0		

if implemented across a larger area or with increased survey intensity. Gray et al. (2023) showed a detection probability of American woodcock (*Scolopax minor*) with thermal cameras of almost 60%. Based on the larger body size of hares, we believe that our detection rate is higher.

A limitation with walking transects using thermal binoculars is that it is not possible to constantly observe the surroundings with thermal binoculars while walking. Thus, the result are more dependent on subjective decisions made by individual observers, introducing a potential source of observer bias (sensu Zvereva and Kozlov 2021), rather than reflecting an objective and independent methodological approach. Such subjectivity would be less pronounced if detections were obtained by a drone performing downward scans along a fixed grid pattern or transect, thereby more fully utilizing the strengths of distance sampling. We foresee that utilisation of drones equipped with monitoring cameras (e.g., Dell et al. 2014) may eventually replace walking transects with thermal binoculars as implemented in our study. However, how drones would perform in dense forest is unknown and detecting hares in their lays from the air may be challenging.

The increasing public interest in society for technical equipment and thermal imaging binoculars for hunting and wildlife observation offers new opportunities for citizen science and could provide nation-wide, cost-effective monitoring data if organised and standardized appropriately. In addition to providing more independent data than reported harvest, these methodological advances may also increase public awareness of population status and conservation challenges facing species such as hares in Sweden. Finally, the ability to locate lays using thermal detection enable assessment of lay characteristics, utilisation, as well as the targeted collection of eDNA samples.

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Author contributions CGT acquired seed funding and administered the project, CGT, PK and GS designed the experiment, all authors (but mainly CB) conducted field work, CB and CGT drafted the manuscript, all authors revised the manuscript and gave their final approval for submission and resubmission to European Journal of Wildlife Research.

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Data availability Data is available in the manuscript and upon request from the corresponding author.

Declarations

Ethical approval The research conducted is in accordance with Swedish and European law. No ethical approval was needed.

Competing interests The authors declare no competing interests.

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