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The influence of anthropogenic pressure on road use by Eurasian lynx (Lynx lynx) in Norway

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Natural resource management & Environmental Sciences

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Abstract

Human-made infrastructures, particularly roads, pervade wildlife habitats. These roads, which extend to many regions in the world, can serve as both obstacles and pathways for wildlife. Our study focuses on the Eurasian lynx (*Lynx lynx*), a cryptic and far-ranging predator, and its interaction with roads. We utilized snow tracking data from across Norway to examine the relationship between human presence and the utilization of roads by lynx.

Our study incorporated lynx tracking data with details on road type, average daily traffic volume, building density, and data from Strava, an application for fitness and activity tracking. For each lynx track found on a road, we also determined the forest cover percentage in the surrounding area, providing an estimate of the available concealment. Our goal was to gain a deeper understanding of the anthropogenic context influencing the use of roads by lynx.

Our findings suggest that lynx typically interact with roads located in areas with a high percentage of forest cover. However, the extent of forest cover did not influence the length lynx travelled on roads, nor did it affect the perception of other variables. Traffic volume and building density significantly reduced the length of lynx tracks on roads. These variables strongly influenced the distance travelled when they were absent or present in small amounts. An additional increase in traffic volume and building density did not heavily affect the distance travelled. Interestingly, the level of recreational activities, as indicated by Strava records in an area, did not influence lynx in their interaction with roads.

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1. Introduction

Roads are a crucial part of our infrastructure. As the human population continues to grow, the construction of more and larger roads is likely (Dæhlen, 2020). While roads are vital for human societies, they induce both positive and negative alterations in the ecosystems they traverse (Hill et al., 2021). One of the negative impacts is habitat fragmentation, as road networks may restrict the orientation of home ranges (Bischof et al., 2017). Species are often required to cross these barriers, exposing themselves to various threats such as traffic and predators (Mata et al., 2020; Moore et al., 2023).

On the other hand, roads can create new food sources for various species, representing a positive change. The edges of roads are frequently maintained by authorities, with larger trees being cut down. This allows grass and shrubs to flourish, providing new food sources for birds, insects, and mammals. Roadkill also serve as a food source, attracting scavengers that regularly patrol roads (Schwartz et al., 2018).

Roads also function as highways for animals. Species can use roads to travel longer distances with increased movement speed (Bischof et al., 2019) and lower energy consumption. Especially larger predators like the Eurasian lynx (*Lynx lynx*), which can have territories as large as 2 600 km^2 (Linnell et al., 2021), may use road like infrastructure to be able to travel faster trough their territory.

The Eurasian lynx is one of four large terrestrial predators in Norway, and the only wild feline species in the country (Rovdata, 2023a). It mainly avoids human-populated areas, particularly during daylight hours. Studies indicate that although lynx tend to avoid areas frequented by humans during the day, they do visit these areas when human activity decreases (Filla et al., 2017; Thorsen et al., 2022). This pattern likely stems from human-related threats being the primary cause of lynx fatalities, such as poaching and vehicular collisions (Andrén et al., 2006; Bunnefeld et al., 2006). Given that roe deer, a primary prey, tend to inhabit open, cultivated lands, lynx must navigate the delicate balance between pursuing prey and the heightened risk of human exposure. A dilemma intensified in regions where prey is scarce (Basille et al., 2009).

With a large predator being part of the natural ecosystem, but at the same time posing an economical risk for livestock, the necessity of extensive data collection and monitoring arises. Norway has implemented thorough predator surveillance measures. In accordance with national legislation and the Berne Convention, the conservation of wildlife, including predatory species, is mandated in Norway (Regjeringa, 2021). The country is segmented into eight distinct zones for predator management, each characterized by varying livestock types and population sizes (Regionale rovviltnemnder, 2021). Certain zones receive heightened focus due to their larger livestock numbers. To protect domestic animals, annual national and regional targets and limitations are established for predator populations and offspring counts. Achieving these population objectives hinges on persistent monitoring and data gathering (Regjeringa, 2021).

The Eurasian Lynx is among five predators included in a national monitoring program in Norway, established in 2000 (Rovdata, 2023b). The program aims to gather data on each predator species to facilitate population tracking. Rovdata, affiliated with the Norwegian Institute for Nature Research (NINA), oversees this monitoring endeavour and the associated data compilation (NINA, 2023a; Rovdata, 2023a). Scandlynx is a collaboration project between NINA and Grimsö research station in Sweden. Since 1993, these institutions have collaboratively collected ecological data throughout Scandinavia. Their main goal is to deepen the understanding of the Eurasian lynx, ultimately informing management strategies and educational programs (NINA, 2023b). A key focus of the Scandlynx study lies in investigating how the Eurasian lynx interacts with and reacts to human-made infrastructures (NINA, 2023b).

Our study seeks to clarify the determinants that affect how lynx interact with different road types. Variables such as human presence, forest density, and the different road types are considered. Human influence is quantifiable through several indicators; this study focuses on the impact of building density and human recreational activities, in addition to traffic volume.

While it is established that lynx utilize human-made infrastructure (Basille et al., 2013), less is known about the specific variables influencing the distance they travel on roads. Questions arise: Does the proximity of buildings, the extent of human recreational activities, or the volume of traffic affect movement choices of lynx? Furthermore, is the forest coverage next to roads a contributing variable? As human activities intensify, along with population expansion and land appropriation, lynx face increasing challenges within their habitats. Thus, pinpointing the key elements that dictate lynx interactions with infrastructures such as roads is vital for their sustainable management and potentially for other species as well. The research questions we aim to address are:

- Do representative variables for human pressure such as buildings, recreational activities and traffic volume influence the extent of road use by lynx?
- Among these variables, which exerts the most significant effect, and how does forest coverage modify their influence on lynx behaviour?

Based on these questions, we propose the following hypotheses:

- All these variables, excluding forest cover, are presumed to negatively affect lynx, given that human activities are the principal threat to their existence.
- Building upon the initial hypothesis, it is anticipated that traffic volume will have the most substantial impact on lynx behaviour.
- The distance lynx travel on roads is anticipated to increase with a higher percentage of forest cover surrounding the roads. Forest cover is hypothesized to mitigate some of the negative effects of human pressure.

2. Method

2.1 Study area

This study was carried out across the majority of Norway’s mainland territories, with the exception of counties Rogaland, Vestland, and Oslo. No lynx tracks were registered in these counties. Consequently, the study’s geographical scope extends from 58.44(110) to 70.42(640) N latitude and from 7.40(581) to 30.68(537) E longitude (Figure 1).

Norway's landscape encompasses diverse climatic and vegetational zones, including cultivated grassland, temperate deciduous forest, arctic tundra, and alpine ecosystems. Due to confidentiality regulations, the tracking data from The Norwegian Environment Agency is not available for public access. Therefore, only a generalized depiction of the study region is presented (Figure 1).

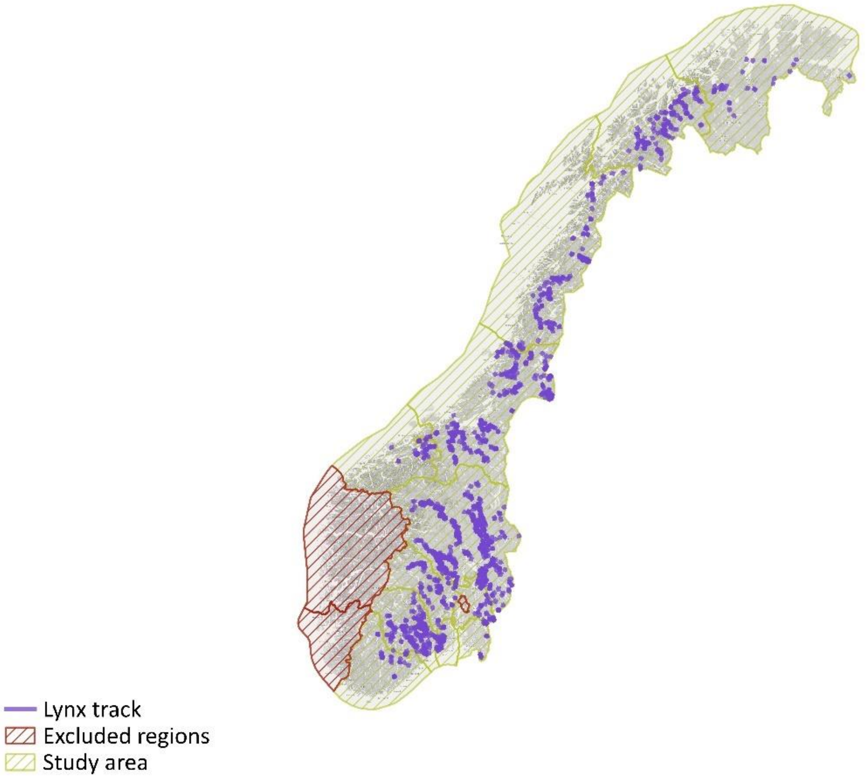

Figure 1: A geographical representation of the study area in Norway (yellow shading), and the excluded regions (red shading). Registered lynx tracks are shown in purple. Created using QGIS 3.36.2.

2.2 Data gathering and processing

2.2.1 Lynx tracks

Our study utilized data collected by the Norwegian Nature Inspectorate (SNO), the field department of The Norwegian Environment Agency. The primary focus of SNO was to track snow prints of lynx family groups, which refer to female lynx accompanied by their kittens (less than one year old). However, the registration process also accounted for solitary lynx. Tracking of lynx occurs from the beginning of October until the end of February, with occasional exceptions when wildlife authorities track lynx outside of these specified times (Rovdata, 2022). These tracks were subsequently followed using handheld GPS devices, resulting in a GPS track that corresponds with the lynx track (Figure 2, S3 and S4). The GPS data included in this study was collected from 2013 to 2022.

The direction of tracking was determined by the ease of navigation for field personnel, considering terrain and vegetation conditions. Consequently, the tracking includes both backtracking and forward tracking. This procedure was conducted on fresh, undisturbed snow that was between one to three days old (Figure S2). If the tracks vanished or ceased, GPS tracking was paused. Minor interruptions in tracking were permissible up to a specified distance. Additional, visible tracks of two or more lynx walking together were also documented.

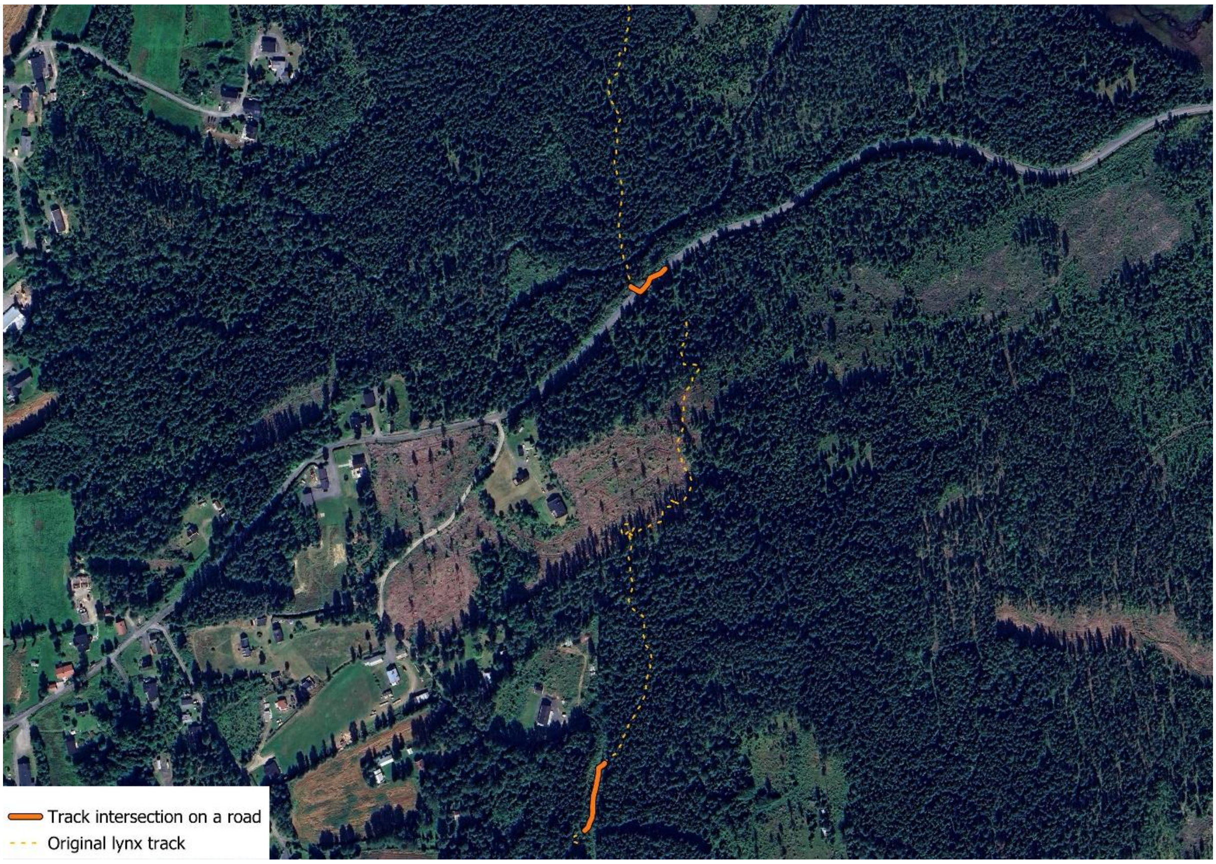

Figure 2: Example of a lynx track (depicted in orange) intersecting with a rough- and normal forestry road. Tracks in the snow were followed with hand-held GPS to recreate the trail. Created using QGIS 3.36.2.

Upon receiving the tracking logs, we reviewed each one, identifying and eliminating any obvious inaccuracies. These inaccuracies, evident as long straight lines across the terrain, could arise from various factores, including GPS errors or movement by vehicles, among others. We did not employ a specific method for the elimination of inaccurate tracks, but rather manually removed any segment of a track showing obvious marginal errors (Figure S1). The removal of obviously inaccurate GPS tracks was preformed using QGIS 3.34.2 Lima (QGIS.org, 2024).

2.2.2 Road network

In this study, we integrated two datasets to form a comprehensive representation of Norway's road network. The 'FKB-Veg' dataset encompasses detailed information on all public and private roads in Norway, represented as highly detailed georeferenced polygons.

However, it excludes smaller forestry roads and human-made hiking paths, which are not accessible to standard vehicles. These features are included in the 'FKB-TraktorvegSti' dataset, which provides detailed information on all registered paths and rough forestry roads, but only represented as centre lines. Both 'FKB' datasets are the result of a collaborative effort among various Norwegian authorities (Kartverket, 2024c).

To accurately depict the full width of the rough forestry roads and walking paths, we applied a buffer of 1.75 meters to the rough forestry roads and 0.75 meters to the walking paths. By legal standards, rough forestry roads must be at least 3.5 meters wide (LMD & LDIR, 2016). Walking paths, however, do not have a legally mandated width as it varies based on usage; thus, we adopted a general total width of 1.5 meters for paths (Glomsaker, 2008).

Rather than adjusting the lynx tracks for the standard 15-meter GPS error margin (Garmin, 2024), we chose to buffer each road type by 25 meters. This additional 10-meter buffer beyond the standard GPS error margin accounts for tracks in close proximity to the roads or those parallel to them. Tunnels were excluded from the road network. Private- and forestry roads, and rough forestry roads and paths were merged into two different road types. This simplification reduced the number of unique road types, facilitating subsequent analysis. The buffering process led to overlaps, which we addressed by implementing a hierarchical system for road types, removing the lower-ranked segments where overlaps occurred. For example, county roads were omitted where they intersected with larger European roads. All data processing to create an extensive and buffered road network was performed using QGIS 3.34.2 Lima (QGIS.org, 2024). The hierarchy of road types, from highest to lowest, is as follows:

E – European roads

R – State highways

F – County roads

K – Municipal roads

PS – Private- and forestry roads

TS – Rough forestry roads and paths

European roads

European roads serve as primary traffic routes across European countries, designed for efficient travel between major cities, with significant variation in size throughout Norway (Figure 3 and 4). These roads have a single lane width of at least 3.50 meters (Lovdata, 1992), allowing for high speeds (60-110 km/h in Norway) and often features multiple lanes in the same direction (Rasmus S. Nordahl, 2024).

Figure 3: European road in Norway (Foto: Karkalatos, Christian A. D.).

Figure 4: European road in Norway (Foto: Killi, Anita).

State highways

State highways are important thoroughfares, frequently branching off from European roads. The dimensions of state highways vary significantly (Figure 5 and 6), with standards dictated by variables such as traffic volume, environmental considerations, and accommodations for wildlife crossings. Unlike European roads, state highways may feature longer stretches with lower speed limits (< 80 km/h) (Rasmus S. Nordahl, 2024; Vegvesen, 2014).

Figure 5: State highway in Norway (Foto: Arnekleiv, Gunnar).

Figure 6: State highway in Norway (Foto: Ous, Kjartan)

County roads and municipal roads

A significant proportion of Norwegian county roads and municipal roads are in poor condition due to inadequate maintenance (Rasmus S. Nordahl, 2024). These roads are typically smaller than state highways but can vary a lot in dimension (Figure 7 and 8). Furthermore, certain roads within these categories may lack pavement and instead feature a gravel surface (Figure 8).

Figure 7: County road in Norway (Foto: Killi, Anita).

Figure 8: Municipal road in Norway (Foto: Killi, Anita).

Private- and forestry road

Private and forestry roads typically represent narrower routes, with maintenance responsibilities falling on the road owners (Kjøllesdal, 2015; Lovdata, 1963; Skogeierforbund, 2024). These roads often feature gravel surfaces and are typically devoid of road markings and guardrails (Figure 9 and 10).

Figure 9: Private road in Norway (Foto: Killi, Anita).

Figure 10: Forestry road in Norway (Foto: Killi, Anita).

Rough forestry roads and paths/trails

Rough forestry roads are subjects to specific usage restrictions, being exclusively intended for agricultural and forestry activities (Statsforvalteren, 2024). While commonly surfaced with gravel or dirt, rough forestry roads can significantly impact the terrain due to the presence of large forestry machinery (Figure 11). Forest trails, on the other hand, is not accessible for vehicles but are primarily utilized by pedestrians, cyclists, and horseback riders. These trails vary in size, influenced by different usage patterns and long-term surface wear (Figure 12).

Figure 11: Rough forestry road in Norway (Foto: Arnekleiv, Maja).

Figure 12: Path in Norway (Foto: Arnekleiv, Maja).

2.2.3 Traffic volume

Traffic data was obtained from the Norwegian Public Roads Administration. It provides the average daily traffic volume for most public roads. These roads are often segmented, with each segment possessing distinct traffic data (Vegvesen, 2024). In addition to utilizing the average daily traffic volume in our study, we calculated the combined average daily traffic for each road type within our study area. This allows for the visualization of the average traffic flow on each of the previously mentioned road type (Table 1 and chapter 2.2.2).

Table 1: Average daily traffic volume (TV) for each road type in our study area.

Road type	**Code**	**TV**
European roads	E	6685
State highways	R	5586
County roads	F	2412
Municipal roads	K	588
Private- and forestry roads	PS	66
Rough forestry roads and paths/trails	TS	0

2.2.4 Buildings

In our study, we utilized the *FKB-Bygning* dataset as a source for evaluating human occupancy in our study area. This comprehensive dataset provides detailed information on the precise locations of documented structures and classifies them according to distinct categories of building types. Additionally, it is directly connected to the Norwegian cadastre (Kartverket, 2024b).

2.2.5 Forest cover

For the analysis of forest coverage, we extracted data from the *FKB-AR5* dataset, which is predominantly utilized for agricultural, forestry, and land management purposes. This dataset offers granular details on land utilization across different regions. We excluded regions labelled as 'Not mapped' within the FKB-AR5 dataset, thereby reducing uncertainties regarding forest cover in those specific areas. We used this data to determine the forest cover extent around roads (Kartverket, 2024a).

2.2.6 Strava data

Strava operates as a global entity providing a social networking service designed for sports enthusiasts seeking communal interaction. Primarily accessible via a mobile application, this platform facilitates the tracking, recording, and sharing of athletic pursuits by users (Strava, 2024). For our study, we utilized Strava data collected from 2016 to 2019, provided by the Norwegian Institute for Nature Research (NINA). Each Strava route is assigned a distinct ID and is associated with a summarization of all recreational activities for each respective year.

2.3 Spatial analysis

2.3.1 Interactions between lynx tracks and roads

We uploaded the pre-buffered road network and lynx track data into R (version 4.3.2) as shapefiles. To identify interactions between each track and the road network, we employed the *st_intersection* function from the *Simple Features* (sf) package (Edzer Pebesma et al., 2024). Each was recorded as a separate observation, depending on following criteria (example Figure 13):

- An intersection was noted whenever a lynx track traversed on, alongside, or within a close proximity (within a 25-meter buffer) of a road.
- In cases where a lynx track followed a road that intersected with another road, the number of intersections was determined by the following criteria:
  - If the original road ranks higher in the hierarchy system (2.2.2) than the intersecting road, it was counted as a single intersection.
  - If the original road ranks lower, three intersections were recorded:
    - One for the lynx traveling along the buffered road.
    - One for crossing a road higher in the hierarchy.
    - One for re-entering the original road post-intersection.
- Additionally, if a lynx entered, exited, and then re-entered the buffered road, this counted for two separate intersections, with additional intersections counted each time the same lynx re-entered the road.

Figure 13: This figure illustrates a recorded track (dashed orange line) as it intersects with several 25-meter buffer zones surrounding different road types (white zone). The journey of the lynx begins on a TS before it crosses a PS, and ultimately reverts to a TS once more (from left to right). This specific track has five intersections with roads, each starting when the track enters a new yellow zone (defined by out method).

To address minor structural breaks within a single track, we combined interruptions if the end of one track and the start of another were within 10 meters of each other and shared the same original ID. This method prevents the creation of excessive new tracks.

Finally, we measured the length of each track segment intersecting with a road using the *st_length* function from the sf package. Each intersection was assigned a unique ID, making it an individual observation in our dataset (Figure 13).

2.3.2 Extracting variables

For each lynx track intersecting with a road, we established a central point, referred to as a *case centre point*, regardless of the length of a track. For each case centre point (TRUE), we generated five control points (FALSE). These control points were randomly placed on roads without buffers outside of urban areas, yet within a 5000-meter radius of the case lynx tracks. It is fair to assume that such a radius depicts an accessible range for lynx in the same area. We excluded two original lynx tracks located entirely within urban settings to eliminate outliers with extreme conditions. Due to the high density of roads in urban areas, we excluded these tracks from our study to prevent control points being placed within highly urban areas. An area qualifies as urban if it meets the following criteria set by the national statistical institute of Norway (Statistics Norway):

- It houses a minimum of 200 residents (approximately 60 – 70 houses).
- The gap between individual houses does not surpass 50 meters.
- Exceptions to this distance are permissible if the intervening space is unsuitable or unavailable for residential development, such as parks, industrial zones, or natural barriers.
- Clusters of houses that are integrally linked to an urban area are included within a 400-meter radius from the urban centre.

For our analysis, we utilized mapped polygons of urban areas, covering all of Norway from 2021, also sourced from Statistics Norway (SSB, 2013). A 25-meter buffer was applied to urban areas to prevent the placement of randomized points immediately adjacent to these areas.

We encircled each case centre point with a 50-meter buffer to aggregate the total Strava activity within this zone and compiled the total traffic volume within the same buffer. Additionally, we assessed the forest cover percentage within the 50-meter buffer zone by using data from the FKB-AR5 dataset and calculating the total area classified as '*Forest*'. A 50-meter buffer was also created around each control point to ascertain the forest cover percentage. To evaluate the impact of buildings, we expanded the buffer to 250 meters and counted the number of buildings within, without distinguishing between building types (Figure 14).

In our study, we intentionally did not extend the buffer to 250 meters for the control points. Additionally, we only assessed forest cover data from the control points. Our objective was to investigate whether forest cover influenced both the length travelled on a road, and the decision to be on that specific road, even though it had access to other roads.

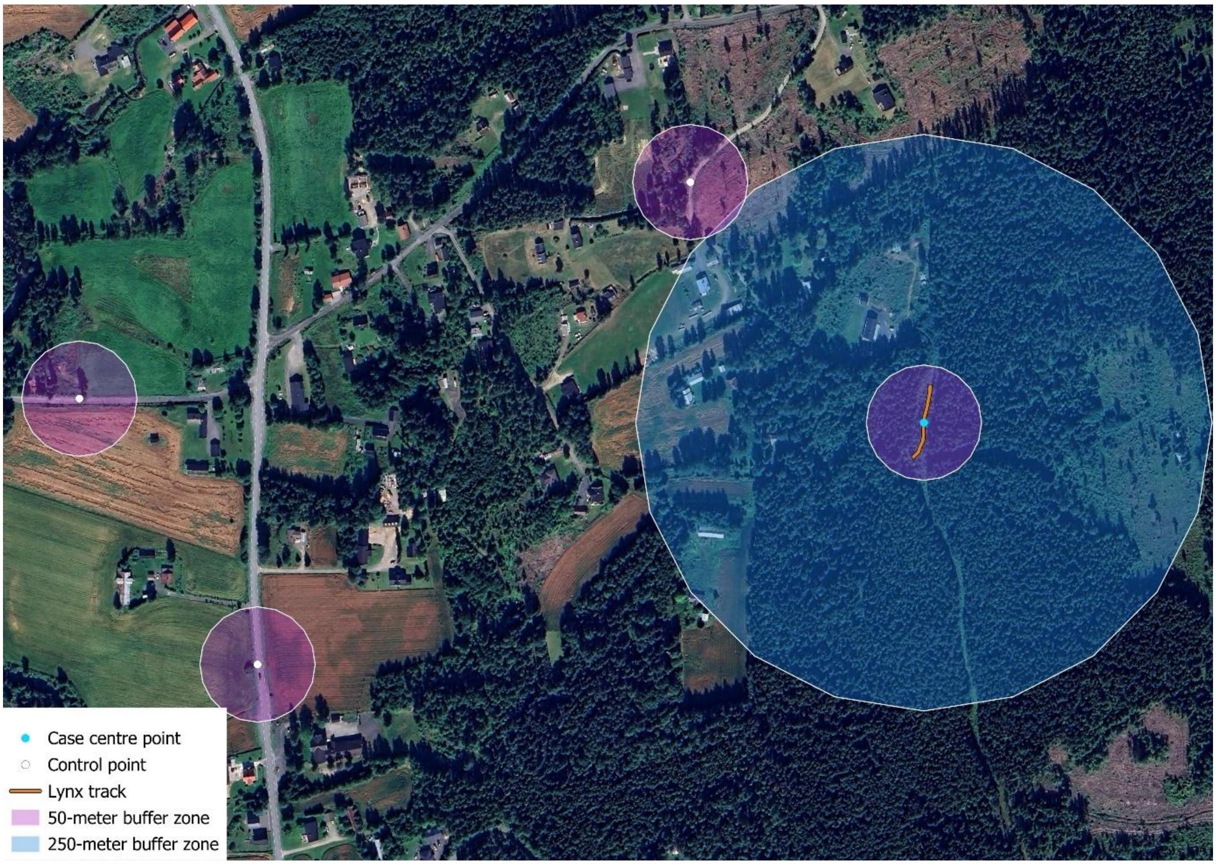

Figure 14: This figure illustrates a lynx track (orange line) intersecting with a rough forestry road. The intersections central point is marked with a blue point, along with randomly sampled white control points. It also illustrates the 50-meter (pink area) and 250-meter (turquoise area) buffer zones. Created using QGIS 3.36.2.

2.4 Statistical analysis

2.4.1 Variables influencing track length

In our analysis, the length of each intersection (measured in meters) served as the response variable. The predictor variables included the total number of buildings, total Strava activities, traffic volume, and the percentage of forest cover. We applied a logarithmic transformation to both the response and predictor variables, except for forest cover, to make their relationship linear.

The presence of forest cover may influence the effects of the other predictor variables, as forests act as concealment and refuge for lynx. We fitted a generalized linear model with a logit link function using the base version of R assuming a standard Gaussian distribution (RDocumentation, 2024). We structured our model, to incorporates the number of buildings (NB), Strava activity (SA), traffic volume (TV), and forest cover (FC) as the key predictor variables influencing track length on roads, eq. (1).

$$glm(log(length) \sim (log(NB) + log(SA) + log(TV)) * FC) \tag{1}$$

To explore various model configurations, we utilized the dredge function from the MuMin package (Barton & Barton, 2015), an automated model selection tool. This function assesses all possible combinations of variables derived from our initial model. Subsequently, we performed a model averaging using the *model.avg()* function from the *MuMin* package, focusing on a subset of models that represent 95% of the cumulative Akaike weight.

2.4.2 Importance of forest cover on road selection

The habitat utilization of lynx is strongly associated with areas covered by forests (Basille et al., 2009). Consequently, we conducted a comparative analysis between our dataset and a set of randomly sampled data points. Given the implementation of a 5000-meter buffer around each lynx track, it is reasonable to assume that virtually all roads within this buffer are potentially available to lynx.

To examine whether the percentage of forest cover is a significant explanatory variable for our case versus control points, we fitted a generalized linear model with a logit link function using the base version of R (RDocumentation, 2024). In this model, the designation of points between case or control was the response variable, while the percentage of forest cover acted as the predictor variable. We assumed a standard Gaussian distribution for the analysis.

3. Results

3.1 Data overview

We examined 2,203 lynx tracks, resulting in 6,317 road intersections. After removing intersections from areas with the value “Not-mapped” in the FKB-AR5 dataset, we were left with 6,292 intersections. The lynx tracks spanned a total distance of approximately 1,045,970 meters (or about 10,460 kilometres) along or in proximity to roads, with an average intersection length of 166 meters.

Within a 250-meter buffer zone of each centre point, we observed an average of 7 buildings. In a narrower 50-meter buffer zone, the average findings included 235 Strava activities, a daily traffic volume of 177 vehicles, and 79% forest cover.

3.2 Model selection

Our automated model selection process evaluated 35 models derived from our primary model (2.4.1). Of these, 11 models represented 95% of the cumulative weight, with the top five models exhibiting a deltaAICc value of < 2 (Table 2). Notably, none of the 35 models incorporated the interaction term *FC * log(TV).*

The first 14 models had a deltaAICc value < 5 and a weight > 0.02. All remaining models had a deltaAICc value > 35 and a weight < 0.001. A distinguishing feature of the first 14 models is that they all accounted for both *log(NB)* and *log(TV).*

Table 2: Showcases the top five models from the automated selection (highlighted in grey) and the first three models with a deltaAICc > 5 (highlighted in orange). Here, FC stands for forest cover, NB = the number of buildings, TV = traffic volume, and SA =Strava activity.

Modell number	FC	log (NB)	log (SA)	log (TV)	FC*log (NB)	FC*log (SA)	FC* (TV)	deltaAICc	weight
1	■	■	■	■	■	■		0.000	0.198
2	■	■	■	■		■		0.176	0.182
3		■		■				1.172	0.110
4		■	■	■				1.844	0.079
5	■	■	■	■	■	■		1.993	0.073
15	🟧		🟧	🟧		🟧		35.77	< 0.001
16		🟧	🟧					36.42	< 0.001
17	🟧	🟧	🟧		🟧	🟧		36.57	< 0.001

3.3 Variables influencing track length

Our analysis reveals that the number of buildings within a 250-meter radius significantly influences the length of lynx tracks on roads, with a negative impact indicated by an estimated coefficient of -0.1226 (SE = 0.0459, z =2.6741, p = 0.0075). Similarly, the traffic volume also negatively affects track length, as indicated by an estimated coefficient of -0.0528 (SE = 0.0161, z =3.2829, p = 0.0010).

Interestingly, the Strava activity did not have a significant impact (p > 0.05), and even showed a trend where increased Strava activities positively influenced the length of the tracks. The percentage of forest cover had minimal to no impact on the track length and was not statistically significant (p > 0.05). Furthermore, no significant interactive relationship was found between the predictor variables and the forest cover (p > 0.05). This suggests that a higher traffic volume and a greater number of buildings in the vicinity are associated with shorter lynx tracks on roads, regardless of the density of the forest cover.

The predicted travel length on smaller roads, such as TS and PS, is up to 35 meters longer on average than on larger roads like K, F, R, and E, depending on the number of buildings in the area (Table 3). The difference in the estimated travel distance between K and E is up to 9 meters, indicating minor variation in the predicted travel distance for the larger roads (Figure 17 and 18).

Table 3: Overview over the difference of the estimated distance lynx travelled (dt.) for each road type (in meters), and the number of buildings (NB).

Road type	Dt.; NB = 0	Dt.; NB = 124	Total dt. decreased
TS	92	61	-31
PS	73	49	-24
K	65	43	-22
F	60	40	-20
R	57	38	-19
E	57	38	-19

The predicted average travel distance is significantly influenced by the presence of buildings, and this holds true for all road types. The number of buildings within a 250-meter buffer around each track centre point ranges from 0 to 124. As the number of buildings in the area increases, the distance travelled on each road type decreases. On average, the distance travelled reduces by up to 31 meters for TS and 19 meters for E (Table 3). For all road types, 50% of the total distance reduction occurs when there are at least 8 buildings in the area (Figure 15 and 16).

In summary, the negative effects of both the number of buildings and traffic volume diminish as their numbers increase. Therefore, these effects are most significant when considering low to no exposure of these variables on lynx. Once lynx are exposed to these variables, they drastically reduce the distance they walk on a road. The effect of exposure also intensifies when both variables are present simultaneously, functioning as an additive effect on each other.

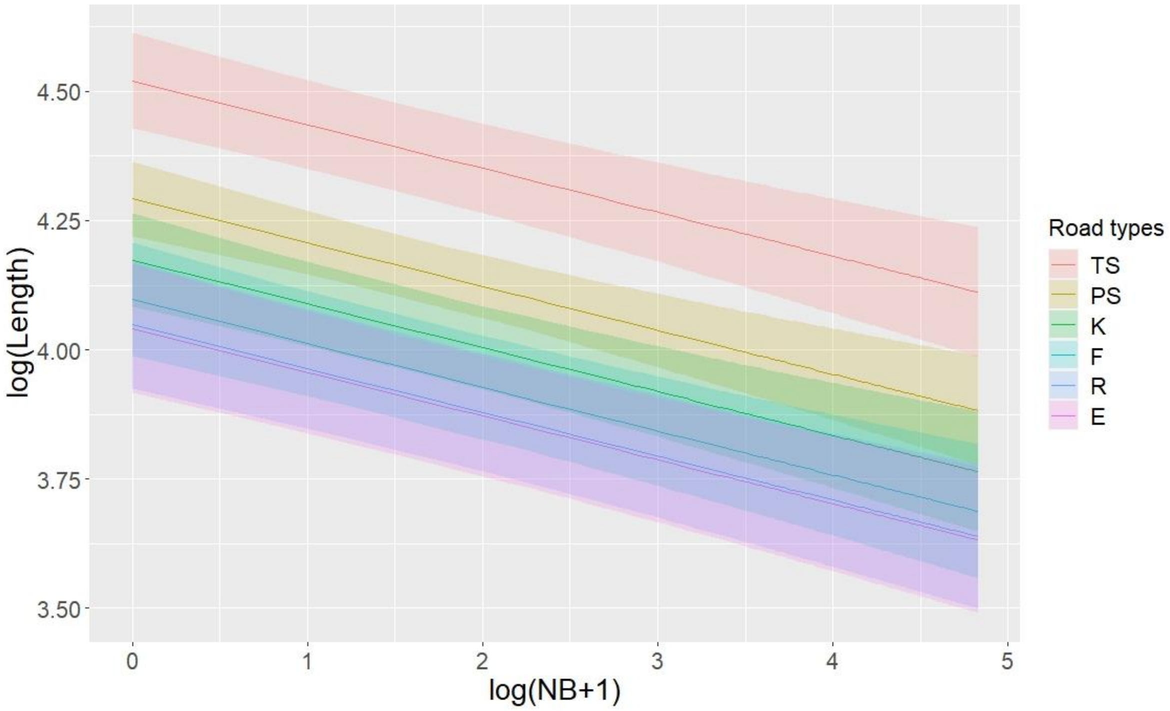

Figure 15: This graph depicts the relationship between lynx track lengths and the log-transformed number of buildings within a 250-meter buffer zone (NB) for various road types (categorized by average traffic volume).

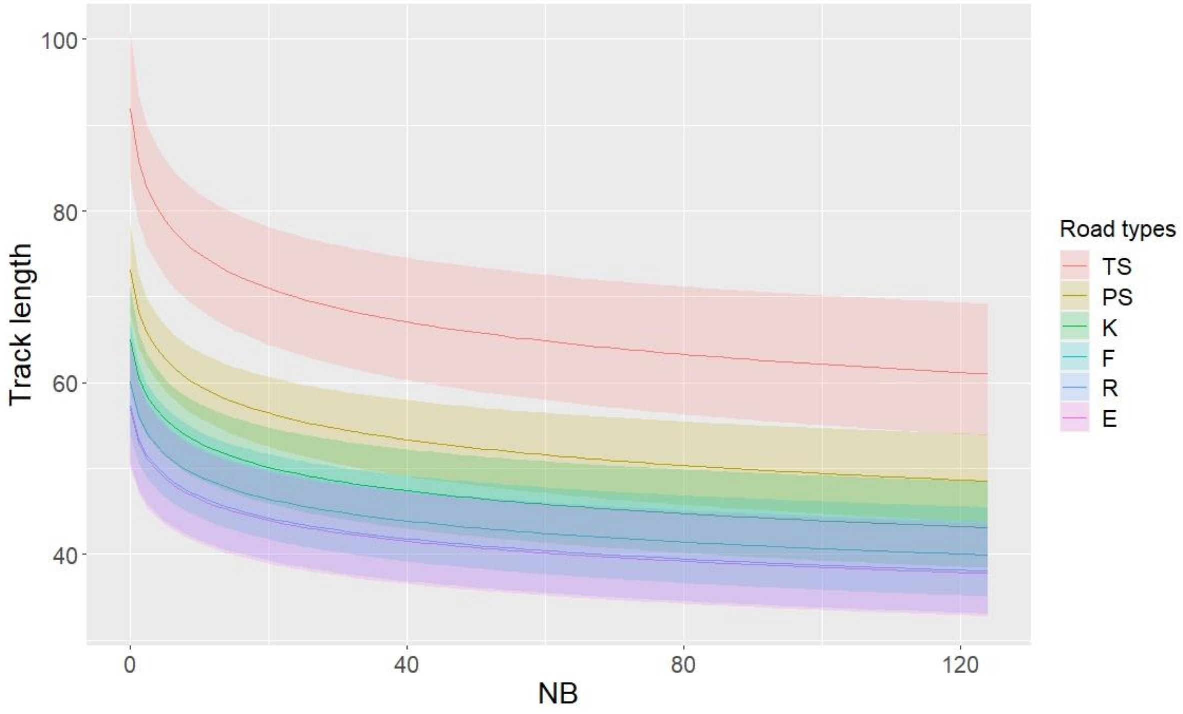

Figure 16: This graph depicts the relationship between lynx track lengths and the number of buildings within a 250-meter buffer zone (NB) for various road types (categorized by average traffic volume).

3.4 Importance of forest cover on road selection

We randomly generated 31,585 random points on roads within a 5000-meter buffer zone surrounding each original lynx track, excluding urban areas. Out of these points, seven were entirely within an area labelled as ‘Not mapped’ (based on the FKB-AR5 data). These seven points were excluded from the study, a procedure that did not impact the results.

Our model clearly demonstrated that lynx tracks were more likely to occur on roads with a higher forest cover compared to the randomly generated points (coefficient estimate 20.52, SE = 0.4655, p = 2e-16). The predicted forest cover for our control points was less than 60%, while the predicted forest cover for our case points was close to 80%.

4. Discussion

Our study indicates that lynx tracks on roads are shorter in areas with increased number of buildings and traffic volume. This suggests that human expansion and busy highways, may interfere with the movement patterns of lynx. Contrary to our expectations, the proximity of forest cover to roads did not significantly influence the length of lynx tracks, nor did it affect the impact of other variables studied. These findings imply that human activities, particularly connect to buildings and traffic, could be more influential than habitat type in determining lynx road-traversing behaviour. Roads may offer a more energy-efficient route for longer-distance travel, as they provide an easier path than moving through dense forest. However, this comes with heightened risks of encounters with vehicles, humans, and other wildlife (Basille et al., 2013). In our study, we chose to use a 50-meter buffer for forest cover, recreation activities and traffic volume, as we believe that these variables have a more direct influence on lynx behaviour at close range. We selected the 250-meter buffer zone for buildings, believing that disturbances associated with buildings could impact lynx behaviour from a distance.

4.1 Traffic volume and road type

We found that increased traffic volume is associated with shorter lynx tracks. A 2006 study identified collisions as the second leading cause of death among lynx older than one year

(Andrén et al., 2006). Our data suggests that lynx traverse shorter distances on roads with heavy traffic, compared to roads with minimal traffic. This pattern indicates that shorter distances travelled on larger roads, such as European and national roads, could potentially mitigate the risk of road collisions. However, a safer alternative might be to choose smaller roads with lower traffic volume. This is likely why we observe that lynx walk longer distances on smaller roads with less traffic volume (Figure 16).

Lynx are known to use linear structures for territorial marking. Roads and trails serve as both barriers and travel corridors, making markings more visible to other individuals (Vogt et al., 2016). Consequently, markings persist longer in low-traffic areas, rendering larger and busier roads less appealing for lynx territorial behaviour.

Our consideration of average traffic volume for each road category provides valuable insights into how each type of road is utilized by lynx. However, since our traffic data encompasses periods beyond the tracking timeframe, including peak seasons like summer holidays, it may not accurately represent the conditions lynx typically face during winter.

In winter, wildlife increasingly utilizes roads for travel, with snow depth being a critical factor in energy conservation (Crête & Larivière, 2003; White & Yousef, 1978). Public roads are usually cleared of snow, unlike private and forest roads, which rely on individual owners for maintenance. Our findings do not indicate that lynx prefer cleared roads. It is possible that lynx do use ploughed roads more frequently, but such activity may remain undetected due to the difficulty of tracking on those roads. Accurate year-round data on lynx road movements would be necessary to be able to fully utilize the traffic volume data used in our study.

4.2 Impact of buildings on Lynx Track Length

Our findings suggest that lynx cover shorter distances on roads surrounded by a higher density of buildings within a 250-meter radius. The presence of buildings seems to disrupt lynx travel patterns, likely due to the disturbances associated with urbanization. Increased building density raises the potential for human-lynx conflicts, including vehicle collisions and negative interactions with pets and livestock. Humans are the primary threat to large carnivores, and lynx are frequently shot near roads (Bunnefeld et al., 2006).

Buildings had the highest impact on the track length, but surprisingly, human recreational activities, showed no significant impact on lynx track length. The difference in human behaviour around buildings versus on Strava trails may account for this discrepancy. Humans tend to linger around buildings, whereas Strava users are transient, quickly passing through an area (Thorsen et al., 2022). This difference in human presence and behaviour might explain the reduction in track length and lynx being able to quickly retreat to the forest when building density is high.

However, previous studies have shown that lynx tend to select areas with moderate levels of human influence due to prey availability, particularly deer which are often found in proximity to human settlements (Bouyer et al., 2015). In our study, all types of buildings were considered, without distinguishing between their purpose. This is an aspect that could be further explored in subsequent studies.

4.3 Forest cover

Contrary to our prediction, we did not detect an effect of the percentage of forest cover around each centre point on the distance lynx walked on roads, nor did it have any effect on how the other variables were perceived by lynx. A study from 1998 showed that lynx tolerated encountering humans at relatively short distances without altering their movement patterns. However, the tolerance of resting lynx was found to be significantly correlated with the visibility and coverage of the forest (Sunde et al., 1998). It is likely that our method of extracting values like the percentage of forest cover plays a role in those unexpected results.

On the other hand, our secondary findings clearly indicate that lynx favour roads with more forest cover, suggesting that forest cover is a critical variable for lynx when deciding to cross or utilize a road.

4.4 Strava

Although Strava was incorporated into our study, it surprisingly exhibited a weakly positive effect, contrary to the anticipated negative impact due to increased human activity. A recent study examining the influence of human recreational activities on the Eurasian lynx's home range found that these activities only affect lynx locally and mostly during daylight hours. Lynx tends to frequent these areas at night, suggesting that human recreation does not significantly displace them from their habitats. The study concluded that the effect of human recreational activities in an area are probably too small to effectively drive out lynx from an area (Thorsen et al., 2022).

The weakly positive effect observed in our analysis might be attributed to human activity creating tracks in the snow, which lynx could use to conserve energy while moving. Although this effect was not statistically significant, it would likely be more pronounced on smaller forestry roads and paths that remain snow-covered throughout winter.

Similar to the average annual traffic volume, Strava data included a year-round representation over four years. Therefore, summer activities are also considered, which might impact the results, since the amount of recreational activities naturally are reduced during winter. The amount of daylight is also greatly reduced during the winter in Norway (Leibowitz & Vittersø, 2020), also contributing to lesser recreational activities during the winter. Since we were not able to filter the registered activities, the impact of recreational activities on the track length, might affect the representation of the results.

4.5 Limitations

Several uncertainties in our data warrant attention. The lynx track data provided by The Norwegian Environment Agency was collected following a specific procedure. The data quality may vary based on the field personnel's expertise. While we eliminated obvious errors, detecting subtler inaccuracies is challenging without detailed context for each track. For instance, tracks that follow roads for extended distances with little deviation may not represent actual lynx movement but could be due to field personnel forgetting to deactivate their GPS devices. Field personnel turning on their GPS immediately after parking their car, might be another possible error that could have been present in our data. This would result in tracks being registered on or near roads, questioning their present at all to begin with. Without any additional information on the start and end of a track, quality proofing the data is impossible. Data quality would greatly improve if field personnel actively marked the start and end of a track with a point. The lynx track data also provides information traversed direction, but we were advised not to use that information, due to the information being too unreliable. It should also be noted that we do not know the time or day lynx chose to traverse on or near roads. This information could give an impression on how the variables impact lynx during different weekdays and hours.

We tried to create a comprehensive and representative road network for our study area, which involved buffering the network to address uncertainties (see 2.2.2). This approach led to overlaps between roads, complicating the analysis of lynx-road interactions. We considered various solutions, such as creating Voronoi diagrams for each road (Aurenhammer & Klein, 2000), but ultimately established a hierarchy system based on the road type. This method influenced the length of each lynx-road intersection and, consequently, the mean length in our data (Figure 13), but we believe it did not significantly alter the overall findings. Future studies might explore alternative approaches to manage overlapping road buffers.

The Strava data only included annual summaries, preventing us from isolating winter-specific activities corresponding to the lynx tracking period. This limitation may have affected our results, potentially explaining the lack of a significant correlation between lynx track length and nearby Strava activities.

Norway covers a relatively long latitudinal gradient with many different vegetational- and climate zones, many of them being inhabited by lynx. The quantity of lynx track data varies significantly across regions, often reflecting local public`s engagement to monitor lynx and local densities of lynx. Therefore, our findings are not region-specific but rather provide a broad national overview. The effects of buildings, traffic volume, recreational activities, and forest cover may differ regionally. For instance, lynx in more populated areas might exhibit less sensitivity to human activity than those in less populated regions (Ritzel & Gallo, 2020).

4.6 Future studies

This study was designed to identify the variables influencing lynx decision-making when traversing on roads. We established a central point on each lynx track found on a roads and gathered data within 50- and 250-meter radii around these points.

This approach of extracting variables around the midpoint of tracks has its limitations. Future research should consider collecting data at both the start and end points of a track. This would necessitate data that clarifies the directionality of lynx tracks, enabling the determination of entry and exit points on a road. Unfortunately, we lacked access to reliable data for this purpose. Enhancing the method in this way could provide insightful information on the variables that lead lynx to cross or traverse roads and the factors affecting their decisions to leave a road.

In combination with data on track direction, future studies should also try to implement data on the time and date for when lynx use roads. Variables such as traffic volume and recreational activities predominantly occur during daylight hours. Acquiring data for these variables during nighttime presents a challenge. Given that lynx activities near human habitats increase at night (Filla et al., 2017), the influence of these variables may change. To obtain precise temporal data for each intersection, tracking lynx with GPS collars is essential. The Scandlynx project is currently engaged in this type of data collection.

Our investigation examined multiple variables, yet there are additional variables that could be explored in similar studies. For instance, the slope is a variable that may significantly affect road use by lynx. The diverse topography of Norway includes varied inclines, which can impact energy expenditure during movement (Carnahan et al., 2021), particularly in winter when snow conditions affect mobility. Roads are engineered to mitigate the natural slope of the terrain (LMD & LDIR, 2016), and those cleared of snow may significantly influence the movement patterns of species like the lynx. We recommend future analyses to consider the role of slopes, in conjunction with track direction data, as the behaviour of lynx and other animals on inclined roads may vary depending on whether they are ascending or descending.

For management purposes, focusing research on a local or regional scale is crucial. The vast landscape of Norway exhibits considerable variation in topography, climate, vegetation, and human population density, which may result in region-specific lynx behaviours. Moreover, the road types classified in our study differ in dimensions, configurations, and traffic volumes across regions. We applied a national average for daily traffic volume to each road type, which does not accurately reflect the distinct traffic conditions of individual regions.

This study incorporated spatial analytical research, using basic tracking data (solely GPS tracks without temporal or directional information) to extract meaningful insights into lynx interactions with infrastructure, such as roads. While our methodology has a potential for enhancement, considering the data quality, project duration, and complexity, we are satisfied with the outcomes. We strongly advocate for future research to employ other methods for variable extraction. Analysing data at the entry and exit points where tracks intersect with roads could yield a more profound understanding of the variables influencing lynx decision-making. Additionally, future research should investigate whether specific types of buildings affect lynx behaviour. It is vital to consider specific time frames for traffic and recreational activity data, when feasible, as these vary throughout the day, night, and seasons.

5. Conclusions

Our findings indicate that human activities have a significant impact on lynx behaviour when interacting with roads. Fixed structures, such as buildings, and the associated human activities, dominantly influence the extent to which lynx utilize roads. Traffic volume is another important variable that affects the distances lynx travel on roads. These observations lend partial support to our first hypothesis. However, the predominant influence of building density on lynx movements does not lend any support for our second hypothesis.

Lynx navigating smaller road types, including rough forestry roads and trails, are more affected by these elements. The impact of these variables lessens when lynx cross or traverse on larger roads. Lynx shows a preference for roads enveloped by forests, which likely offer them a sense of security and potential escape paths.

Nevertheless, the presence of forest cover does not alter the distance lynx travel on roads, nor does it counteract the negative effects of buildings or traffic volume. Therefore, this is partially not lending support for our third hypothesis. Recreational activities, as recorded by the Strava app, seemed to have no effect on the travelled distance, partially disproving our first hypothesis. However, the data we analysed only encompassed summarized annual activities for each Strava route. Since our study concentrated on the winter period, the inflated data from recreational activities in the spring, summer, and fall could distort the representativeness of our findings. Future research utilizing Strava data should endeavour to secure data that aligns with their specific study timeframe.

The method of extracting variables around the midpoint of a track presents certain shortcomings. We acknowledge that our inability to obtain directional data for the tracks prevented us from accurately identifying the exact entry and exit points of each track. Integrating data from both entry and exit points along with the distance travelled on roads could provide a more comprehensive understanding of the decision-making processes and road-travel distances of lynx and other wildlife.

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Appendix

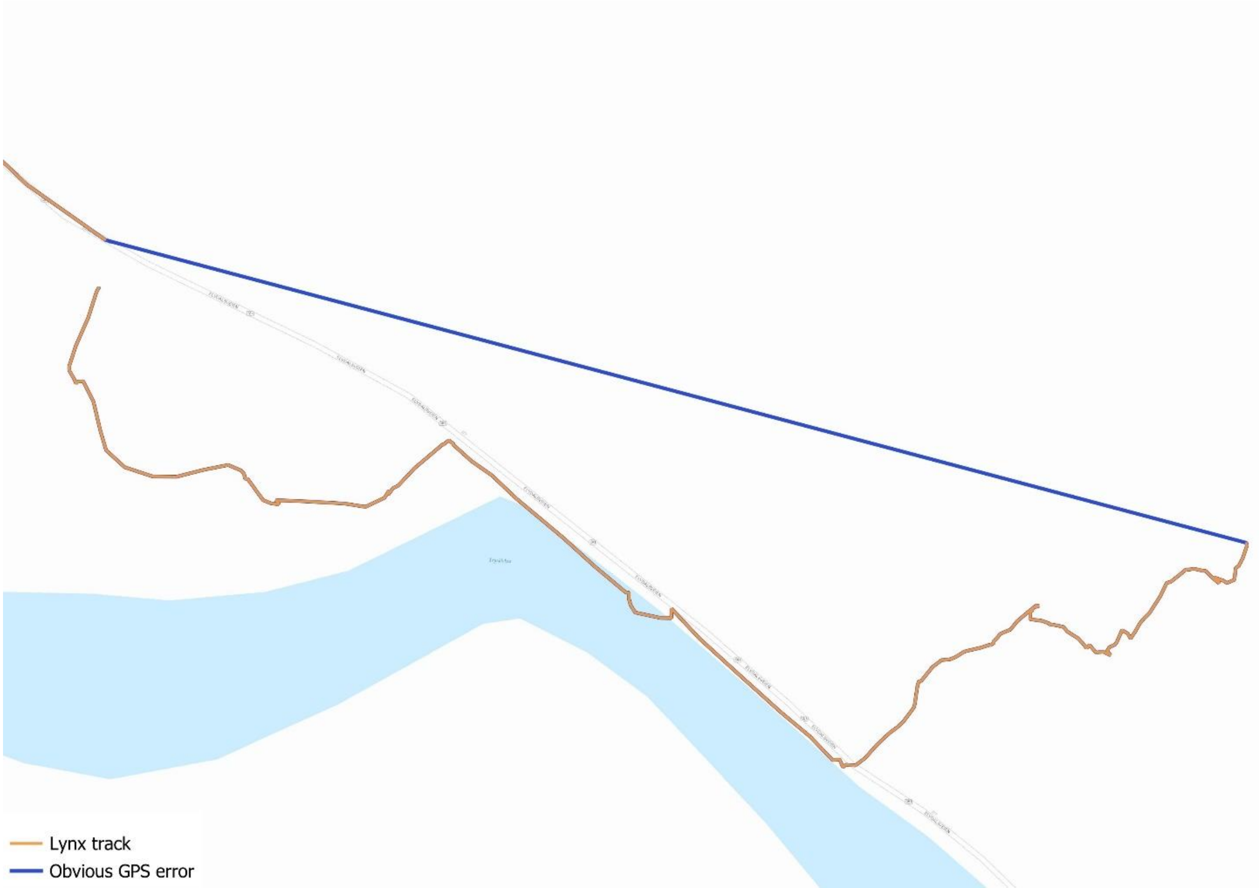

Figure S1: Display of a lynx track (brown line) with an obvious GPS error (blue line), which was removed from the track.

Figure S2: Lynx tracking done on fresh undisturbed snow April 2023 (Foto: Arnekleiv, Maja).

Figure S3: Example of lynx track on a road (Foto: Karkalatos, Christian A. D.).

Figure S4: Example of lynx traveling on a road (Foto: Karkalatos, Christian A. D.).

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