Advancing wildlife monitoring

By Lasse Lange Jensen

A very important aspect of conservational biology is the methods of wildlife monitoring. This is since the success of the management of endangered species, communities or whole ecosystems depends on how correctly population sizes and demographic parameters are assessed, as well as on how interactions with the environment as well as between species can be studied (Moussy, et al., 2022). Traditional wildlife monitoring methods are laborious intensive and have limitations in scale and scope, often relying on GPS tracking and camera traps (Lahoz-Monfort et al., 2021). Monitoring methods are used for studying the distribution of populations, demography, ecological interactions, human interactions, habitat use and behaviours which all guide conservation and management efforts. Misguided management can result in unforeseen consequences as for example in the case of the reintroduction of the Przewalski's horse (*Equus ferus przewalskii*) to the Mongolian steppes (Xia, et al., 2014). The reintroduction of the native Przewalski's horse intended to rescue it from extinction in the wild, while benefitting from its positive effects as habitat managers increasing biodiversity and keeping the vegetation low and in early succession. However, the reintroduction resulted in overgrazing of the steppe, since the horse would compete with livestock for food. The failed initiatives were a result of a lack of knowledge about interactions with the existing flora and fauna, particularly about how the horse would compete with existing grazing species, and how this would affect the vegetation in the long run (Xia, et al., 2014). Knowledge of vegetation preference of the horses could not be properly acquired beforehand since the horse was extinct in nature.

Key knowledge on distribution, demography and ecology of the species is in most cases attainable and guide management projects around the world. Advancements in the methods applied in monitoring of wild animals therefore have implications for management practices. One of the latest major advancements is the combination of drones with advanced light, sound and air parameter sensors and automated data processing, utilising machine learning algorithms. This combination has proven applicable in a wide range of scenarios. A study by Rahman et al. (2023) used drones to photogrammetrically determine age and population structure of Sumatran elephants without disturbance of their behaviour and habitats which is more likely in more conventional methods (Rahman, et al., 2023). Varela-Jaramillo et al. (2023) compared a drone-based method for counting Iguanas with the traditional capture-mark-resight method in Galapagos and found the advantages of the drone-based method to be many. They emphasised that drones were especially well-suited for monitoring endangered biodiversity in remote, protected and inaccessible areas (Varela-Jaramillo et al., 2023). A study by Povlsen et al. (2024) developed an object detection model on the CNN (convolutional neural network) named YOLO (You Only Look Once) for identification of Hare (*Lepus europaeus*) and roe deer (*Capreolus capreolus*) in aerial footage recorded from drones. They further suggested a method in future for automated monitoring of the two species by equipping drones with onboard computers capable of using the developed model for detecting individuals of the two species along a predesignated flight path while recording the coordinates of their location utilizing a laser rangefinder (Povlsen et al., 2024).

Utilising drones and machine learning in studies of ungulates

In the primary paper of this master's thesis, "The Use of Open Vegetation by Red Deer (*Cervus elaphus*) and Fallow Deer (*Dama dama*) Determined by Object Detection Models" by Lasse Lange Jensen, Sussie Pagh and Cino Pertoldi, YOLO was used to assess the habitat and vegetation use of red deer (*Cervus elaphus*) and fallow deer (*Dama dama*) and the interactions between the two species (Jensen et al., 2025). For this purpose, a behaviour classification model was developed on the YOLOv8 (version eight of YOLO, URL: https://docs.ultralytics.com) which differentiated between the behaviour classes "standing", "lying", "foraging" and "locomoting" in individual frames. The footage collected from the drone was thermal and of relatively low resolution (640x512) and the flights were conducted throughout the night where the species are known to actively forage within the study area. Much knowledge on the habitat and vegetation use can be acquired from these simple and easily distinguished behaviour classes. The time used for foraging relative to locomoting gives an indirect estimate of how scarcely or patchily the preferred vegetation is distributed. The time spent standing gives an indirect estimate of how cautious of predators or humans the animals are, and lying can be indicative of rumination. Drone flights were scheduled and designed to ensure equal temporal representation throughout the study area enabling insights into the daily migration and vegetation use patterns of the two species. As explained in the paper, this method is still in its early developmental stage and has several technical challenges, particularly in the scenario within which it was applied. Firstly, the two species look very similar in thermal footage which makes it difficult to differentiate them automatically with object detection models. Secondly, tracking is essential for the validity of the biological conclusions derived from the results. When individuals are not tracked and proportion of time spent on behaviour classes are averaged between the individuals within the frame, individuals in larger groups will be underrepresented in the statistical analysis. A study by Duporge et al. (2024) succeeded in developing models for baboon behaviour classification as well as baboon tracking. The YOLOv8-X behaviour classification model had a mAP (mean average precision) of 92.62% and the highest performing tracking algorithm had a MOTA (multiple object tracking precision) of 63.81% (Duporge et al., 2024).

Tracking is possible in combination with YOLO object detection. However, a new open-source computational tool has been developed which possibly combines all the needs of biologists into one tool. It is called LabGym (URL: https://github.com/umyelab/LabGym) and is capable of both identifying species and their behaviour classes while tracking individuals. Its application has been limited due to its recent development but will potentially accelerate the application of object detection in biology, especially due to its ease of use. Biologists with no knowledge in coding languages or machine learning can relatively easily train models all within a GUI (graphical user interface) complete with explanations and references to an online guide (Hu, et al., 2023). The tool is divided into a detector, which is trained to draw the outline of the individuals, and a classifier, which is trained to classify the behaviours and is trained on segments of 15 frames generated by the detector. The detector is therefore independent of the behaviour classification and can be reused in classification of other behaviour classes, reducing the time used for model development.

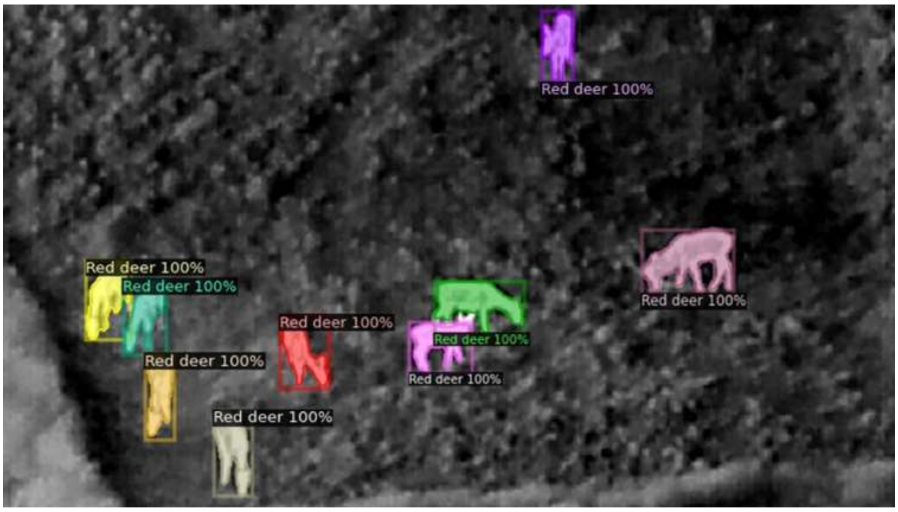

Figure 1: Predictions of outlines of several red deer produced by LabGym's detector. The detector was trained on approximately 200 frames with varying backgrounds, distances, angles and numbers of individuals.

Alternative wildlife monitoring methods

In the second paper of this master's thesis, "Monitoring Urban European Hares (*Lepus europaeus,* Pallas) with Citizen Science and a Thermal Spotter" by Lasse Lange Jensen, Sussie Pagh and Cino Pertoldi, such an approach was tested in the urban environment of two Danish cities, Aalborg and Aarhus. The distribution of the European hare (*Lepus europaeus,* Pallas) within the complex urban environments of these cities was studied combining a citizen science project by asking the residents to report hare sightings by e-mail to scientists at the University of Aalborg and monitoring with a thermal spotter. In the city science project, the public were asked to report the location, date and time of day of the sightings of hares as well as whether the hare was a leveret or an adult. No other species of hare or rabbit are known to inhabit the cities which makes mistakes in species identification on behalf of the citizens very unlikely. The citizens were asked to provide a photograph of the sights if possible. An almost perfect polynomial relationship between the density of hares and the distance from the city center was found for both cities (Aalborg: $Y = 1.30 \times 2 - 1585x + 48.2$, $R^2 = 0.98$, $p < 0.001$ and Aarhus: $Y = 0.93 \times 2 - 11.21x + 35.59$, $R^2 = 0.97$, $p < 0.001$). A result like this should be discussed in relation to the possibility that the density of human observers potentially follows the same trend, hence explaining some of the relationship. However, the density of hare was also higher in areas with apartment blocks than in areas with private gardens, indicating that hares prefer apartment blocks as habitat over private gardens. The degree to which a resident in an area of apartment blocks is likely to report sightings compared to a resident in an area of private gardens may not be the same, and the effect of this should be further investigated. The density of hares was 5.4 and 4.7 times higher in apartment blocks than in private gardens in Aalborg and Aarhus respectively. It is unlikely that bias in observers can explain all the difference in density between the two urban areas, and this kind of information is highly relevant in managing the populations of hare in the cities, who probably are there because of habitat fragmentation and agricultural expansion encroaching on their natural habitats.

Decline in populations in agricultural areas of many species of mammals and birds and simultaneous rise in populations within urban areas emphasises the importance of developing methods of monitoring that are adapted to the circumstances of urban environments. Surveying with drones or wildlife cameras is impractical and illegal in many urban areas, and conventional methods such as spotlight counting are disturbing to the residents. Citizen science may therefore become an important tool in managing urban species. Despite its apparent challenges regarding all sorts of observer biases, it can give urban planners insights into locations of hotspots and give biologists insights into the environmental factors determining the distribution of species in these environments. This is valuable and can guide city planning in modifying cities to enable the habitation of many of the species who's natural habitats are in regression.

Artificial intelligence (AI) can potentially be transformative in urban biodiversity management. CNN's capable of species detection and monitoring have been tested in urban environments due to their scalability and efficiency in monitoring across various taxa and environments. In the highly diverse tropical urban environment of Rio de Janeiro, Martins et al. achieved F1 scores of $79.3 \pm 8.6\%$ in mapping of nine tree species (Martins, et al., 2021). In the urban environment of Hong Kong, Guo et al. (2024) developed a model for detection of feral pigeons which can aid in monitoring the trend in overpopulation of feral pigeons, whose excessive droppings contaminate air and water resources and affects the urban environment (Guo, et al., 2024). However, wildlife monitoring in urban environments may also benefit from less technological but still unconventional methods. Urban environments have the advantage of inhabiting dense populations of people capable of identifying easily identifiable species and reporting sightings to biologists.

The future of wildlife monitoring

The future of wildlife depends highly on our ability to monitor it. This is because the success of managements, restorations and reintroductions relies on highly accurate information on demographic compositions, population sizes, habitat use patterns, interactions and behaviours which all depends on our ability to monitor. While it is becoming increasingly evident that anthropogenic activity affects many species of animals negatively by land use and climate change, the correction for this may be found in increasing our knowledge of these species, enabling us to successfully restore and maintain their natural habitats. It is important that better, more accessible and less expensive monitoring methods are developed since the future of many species depends on our ability to gather knowledge on their ecology. The future of wildlife monitoring will depend on the ingenuity of conservational biologists, who explore the application of technologies such as drones and machine learning in their own studies. Despite the new paradigm's early stage, it has already proven reliable and efficient in very different applications. From using YOLO on orthophotos for detecting and counting bird nests of the Antarctic shag to using YOLO on drone footage for species and behaviour classification of deer and hare species, the utility of both drones and machine learning in biology is promising (Povlsen, Bruhn, Durdevic, & Pertoldi, 2024), (Jensen, Pertoldi, & pagh, 2025), (Cusick, et al., 2024). And with the potential blessing of wildlife moving into our cities, it is even more important that biologists develop new methods for monitoring these species. Both since their natural habitats have been regressed by our activity, but also since they bring value to residents of these environments.

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Article

The Use of Open Vegetation by Red Deer (*Cervus elaphus*) and Fallow Deer (*Dama dama*) Determined by Object Detection Models

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Abstract: Studies of habitat-related behaviour of mammals are time-consuming. This study aims to develop a model for monitoring the behaviour of mammals in different habitat types using drones mounted with thermal cameras in combination with a YOLO object detection model. Red deer (*Cervus elaphus*) and fallow deer (*Dama dama*) were used as model species. The data were collected in the nature reserve, Hanstholm, Northern Denmark. The aim is to develop an AI model capable of distinguishing between four behaviours, "foraging", "locomoting", "lying" and "standing", allowing for insights into the rumination and foraging cycle of the two species. At the same time, the behaviour was linked to habitat types by geocoding individuals. The method developed in this study proved to be time-efficient and provided information about how the two deer species used vegetation types and interspecific interaction between the two species. Technical challenges were to follow individuals and the possibility of missing cyclical behaviour. It was found that the degree to which the ungulates actively foraged was significantly different between the two species and that they were clearly geographically separated within the study area.

Keywords: machine learning; artificial intelligence; drone; UAV; behaviour; YOLO

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1. Introduction

Recent advancements in both the field of machine learning and drone technology have increased the repertoire of methods for biologists studying population dynamics and sizes as well as behaviour [1–3]. Many of these methods have proved to be better than conventional monitoring and behaviour assessment methods, such as wildlife surveillance and transect counts, and at the same time, less time-consuming [3–7]. Machine learning algorithms can automatically execute behaviour or species identification after being trained. The algorithms can be evaluated, meaning that their errors are transparent and interpretable, providing researchers the opportunity to decide which behaviour classes, nodes or species the model can distinguish between and decide if the model can be used for further analysis or must be improved [8]. When the drone is equipped with onboard chips that process a live video with object detection models, the drone can be pre-programmed to fly specific routes and to stop and record when encountering animals [9]. These advantages make the new technologies superior to conventional methods, but they still have many challenges. Many of these challenges are comparable to those of conventional methods, such as the likelihood of recounting individuals. Also, the potential disturbance of animals caused by the presence of researchers in the field may bias results [3]. Object detection models, which predict object classes, and pose tracking models, which predict the position of morphological points, must be trained and evaluated on a diverse material to ensure high robustness as well as precision and recall of predictions [10]. There is a need for thorough collection of training material representative of the diversity of a study area to ensure equally accurate predictions throughout the study area [10]. Infrared cameras are often used since they make the spotting of individuals easier and since nocturnal species cannot be monitored with RGB cameras. But they have low resolution, which limits the distance from which video material can be recorded and the precision with which the model can distinguish between behaviours, sexes, ages and species. Tracking of individuals is especially challenging in herd species since they often move in front of each other within the frame, resulting in models losing track of individuals. This challenge can be avoided by simply not tracking the individuals and instead perceiving the groups as units, consequently resulting in much lower sample sizes [3]. The development of better algorithms for object detection, as well as algorithms specialised in animal identification, is in rapid progress, and the Yolov8 algorithm, which is used in this study, is commonly used in wildlife biology [11]. Its usability is partially due to its high efficiency in real-time performance and accuracy in many applications and partially due to its relative ease of use [11]. YOLO has been used in many applications in wildlife biology, such as in the estimation of the number of breeding pairs of the Antarctic shag (*Leucocarbo atriceps*) by detecting nests [12] or in the classification of baboon and ungulate behaviour [3,13]. Other studies have further developed this algorithm to specifically be designed for wildlife classification and with an improved Kalman filter for better multi-object tracking [14].

Accurate temporal and geographical representation is especially important in studies of daily migration patterns and is possibly attainable with drones and thermal cameras. This would, depending on the size of the study area, require multiple drones simultaneously surveying the entire area if the daily migration patterns change each day. One drone could possibly accomplish accurate temporal and geographical representation if the daily migration patterns are stable since the whole study area could be represented at all time intervals over multiple days of data collection. In Denmark, red deer are known to have relatively stable daily migration patterns, where individuals typically spend the daytime in forests or scrubs and the nighttime, where human disturbance is lower, in open vegetation types or fields [15]. Fallow deer generally spend the day resting and ruminating while lying and move to open areas for foraging during the night [16]. This study aims to demonstrate the applicability of the combination of drone-mounted thermal cameras and object detection models for studies of behaviour in deer by investigating the following:

1. The distribution of populations of red and fallow deer within Hanstholm Nature Reserve;
2. Their preference for different natural vegetation types and habitat-related behaviour;
3. The daily migration patterns of populations of red deer and fallow deer within Hanstholm Nature Reserve.

2. Materials and Methods

2.1. Study Area

This study was conducted in Hanstholm Nature Reserve, located in the northwestern part of the Danish peninsula, Jutland. This area is a moor consisting of patches of open vegetation types such as humid dune slacks and grey dunes, as well as some forest and scrubs. Material was collected on the four nights, 14−15 October, 15−16 October, 16−17 October and 17−18 October, of 2024 within three temporal intervals: 4:09 a.m. to 6:58 a.m., 6:30 p.m. to 8:35 p.m. and 11:26 p.m. to 1:34 a.m. Two take-off points were chosen from which a radius of approximately two kilometres was covered (see Figure 1). They were chosen to maximise the area coverage of the drone, hence a point in the northern part and one in the central part of the study area.

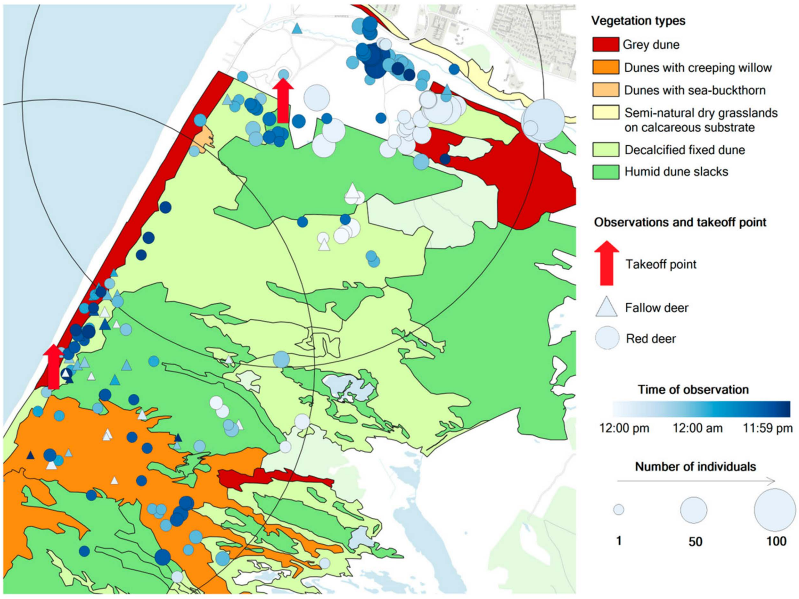

Figure 1. Map of the study area within Hanstholm Nature Reserve. Take-off points are indicated with red arrows, and the approximate range of data collection is indicated by the circular arcs (radius = 2 km). Triangles indicate observations of fallow deer, and circles indicate observations of red deer. The size of these symbols indicates the number of individuals observed, and the intensity of the blue fill colour of these symbols indicates the time of observation. Vegetation types are indicated by colours ranging from red to green.

The ranges from each take-off point were covered in all three temporal intervals multiple times to ensure sufficient and equal temporal coverage of the take-off point ranges. Data collection was cancelled when weather conditions entailed low visibility or when wind speeds were too high for safe flight. The average temperature throughout the collection period was 9.9 °C, and the maximum wind gust was 18.8 m/s. The area of the covered study area was approximately 11.42 km^2.

2.2. Collection of Material and Data

In this study, video material was collected with a DJI Matrice 300 RTK (M300 UAS) (SZ DJI Technology Co., Nanshan, Shenzhen, China) drone equipped with a high-resolution thermal camera, Zenmuse H20N (SZ DJI Technology Co., Nanshan, Shenzhen, China). The Zenmuse H20N is equipped with two thermal cameras and an RGB camera, enabling a thermal resolution of 640 × 512 and up to 8× optical zoom. The video was recorded with 30 FPS and was later compressed for data analysis. The drone is equipped with a laser rangefinder facilitating automatic coordinate estimation through a pinpoint marker function. The drone was piloted manually and within a restricted zone for which a permit was acquired. The altitude was always restricted to between 70 and 120 m (except during take-off and landing) to ensure minimal disturbance of the animals during the collection of material. Observations where animals clearly noticed the presence of the drone were removed from the statistical analysis. Flights were conducted in accordance with the scouring drone method developed by Povlsen et al. [17]. This entails that animals generally were spotted at higher flight altitudes around the take-off points, after which the distance to the spotted animals was reduced and the altitude slightly lowered before initiation of recording. Each group was recorded for one minute. Initially, the zoom was adjusted to include the whole group within the frame to enable the counting of group size. In cases where sufficient resolution for behaviour classification was not possible when all individuals of the group were located within the frame, the zoom was adjusted so that only a smaller subset of the group was within the frame. The frame was then moved around the group every minute to ensure representation of all individuals. After a group was recorded, the altitude was increased and the area was explored from the new location. If other groups were spotted from the new location, the process of reduction in distance and lowering of altitude would begin again. If no other groups were visible, the drone was brought back to the take-off spot from which the area would be explored again.

2.3. Species Identification

Both red and fallow deer were present within the study area throughout the collection period. Species were identified manually from morphological and behavioural differences, as described by Fugl et al. [3]. This includes identification based on differences in limb movement speed in locomoting individuals, where red deer move more slowly, as well as morphological differences such as the elongated faces of red deer or the visible white markings around the neck or backside of fallow deer, which are visible on thermal imagery [3].

2.4. Behaviour Classification

Behaviour was classified with an object detection model [18]. Annotation was performed with Roboflow (version 1.0), which provided the training material for the object detection algorithm YOLOv8 (You Only Look Once) by Ultralytics (Los Angeles, CA, USA) [18,19]. The behavioural classes were limited to "foraging", "interacting", "locomoting", "lying", "standing" and "other" and are defined in the ethogram (see Table 1). Behaviour was differentiated into these classes since, by examination of the collected video material, it was concluded, that these were general enough that most observations could be classified as one of these, and since the consequently relatively low resolution of behaviour was expected to be sufficient to acquire valuable biological information. The training material consisted of 10 recordings that were compressed to between 1 frame per 30 frames and 1 frame per 5 frames. This resulted in 3447 frames with a total of 6128 annotations. Video material for model training was collected in Lyngby Hede, Thy, Denmark, which has similar vegetation to that of the study area. Video material for training the object detection model was collected at a separate site to ensure that the precision of predictions was not biased by the model being trained on the same video material used for statistical analysis. The videos were intentionally selected to ensure a similar representation of all behaviour classes from multiple viewing angles.

Table 1. Ethogram for deer behaviour.

Behaviour	Description
Foraging	Head of animal placed lower than shoulders
Interacting	Head of one animal touching the body of another animal
Locomoting	Animals moving
Lying	Animals lying and limbs are not visible
Standing	Animals standing upright and not moving
Other	Other behaviours, transitioning from one behaviour to another or behaviour determination inconclusive

The 6128 annotations were split into datasets for training, validating and testing. The training dataset received 4488 frames (~73%), the validating dataset received 1151 (~19%) frames and the testing dataset received 489 (~8%) frames. The mode of the Yolov8 algorithm was set to "detection" for the training. The trained model was evaluated on precision, recall and mAP50 (mean average precision with a union threshold of 0.5) of predictions of each behaviour class.

2.5. Data Analysis and Definition of Variables

Each recording was compressed to 1/30 of the original length, resulting in each second being represented by one frame. The temporal resolution of behaviour was therefore 1 s. This length was a compromise between having sufficient temporal resolution and assuring reasonable computation time. Four behaviours were predicted with sufficient precision for use in behaviour analysis. These were the behaviours: "foraging", "locomoting", "standing" and "lying". Validation metrics of behaviours are presented in Section 3.1 Model Performance Metrics. For each group, the total number of predictions of each behaviour was divided by the total number of predictions of any behaviour, resulting in the proportions of time spent on each behaviour for each group. Their proportions are expressed as follows:

$$\text{Proportion of time spent on specific behaviour} = \text{Total time specific behaviour predicted}/\text{Total time any behaviour predicted} \quad (1)$$

These proportions were the primary dependent variables used in the statistical analysis, together with the number of individuals within each group, which was counted manually from thermal footage.

2.5.1. Vegetation Type and State

The groups were, by their coordinates, assigned a vegetation type from the Danish Environmental Agency. This agency also records information on the state of vegetation separated into structural state indicators and indicator species. This information was also used in the statistical analysis. These assignments were executed in QGIS version 3.40 (QGIS.org, 2024, QGIS Geographic Information System, QGIS Association (available online: http://www.qgis.org, accessed on 2 December 2024)).

2.5.2. Statistical Analysis

The behaviour classes foraging, locomoting, lying and standing, as well as vegetation variables, were tested for normality with the Shapiro–Wilk test [20] within each group, and the homogeneity of variance between each group was tested with the Bartlett test [21]. The only normally distributed variable was the proportion of time spent standing, and this was only the case when comparing vegetation types within observations of fallow deer. For this case, ANOVA was used to compare vegetation types. All other comparisons were performed with nonparametric tests. The Mann–Whitney U test was used for pairwise comparisons, and the Kruskal–Wallis test was used for comparisons of multiple groups. Mann–Whitney U test was used for nonparametric post hoc analysis, and Tukey's test was used for parametric post hoc analysis. The Mann–Whitney U test was used since it is unknown whether the individuals observed are the same across observation periods. The samples should therefore be considered independent. Behavioural instability was also investigated in this study. Therefore, MAD (mean absolute deviation) kurtosis and skewness were calculated for each behaviour proportion within each species and vegetation type. Correlations were tested with Spearman's rank correlation test [22]. All comparisons and correlation tests were performed in RStudio ("The R Project for Statistical Computing", v. 4.3.2, available online: https://www.r-project.org (accessed on 18 December 2024)).

3. Results

3.1. Model Performance Metrics

The final model predicts the four behaviours, “foraging”, “locomoting”, “lying” and “standing”, with high precision and low confusion, enabling the analysis of forage behaviour and migration in the present vegetation types. These behaviours were predicted with sufficient precision, that being mAP50 metric exceeding 0.7 (see Table 2).

Table 2. Performance metrics of the final model that was used for behaviour classification. The column “Class” is the behaviour class, the column “Images” is the number of images containing instances of the behaviour class in the validation dataset, the column “Instances” is the total number of instances of the behaviour class in all the images, the column “mAP50” is the mean average precision with union threshold equal to 0.5 and the column “mAP50–95” is the mean average precision across multiple union thresholds up to 0.95.

Class	Images	Instances	mAP50	mAP50−95
All	730	1430	0.664	0.516
Foraging	225	489	0.841	0.686
Interacting	6	6	0.259	0.183
Locomoting	134	273	0.747	0.616
Lying	72	132	0.821	0.624
Other	77	118	0.528	0.340
Standing	227	412	0.787	0.649

Fine-tuning was performed by adding additional images with the behaviour “locomoting” and “standing” since the model was not predicting “locomoting” with sufficient precision and since it often mistook “standing” for “locomoting”. However, after the addition of approximately 100 images containing these behaviours, the precision of “locomoting” exceeded 0.7, and false predictions of “standing” when “locomoting” were decreased (see Figure 2).

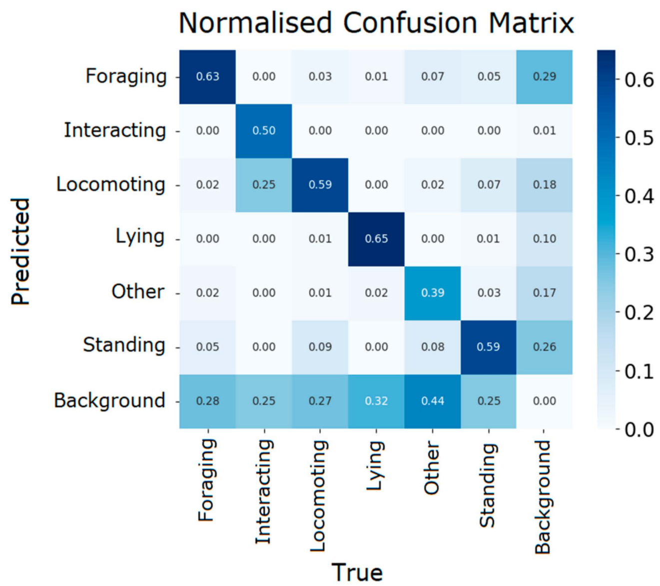

Figure 2. Confusion matrix produced by the validation of the model on approximately 1100 images. All classes are slightly confused with the background but not very confused with each other.

The precision–recall curve in Figure 3 shows that the model can retain high precision and recall simultaneously for the relevant behaviour classes “foraging”, “locomoting”, “lying” and “standing”. Predictions of “other” and “interacting” were not used in statistical analysis because of insufficient precision and recall. High precision and recall are important characteristics of the model's predictions since both falsely identifying the specific behaviour as another behaviour as well as falsely identifying another behaviour as the specific behaviour has implications for the validity of the data.

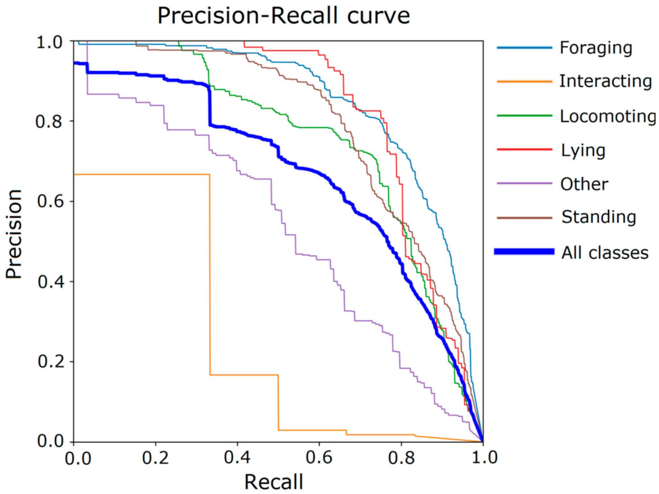

Figure 3. Precision–recall curve of the final model. All relevant behaviour classes retain high precision when the threshold is adjusted to increase recall until a drop at a recall of 0.6. Predictions of "other" and "interacting" were not used in statistical analysis because of insufficient precision and recall.

The models' performance was also evaluated visually by inspection of predictions. A random sample of such predictions can be seen in Figure 4.

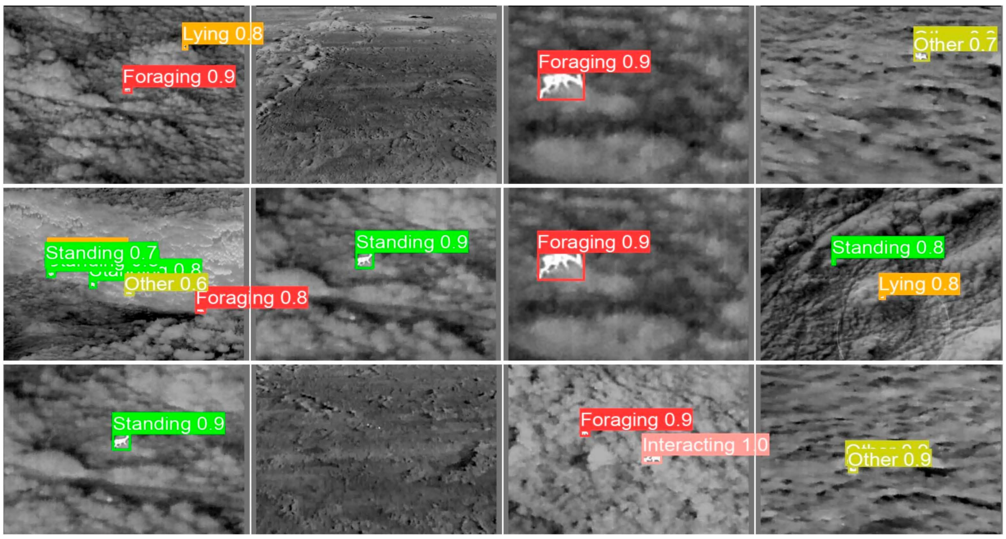

Figure 4. Random sample of predictions produced by the model and used in the evaluation. Each class is indicated by the colour of the bounding boxes and in text alongside the class probability.

High precision is important in predictions of behaviour classes since falsely identifying background as a behaviour class introduces an error that could potentially be background dependent. This could introduce vegetation type-specific differences in predictions, which would bias the results. Similar precision across behaviour classes and low confusion between behaviour classes is at least as important since uneven confusion would entail varying false discovery rates of behaviour classes. Misclassification would not be random but biased towards specific behaviour classes. In this study, the mAP50 ranged from 0.747 in predictions of "locomoting" to 0.841 in predictions of "foraging", and the highest false recall rate was in predictions of "locomoting" that actually were "interacting" at around 0.25. All other false recall rates between behaviour classes were close to zero, indicating low confusion between behaviour classes and low bias towards specific behaviour classes.

3.2. Distribution of Red and Fallow Deer Within Study Area

The vegetation types that were present within the range of data collection were grey dunes, decalcified fixed dunes, humid dune slacks, dunes with creeping willow, dunes with sea-buckthorn and semi-natural dry grasslands on calcareous substrates. However, deer were only observed in the four first-mentioned vegetation types, as seen in Table 3. In the northern area of the reserve, no data on vegetation types were present, consequently resulting in observations with no vegetation data, as seen in Table 3.

Table 3. Number of groups of red and fallow deer observed in the four vegetation types and in areas with no vegetation type data (n), the total area coverage of vegetation types (km^2), as well as the density of observations of individuals of red and fallow deer within each vegetation type (individuals/km^2). "N/A" indicates areas with no vegetation data.

Vegetation Type	Red Deer (n)	Fallow Deer (n)	Total Area (km^2)	Density of Red Deer (Individuals/km^2)	Fallow Deer Density (Individuals/km^2)
Grey dune	11	3	0.7	55.5	5.4
Decalcified fixed dune	46	12	3.2	85.2	6.6
Humid dune slacks	30	15	3.6	92.7	8.2
Dunes with creeping willow	16	7	1.7	22.4	5.6
Dunes with sea-buckthorn	0	0	0.1	0	0
Semi-natural dry grasslands on calcareous substrates	0	0	0.2	0	0
N/A	51	1	2.0	271.0	1.0
Total	154	39	11.4		

Red deer were observed in locations with significantly higher latitudes than fallow deer ($p < 0.001$, Mann–Whitney U test), as shown in Figure 5. This indicates a clear geographical separation between the two species within the study area. The latitude of observations was also significantly different between vegetation types, where observations within decalcified fixed dunes had significantly higher latitudes than observations within dunes with creeping willow and humid dune slacks ($p < 0.01$, Dunn's test). This indicates a geographical separation of the two vegetation types, where observations within decalcified fixed dunes are more northern than those of dunes with creeping willow. The latitude of observations of deer within decalcified fixed dunes and grey dunes did not differ significantly, indicating that these vegetation types were evenly distributed throughout the area of data collection.

There was no significant difference in the time of observation of red deer between any vegetation types. However, the boxplot of dunes with creeping willow in Figure 6 is located above 12:00 pm, meaning that no red deer were observed in this vegetation type before noon, whereas all other vegetation types had observations of red deer throughout the hours of data collection.

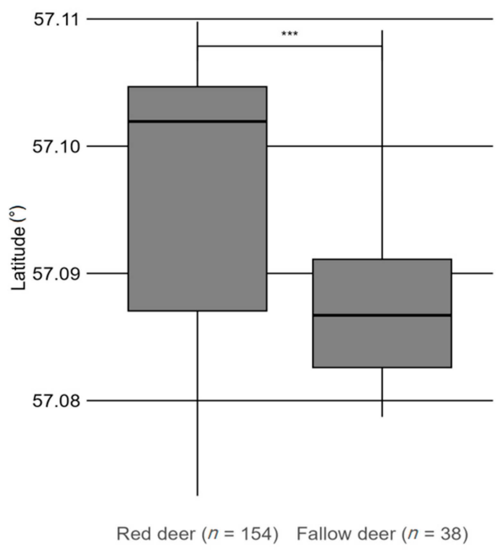

Figure 5. Boxplots showing the latitude (°) of observations of red deer (**left**) and fallow deer (**right**). Latitude of observations was significantly higher in the population of red deer than in the population of fallow deer, indicated by "***" ($p < 0.001$, Mann–Whitney U test).

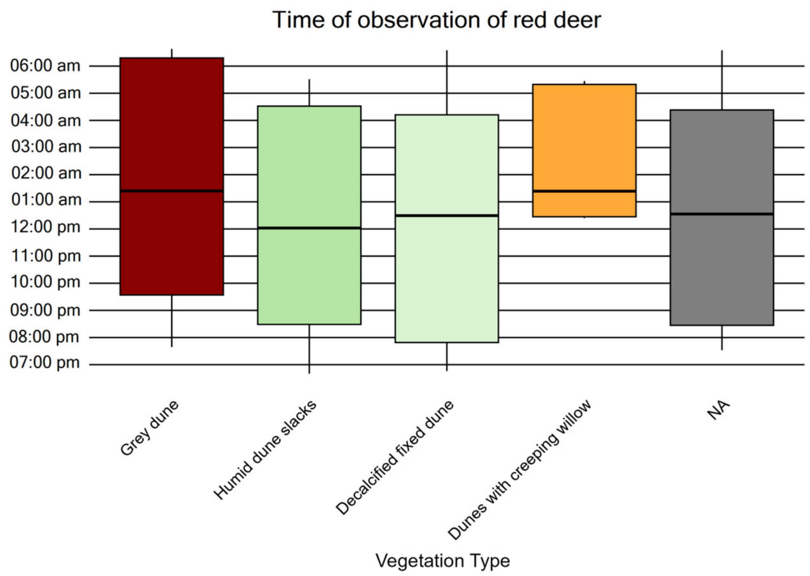

Figure 6. Boxplots of the time of observation of red deer within the vegetation types. There was no significant difference in time of observation between any two vegetation types ($p > 0.05$, Kruskal–Wallis test).

There was no significant difference in the time of observation of fallow deer between any vegetation types (see Figure 7). However, after noon, most groups of fallow deer were observed in grey dunes and humid dune slacks. Before noon, fallow deer were observed in humid dune slacks, decalcified fixed dune and dunes with creeping willows

There was a significant difference in the time of observation of the two deer species within "dunes with creeping willow" ($p < 0.05$, Mann–Whitney U test), indicating that fallow deer were observed earlier than red deer in this vegetation type. There was no significant difference in the time of observation of the two deer species within any other vegetation type.

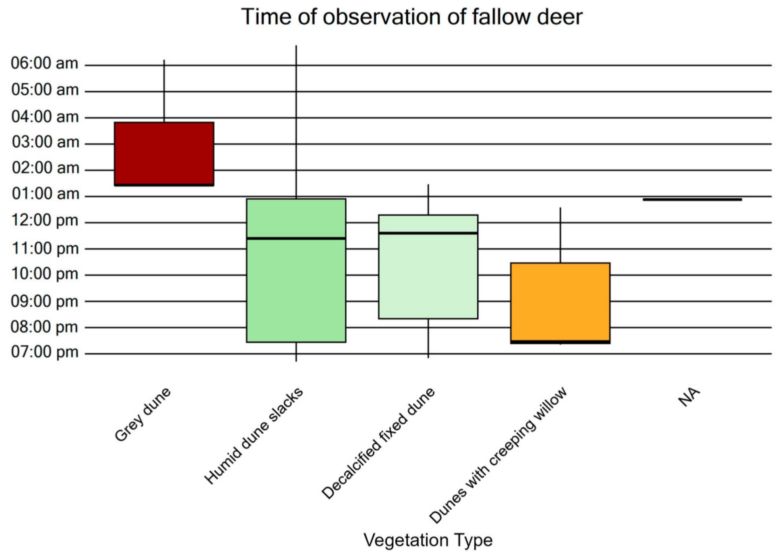

Figure 7. Boxplots of the time of observation of fallow deer within the vegetation types. There was no significant difference in time of observation between any two vegetation types ($p > 0.05$, Kruskal–Wallis test).

3.3. Behaviour Proportions in Vegetation Types and Within Species

Within the vegetation types that red deer were observed, there was no difference in the proportion of time spent foraging. They were moving a significantly larger proportion of time in humid dune slacks than in dunes with creeping willow ($p < 0.05$, Mann–Whitney U test) but were generally not locomoting much in the hours of data collection, as seen in Figure 8. Red deer were observed lying for a significantly smaller proportion of time in humid dune slacks compared to decalcified fixed dunes ($p < 0.05$, Mann–Whitney U test), indicating a preference for resting in decalcified fixed dunes or just at the locations where this vegetation type was present. Red deer were observed standing for a significantly larger proportion of time in humid dune slacks than in dunes with creeping willow. Fallow deer similarly did not seem to have a preference for any vegetation type for foraging when the proportion of time spent foraging is exclusively considered ($p > 0.05$, Kruskal–Wallis test). No behaviour class differed significantly between any two vegetation types for fallow deer ($p > 0.05$, Kruskal–Wallis test and ANOVA). The comparisons of behaviour proportions between the two species within vegetation types can be seen in Figure 8.

3.4. Behavioural Instability

Fallow deer had a higher MAD in the behaviours "foraging" and "lying" in the vegetation type "grey dune" compared to the other vegetation types. MAD in behaviours was similar between red deer and fallow in all other vegetation types. All values of MAD can be seen in Figure 9.

The kurtosis is subtracted 3, resulting in the value "0" being mesokurtic distribution around the mean. The distribution of the behaviour "foraging" was platykurtic in both deer species, except in the population of fallow deer within humid dune slacks, indicating few extreme values. The distribution of the behaviour "locomoting" was leptokurtic in the red deer population, indicating a greater likelihood of extreme values of "locomoting", while the distribution of the same behaviour in the fallow deer population was platykurtic, indicating fewer extreme values. "Locomoting" was therefore more stable in the population of fallow deer than in the population of red deer. The behaviour "lying" was platykurtic within populations of red deer in the vegetation type "decalcified fixed dune", whereas it was leptokurtic in fallow deer. "Standing" was leptokurtic in the population of red deer in "dunes with creeping willow" and platykurtic in the population of fallow deer. All values of kurtosis can be seen in Figure 10.

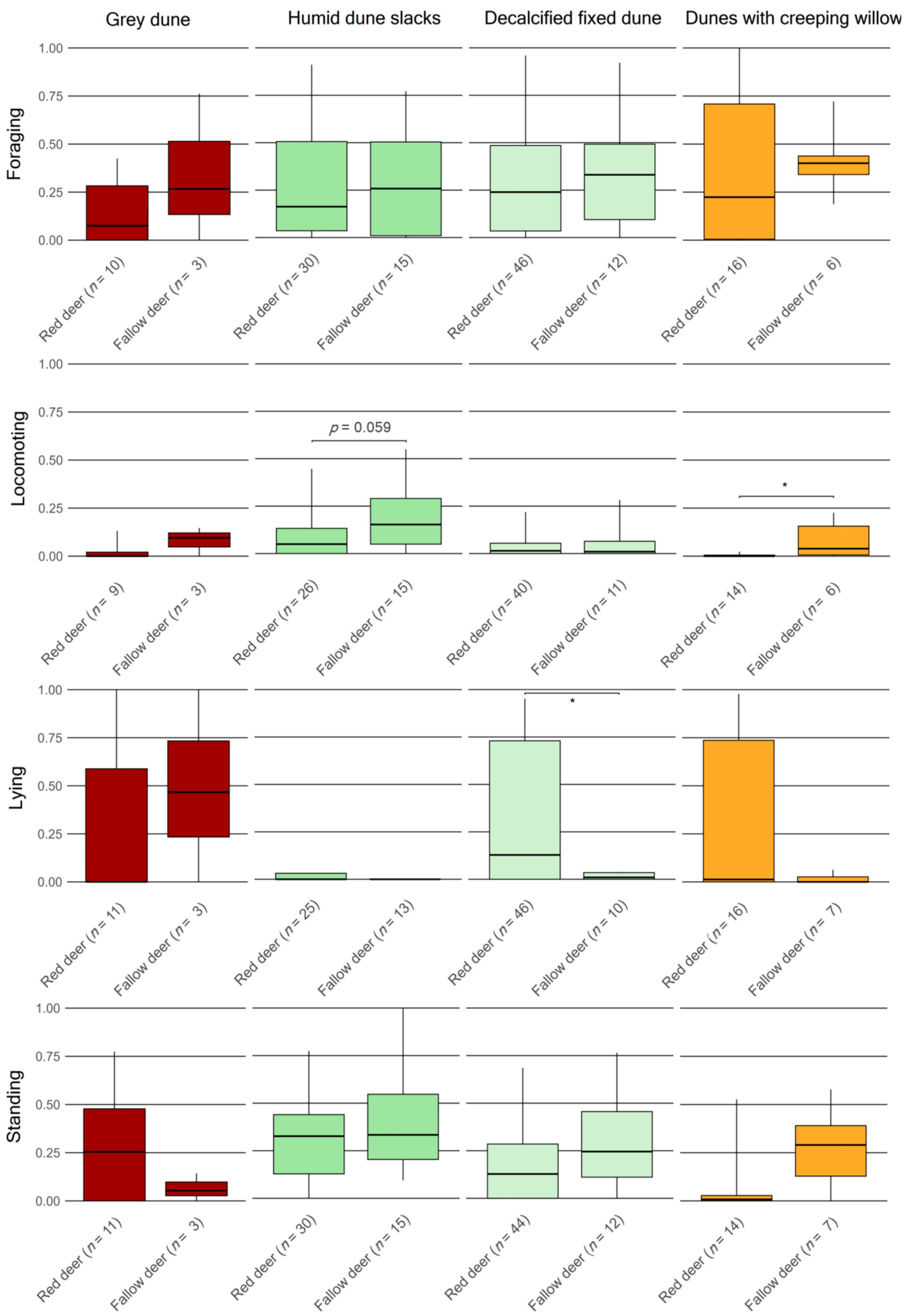

Figure 8. Boxplots of proportion of time spent on the four behaviours visualised as rows and separated in vegetation types visualised as columns and colours. For each combination of behaviour and vegetation type, red deer is the left plot, and fallow deer is the right plot. Only comparisons between the two species are visualised in this plot. Sample size is indicated for each sample, and *p*-values are written for each close-to-significant comparison. Significant difference after Bonferroni correction is indicated with "*" ($p < 0.05$).

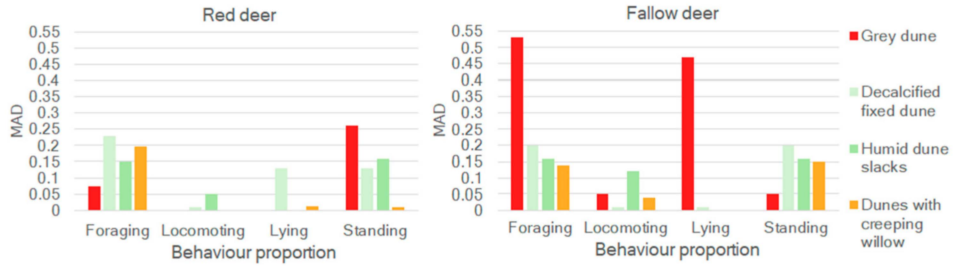

Figure 9. Mean absolute deviation (MAD) of the four behaviour classes "foraging", "locomoting", "lying" and "standing" within the population of red deer (**left**) and fallow deer (**right**) in different vegetation types. Red bars are "grey dune", light green bars are "decalcified fixed dune", darker green bars are "humid dune slacks" and orange bars are "dunes with creeping willow".

Figure 10. Kurtosis of the four behaviour classes "foraging", "locomoting", "lying" and "standing" within the population of red deer (**left**) and fallow deer (**right**) in different vegetation types. Red bars are "grey dune", light green bars are "decalcified fixed dune", darker green bars are "humid dune slacks" and orange bars are "dunes with creeping willow".

Almost all distributions were positively skewed, indicating that most of the observations were located around the mean, but extreme observations had high values of behaviour proportions. This was not the case for any behaviour proportion in the population of fallow deer within grey dunes, where skewness is close to 0, indicating equal amounts of low and high extreme values of behaviour proportions. All values of skewness can be seen in Figure 11.

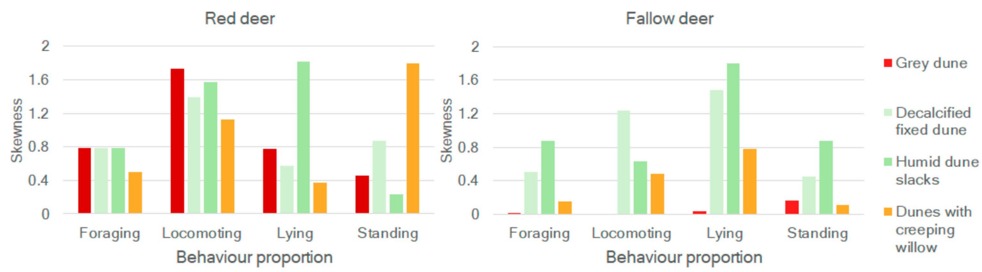

Figure 11. Skewness of the four behaviour classes "foraging", "locomoting", "lying" and "standing" within the population of red deer (**left**) and fallow deer (**right**) in different vegetation types. Red bars are "grey dune", light green bars are "decalcified fixed dune", darker green bars are "humid dune slacks" and orange bars are "dunes with creeping willow".

3.5. Correlations of Vegetative State Data with Behaviour Proportions

Neither state index nor species index correlated with any behaviour proportion in the red deer population. The time spent lying and the vegetation index within the fallow deer population were marginally negatively correlated ($p = 0.073$, $\rho = -0.30$, Spearman's rank correlation test). A significant correlation was found between the structure index and the proportion of time spent locomoting in the red deer population ($p < 0.01$, $\rho = -0.30$, Spearman's rank correlation test).

4. Discussion

4.1. Methodological Considerations

To assess whether the lack of tracking has detrimental effects on the value of the results produced, a comparison between a tracking and non-tracking approach would be necessary. However, successful tracking of individuals instead of consideration of groups as the unit of observation in behaviour studies will benefit the statistical analysis with a much larger sample size and increase the quality and validity of the results. This is because tracking individuals will secure a true representation of the behaviour of individuals where each individual has the same weight in the statistical analysis. When not tracked, individuals in larger groups are less represented in the analysis than individuals in smaller groups; consequently, the behaviour of smaller groups will be overrepresented compared to that of larger groups. This may have implications for the biological accuracy of the results, which stresses the need for the development of a model that is capable of tracking individuals. Achieving high precision in behaviour studies is generally hard compared to species detection, especially with imagery of low resolution, and not many such studies have been performed. For this reason, a less-than-ideal mAP50 threshold of 0.7 was implemented similarly to the study by Fugl et al. 2024 [3]. Species differentiation was performed manually in this study, but future studies should aim to perform species identification with either object detection models or pose estimation models. However, this would require more simultaneous RGB and thermal footage not collected in this study. Using a single drone for data collection is probably sufficient when the collection period is extended to multiple days to ensure equal temporal coverage in the entire area of data collection. To minimise the size of temporal holes of data collection, two drones would be preferred since one drone could collect material while the other's batteries would charge. This would both increase the amount of material and minimise the chance of missing cyclical behaviours, such as rumination and foraging. Additionally, the confusion of the behaviour classes with the background was not equal between behaviour classes, which resulted in error. Future studies should aim to decrease the confusion by adding instances of the most confused behaviour classes. This would equalise the confusion across behaviour types. Finally, it must be mentioned that the movement and distribution, as well as rumination and forage behaviour of both deer species, is expected to change seasonally, which limits the generality of the conclusions of this study since data were only collected over four consecutive nights in October. Future studies should aim to include multiple seasons and preferably multiple data collection periods per season.

4.2. Distribution of Red and Fallow Deer Within Hanstholm Nature Reserve and Their Use of Natural Vegetation

The two deer species were, during the study period, separated in latitude within the area of data collection. Groups of red deer were observed in higher numbers in the northern part of the nature reserve, and groups of fallow deer were observed in higher numbers in the central part of the nature reserve. The vegetation types decalcified fixed dunes and dunes with creeping willow were also geographically separated, where observations within decalcified fixed dunes had higher latitudes than observations within dunes with creeping willow. The separation in latitude and simultaneously in vegetation types is also indicated by the higher relative density of fallow deer in dunes with creeping willow compared to red deer. The geographical separation of the two deer species indicates that red deer prefer decalcified fixed dunes and fallow deer prefer dunes with creeping willow for foraging. However, there was no significant difference in the proportion of time spent foraging between the two species within any of the vegetation types, as seen in Figure 8, indicating that when present, both species use similar vegetation types for foraging. This is further supported by the analysis of behavioural instability. The MAD of the proportion of time spent foraging was similar between the two species within all vegetation types except grey dunes, within which the sample size of fallow deer was only three. This indicates a similar size of variation in the forage behaviour of groups of both species. The variation was also characterised by a few extreme values in both species since the distributions of the proportion of time spent foraging in both species were platykurtic within most vegetation types. The extreme values of the behaviour proportion were, for both species, mostly higher than the mean in all vegetation types, as seen by the values of skewness. This indicates that the two species of deer spend similar amounts of time foraging in the present vegetation types. Geographical separation between species of deer that coexist within the same area could be a consequence of an evolutionary process where past competition has driven physiological and behavioural differences between species, minimising the interspecific competitive interactions seen today [23]. Dunes with creeping willow often emerge by the invasion of creeping willow in humid dune slacks [24,25]. The vegetation besides creeping willow therefore depends on the hydrology, though creeping willow mostly invades less humid dune slacks. Some common plants in humid dune slacks where humidity is high are the common reed (*Phragmites australis*) and the sedge *Bolboschoenus maritimus*, whereas species of grasses and sedges usually found in meadows and pastures are more commonly found in dune slacks where hydrology is lower, and where creeping willow is more likely to invade [25]. It would therefore be expected that the dunes with creeping willow are rich in grass and sedge species, which are both commonly foraged by both deer species [16,26]. Red deer, being intermediate feeders, would more likely forage on scrubs like creeping willow than fallow deer, which are a more grazing-dominant species. But both species are known to browse on scrubs and woody plants throughout the year, and fallow deer prefer residence and potentially foraging in dunes with creeping willow, which is likely linked to the present vegetation, including creeping willow. Decalcified fixed dunes, which seemed to be preferred for residence and likely for foraging by red deer, are a later successional state than humid dune slacks, which are threatened by lowering of water tables, and dunes with creeping willow, which often arise as an invasion of creeping willows on humid dune slacks [24,25]. The two species were observed in dunes with creeping willow at different times of the night. Red deer were only observed after noon and fallow deer only before noon. This could indicate that the two species actively minimise their interspecific interactions by residing in this vegetation type at different times.

Both species seemed to spend more time moving around "locomoting" in humid dune slacks compared to the other vegetation types, though this was not significant. The characteristics of the distributions of time spent locomoting were slightly different between the two species in this vegetation type. Both species had low MAD in this behaviour and were positively skewed, but the distribution within red deer was leptokurtic, hence more extreme values, and the distribution within fallow deer was platykurtic, hence less extreme values. Together with the fact that both species spent similar amounts of time foraging in humid dune slacks compared to the other vegetation types, it could indicate that the two species are more actively foraging in this vegetation type, either because food is sparse or patchy, and that this active forage behaviour was more stable in fallow deer as indicated by the platykurtic distribution of the proportion of time spent locomoting. Humid dune slacks are very rich in plant species and in habitats ranging from dune lakes to humid grass and reed patches, possibly explaining the need for active foraging [25]. In dunes with creeping willow, fallow deer were locomoting a significantly larger proportion of time than red deer. This is indicative of more active forage behaviour in fallow deer than red deer in this vegetation type, possibly explained by red deer more commonly browsing on scrubs and bushes, like creeping willow, than fallow deer, and availability of creeping willow, thereby decreasing the degree to which active foraging is necessary for red deer [25]. The characteristics of the distributions of proportion of time spent locomoting within dunes with creeping willow were also similar between the species, but distribution within the red deer population was more positively skewed, indicating that some red deer were actively foraging in a degree more similar to fallow deer.

Fallow deer were generally not lying much, but more in grey dunes than in the other vegetation types, though not significantly more, probably because of the low sample size (n = 3) of observations of fallow deer in this vegetation type. Red deer spent similar amounts of time lying in all vegetation types except humid dune slacks, where they spent less time lying compared to the other vegetation types and significantly less time lying than in decalcified fixed dunes. Both red and fallow deer are crepuscular species, and their activity is affected by many factors such as food availability, predation risk, mating activity, intra- and interspecific interactions and human disturbances [16,26]. Lying is an indicator of rumination, and both species are known to cycle between feeding and lying down for rumination. The low proportions of time spent lying in groups of fallow deer is indicative of maximisation of foraging at the cost of less rumination time. This could be caused by interspecific interactions with red deer, who are in much higher numbers, forcing the fallow deer to spend more time actively foraging to secure sufficient feed intake. Fallow deer were generally not observed much after noon within the area of data collection, as seen in Figure 7. This indicates that fallow deer migrate back to the forests earlier than red deer.

The only vegetation state indicator that any behaviour correlated significantly with was the structure index, and it was only in the red deer population. The correlation was weakly negative, indicating that a high structure index results in less time spent locomoting by groups of red deer. Structure index is estimated by evaluation of vegetative characteristics related to the health of the vegetation type, such as the number of invasive species, the proportion of area covered by grasses and herbs in different heights and the proportion of area covered by dwarf shrubs and woody plants [27]. The value of these characteristics relates to the state of the specific vegetation types and does not tell anything by themselves since what is considered healthy values depends on the vegetation type. The weak correlation therefore indicates that red deer forage less actively when the structural health of the vegetation type is high, probably because of a preference for the plant species emerging when the vegetation is not affected by invasive species and a preference for the ratio between grasses and herbs.

5. Conclusions

In this study, it was demonstrated that thermal camera-mounted drones and object detection models are time-efficient and valuable tools for biologists and conservationists that can provide information on behaviour of deer in different vegetation types despite the method's early developmental stage and technical challenges that need to be solved. This study indicates that red deer and fallow deer chose to forage in different vegetation types, but this needs further seasonal confirmation. The two species showed different foraging strategies and possible different impacts on vegetation types. Fallow deer were found in vegetation types of earlier successional stages than red deer. In future studies, it is important to investigate how the two species affect the vegetation and vice versa to gain knowledge of how the vegetation types affect the foraging behaviour and population size of the species.

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supervision, C.P. and S.P.; project administration, C.P. and S.P.; funding acquisition, C.P. and S.P. All authors have read and agreed to the published version of the manuscript.

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Monitoring Urban European Hares (*Lepus europaeus* Pallas) with Citizen Science and a Thermal Spotter

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Abstract: Populations of the European hare (*Lepus europaeus* Pallas) have declined in agricultural areas throughout Europe, primarily due to habitat loss caused by the industrialization of agriculture. The growth of cities displaces native habitats, and a decline in hare densities would be expected also in cities; however, several medium-sized mammals thrive in urban areas. In this study, hares in two Danish cities, Aalborg and Aarhus (approx. 145,000 and 300,000 citizens, respectively), were monitored using a combination of citizen science and a thermal spotter. Citizen reports of hares (in all 1874) were highest in the center of the city (26 to 33 locations per km^2). Hare observation densities declined significantly with increasing distance to the center. Breeding hares were recorded in both cities. The thermal spotter proved to be useful to spot hares in the city and it did not draw attention as the spotlights normally used to detect the light reflected from the hares' eyes. Based on the hares spotted at 12 locations where citizens had reported hares, densities of 40.3 (±10.8 SE) hares per km^2 were estimated. The increasing awareness for biodiversity and for not using pesticides in Danish cities allow for wild plants to be established in lawns, which benefits the hares.

Keywords: urban mammal; urban wildlife; urban biodiversity; conservation

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1. Introduction

The native habitat for the European hare (*Lepus europaeus* Pallas), hereafter, the hare, is the open grasslands of Central Europe and Central Asia [1]. Hares most probably became common in Denmark after the extensive deforestation of the country in the Neolithic Age, i.e., 5500 years ago, long after many other native mammals immigrated shortly after the Ice Age (around 11,000 years ago) [2,3]. At the beginning of the 20th century, agricultural areas were ideal habitats for hares, as fields were smaller, and farming was extensive with more weeds in native habitats. Before 1960, up to half a million hares were shot annually in Denmark, but the National hunting game bags gradually decreased, and in recent years, the annual game bag of hares has been less than 40,000 [4]. The decline in the hare populations has occurred throughout Europe, and there is a broad agreement that the decline in the hare population is primarily due to habitat loss, i.e., industrialization of agriculture with increasing field sizes, the removal of field boundaries, and other native habitats in agricultural land [1,5–10]. In Denmark, the hare was red-listed in 2007 as vulnerable (VU) after the national population declined by more than 30% over the years [11]. Since 2018, the hare in Denmark and international is listed as "least concern" (LC).

There are only a few reports of hares in urban areas in Europe. However, these studies, e.g., in Denmark and Sweden (also, mountain hare (*L. timidus* L.) and rabbit (*Oryctolagus* *cuniculus* L.), in the Czech Republic and Austria have witnessed that hares are living in more European cities [12–14].

Hares are primarily herbivorous and prefer weeds, grasses, and various crop types while avoiding cereals [1,15]. This preference is particularly relevant during the summer when crops grow tall, potentially limiting food availability in agricultural areas, whereas urban areas may provide a more stable food supply year-round.

Especially in the United Kingdom, other medium-sized mammals, including the non-native Eastern gray squirrel (*Scirus carolinensis* Gmelin), European hedgehog (*Erinaceus europaeus* L.), red fox (*Vulpes vulpes* L.), and European badger (*Meles meles* L.), are known to thrive in urban habitats [16–22]. Foxes and gray squirrels are considered to be the best adapted with the most suitable habitats in central London, while hedgehogs and badgers prefer suburban and rural areas, respectively [20]. Cities have become greener both in Denmark and other parts of the world to promote human well-being, and at the same time, these green areas attract wildlife [12,20,23,24]. In modern times, hares are known to have been present in Aarhus, Denmark [14]. In the former study [14] of hares in Aarhus in 2018, the density of hares, based on line transects, was estimated to be 8 hares per km^2 when excluding buildings [14].

Monitoring hares and other mammals in agricultural areas and other more native habitats has previously been conducted using wildlife cameras, spotlight counts, or, more recently, drones fitted with cameras have been used [25]. Such monitoring data are crucial to support sound conservation planning for hares and other species. However, monitoring hares in cities poses challenges, as wildlife cameras are only allowed on private property, drones are not legal to fly in cities without special permission, and strong spotlights may cause unnecessary concern among city residents [14,25].

As cities may have a conservation significance for wildlife that has been displaced from the intensively cultivated farmland, it is of great interest to develop methods to monitor hares and other wildlife in cities and to gain knowledge about their preferred habitats, reproduction, and mortality.

The aim of this study is to test two methods for monitoring hares in the urban environment and to identify locations preferred by the hares within the cities of Aarhus and Aalborg, Denmark. We believe that our evaluation of the citizen science method and a novel monitoring method will be beneficial for future monitoring programs for hares and other wildlife in the urban environment.

2. Materials and Methods

2.1. Citizens Science

To contact citizens in Aalborg and Aarhus an article describing a citizen science study of hares was published in a nationwide newspaper on 14 July 2022. In this article, the citizens of the two Danish cities, the second and fourth largest in Denmark, were asked to write an e-mail to a scientist at the University of Aalborg and to report their hare sightings. The study was carried out in Aarhus, approx. 300,000 citizens, and Aalborg approx. 145,000. Through the announcements, the citizens were asked to report hare sightings within 100 m of buildings, together with the date, time of day, and location provided as either an address or GPS coordinates. Additionally, they were asked to indicate whether the hare was a leveret or an adult. If possible, citizens were asked to send a photo of the hare. The media coverage of the announcement of the hares spread to at least 25 different media outlets, both newspapers and radio during July 2022. We assumed hares to be so characteristic that they would not be confused with other mammals, as wild rabbits are not present in the area. Citizens were not trained or asked to report hare sightings repeatedly; they were asked to report the localities where they had observed hares. All citizens who sent information received a response and thanks from the researcher.

2.2. Survey with Thermal Spotter

To test the usability of a Pulsar Axion XM30S Pro Thermal Spotter, LT-06326, Vilnius Lithuania (resolution 320 × 240 pixels and digital 4.5–18 zoom, detection range 1300 m), 12 locations that covered different city habitats and had been reported as hare locations by the citizens in Aalborg were visited. At these locations, hares were spotted and video recorded with the thermal spotter. A thermal camera creates an image of an object by using thermography, which allows the user to see variations in temperature, e.g., a warm-bodied animal. For two nights, one in May and one in September 2023, the areas of the 12 locations were scanned, and the density of hares per km^2 was estimated from the number of hares spotted and the area covered.

2.3. Data Analysis

All addresses of hare observations were transformed into GPS coordinates. In cases where multiple reports were from the same location, only the report with the largest number of hares was retained, and all other reports from that location were removed. A heat map of hare recordings from citizens of each city was created with eight circles, starting from the city center (the railway station) and outwards with a distance between circles of 1 km. The areas covered with different location types were digitized, and areas with apartment blocks and private households with gardens were calculated using QGIS, based on the Danish Data Supply, Creative Commons Attribution 4.0 International [26].

The number of reported locations with hares per km^2 (density of hares) at different distances from the two cities (Aalborg and Aarhus) centers was tested for correlations with a linear and polynomial regression analysis to detect a trend in the density of hares from the city center to the periphery. The correlations between the cumulative percentile curves of the time at which the hares were observed in the different localities (apartment areas, private gardens, city centers, port areas, and commercial districts) were calculated in order to test if there were any biases in the times at which the hares were observed in the different localities. A Chi-square test was used to compare the frequency of double recordings (the same address within 24 h) of hares. The significance level was $p < 0.05$. The statistical software used to conduct the analyses was Past version 4.03 [27].

3. Results

3.1. Citizens Science in Aalborg and Aarhus

3.1.1. Number of Reports

In total, 1874 hare sightings were reported by citizens in Aarhus and Aalborg; of these, 1626 were reported from July to August 2022, at different addresses within 24 h. Of these, 629 hares were seen at unique locations in Aarhus and at 659 locations in Aalborg. Of the hares spotted in Aalborg, 64 were reported as leverets, and 80 were reported as leverets in Aarhus (Figure A1). Hence, 10% and 13% of the hares in Aalborg and Aarhus were leverets, respectively.

In both Aarhus and Aalborg, hares were reported from many different location types such as apartment blocks, private gardens, cemeteries, parks, and lawns around hospitals, universities, and commercial districts (Table 1).

Table 1. Localities from where hares were reported: Aarhus and Aalborg.

Type of Location	Aarhus n = 629	Aalborg n = 659
Apartments areas	309	257
Private gardens	137	205
Parks	55	19
City centers	35	39
Port areas	23	56
Commercial districts	23	49
University parks	11	10
Hospital lawns	11	2
Cemeteries	11	7
Allotment	10	10
Holiday home area	1	0
Field	2	0
Construction site	1	0
Salt meadow	0	1
Football pitch	0	2
Calk mining pit	0	1
City wood	0	1

3.1.2. Densities of Hares in Different City Zones

In both Aarhus and Aalborg, most observations with hares were from the central part of the city. Within 1 km from the city center the density of locations with hare observations were 33 and 26 per km^2, for Aalborg and Aarhus, respectively. The density of reported hares decreased gradually with distance from the city center and outwards (Figure 1).

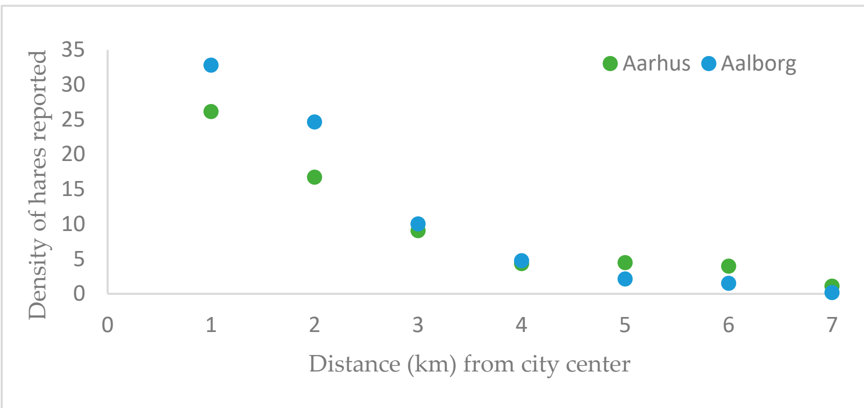
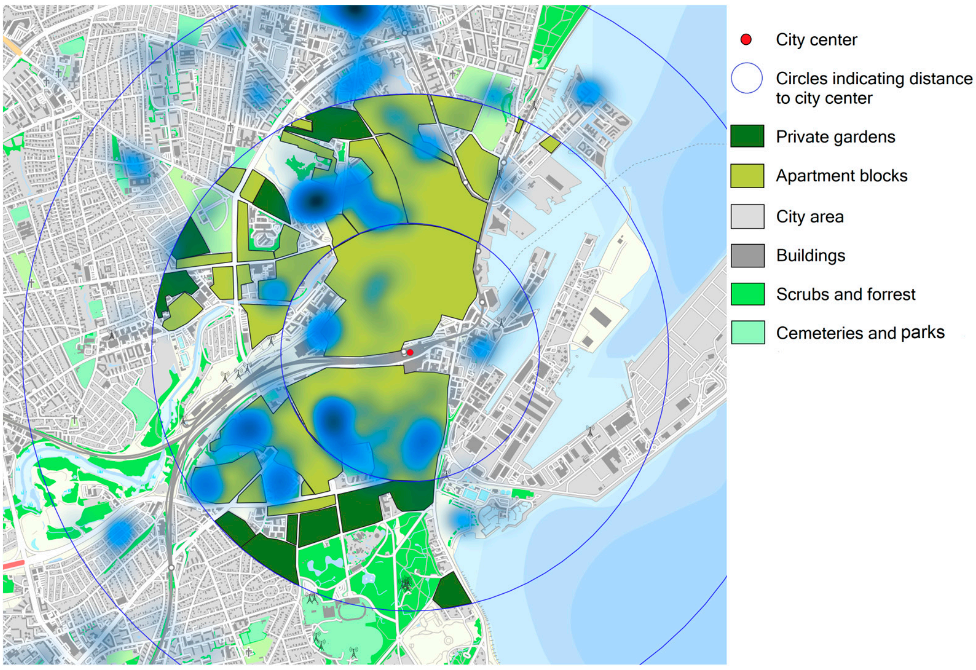


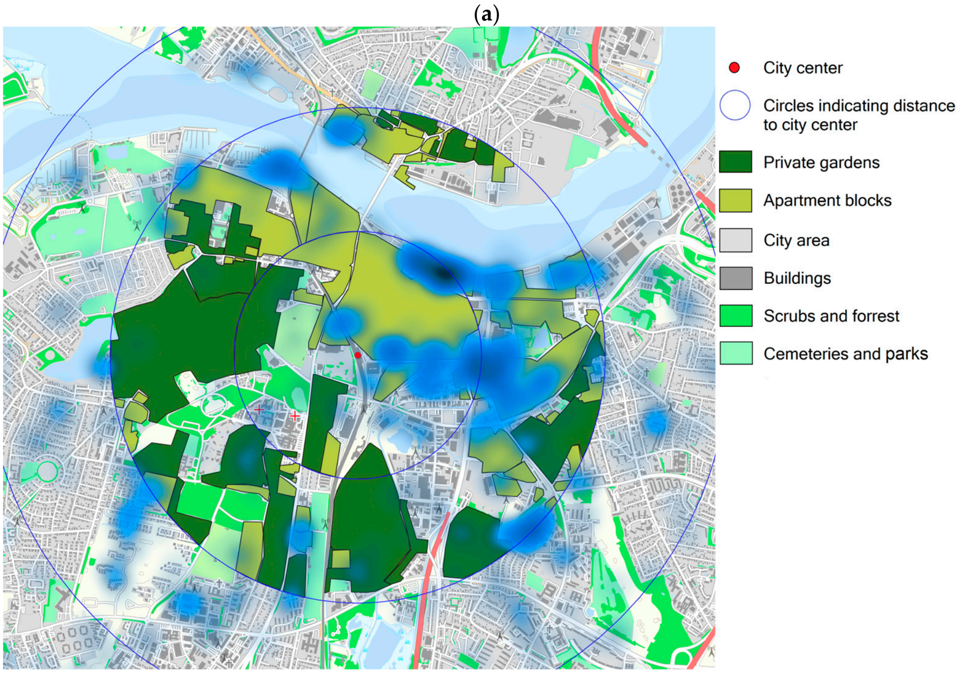
Figure 1. The number of reported locations with hares per km^2 in different distances to the city center (Table A1).

The regression analyses, including linear and polynomial regression, showed a significant declining trend in the density of detected hares from the city center to the periphery (Aalborg: Linear regression: Y = −5.43 + 32.57, R^2 = 0.84, p < 0.01; Polynomial regression: Y = 1.30 × 2 – 1585x + 48.2, R^2 = 0.98, p < 0.001; Aarhus: Linear regression: Y = −3.76 + 24.41, R^2 = 0.82, p < 0.01; Polynomial regression: Y = 0.93 × 2 − 11.21x + 35.59, R^2 = 0.97, p < 0.001).

The density of reported locations with hares was higher in areas with apartment blocks than in areas with private gardens. In the area between one and two km from the city center, where both apartment blocks and private gardens occur, the locations reported with hares were 5.4 times higher in apartment blocks than in private gardens in Aalborg and 4.7 times higher in Aarhus (Figure 2a,b).



(**a**)



(**b**)

Figure 2. (**a**). Heat map of hare reports (blue) by citizens of Aarhus in the three inner circles of the city. (**b**). Heat map of hare reports (blue) by citizens of Aalborg in the three inner circles of the city.

A test of duplicate sightings at addresses of hares in different areas of the city showed no difference between apartment blocks (5.4% duplicates) and residential areas (4.5% duplicates). However, there were significantly more duplicates in parks and cemeteries (14.5%) than in private gardens ($p < 0.001$) and between apartment blocks ($p < 0.01$) (Table A2).

3.1.3. Time of Day When Hares Were Seen by Citizens

There were 683 citizens who had reported the time when they had observed the hare. Most hares were seen in the morning hours between 6 am and 8 am, around two hours after sunrise, and later at night between 8 pm and 10 pm in the twilight hours around sunset (Figure 3).

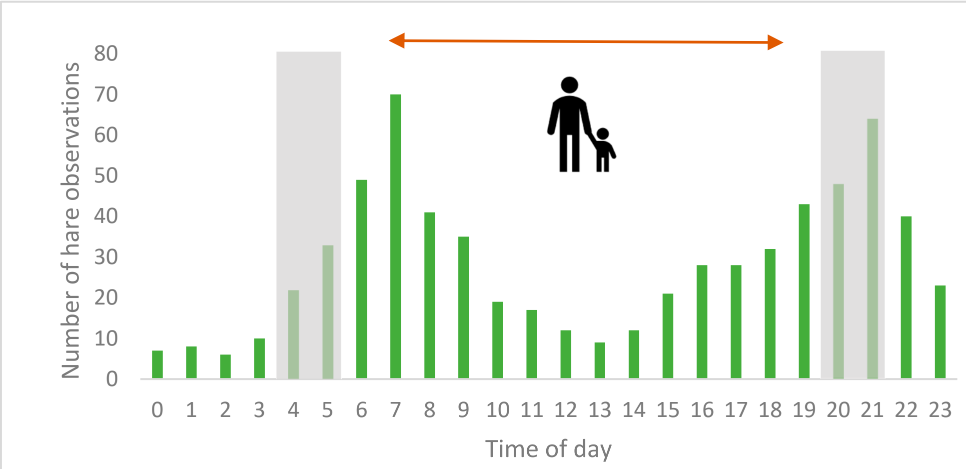


Figure 3. Time of day when hares were seen by citizens (n = 683). The horizontal arrow marks the time of day that humans are expected to be most active during the summer months. The vertical shadings represent twilight before and after sunrise and sunset from July to September.

The correlations between the cumulative percentile curves of the time at which the hares were observed in the different localities (apartment areas, private gardens, city centers, port areas, and commercial districts) were all highly correlated (range of r: 0.98–0.99; all: $p < 0.0001$) (Figure 4).

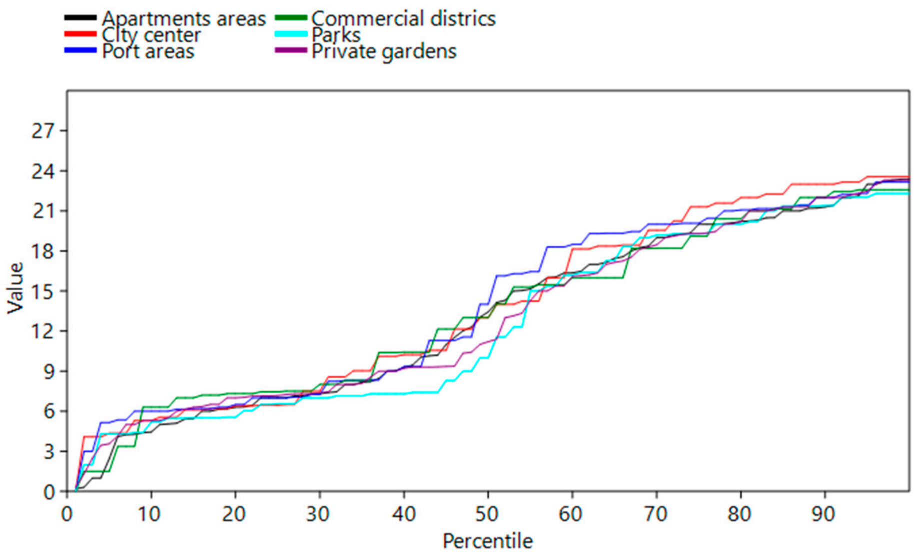


Figure 4. Correlations between the cumulative percentile curves of the time at which the hares were observed in the different localities (apartment areas, private gardens, city centers, port areas, and commercial districts) were all highly correlated (range of r; 0.98–0.99, all: $p < 0.0001$).

3.2. Monitoring Hares with a Thermal Spotter

Hares could easily be identified with the thermal spotter between the buildings at a distance of 50 m and due to the long ears of hares, they could be relatively easily separated from other mammals in the city (Figure 5). During the two nights at 12 locations, where citizens had reported hare sightings, the thermal spotter was used to scan the areas between 1800 and 2400 h (Table A3). No significant correlation was found between the number of hares reported at the locations by the citizens and the hares counted with the spotter. The thermal spotter revealed high densities of hares at the visited spots with an estimated mean of 40.0 (±10.9 SE) hares per km^2. The number of hares seen by citizens at the 12 locations was 4–7 times higher than hares seen using the spotter (Table A3).

Figure 5. Photos of hares taken from video clips recorded using a thermal spotter. In the photo on the right-hand side, a hare can be seen in front of a parked vehicle (left in the photo).

4. Discussion

4.1. Are Urban Areas Better Habitats than Rural Habitats for Hares?

The decline in the hare population in agricultural areas, not only in Denmark but throughout Europe, gives reason to search for remaining quality habitats for hares. The increasing awareness of conserving biodiversity and not using pesticides in Danish cities and private gardens, allows wild weeds to grow in the green areas of urban areas. Greenspaces between apartment blocks in the city center of Danish cities may offer quality habitats for hares and may, therefore, have a conservation value for them. In areas where hares were spotted by the thermal spotter, the estimated mean number of hares (40 per km^2) was comparable with the highest densities of hares found in Europe in arable and mixed areas, where densities were on average 28 and 43 hares per km^2, respectively [7]. In contrast, in a recent Danish study in agricultural areas of Northern Jutland, the hare densities ranged from 1.5 to 10 hares per km^2 using spotlight counts and 4.8 to 14.1 hares per km^2 using a thermal drone [25].

If the habitats in urban areas are more densely populated with hares than in agricultural areas, a source–sink condition may occur where hares reproduce and disperse from urban areas to surrounding agricultural areas. The source–sink model implies that in a heterogeneous environment, some quality habitats may be important for the long-term survival of a population, and considering the presence of source–sink dynamics will help inform conservation decisions [28–30]. However, to act as a source habitat, urban areas need to have more advantages for hares, e.g., higher food availability and reproduction, than disadvantages caused by human interference (e.g., disturbance), leverets taken by dogs, cats, and foxes, and mortality due to other factors such as vehicles [30,31]. Population densities and breeding performance of some species are in fact higher, and home-range sizes are smaller in urban areas compared to surrounding agricultural areas [22,32–34]. As hunting is illegal in Danish cities, mortality due to hunting is eliminated, and predation risk may in some urban areas be reduced [24,35]; however, foxes are common in both Aarhus and Aalborg [36].

Some animals may display increased tolerance of humans, which agrees with reports from citizens of Aalborg and Aarhus, describing observations of hares not acting fearfully toward people passing by. In a study in urban and farmland areas in the Czech Republic and Austria, hares were found to adjust their escape behavior and escaped significantly earlier in farmland (rural) habitats than in urban habitats, indicating that the former populations were not conditioned to the presence of people [12].

4.2. Density of Hares in Different City Zones

Surprisingly, reports of hares were denser in the center of Aarhus and Aalborg, and the density of hares around apartment blocks was five times higher than reported from private gardens. As the comparison between apartment blocks and private gardens was based on sightings in the circular section between 1 km and 2 km from the city center, the preference is thought to reflect the density of hares and not the abundance of observers. We have no explanation for the preference for the lawns around apartment blocks rather than those of private gardens, other than it may be easier to spot predators from a longer distance. Another explanation may be that lawns around apartment blocks provide better feed throughout the year. Private gardens may also be more disturbed by peoples' dogs and cats. There are no stray dogs in Denmark, and predators in the city center are foxes, herring gulls (*Larus argentatus*), and corvids [36,37]. The significant declining trend in hare observation densities documented in this study shows a clear decline from the city center and outward for both cities. This declining trend may be due to the composition and amount of available acceptable habitats for the hares outside the city center.

4.3. Methods for Monitoring Hares in Urban Areas

Hares have not been studied in European cities to the same extent as foxes, badgers, and hedgehogs [16,17,38–40]. It is therefore not known whether hares have entered cities more recently than the other mammal species. Methods have been developed to estimate the population size of foxes using the density of scats or fox dens [41–45]. As hares do not den, only the densities of scats may be relevant to compare to citizen science methods or hares monitored by the thermal spotter. These methods will not always give the exact population size but a relative measure to compare fox densities between habitats.

Citizen reports can efficiently help to reveal hot spots for hares and other mammals within a city. However, citizen science data may be biased, because observers may not be evenly distributed in different parts of the city [21]. It is noteworthy that the very high correlations between the cumulative percentile curves confirm that there are very small biases in the times at which the hares are observed in the different localities. Also, there was no significant difference between the duplicate reports of hares that had been reported at the address between apartment blocks and private gardens, although the density of observers is expected to be higher around apartment blocks than in residential areas. There was, however, a significant difference between duplicate hare sightings in apartment areas, residential areas, and recreational areas such as parks and cemeteries. People may be more aware of their surroundings in their spare time.

In this study, a comparison between the density of hare reports by citizens compared to the counts by the thermal spotter revealed that reported densities by citizens most likely will overestimate the population size by four to seven times compared to the counts made by the thermal spotter. Hares move around, and the observations from citizens will be a concentration of observations over a longer period. Hares were seen at all times of the day, with a peak two hours before sunrise and just before sundown. The peaks around sunrise and sunset may not only reflect human activity but also hare activity. Also, hares in Southwest England during the summer period were found to be partly diurnal, with peaks in activity post-sunrise and pre-sunset, for a total of 6 h [46].

The estimated density of hares In areas pointed out as hare locations (mean 40 hares per km^2) was higher than the densities of hares found in the previous study in 2018 Aarhus (8 hares per km^2). However, this may be due to the different methods. In our study, we monitored hares by a thermal spotter at locations formally reported as hare locations, while in the study in Aarhus in 2018 the scientists walked in line transects during dusk. Also, most likely hares are more easily spotted with a thermal spotter than at dusk by the naked eye.

Citizen sightings were effective in identifying locations and habitats used by hares, but they were not an appropriate method to estimate population size. The thermal spotter with video function was shown to be valuable for detecting hares between buildings in highly populated areas. Hares could easily be spotted at a distance of up to 50 m, and the spotter did not cause unnecessary anxiety as the traditional spotlight counts of hares in cities. In future studies of hares in urban environments, we suggest a combination of citizen science and counts by the thermal spotter to reveal the actual population size. The thermal spotter could advantageously be used over a few nights during spring and autumn, to estimate the yearly population change in the city.

Cities with the proper management of green spaces may become important habitats for many different mammal species, including hares. There is a need for a better understanding of the urban habitat and population dynamics of mammalian species living in urban areas to improve cities for the benefit of and conservation of wildlife. Future monitoring studies using thermal spotters may point out urban habitats with the highest densities of hares. Such knowledge is of great importance for the future management of urban hares and other wildlife.

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Data Availability Statement: Data are unavailable due to privacy of citizens.

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Conflicts of Interest: The authors declare no conflicts of interest.

Appendix A

Figure A1. Examples of photos (13 pieces) of leverets send by citizens from Aalborg and Aarhus.

Table A1. The number of hares observed at different distances from the city center to outlying areas.

	Distance to Center	No. of Hare Locations Within Distance	No. of Hare Locations Inside Circle the Section	Area of Circle Section	Density of Hare Locations
Aarhus It il	1 km	77	77	2.95	26.12
	2 km	207	130	7.78	16.72
	3 km	307	100	11.10	9.04
	4 km	368	61	14.10	4.33
	5 km	444	76	17.04	4.46
	6 km	531	87	21.96	3.96
	7 km	560	29	26.57	1.09
Aalborg	1 km	103	103	3.14	32.79
	2 km	306	203	8.24	24.63
	3 km	451	145	14.88	10.02
	4 km	542	91	19.23	4.73
	5 km	595	53	24.98	2.12
	6 km	642	47	31.23	1.51
	7 km	648	6	36.08	0.17

Table A2. Chi^2 square test of double sightings of hares at the same address within 24 h in different parts of the city.

Location	Apartment Blocks	Private Gardens	Cemeteries/Parks	Industrial and Harbor Area
Apartment blocks	-	$\chi^2 = 0.19$, $p = 0.66$	$\chi^2 i^2 = 6.8$, $p < 0.01$	$\chi^2 = 3.8$, $p = 0.07$
Private gardens	$\chi^2 = 0.19$, $p = 0.66$	-	$\chi^2 = 11.1$, $p < 0.001$	$\chi^2 = 4.0$, $p < 0.05$
Cemeteries/Parks	$\chi^2 = 6.8$, $p < 0.01$	$\chi^2 = 11.1$, $p < 0.001$	-	$\chi^2 = 1.3$, $p = 0.26$
Industrial and harbor areas	$\chi^2 = 3.8$, $p = 0.07$	$\chi^2 = 4.0$, $p < 0.05$	$\chi^2 = 1.3$, $p = 0.26$	-

Table A3. Number of hares reported by citizens at various locations in Aalborg compared to hares spotted with thermal binoculars. Reported by citizens as incidences and (minimum number of hares).

Locality	Date	Time	Area Scanned	Reported by Citizens	Number Spotted	Hares per km^2/100 ha
Park and playground “Karolinelund”	30 May	18:08	3.84 ha	11 (16)	1	26
Cemetary Vesterbro	30 May	20:00	10.56 ha	11 (21)	3	27
Green site “Fjordmarken”	30 May	21:00	7.87 ha	3 (4)	4	51
Salt marsh Lindholm beach park	30 May	22:00	10. 20 ha	3 (7)	3	29
Area around apartment blocks “Carl Klitgårdsvej”	30 May	22:40	6.46 ha	9 (20)	0	0
Area around apartment blocks “Blegkilde”	18 September	20:40	9.65 ha	15 (24)	5	52
Area around apartment blocks “Borgmester Jørgensens Vej”	18 September	21:33	6.57 ha	4 (11)	4	61
Area around apartment blocks “Rughaven”	18 September	22:06	3.77 ha	6 (12)	3	25
Residential area “Øgadekvarteret”	18 September	22:31	10.43 ha	14 (18)	9	87
Green area at the harbor area	18 September	23:23	2.37 ha	26 (51)	3	125
Castle Park	18 September	23:38	1.48 ha	5 (6)	0	0
Park “Jomfru Ane”	18 September	23:54	1.09 ha	1 (1)	0	0
Mean number of hares per ha/km^2	-	-	-	168/297	-	40

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