

Using GPS Radiotelemetry Locations to Interpret Road and Trail Use by Canada Lynx
(*Lynx canadensis*) in Minnesota

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DEDICATION

This thesis is dedicated to my parents, Art and Carole, my sister Lindsey, my partner, Joshua and my furry companion, Hudson. This journey has been long and arduous, and your unwavering love, patience, and support have lifted and carried me through. You have always encouraged my curiosity and hunger for learning, and none of my success would be possible without you. This triumph is as much yours as it is mine...thank you! To those we lost this year and those who left us before, I close this chapter and step out into the world in your honor and memory. And, finally for the little ones...

“You have brains in your head. You have feet in your shoes. You can steer yourself in any direction you choose.” – Oh, The Places You’ll Go! Dr. Seuss

THESIS ABSTRACT

The continental United States, including northeastern Minnesota, represents the southern extent of the Canada lynx (*Lynx canadensis*) range. Legally differentiating them from lynx in Canada and Alaska, lynx within the contiguous U.S. are considered a Distinct Population Segment, and are designated as Threatened under the Endangered Species Act. Due to higher human population densities, larger home ranges, lower prey densities, increased habitat heterogeneity and the fragmented nature of lynx habitat at southern latitudes, the Distinct Population Segment is exposed to human development and infrastructure, and is subject to metapopulation dynamics, both of which may affect persistence of the U.S. lynx population. Based on 6 years of radiotelemetry data for Canada lynx in the Superior National Forest of Minnesota, I examined methods for addressing data gaps common to global positioning system (GPS) telemetry monitoring of free-ranging animals, and examined space use of lynx within their home ranges, particularly their proximity to and use of road infrastructure.

Unsuccessful GPS location attempts occur due to various geophysical, environmental and animal characteristics, and although they can influence inferences about resource and space use, are not always addressed in analysis of habitat use, movements and resource selection. Using successful GPS radiotelemetry locations for 7 Canada lynx (4 males and 3 females) separated by 0.5 hr, 1 hr and 6 hr intervals I systematically excluded known locations and tested two methods for interpolating their position. These methods estimated the position of a missed location (1) using

displacement distances and movement angles between known locations or (2) as the midpoint between successful location attempts. After comparing the imputed locations to their known counterparts, I found that locations interpolated as the midpoint between successful location attempts more accurately estimated the position and cover type of excluded locations than locations estimated based on paired movement angles and displacement distances. Accuracy of both cover type prediction and position were improved for location attempts separated by a shorter interval and for locations in larger habitat patches. Though locations interpolated as the midpoint between successful locations more accurately predicted cover type and lynx position, especially for shorter intervals between location attempts, success of cover type assignment by this method was $\leq 73\%$ and position error was ≥ 95 m. Large variance in the movement angle of a lynx path between locations, potentially irregular habitat borders and patchiness of preferred cover types in the study area, and a likely preference for habitat edges among the study animals, may explain the limited utility of midpoints as replacements for missed locations.

Free-ranging animals like Canada lynx use human infrastructure, such as roads and trails, when these features are present in their home ranges. I used approximately 4,500 GPS locations from 7 individuals (4 males and 3 females) to examine the use of road infrastructure by lynx in Minnesota within seventeen seasonal 95% kernel home ranges to determine whether road features might benefit lynx by improving travel or conversely increase mortality risk through vehicle collisions and other human-lynx interactions. I found that approximately 3% of lynx locations within home ranges

occurred on roads and trails, and lynx crossed roads and trails about 3 times/day.

Comparison of the distance to the nearest road or trail with the distance to other linear corridors, including various water features indicated that lynx locations were closer to road infrastructure than most water features. When compared to random locations within the home range, lynx were not closer to road infrastructure than random expectation at a broad scale, but may have been selecting for roads and trails at smaller scales (within 50 m of road features).

Using Akaike's Information Criterion (AIC) to rank linear-mixed effect models that included sex and season as fixed effects and individual lynx as a random effect, I found that female lynx tended to occur closer to road features than males, but given that individual differences accounted for a large proportion of variance in these data, sex may not be a significant predictor of proximity to roads and trails. Furthermore, the difference in distance to road features between males and females (< 175 m) is small and therefore may lack biological significance. I also calculated movement rates along straight-line paths between consecutive locations to determine whether roads and trails might improve or impede lynx travel. Based on AIC model rankings, both sex and season were covariates of movement rate. Specifically, movement rates were slower for females by approximately 85 m/hr and slower in winter by around 22 m/hr. I suspect, however, that these small differences in movement rate between male and female lynx and among seasons may be more statistically than biologically meaningful. Finally, road and trail density was nearly consistent across home ranges, sexes, seasons and individuals. This is likely due to management in the Superior National Forest, which aims to maintain

consistent road densities at a scale approximating that of a lynx home range. Though distance to the nearest road feature decreased with increasing road and trail density, movement rate between consecutive locations was not correlated with road and trail density within the home range. Movement rate between the small number of consecutive locations on a road or trail was, however, 60 m/hr faster than movement rate between successive locations not on a road or trail. Together these findings suggests that travel on road features may increase the efficiency of movement for Canada lynx, but the presence of road infrastructure may not necessarily increase travel rate, as lynx may be slowed by foraging opportunities, interactions with interspecific competitors (e.g., coyotes [*Canis latrans*] and bobcats [*Lynx rufus*]), or human activities. Determining the potential risks of road features to lynx survival and thus population persistence will require an assessment of road and trail use at smaller geographic scales (i.e., the core home range) and smaller temporal scales (i.e., GPS locations separated by shorter intervals), an examination of traffic volume as it relates to road and trail use, and evaluation of other predictors of Canada lynx mortality in relation to roads and other human infrastructure.

THESIS INTRODUCTION

In the northern portion of their range Canada lynx (*Lynx canadensis*) occur primarily in boreal forest, particularly in regenerating stands where their preferred prey, snowshoe hare (*Lepus americanus*), occurs (Mowat et al. 2000). However, in the southern extent of the lynx range, habitat is more heterogeneous than in northern boreal forest, and to overlap areas with sufficient snowshoe hare densities, lynx maintain larger home ranges and utilize mid-successional coniferous forest and edge habitat where hare abundance is high (Aubry et al. 2000; Fuller et al. 2007; Burdett 2008; Maletzke et al. 2008; Murray et al. 2008; Vashon et al. 2008). In addition, the 8-11 year cyclical population dynamics of lynx in response to snowshoe hare populations may occur with reduced amplitude for southern lynx populations (Elton and Nicholson 1942; Hodges 2000; Krebs et al. 2001). Nonetheless, during the cyclic decline in prey numbers, lynx in the southern range may experience lower fecundity, reduced litter sizes, increased kitten mortality and reduced adult survival like their northern counterparts, and may respond behaviorally to changes in hare abundance by switching to alternative prey during the hare decline (Brand and Keith 1979; O'Donoghue et al. 1997, 1998). Conversely, when hare numbers increase lynx may increase their kill rate, or as lynx numbers irrupt in the northern boreal forest, may disperse to the edge of the species' range, resulting in lynx invasions of habitat at southern latitudes (Gunderson 1978; O'Donoghue et al. 1997, 1998; Mech 1973; 1977).

Though historically observed in 24 states, Canada lynx in the continental United States are listed as “threatened” under the U.S. Endangered Species Act and are considered a Distinct Population Segment in the 14 states that previously supported resident populations (McKelvey et al. 2000; Ruediger et al. 2000; U.S. Department of the Interior 2000, 2003, 2009; Interagency Lynx Biology Team 2013). This has led to the designation of over 100,000 km² of critical habitat in Minnesota, Maine, Montana, Wyoming, Idaho and Washington, where reproducing populations currently exist, and has increased legal protection for both lynx and the ecosystems they require in the southern extent of the species’ range. Given greater habitat heterogeneity and the fragmented nature of preferred lynx habitat in the southern portion of the species’ range, as well as the dispersal abilities of lynx, lynx in the U.S. are exposed to increased prevalence of human activities and are likely subject to source-sink dynamics that may affect local population viability (McKelvey et al. 2000; Murray et al. 2008). However, the long-term viability of the U.S. lynx population is unknown, as are the risks to the discrete subpopulations at the southern edge of the lynx range or the behavioral responses of these southern lynx to habitat fragmentation and human activities associated with higher human densities at lower latitudes.

One way to remotely monitor space use, movements, and habitat preference of free-ranging animals, such as Canada lynx, is with radiotelemetry, particularly global positioning system (GPS) radiocollars. Though these allow more accurate and more frequent estimates of position than previous telemetry technology, GPS telemetry data are affected by error in the form of spatial inaccuracy and missed locations (i.e., missed fixes

or unsuccessful data acquisition attempts), which can affect estimates of animal movements and habitat selection (Frair et al. 2004; Cagnacci et al. 2010; Frair et al 2010; Tomkiewicz et al. 2010). Such errors, especially missed location attempts, however, are either ignored in data analysis or are addressed with *ad hoc* correction methods that can affect conclusions about resource selection and space use in various ways (Frair et al. 2010).

Over a 6 year period between 2003 and 2009, Canada lynx were captured and monitored via GPS radiotelemetry in the Superior National Forest of northeastern Minnesota, resulting in nearly 15,000 GPS locations for 12 animals (Moen et al. 2008). Most GPS radiocollars were set to collect locations at 6 hr intervals, but some collars attempted locations at intervals as short as 30 min or 1 hr. However, these data include missed location attempts that could potentially influence inferences about space and habitat use in the study area. Thus, in Chapter 1 I used successful GPS locations from 7 lynx, separated by 0.5 hr, 1 hr and 6 hrs to test two methods for imputing missed location attempts. The first method used paired movement angles and distances between known locations to calculate the coordinates of missed locations, while the second method estimated a missed location as the midpoint between successful location attempts. By systematically removing a subset of locations and treating those locations as if they had been missed, I was able to compare the position and habitat type of successful locations with that of the interpolated locations, and examine whether either method could be used to impute missed locations. In addition, I was able to test how the interval between

location attempts influenced the position error and accuracy of predicting the cover type of the hypothetically missed location.

Based on the GPS locations collected for Canada lynx in the Superior National Forest, numerous characteristics of the Minnesota lynx population have been evaluated, including movements, habitat preference, home range characteristics and habitat use during extra-territorial movements outside of the home range (Burdett et al. 2007; Burdett 2008; Moen et al. 2008; Moen et al. 2010). In Minnesota, the Canada lynx is recognized as a Species in Greatest Conservation Need by the Minnesota State Wildlife Action Plan (MnDNR 2006, 2016). Thus it is critical to evaluate factors that may influence the persistence of the Minnesota lynx sub-population. Because they occur at the southern edge of the species' range, Minnesota lynx are subject to increased human population densities, human activities and development, including roads and other infrastructure, and human-lynx interactions, including incidental shooting and trapping, and vehicle collisions (Moen 2009). These factors influence mortality rates and may potentially affect long-term population persistence. Alternatively, infrastructure, such as roads and trails, may benefit lynx by increasing efficiency of movement and opportunities for foraging. Among lynx populations across North America, responses to road features and associated disturbances vary from avoidance to tolerance or selection (Apps 2000; Aubry et al. 2000; Mowat et al. 2000; Fuller et al. 2007; Murray et al. 2008). In Minnesota, lynx have been observed traveling along and crossing roads, and during long-distance extra-territorial migrations, approximately 2/3 of lynx locations occurred within 200 m of a road or trail (Ron Moen, *personal communication*; Moen et al. 2010).

Use of road features and other corridors, such as rivers, streams or the edges of lakes and wetlands within home ranges, however, had not been evaluated for lynx in Minnesota. Therefore in Chapter 2, I used GPS radiotelemetry locations separated by a 6 hr interval to determine whether distance to the nearest road feature differed from the distance to other linear corridors, and compared proximity to road features between known locations and random locations within the seasonal 95% kernel home ranges of 7 Canada lynx. Because roads and trails may alter the movement speed of traveling lynx, I also examined the movement rate over the 6 hr period between locations, and compared this rate between locations occurring on a road or trail and those not occurring on a road or trail. I also assessed how road density in the 3-county study area (Cook, Lake and St. Louis counties) correlated with distance to the nearest road feature and movement rate between GPS locations. Finally, I ranked various linear mixed-effect models for distance to road infrastructure and movement rate, to determine whether these responses to roads and trails varied between individual animals, male and female lynx, or among seasons.

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CHAPTER 1

Figure 1.1

Schematic diagram of a triplet of Canada lynx GPS radiotelemetry locations with (a) actual Points 1, 2 and 3, the movement angle and displacement distances between actual points, (b) Point 2 excluded, one simulated Point 2 replicate generated from a paired movement angle and displacement distance, and the midpoint between actual Points 1 and 3. Lynx locations were collected via GPS radiotelemetry from 2003-2009 in northeastern Minnesota for 7 individuals (4M, 3F)29

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CHAPTER 1

Interpolating Missed GPS Radiocollar Location Attempts from Successful GPS Location Attempts in Canada lynx (*Lynx canadensis*)

SUMMARY

Global Positioning System (GPS) radiocollars permit the collection of many animal locations with improved spatial accuracy and temporal resolution compared to earlier telemetry techniques. However, position error and failed location attempts still exist with GPS telemetry and could potentially lead to incorrect inferences about wildlife space use, movements, or habitat and resource selection. Missed locations have either been ignored in data processing or addressed with *ad hoc* corrections. We used GPS telemetry locations for Canada lynx (*Lynx canadensis*) separated by 0.5, 1 and 6 hr sampling intervals to test two methods of imputation for missed GPS location attempts. The first method estimated the coordinates of missed locations using the distribution of angles and displacement distances between actual locations, and the second estimated the coordinates of missed locations as the midpoint between successful location attempts. By systematically removing a subset of locations and treating those locations as if they had been missed, we were able to compare the position and habitat type of known locations with that of the imputed locations. We found that missed locations interpolated as the midpoint between successful location attempts more accurately estimated the position

and cover type of actual locations than those determined from known movement angles and displacement distances. As predicted, the accuracy of position estimation increased for shorter sampling intervals between location attempts and cover type prediction for interpolated locations was improved for locations in larger habitat patches. Although mean movement angles suggested that lynx moved along a relatively straight path, we observed large variances in movement angle, which may partially explain the remaining position error and failure of our imputation methods to consistently predict cover type correctly, even for locations separated by a short interval. These methods for imputing missed locations would be best applied to landscapes with large, contiguous habitat patches and for telemetry data with short intervals between location attempts.

INTRODUCTION

Global Positioning System (GPS) radiocollars enable remote collection of animal locations with greater spatial precision and accuracy, and increased temporal resolution or frequency than traditional radiotelemetry techniques (Cagnacci et al. 2010; Tomkiewicz et al. 2010). However, GPS telemetry location attempts are not always successful, and spatial imprecision will still affect collected locations, resulting in position error (Frair et al. 2010). A variety of factors influence position error, including environmental conditions, cover type, satellite geometry, and satellite availability (Rempel et al. 1995; Moen et al. 1997). Success of location attempts, or the ability of a GPS radiocollar to obtain a “fix,” is dependent on topography, satellite geometry, season, time of day, and vegetation characteristics, including canopy height, canopy cover and cover type (Rempel et al. 1995; Moen et al. 1996; Moen et al. 1997; Edenius 1997; Rempel and Rodgers 1997; Dussault et al. 1999; D’eon et al. 2002; D’eon 2003; Cain et al. 2005). Specifically, leaf and tree presence can reduce success of location attempts, with lower success observed in fall compared to winter, and in closed forest canopies compared to open canopies (Moen et al. 1996; Dussault et al. 1999).

Animal activity also affects success of location attempts. Fewer successful locations are obtained for free-ranging animals relative to stationary radio-collars (Edenius 1997; Dussault et al. 1999). From 69% to 100% of location attempts are successful when radio-collars are stationary (Edenius 1997; Moen et al. 1997; Dussault et al. 1999; D’eon et al. 2002). On free-ranging animals success of location attempts ranges

widely, from as low as 27% to about 95% (Moen et al. 1996; Edenius 1997; Moen et al. 1997; Merrill et al. 1998; Dussault et al. 1999; D'eon 2003; Graves and Waller 2006). Animal size and movement affect satellite reception and thus success of obtaining a location for free-ranging animals, with greater success of location attempts for smaller individuals and for inactive versus active animals (Edenius 1997; Obbard et al. 1998; Dussault et al. 1999; Moen et al. 2001; D'eon and Delparte 2005; Graves and Waller 2006).

Missed locations (i.e., observation bias) may lead to inaccurate estimates of space use, movement paths and habitat selection. Missed location attempts that are biased towards particular habitats, activities, or times of day or year could lead to incorrect inferences about cover type use and resource selection of free-ranging animals (Rettie and McLoughlin 1999; D'eon and Delparte 2005; Nielson et al. 2009; Frair et al. 2010). Home range estimates may also be biased by missed location attempts if the probability of obtaining locations is not equal across all areas of the home range; however the extent of this bias is dependent on the spatial arrangement of habitat patches with different location success rates, the home range model used and the number of locations (i.e., sample size) used to estimate the home range (Horne et al. 2007). Loss of data caused by missed locations, as well as the resulting increase in the time interval between successful locations, also affects estimates of turning angle, movement speed, and distance moved by an individual (Pepin et al. 2004; Jerde and Visscher 2005; Swain et al. 2008; Frair et al. 2010).

Despite the potential biases resulting from missed locations, they have been largely ignored in analyses of animal space and habitat use or accounted for with *ad hoc* correction methods. These have generally included sample weighting, where locations are adjusted by the inverse of their probability of being acquired ($1/P_{\text{fix}}$), or iterative simulation, where locations are iteratively added to a dataset using both P_{fix} and the geographical area where a missed location was likely to have occurred (Frair et al. 2010). However, outcomes of these solutions and other corrections for missed locations have been variable.

Identification of resource selection by free-ranging wapiti (*Cervus elaphus*) improved when successful locations were weighted by their probability of being acquired or missed locations were generated as coordinates within an area enclosing the previous and next successful location (Frair et al. 2004). Estimating the coordinates of missed locations as the midpoint between two successful locations was possible for grizzly bears (*Ursus arctos*) because location attempts were made at an interval of 1 hr and movement between location attempts was small (Graves and Waller 2006). Calculating habitat use as proportional composition within circular buffers around animal locations, rather than habitat type at individual points, may also improve conclusions about habitat selection when GPS data are biased by habitat-specific spatial inaccuracy and/or fix success (Rettie and McLoughlin 1999). In contrast, weighting black bear (*Ursus americanus*) locations by the inverse of their detection probability, as determined from a predictive model of fix success, only marginally improved adjusted success rates and did not account for seasonal or daily patterns of data loss (Sager-Fradkin et al. 2007). No difference in

habitat preference was found between uncorrected mule deer data and data corrected for habitat induced fix–rate bias; however less than 10% of locations were assumed to be missed, underestimating data loss for free-ranging individuals given the radiocollar technology at the time (D’eon 2003). Improvements in GPS technology have led to reduced position error and/or fewer missed location attempts for some species or equipment compared to older technology (Frair et al. 2010). However, some newer GPS technology, such as mini-loggers, though designed to collect locations at frequent intervals, still miss upwards of 35% of location attempts on free-ranging animals (e.g., wood turtles [*Glyptemys insculpta*]; Ron Moen, *personal communication*), which approximates the predicted success of radiocollar technology deployed here.

We tested two methods for estimating missed GPS locations for radiocollared Canada lynx (*Lynx canadensis*) in northeastern Minnesota, to determine whether missed locations could be imputed by one or both methods. By removing a subset of known lynx locations and treating them as missed location attempts, we were able to compare the position and cover type of actual, successful locations with the estimated coordinates and habitat type of interpolated locations. In addition, because we had a large sample size of known locations, we were able to test for differences in the utility of our interpolation methods in all habitat types used by lynx. Specifically, we used GPS location data with 0.5, 1, and 6 hr intervals between location attempts to predict the coordinates of hypothetically missed locations: (1) based on the distribution of angles and distances between successful locations, and (2) as the midpoint between the previous and next successful location. We examined the habitat type of imputed locations and

calculated the distance between interpolated and actual coordinates to compare how accurately our two methods predicted habitat and position for a missed location. We hypothesized that position error for imputed locations would decrease for shorter intervals between location attempts and that imputed locations would more accurately predict the cover type of actual locations in less complex habitat.

STUDY AREA

The study area in which Canada lynx locations were collected included the central and eastern portions of the Superior National Forest in Cook, Lake and St. Louis counties, including the Boundary Waters Canoe Area and Wilderness in northeastern Minnesota (Burdett et al. 2007). Forest composition in this region is considered hemiboreal or transitional between the boreal forest characteristic of southern Ontario and the Great Lakes-St. Lawrence northern hardwood forest found to the south (Pastor and Mladenoff 1992; Heinselman 1973). Mixed forest, dominated by quaking aspen (*Populus tremuloides*) and paper birch (*Betula papyrifera*), is common, as are other boreal tree types including balsam fir (*Abies balsamea*), black spruce (*Picea mariana*), white spruce (*P. glauca*), white cedar (*Thuja occidentalis*) and tamarack (*Larix laricina*), which generally occur at lowland sites (Heinselman 1973). Northern hardwoods, such as yellow birch (*Betula lutea*) occur on upland sites, and jack pine (*Pinus banksiana*) and red pine (*P. resinosa*) comprise managed upland stands (Flaccus and Ohmann 1964; Burdett et al. 2007). Successional forest, resulting from lumber removal and fire, mainly

contain aspen and paper birch (Flaccus and Ohmann 1964). There are also numerous lakes and both forested and non-forested wetlands, composed of alder (*Alnus* spp.), willow (*Salix* spp.), black spruce (*Picea mariana*) and cedar (*Thuja occidentalis*), and understory vegetation includes beaked hazel (*Corylus cornuta*), fly honeysuckle (*Lonicera canadensis*) and mountain maple (*Acer spicatum*) (Burdett et al. 2007).

METHODS

GIS and Statistical Analyses

GIS mapping and analyses were completed using ArcMap 9.2 (ESRI 2006) and statistical analyses were performed using R 2.9.1 and R 3.3.2 (The R Foundation for Statistical Computing 2009, 2016) and the statistical functions in Microsoft Excel (Microsoft 2007). For all statistical tests, $p < 0.05$ was considered statistically significant.

Canada Lynx Locations

We used GPS locations for 7 Canada lynx (4M and 3F) captured and radiocollared between 2003 and 2009 (Burdett et al. 2007; Burdett 2008; Moen et al. 2008). Locations further than 15 km from the centroid of an individual's 95% kernel home range were considered long-distance movements and were eliminated from analyses (Burdett et al. 2007; Moen et al. 2010). For most collar periods, defined as consecutive days between collar attachment and collar removal, the time separating successive locations was 6 hrs, but some periods had variable sampling intervals or

intervals as short as 0.5 hr between locations. We determined the percent of missed locations for 0.5, 1, 1.5, 2, 4 and 6 hr intervals between locations attempts. Because they were the most common intervals between location attempts, or in the case of the 1 hr interval easily generated by combining successive 0.5 hr location attempts, locations were sub-sampled to have time differences of 0.5, 1 and 6 hrs for all subsequent analyses.

Lynx Movement Path- Movement Angle

We identified all triplets of successful consecutive location attempts within a collar period separated by 0.5, 1, and 6 hr time intervals. Triplets were allowed to overlap, such that points in one triplet could also be part of the next triplet. For each triplet we determined the net displacement between consecutive locations (hereafter, Point 1, Point 2 and Point 3) and the net displacement between Point 1 and Point 3. Using these displacement distances and the triangle formed by the triplet of lynx locations, we determined the internal angle formed by the straight-line segment between Points 1 and 2 and the line between Points 1 and 3 (Fig. 1.1a). This movement angle represented the deviation of a lynx path from a straight line between locations in a triplet based on the direction of the path to Point 2 relative to the hypothetical line from Point 1 to Point 3. We calculated mean movement angle and circular standard deviation (Zar 1984) overall, by sex, and by individual lynx for the 0.5, 1 and 6 hr intervals. We also compared movement angles between male and female lynx, but due to the non-normal distribution of angles when represented as ranging from 0° to 360° , we transformed all movement angles to range from -180° to 180° .

Simulation of Missed Locations and Midpoints

We generated missed locations by removing Point 2 of each triplet and treating it as a missed location attempt. We then employed two methods of imputation to estimate the position of missed locations. First we used the joint empirical distribution of displacement distances and movement angles to randomly assign a paired distance and angle to Point 2 for all triplets. Paired angles and distances were used to account for potential correlations between movement angle and displacement distance. Using the paired angle and distance, we determined the X and Y coordinates of the simulated Point 2 in each triplet (Fig. 1.1b). Random assignment of a paired angle and distance, and calculation of coordinates for the simulated Point 2 was replicated 10 times per triplet. Second, we treated the coordinates of the midpoint between Point 1 and Point 3 as the estimated position of Point 2 for all triplets separated by 0.5, 1 and 6 hrs (Fig. 1.1b).

Cover Type of Actual Locations, Simulated Locations and Midpoints

Using a 30 m resolution land use/land cover (LULC) dataset derived from LANDSAT Thematic Mapper satellite imagery collected in 1995 and 1996 (MnDNR 2008) we assigned LULC cover types to all actual locations, simulated Point 2 locations and midpoints. This data set has > 95% overall classification accuracy (Minnesota Land Management Information Center, St. Paul, Minnesota), and while it cannot account for timber harvest at the time of lynx monitoring, does include a regenerating or successional forest type for stands disturbed 10-30 years prior to radiotelemetry data collection (Burdett 2008). Of the 15 LULC cover types, the cover types used here included coniferous forest, mixedwood forest, regeneration/young forest, shrubby grassland,

wetlands-bogs and wetlands-marsh and fen, which were the LULC cover types at 99% of all actual lynx locations collected from 2003-2009 and which comprise 80% of the 3-county study area (Burdett 2008; McCann 2006; Moen et al. 2008; McCann and Moen 2011).

We determined how frequently the cover type of Point 2 in a triplet was correctly predicted by determining the number of replicates for which the cover type of the simulated Point 2 matched the cover type of the actual Point 2, and calculated the mean percent correct cover type assignment for the 0.5, 1 and 6 hr time intervals. Among midpoints, frequency of correct cover type assignment was calculated for each time interval as the percent of triplets for which the cover type of the midpoint was the same as the cover type at the corresponding actual Point 2 location. For both simulated locations and midpoints, we determined whether the frequency of correct cover type assignment varied by cover type, and used linear regression to test whether correct assignment was correlated with cover type composition of the study area or area of the habitat patch containing the actual Point 2 location.

Position Error and Distance Between Actual Locations

For each triplet we determined the distance between actual Point 2 locations and simulated Point 2 replicates, and between actual Point 2 locations and midpoints. This distance was used as a measure of position error for the two types of imputed locations. We calculated mean position error for both simulated locations and midpoints for the 0.5, 1 and 6 hr intervals. The relationship between percent correct cover type assignment and mean position error for simulated Point 2 replicates was evaluated for each time interval.

We also compared position error between instances of correct versus incorrect habitat assignment at midpoint locations.

We calculated the mean distance between actual Point 1 and Point 3 locations to determine how cover type prediction varies with distance between known locations, and examined how the cover type of actual locations in a triplet affects the accuracy of cover type assignment for simulated and midpoint locations. Finally, we compared the mean distance between actual Point 1 locations and midpoints to the mean distance between actual Point 1 and actual Point 2 locations to determine whether the midpoint is an accurate proxy for the actual distance moved by a lynx during a given time interval (i.e. 0.5, 1, 6 hrs).

RESULTS

Missed GPS Locations

Of 15,201 location attempts, 2,096 were missed, representing a loss of 13.8% of GPS location data. Percent of missed locations increased with increasing time interval between location attempts. For the 0.5, 1, 1.5, 2, 4 and 6 hr intervals 4%, 3%, 4%, 8%, 11%, and 35% of location attempts failed, respectively. This pattern of increasing data loss with increasing interval between location attempts was observed for all individual lynx. For location attempts separated by 0.5 hr interval, 96% of locations attempts were successful. Of the 4% of attempts that were unsuccessful, 82% were a single missed location, which if corrected would increase the number of usable locations separated by a

0.5 hr interval to nearly 99% of those attempted. Fewer locations could be recovered for longer intervals between location attempts, as a larger proportion of missed location attempts were consecutive. In the case of the 6 hr interval, 65% of location attempts were successful, but only 62% of those missed were single missed attempts. This indicated that approximately 86% of all location attempts separated by a 6 hr interval could be used if those missed were corrected.

Movement Angle

We identified 3,595, 921 and 3,002 triplets of lynx locations separated by 0.5, 1 and 6 hrs, respectively. The mean movement angles calculated from these triplets suggested that lynx moved in a nearly straight line between locations in a triplet (Table 1.1). For all three intervals, approximately 37% of movement angles were $\leq 15^\circ$ (i.e., $\leq 15^\circ$ or $\geq 345^\circ$, Fig. 1.2); however, movement angles had large standard deviations. For the 0.5, 1 and 6 hr intervals between location attempts, values of movement angle (transformed by subtracting 360°) did not differ between triplets of male and female lynx (0.5 hr: *t*-test, $t_{3414} = -1.4$, $p = 0.2$; 1 hr: *t*-test, $t_{861} = -0.1$, $p = 0.9$; 6 hr: *t*-test, $t_{2673} = 0.6$, $p = 0.6$).

Cover Type of Actual, Simulated and Midpoint Locations

Correct cover type assignment declined with increasing interval between location attempts when Point 2 replicates were simulated from randomly assigned movement angles and displacement distances (Table 1.2). Success of cover type prediction also decreased as the time interval between locations increased for midpoint locations, and

percent of locations with correct cover type assignment was higher for midpoint locations than for simulated locations for all intervals between location attempts (Table 1.2).

Correct cover type prediction at simulated Point 2 locations and midpoints varied by cover type for the six LULC types comprising the greatest proportion of lynx use (Fig. 1.3). There was a trend of increasing accuracy of cover type assignment to simulated and midpoint locations with increasing landscape area of the six LULC types in the study area. However, this relationship was not significant for either simulated locations or midpoints when mixedwood forest, the cover type comprising the greatest percent of the landscape (38%), was excluded from regression analyses (Simulated locations- 0.5 hr: $\beta = 1.1$, $t_3 = 0.6$, $p = 0.6$; 1 hr: $\beta = 1.5$, $t_3 = 1.1$, $p = 0.4$; 6 hr: $\beta = 1.0$, $t_3 = 0.9$, $p = 0.4$; Midpoints- 0.5 hr: $\beta = 0.6$, $t_3 = 0.3$, $p = 0.8$; 1 hr: $\beta = 0.6$, $t_3 = 0.2$, $p = 0.9$; 6 hr: $\beta = 1.7$, $t_3 = 1.3$, $p = 0.3$).

Accuracy of cover type assignment to simulated locations increased as the area of the patch occupied by the actual Point 2 location increased (Fig. 1.4a; 0.5 hr: $\beta = 0.05$, $t_9 = 5.3$, $p < 0.01$; 1 hr: $\beta = 0.03$, $t_9 = 6.1$, $p < 0.01$; 6 hr: $\beta = 0.03$, $t_9 = 9.9$, $p < 0.01$). Similarly, mean patch area of the patch containing the actual Point 2 location was significantly larger for cases where cover type assignment to midpoint locations was correct than for those cases when cover type assignment was incorrect (Fig. 1.4b; 0.5 hr: t -test, $t_{2815} = 5.5$, $p < 0.01$; 1 hr: t -test, $t_{719} = 4.5$, $p < 0.01$; 6 hr: t -test, $t_{2840} = 4.2$, $p < 0.01$). Mean area of patches containing actual Point 2 locations was 1,064 ha (± 44.1). When mixedwood forest patches were excluded, the mean area of patches containing actual Point 2 locations was 154 ha (± 19.5).

Position Error for Simulated and Midpoint Locations

The mean position error for simulated Point 2 replicates and midpoints increased as the time interval between location attempts increased (Table 1.2; Fig. 1.5). For both imputation methods, the mean position error increased at a ratio of approximately 1:2:8 as the time interval increased between location attempts (0.5hr:1hr:6hr). There was also a pattern of decreasing accuracy of cover type assignment to simulated locations as the position error increased for all intervals between location attempts (Fig. 1.6a). Among simulated locations, 3-21% of replicates had position errors ≤ 30 m, with the largest percent corresponding to the 0.5 hr interval. Of those simulated replicates with position error ≤ 30 m, 89-91% were correctly assigned the cover type of the actual Point 2 location. Mean position error was also significantly larger for cases of incorrect cover type assignment at midpoint locations than for those with correct cover type assignment, and this relationship applied to all intervals between locations (Fig. 1.6b; 0.5 hr: *t*-test, $t_{1401} = -20.5, p < 0.01$; 1 hr: *t*-test, $t_{524} = -9.8, p < 0.01$; 6 hr: *t*-test, $t_{2872} = -13.8, p < 0.01$). Specifically, 12-40% of midpoints had position errors ≤ 30 m. Of those midpoints, 91-93% occurred in the same cover type as the actual Point 2 location.

Distance Between Actual Locations and Accuracy of Cover Type Assignment

Mean distance between actual locations increased with increasing time interval between location attempts (Table 1.1). Additionally, cover type assignment to simulated Point 2 replicates was more accurate for shorter mean distances between actual Point 1 and actual Point 3 locations (Fig.1.7a). Likewise, mean distance between actual Point 1 and actual Point 3 locations was significantly smaller for instances of correct cover type

assignment than incorrect assignment for midpoint locations (Fig. 1.7b; 0.5 hr: t -test, $t_{1387} = -16.1, p < 0.01$; 1 hr: t -test, $t_{553} = -8.5, p < 0.01$; 6 hr: t -test, $t_{2868} = -11.6, p < 0.01$).

Mean distance between Point 1 and Point 3 was significantly smaller in cases where all actual locations in a triplet occurred in the same cover type, as compared to cases where actual locations occurred in different cover types. Mean distance between actual Point 1 and Point 3 locations was 149 m (± 6.4) for the 0.5 hr interval when all locations in a triplet were in the same cover type, and 445 m (± 11.2) when actual locations occurred in different cover types (t -test, $t_{2431} = -22.9, p < 0.01$). For the 1 hr and 6 hr intervals, respectively, mean distance values (\pm SE) were 270 m (± 25.5) and 696 m (± 31.6) (t -test, $t_{866} = -10.5, p < 0.01$), and 811 m (± 44.7) and 2,027 m (± 41.6) (t -test, $t_{2276} = -19.9, p < 0.01$), when all triplet locations occurred in the same versus different cover types.

For simulated locations, mean percent correct cover type assignment was higher when all actual locations in a triplet occurred in the same cover type than when triplet locations occurred in different types (Fig. 1.8a; 0.5 hr: t -test, $t_{2319} = 47.4, p < 0.01$; 1 hr: t -test, $t_{815} = 24.6, p < 0.01$; 6 hr: t -test, $t_{1730} = 31.6, p < 0.01$). Among midpoints correctly assigned to the cover type of its known counterpart, a greater proportion belonged to triplets with all actual locations in the same cover type than to triplets with actual locations in different cover types (Fig. 1.8b). This was true for the 0.5 hr and 1 hr time intervals, but not the 6 hr (50% vs. 50%) interval between location attempts, which had an equal proportion of correctly assigned locations in each group.

As expected, the distance between actual Point 1 and actual Point 2 locations increased with increasing interval between location attempts. Nonetheless, the mean distance between actual Point 1 and midpoint locations was significantly smaller than the mean distance between actual Point 1 and actual Point 2 locations for all time intervals between location attempts (0.5 hr: paired t -test, $t_{3553} = 9.3$, $p < 0.01$; 1 hr: paired t -test, $t_{906} = 4.3$, $p < 0.01$; 6 hr: paired t -test, $t_{2942} = 14.7$, $p < 0.01$). For the 0.5, 1 and 6 hr intervals, the mean distance between actual Point 1 and actual Point 2 locations was on average larger than the mean distance between actual Point 1 locations and midpoints by 18 m (± 1.9), 30 m (± 7.0) and 230 m (± 15.7), respectively.

DISCUSSION

Estimating missed GPS locations as the midpoint between two successful locations was a more accurate method for predicting cover type or estimating the position of missed location attempts in Canada lynx than estimating missed locations based on net displacement distances and movement angles calculated from known locations. Midpoints were more accurate in terms of both cover type prediction and position for location attempts separated by shorter intervals. Using midpoints to estimate the position of missed locations was similarly useful for developing models of fix success in grizzly bears because of the short interval between location attempts and the high explanatory power of movement rates (Graves and Waller 2006). Such utility of midpoints as a proxy for missed locations is not unexpected, given that a straight-line path between

consecutive locations is considered an increasingly accurate approximation of an animal's actual movement path as the time between location attempts decreases (Siniff and Tester 1965). In fact, we observed relatively small mean differences between the distance from actual Point 1 and Point 2 locations and the distance from actual Point 1 and midpoint locations, especially for the 0.5 and 1 hr intervals between location attempts. However, because actual displacement distances were significantly larger than the distances to midpoints, by as much as 819 m for the 0.5 hr interval, 1,255 m for the 1 hr interval, and 6,947 m for the 6 hr interval between location attempts, incorrect cover type was assigned for upwards of 55% of midpoint locations. We are thus faced with a trade-off associated with imputing a missed location as the midpoint between successful locations. Midpoints have reduced position error when compared to locations imputed using known movement angles and displacement distances, but may occur in incorrect cover types, thus potentially affecting inferences about habitat use if included in analyses.

We observed higher accuracy of cover type assignment to locations within larger habitat patches, and found that cover type prediction tended to be more accurate for cover types that comprise a larger proportion of the study area, particularly mixedwood forest. In the case of resource selection functions, increased accuracy requires higher rates of location attempts as patch area decreases, because errors occur when location attempts are infrequent and patch area is small (Swain et al. 2008). Our results reinforce this pattern, demonstrating increasingly correct cover type assignment for larger patches and shorter intervals between location attempts. As we hypothesized, use of the methods described here for estimating missed locations will be more accurate in landscapes with

large, contiguous patches of habitat and when frequency of location attempts is high. However, caution should be taken when planning location schedules, as decreasing the interval between location attempts may increase autocorrelation in location data if a consistent interval is not used between location attempts (Frair et al. 2010).

Position error between actual locations and both simulated locations and midpoints increased as the time between location attempts increased. Furthermore, the accuracy of cover type assignment decreased with increasing position error. This suggests that patch dimensions in the study area were smaller than the position error observed between actual lynx locations and simulated locations or midpoints. However, we found that the area of patches used by lynx was quite large relative to the distance moved between successive locations, suggesting that boundaries of these habitat patches are likely irregular, the landscape is characterized by smaller habitat patches within larger patches of different cover types, or that lynx were occurring along the edges of adjacent habitat types. In the southern extent of the lynx range, including Minnesota, habitat is more heterogenous and Canada lynx do select for edges between mature coniferous forest and successional or regenerating forest types (Murray et al. 2008; Burdett 2008). Lynx preference for such edge habitat may relate to foraging efficiency, including both prey density and accessibility (Fuller et al. 2007).

Position error among midpoint locations was also smaller than the GPS error reported for the collar models deployed on lynx in this study (approximately 5 m) for 2% to 9% of midpoint locations for the three time intervals between location attempts. Of those midpoints with a position error less than or equal to GPS error, > 94% of those

midpoints were successfully assigned to the correct cover type. Position error was also less than the 30 m resolution of the LULC cover type data for upwards of 40% of midpoint locations. This was especially true for the shorter intervals between location attempts, and of those midpoints with small values of position error relative to cover type resolution, a large proportion were correctly assigned to the cover type of the associated actual location. Small error, both collar error and position error, relative to patch size are crucial for classification of habitat selection because habitat misclassification can occur when error is large relative to habitat patch size (Nams 1989, Kauhala and Tiilikainen 2002).

Accuracy of cover type assignment to simulated locations and midpoints was higher for smaller distances between actual (Point 1 and Point 3) locations, and distances between actual locations were smaller when all actual locations in a triplet were in the same cover type. Cover type assignment to simulated locations and midpoints was also correct more often when all actual locations in a triplet occurred in the same cover type. This suggests that the reduced accuracy of cover type prediction with increasing interval between location attempts was related to distance moved and the likelihood that a lynx changed cover types between locations or the possibility they were using habitat edges, resulting in frequent encounters with different habitat types.

While the use of midpoints for interpolating hypothetically missed locations resulted in relatively accurate cover type prediction and estimates of lynx position, especially for shorter intervals between location attempts, success of cover type assignment was only as high as 73% and position error was greater than 95 m. Given the

small mean movement angles observed here, we would expect the midpoint between successful location attempts to be a more accurate estimate for a missed location, because the mean movement angle for each time interval calculated by sex and individual suggested that lynx tended to walk a straight path between locations. In Maine, lynx movement paths were straighter at finer spatial scales (Fuller and Harrison 2010). We therefore would expect the midpoint between two successful locations to be a reasonable approximation of a missed location at smaller spatial and temporal scales, such as those observed for the 0.5 hr and 1 hr intervals between location attempts. The observed standard deviation, however, indicated a large amount of variance in the movement angle of a lynx path for location attempts separated by 0.5, 1 and 6 hrs. This variation in the angle of lynx movement paths may partially explain the limited ability of midpoints to serve as replacements for missed location attempts, as lynx paths may have been more sinuous than assumed. Though male lynx in Maine tended to walk straighter paths than female lynx, both sexes followed more tortuous paths in preferred habitat where foraging success was higher (Fuller and Harrison 2010). Perhaps the limitations of estimating a missed location as the midpoint between successful locations occurred in part because the lynx observed here often used habitat types where snowshoe hare availability is higher (McCann 2006, McCann and Moen 2011), and thus followed more sinuous movement paths to increase foraging efficiency.

MANAGEMENT IMPLICATIONS

We found that missed location attempts in Canada lynx were best interpolated as the midpoint between two successful locations. However, accuracy of position and cover type prediction was dependent on habitat patch area and the interval between location attempts. For these imputation methods to accurately predict cover type of missed locations, we recommend that they be used in landscapes with large, contiguous patches of habitat, or for species that are relatively specialized in their habitat selection. We also recommend limiting the use of midpoints for estimating missed locations to cases where the interval between location attempts is short (i.e., 0.5 hr or 1 hr), as this reduced position error and improved success of predicting the cover type of the interpolated location.

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Table 1.1. Summary data, including number of triplets, mean distance (m) between actual Point 1 and actual Point 2 locations (\pm standard error, SE), mean distance (m) between actual Point 2 and actual Point 3 locations, and mean movement angle (degrees) (\pm circular standard deviation, sd), for the 0.5, 1 and 6 hr intervals between GPS radiotelemetry location attempts for 7 Canada lynx (4M, 3F) monitored via GPS radiotelemetry from 2003-2009 in northeastern Minnesota.

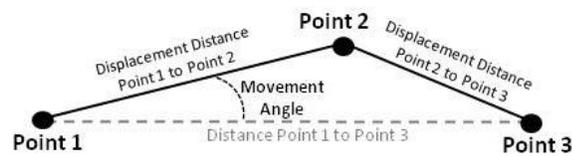
Interval Between Location Attempts (Hrs)	Number of Triplets	Mean Distance Point 1-Point 2 \pm SE (m)	Mean Distance Point 2-Point 3 \pm SE (m)	Mean Distance Point 1-Point 3 \pm SE (m)	Mean Movement Angle \pm circular sd (degrees)
0.5	3595	155 \pm 4	161 \pm 4	274 \pm 6	0.7 \pm 61.2
1	921	273 \pm 13	279 \pm 13	485 \pm 21	2.4 \pm 63.2
6	3002	1067 \pm 23	1074 \pm 23	1673 \pm 33	1.3 \pm 62.2

Table 1.2. Percent correct cover type prediction and mean position error (m) (\pm SE) for simulated Point 2 replicates and midpoint locations by time interval between location attempts (0.5, 1, and 6 hrs). GPS locations and location attempts were collected for 7 Canada lynx (4M, 3F) monitored with GPS radiotelemetry in northeastern Minnesota from 2003-2009.

Interval Between Location Attempts (Hrs)	Correct Cover Type Prediction (%)		Mean Position Error (m)	
	Simulated Locations \pm SE	Midpoints \pm SE	Simulated Locations \pm SE	Midpoints \pm SE
0.5	61 \pm 0.5	73 \pm 0.4	232 \pm 2.8	95 \pm 1.9
1	54 \pm 1.0	66 \pm 1.6	410 \pm 10.1	174 \pm 6.9
6	37 \pm 0.5	44 \pm 2.9	1514 \pm 16.9	768 \pm 14.9

Figure 1.1. Schematic diagram of a triplet of Canada lynx GPS radiotelemetry locations with (a) actual Points 1, 2 and 3, the movement angle and displacement distances between actual points, (b) Point 2 excluded, one simulated Point 2 replicate generated from a paired movement angle and displacement distance, and the midpoint between actual Points 1 and 3. Lynx locations were collected via GPS radiotelemetry from 2003-2009 in northeastern Minnesota for 7 individuals (4M, 3F).

(a)



(b)

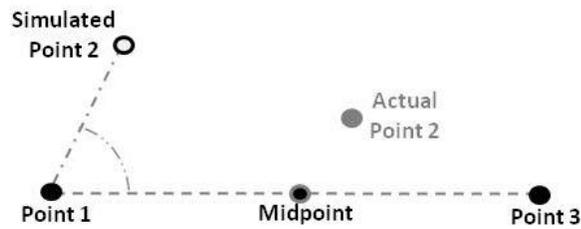


Figure 1.2. Cumulative percent of movement angles (degrees) by interval between location attempts for triplets of Canada lynx GPS radiotelemetry locations separated by a 0.5 hr interval (solid line), 1 hr interval (dashed line), and 6 hr interval (dotted line). GPS radiotelemetry locations were collected from 2003-2009 for 7 lynx (4M, 3F) in northeastern Minnesota.

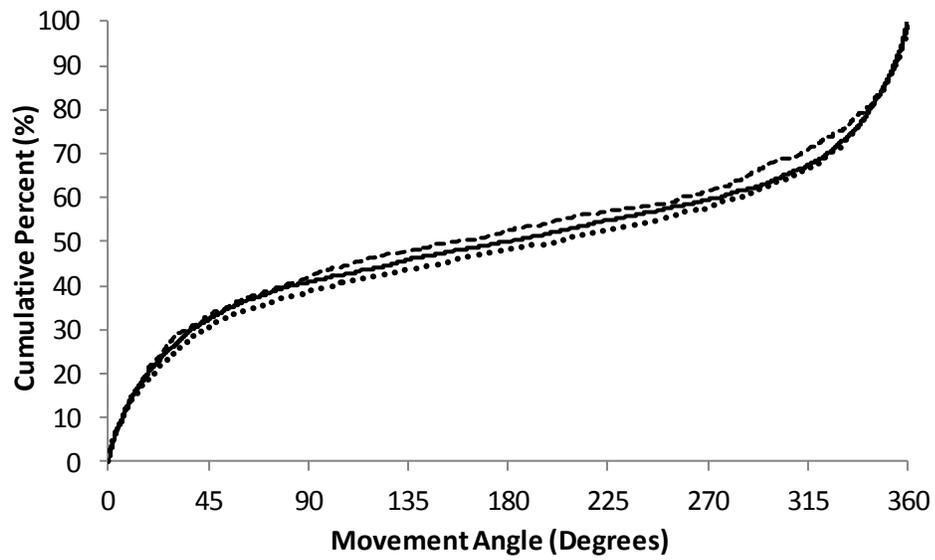


Figure 1.3. Percent of Canada lynx locations for which cover type assignment was correct for simulated Point 2 locations (solid bars) and midpoint locations (textured bars) for the most common and most commonly used land use/land cover (LULC) habitat types in northeastern Minnesota. Percentages are shown for the 0.5, 1 and 6 hr intervals between GPS radiocollar location attempts. Locations and location attempts were collected for 7 lynx (4M, 3F) monitored via GPS radiotelemetry from 2003-2009 in northeastern Minnesota. Percent of the 3-county (Cook, Lake, and St. Louis) landscape area comprised by each cover type is also indicated.

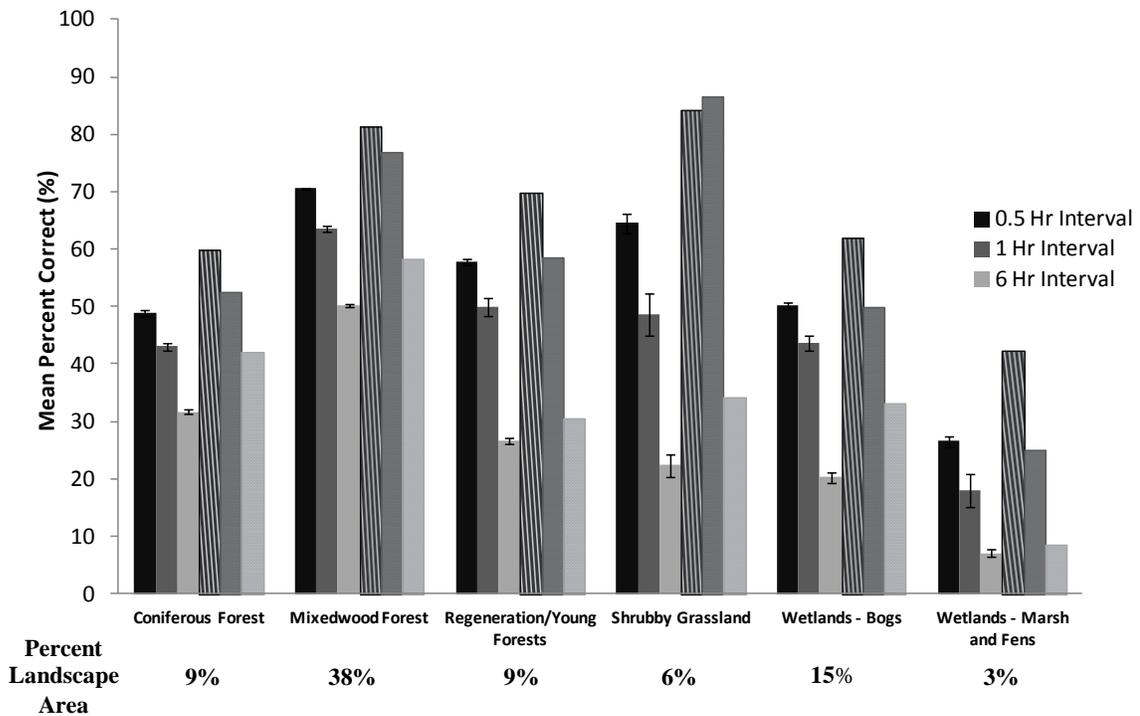
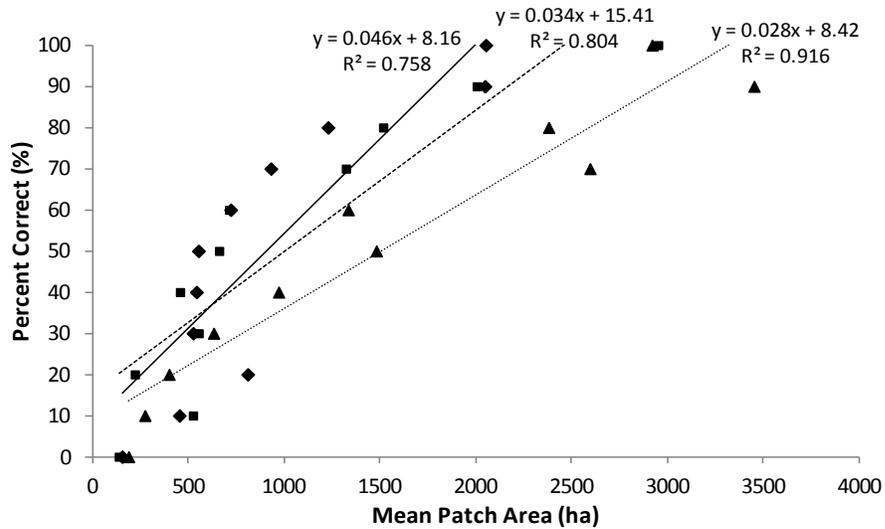


Figure 1.4. (a) Linear regression of mean patch area (ha) of the habitat patch containing the actual Point 2 location and the percent correct land use/land cover (LULC) type assignment for simulated Point 2 replicates for the 0.5 (◆, solid line), 1 (■, dashed line) and 6 (▲, dotted line) hr intervals between Canada lynx GPS radiocollar location attempts. (b) Mean patch area (ha) of the habitat patch containing the actual Point 2 location for midpoints with correctly and incorrectly assigned LULC cover types for the 0.5, 1 and 6 hr intervals between location attempts. GPS locations and location attempts were collected for 7 lynx (4M, 3F) monitored from 2003-2009 in northeastern Minnesota.

(a)



(b)

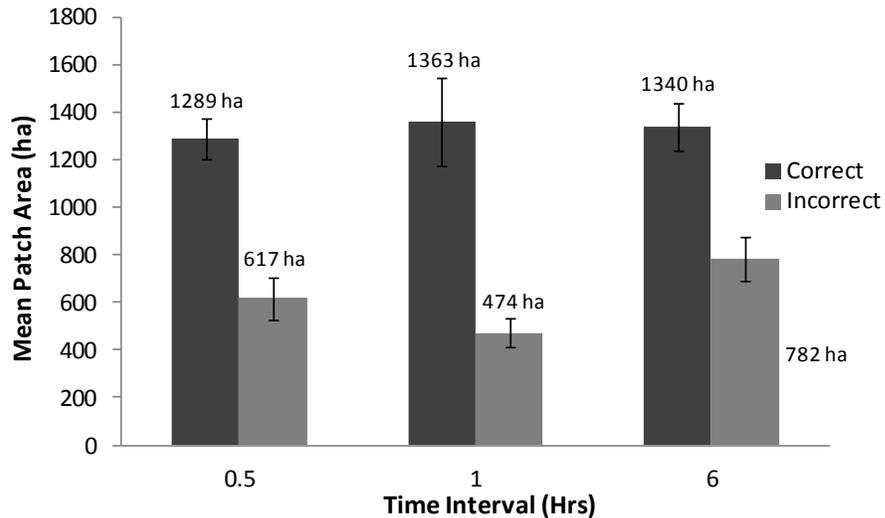
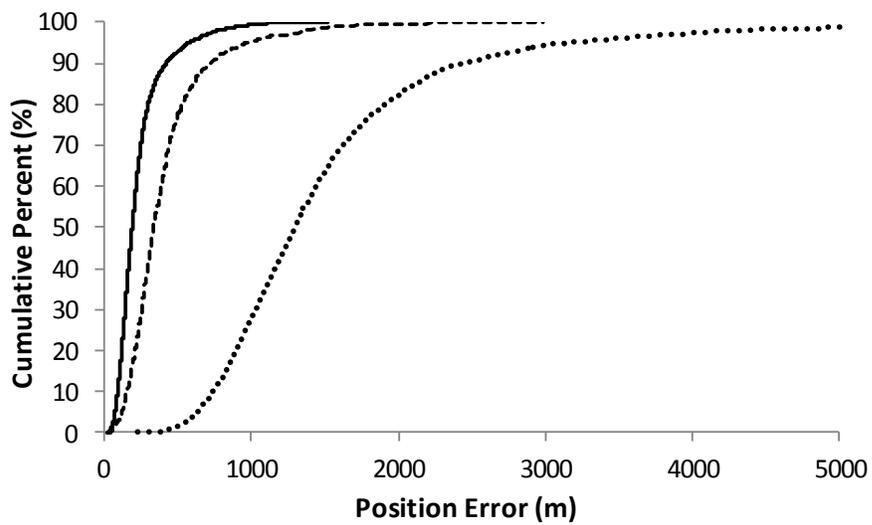


Figure 1.5. Cumulative percent of (a) mean position error (m) for simulated Point 2 locations, calculated as the mean distance between known Point 2 locations and simulated Point 2 replicates, and (b) position error (m) for midpoint locations, calculated as the distance from known Point 2 locations to midpoints, for Canada lynx locations separated by a 0.5 hr interval (solid line), 1 hr interval (dashed line) and 6 hr interval (dotted line). Locations were collected for 7 individuals (4M, 3F) monitored via GPS radiotelemetry from 2003-2009 in northeastern Minnesota.

(a)



(b)

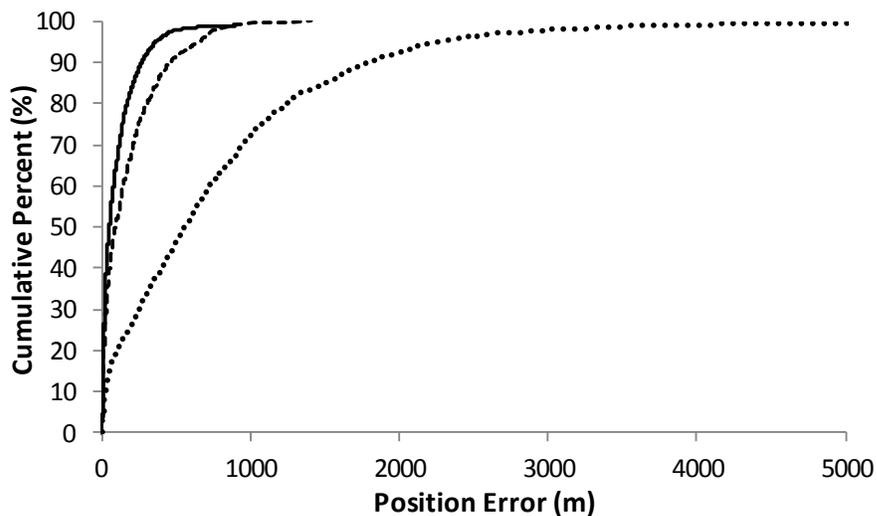
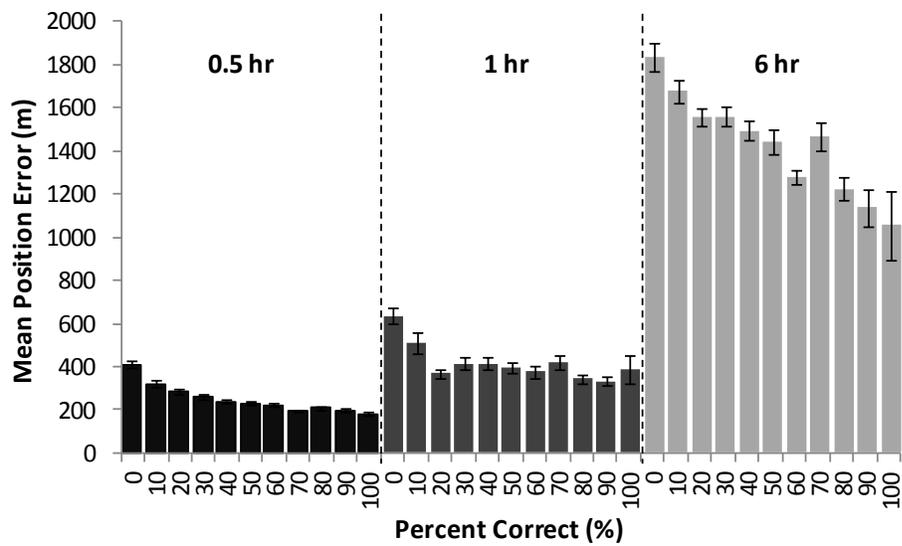


Figure 1.6. (a) Mean position error (m) for values of percent correctly assigned land use/land cover (LULC) types for simulated Point 2 locations. (b) Mean position error (m) for cases of correct and incorrect LULC cover assignment to midpoint locations. Percent correct cover type assignment and position error are shown for 0.5, 1 and 6 hr intervals between GPS radiocollar location attempts for 7 Canada lynx (4M, 3F) monitored with GPS radiotelemetry from 2003-2009 in northeastern Minnesota.

(a)



(b)

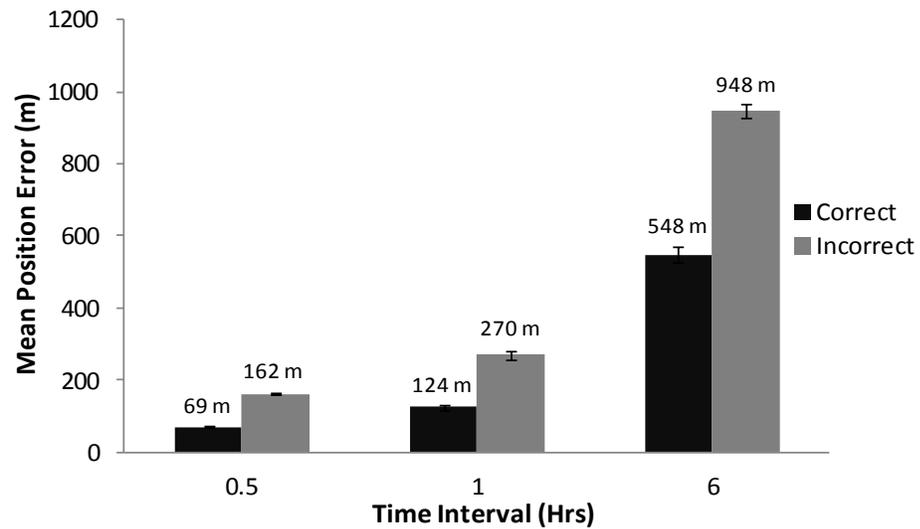
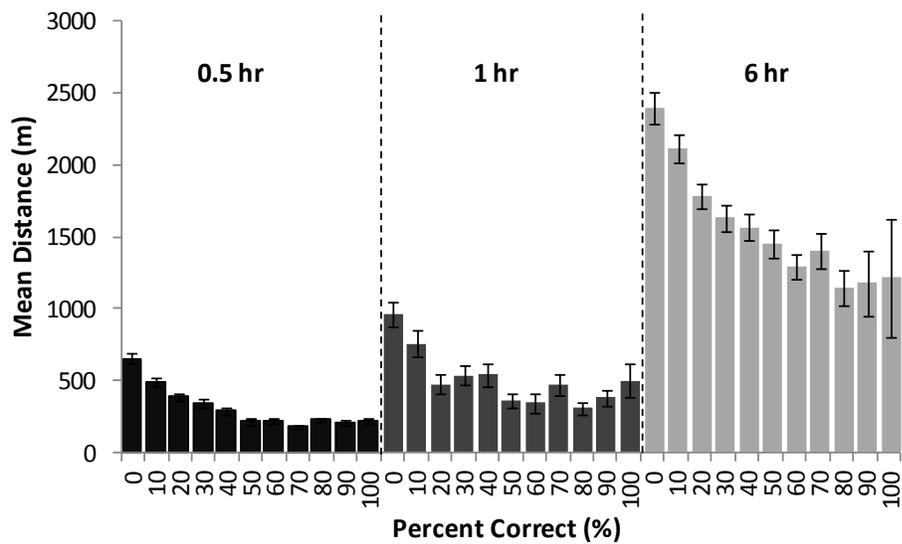


Figure 1.7. (a) Mean distance (m) between actual Point 1 and actual Point 3 locations versus percent correct land use/land cover (LULC) type assignment to simulated Point 2 replicates for the 0.5, 1 and 6 hr intervals between GPS radiocollar location attempts. (b) Mean distance (m) between actual Point 1 and actual Point 3 locations for correct and incorrect LULC cover type assignment to midpoints for 0.5, 1 and 6 hr intervals between location attempts. GPS locations and attempts were collected for 7 Canada lynx (4M, 3F) monitored via GPS radiotelemetry from 2003-2009 in northeastern Minnesota.

(a)



(b)

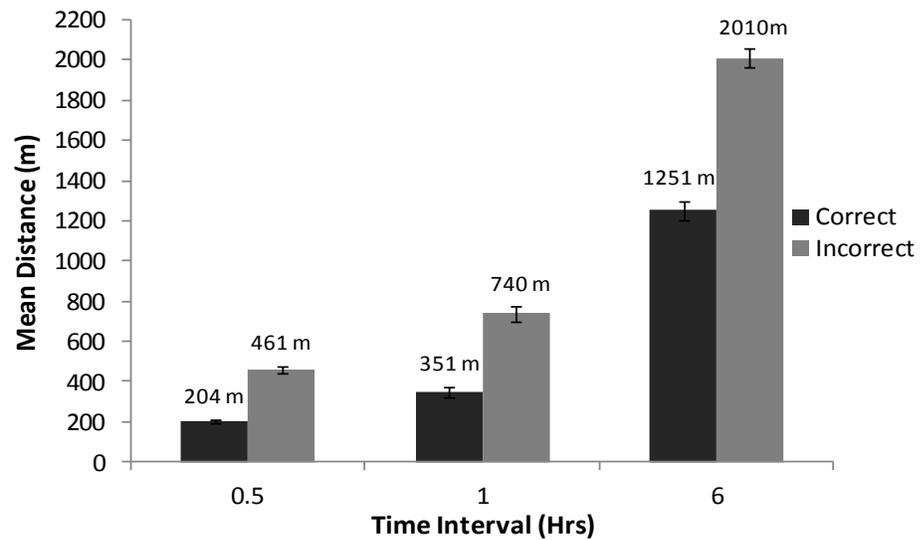
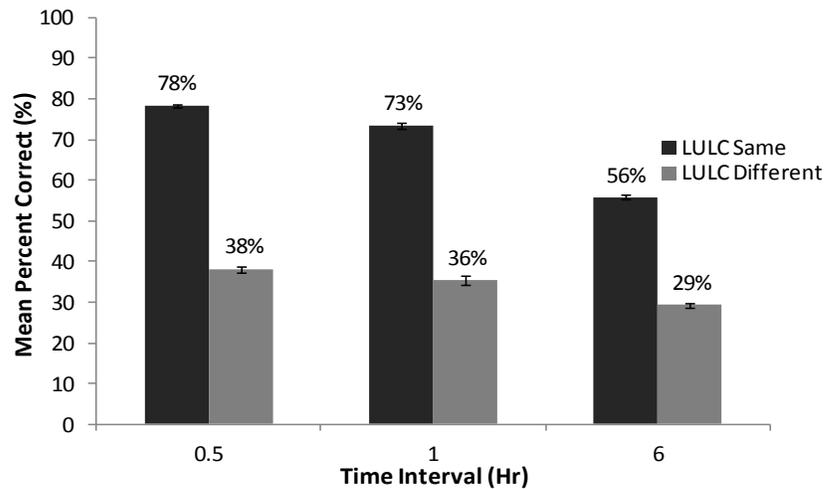
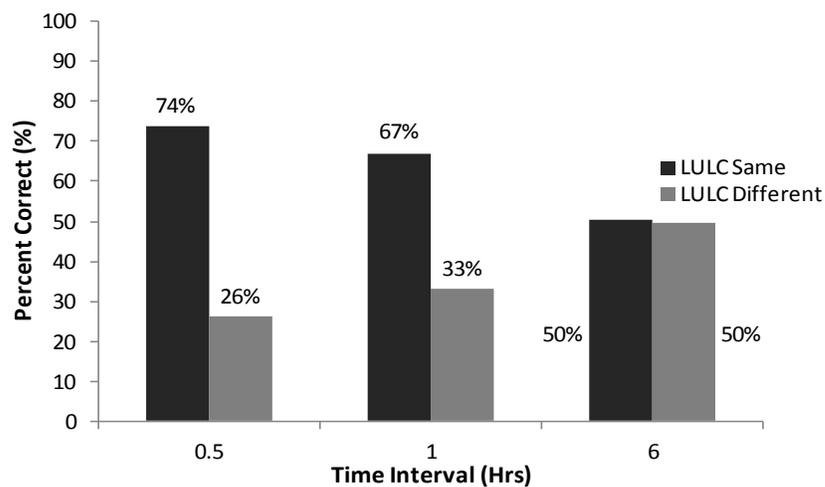


Figure 1.8. (a) Mean percent correct land use/land cover (LULC) type assignment to simulated Point 2 replicates for cases when all actual Canada lynx GPS radiocollar locations in a triplet were in the same LULC cover type versus cases when all actual locations were not in the same cover type. (b) Percent of midpoints correctly assigned to LULC cover types for triplets with all actual locations in the same LULC cover type versus triplets with actual locations not in the same cover type. Percent correct cover type assignment is shown for 0.5, 1 and 6 hr intervals between location attempts for 7 Canada lynx (4M, 3F) monitored with GPS radiotelemetry from 2003-2009 in northeastern Minnesota.

(a)



(b)



CHAPTER 2

Canada lynx (*Lynx canadensis*) in Minnesota: Road and Trail Use within the Home Range

SUMMARY

Responses of Canada lynx (*Lynx canadensis*) to linear corridors, particularly roads and trails, depend on geographic area, characteristics of individual lynx, type of road, and local habitat. Roads and trails could benefit lynx by increasing both the ease and speed of travel between use areas. However, use of road features may increase the probability of human-lynx interactions and the risk of mortality from vehicle collisions and incidental human-caused mortality. In Minnesota, lynx frequently travel on and cross roads and trails, and proximity to road features occurs both within home ranges and during long-distance movements outside of established territories. We assessed the use of linear features by Canada lynx within seasonal home ranges using approximately 4,500 GPS locations from 7 lynx collected during a 6 year radiotelemetry study in the Superior National Forest, Minnesota. Within home ranges, lynx were closer to roads and trails than they were to streams, lakes and rivers, and wooded swamps, and about 3% of locations occurred on roads and trails. Based on Akaike's Information Criterion (AIC) ranking of linear mixed-effects models that included sex and season as fixed effects and individual as a random effect, neither sex nor season was considered a covariate of

distance to the nearest road feature, and approximately 26% of variance in distance to road features was explained by differences among individual animals. Selection of this model may have been influenced by one male, as the model including sex as a covariate was supported when this individual was excluded. According to this model female lynx occurred closer to road features than males by approximately 171 m; however this small difference may be statistically significant, but not necessarily biologically meaningful. Distance to roads and trails did not differ between actual locations and random locations within the home range. Thus lynx were not selecting for or avoiding road features within their home ranges at broad spatial scales. However, within 50 m of a road or trail some lynx were closer to road features than random expectation, indicating that selection for roads may occur at smaller spatial scales or in areas close to road infrastructure. Based on AIC ranking of linear mixed-effect models for movement rate between locations separated by 6 hrs, the most parsimonious model included sex and season as covariates of movement rate. Female lynx had slower movement rates than male lynx and movement rates were slower in winter than the denning season. Furthermore, only 14.5% of variance in these data was explained by differences among individuals. Movement rates were also faster for consecutive locations on a road or trail than consecutive locations not on a road or trail. However, movement rates were not affected by road and trail density, as road and trail density was similar among individual lynx, home ranges and seasons. Interactions with prey and encounters with human activities, vehicles and competitors near roads and trails may explain why movement rates were not increased by road and trail presence. Frequency of road crossings was also not related to road density, and was

proportional to the total length of various road surface types present within a home range. The managed road density of 1-2 km/km² across the study area may partially account for the lack of relationship between road density and use of roads and trails by lynx, as well as the lack of difference in proximity to road infrastructure between lynx locations and random locations at broad spatial scales. The frequency of lynx occurrence near roads and trails both within the home range and during long-distance movements exposes Canada lynx in Minnesota to mortality associated with roads and other human activities, although the extent of this potential threat to lynx in Minnesota is unknown.

INTRODUCTION

Canada lynx (*Lynx canadensis*) maintain larger home ranges in southern boreal forests than their northern counterparts due to the need to incorporate diverse habitats with sufficient prey densities at the southern edge of the lynx range (Aubry et al. 2000; Murray et al. 2008). Increased habitat diversity, as well as greater habitat fragmentation and higher human population densities expose southern lynx populations to more human disturbances, including roads and development, than northern lynx populations (Murray et al. 2008). However, reported effects of roads and other human infrastructure on the behavior of Canada lynx have been varied because individual characteristics, local habitat conditions, road width, traffic volume, and other factors affect measured responses to these features (Aubry et al. 2000; Murray et al. 2008).

To date, research on road use among Canada lynx is equivocal. Lynx selected against roads and road edges, and crossed highways less than expected within home ranges in Maine and British Columbia (Apps 2000; Fuller et al. 2007). In contrast, lynx neither preferred nor avoided roads when selecting habitat within home ranges or within home range core areas in Maine (Vashon et al. 2008). In northern Canada and Alaska, lynx crossed and were observed along highways, maintained home ranges neighboring roads, and did not alter home ranges or movements in response to intermediate levels of mechanized vehicle (i.e. snowmobile) traffic (Mowat et al. 2000). Though lynx selected den sites away from roads in Montana, lynx did not den further from roads open to

vehicle traffic; however preference for other habitat characteristics, rather than avoidance of human activity, may have driven den site selection (Squires et al. 2008).

Regardless of geographic location, roads may benefit lynx by increasing efficiency of movement between preferred use areas. Roads may also increase hunting opportunities and hunting efficiency, as snowshoe hare (*Lepus americanus*), the preferred prey of lynx, often browse along roads (Pietz and Tester 1983). Conversely, roads may increase the risk of vehicle collisions or incidental human-caused mortality during dispersal among suitable habitat patches (Trombulak and Frissell 2000; Bateman and Fleming 2012; Rytwinski and Fahrig 2012). Increased competition with sympatric carnivores (i.e., coyotes [*Canis latrans*] and bobcats [*Lynx rufus*]), disturbance, snow compaction, habitat fragmentation, habitat modification and habitat loss are other possible negative effects of roads on lynx (Aubry et al. 2000; Buskirk et al. 2000).

In Minnesota, lynx cross and travel along roads and other linear features, and occurrence near roads is also common during long-distance movements between the U.S. and Canada (Moen et al. 2008, 2010). However, most reported lynx deaths have been associated with vehicle collisions, trapping or shooting, suggesting that proximity to roads may negatively affect the lynx population in Minnesota (Moen et al. 2008). We used Global Positioning System (GPS) locations from Canada lynx fitted with GPS radiocollars in the Superior National Forest to examine the use of roads and trails by lynx. During long-distance movements (i.e. locations greater than 15 km from the home range centroid) approximately 20% of locations occurred on (≤ 6 m) road infrastructure, and lynx occurred an average of 200 m from roads and trails within the Superior National

Forest (Moen et al. 2010). However, roads were not necessary for long-distance movements, as indicated by straight-line movements across both the portions of Minnesota with roads and the roadless Boundary Waters Canoe Area and Wilderness (BWCAW).

Given the use of road infrastructure during long-distance movements, we tested whether Canada lynx modified space use with respect to presence of roads and other linear features within their home ranges at a scale that could be detected with GPS radiocollar locations. We used locations collected 6 hrs apart for 7 lynx and seasonal home ranges to examine lynx association with linear corridors, including road infrastructure and water features, within their home ranges (Burdett et al. 2007; Moen et al. 2008). We assessed whether proximity to road features within the home range varied by animal, sex and/or season, and whether road density influenced associations with road infrastructure. We also calculated movement rates between locations and quantified the relationship between movement rate and road and trail density to determine whether road features affected travel time. Finally, we estimated the frequency of occurrence on roads and trails and the frequency with which lynx crossed roads and trails between recorded collar locations within home ranges and assessed whether these estimates varied seasonally or among road and trail types.

STUDY AREA

The study area where lynx were monitored included parts of Cook, Lake, and St. Louis counties in northeastern Minnesota. Among radiocollared lynx, 17 seasonal and 5 annual lynx home ranges occurred within the Superior National Forest (Fig. 2.1). Roads and trails are present throughout the study area, with the exception of the roadless Boundary Waters Canoe Area and Wilderness (BWCAW), which includes only portage trails and overlapped only a portion of one seasonal home range.

Forest composition in the study area is transitional between boreal forest and the Great Lakes-St. Lawrence northern hardwood forest (i.e., hemiboreal; Pastor and Mladenoff 1992; Heinselman 1973). Mixed forest is common at lowland sites, as are other boreal forest types (Heinselman 1973). Northern hardwoods occur on upland sites, and pine (*Pinus* spp.) comprises managed upland stands (Flaccus and Ohmann 1964; Burdett et al. 2007). Successional forest, resulting from lumber removal and fire, is present, and there are also numerous lakes and both forested and non-forested wetlands (Burdett et al. 2007).

METHODS

GIS and Statistical Analyses

GIS mapping and analysis were completed using ArcMap 10 (ESRI 2010) and Geospatial Modelling Environment (Spatial Ecology, LLC 2011). Statistical analyses

were performed using R 2.13.1 (The R Foundation for Statistical Computing 2011), R 3.3.2 (The R Foundation for Statistical Computing 2016) and the statistical functions in Microsoft Excel (Microsoft 2007).

Canada Lynx Radiotelemetry Locations and Home Ranges

We used 4,545 GPS locations for 7 Canada lynx (4M and 3F) captured and radiocollared between 2003 and 2009 (Burdett et al. 2007; Moen et al. 2008; Moen 2009). This sample included locations collected when GPS radiocollars were set to attempt locations at a 6 hr interval, and included only those locations within the seasonal home ranges of the 7 focal animals. Home ranges were calculated as 95% fixed-kernels, and included winter (1 December–30 April), denning (1 May–30 June), and summer–fall (1 July–30 November) home ranges (Burdett et al. 2007). Of the 17 home ranges examined, 9 were winter home ranges, 5 were denning season home ranges, and 3 were summer-fall home ranges. There were no summer-fall home ranges for male lynx due to collar malfunction.

GIS Coverages- Road Infrastructure, Water Features and Cover Type

GIS data were provided by the U.S. Forest Service Superior National Forest (Susan Catton, *personal communication*) or obtained from the Minnesota Department of Natural Resources (MnDNR 2008). Road and trail data were compiled to include all U.S. Forest Service designated roads and trails in the Superior National Forest, all classes of roads recognized by the Minnesota Department of Transportation (MnDOT), as well as snowmobile trails and railroads. Water coverages included streams, as well as lakes and rivers within the study area. Wetland data were derived from the U.S. Fish and

Wildlife Service National Wetlands Inventory. This classification includes 12 wetland types found in Minnesota and was subsampled here to include only shrub swamp and wooded swamp cover types that are likely to support snowshoe hare populations.

Use of Roads and Trails and Water Features

We determined the distance to the nearest road or trail for all locations and calculated the mean distance to the nearest road or trail by individual lynx, seasonal home range, sex and season. We also determined the distance from each location to the nearest stream, lake edge and river bank (lake/river), shrub swamp edge, and wooded swamp edge and tested whether the difference between the distance to each of these features and the distance to the nearest road or trail differed from zero. This accounted for the fact that distance to road and water features were log-normally distributed.

We conducted a model selection process of all possible combinations (4 models, including the null model) of linear mixed-effects models (LMM, lmer function in lme4 package for R) for distance to the nearest road or trail ($n = 4,545$ replicates, one for each lynx location), that included sex and season (i.e. denning, winter and summer-fall) as fixed effects, and individual lynx ($n = 7$) as a random effect. Including individual lynx as a random effect accounted for the large number of locations from a few animals and potential variation in distance to roads and trails among animals (Burnham and Anderson 2002). We used Akaike's Information Criterion (AIC) to rank models, and considered models within 2 AIC units of the most parsimonious model to have support.

We also compared the distance to roads and trails for actual lynx locations and random locations. Within each seasonal home range we generated ten samples of random

locations equivalent to the number of actual locations and determined the distance from each random location to the nearest road or trail. To compare random locations to actual locations within each home range, we tested whether the actual mean distance to roads or trails was within the 95% confidence interval for the mean distance of all random locations. We then determined the percent of home ranges for which the actual mean distance to road infrastructure was greater than, less than, or did not differ from the mean distance for random locations. We also compared the frequency with which actual lynx locations were closer than random expectation to road and trail features for the subset of locations within 5 m, 10 m, 25 m, and 50 m of a road or trail. Finally, we compared the cumulative frequency distribution for distance to roads and trails between actual lynx locations and random locations.

To evaluate road and trail use within home ranges, we determined the number of lynx locations on road features. We defined these as locations ≤ 5 m from a road or trail, as this distance is within GPS position error for the radiocollars used in this study. We estimated road and trail use for male and female lynx and during winter, summer-fall, and the denning season. We also calculated the frequency with which consecutive locations occurred on a road or trail.

Movement Rates

Displacement distance was determined for all pairs of consecutive locations separated by a 6 hr interval and used to calculate the movement rate between successive locations. We determined the mean movement rate by individual, as well as by sex. We used AIC to rank and select among all combinations (4 models, including the null model)

of linear mixed-effects models (LMM, lmer function in lme4 package for R) for movement rate ($n = 4,528$ replicates, representing consecutive locations collected for the same animal during the same collar period), that included sex and season as fixed effects, and individual lynx ($n = 7$) as a random effect. Again, we considered models within 2 AIC units of the most parsimonious model to have support.

We also determined the movement rate between pairs of consecutive locations that were on a road or trail and compared it to the movement rate between locations not on a road or trail. Statistical tests could not be performed due to the limited sample of consecutive locations on road features.

Road and Trail Density and Home Range Area

For each of the 17 seasonal home ranges we determined the home range area and total length of all roads and trails, and calculated the road and trail density. Road and trail density and home range area was compared qualitatively among seasonal home ranges. We also compared road and trail density and home range area among seasons and between male and female lynx. Using linear regression we examined the relationship between road and trail density and distance to the nearest road feature by seasonal home range. Linear regression was also used to examine the relationship between movement rate (for locations collected at 6 hr intervals) and road and trail density by seasonal home range.

Crossing of Roads and Trails

We calculated the frequency with which each lynx crossed road features, by drawing line segments between consecutive locations and determining the number of

times these paths crossed or intersected roads or trails. Based on the total number of days that each individual was radiocollared, we estimated the daily rate of road and trail crossing for each animal and compared this rate between male and female lynx. We also used linear regression to examine the relationship between daily intersection with roads and trails and road and trail density by individual. For each lynx we calculated percent of road and trail crossings and percent total road and trail length within the home range comprised of different road surface types. Surface type was based on U.S. Forest Service surface type designations and included asphalt, crushed aggregate or gravel, frozen soil, improved native material, native material and snowmobile trails.

RESULTS

Proximity to Roads and Trails and Water Features

Within the home range, lynx were 302 ± 4 m from the nearest road or trail, and significantly closer than they were to the nearest stream (568 ± 6 m; t -test, $t_{4544} = 38.7$, $p < 0.01$), or the nearest lake or river (649 ± 6 m; t -test, $t_{4544} = 53.6$, $p < 0.01$). Lynx also occurred significantly closer to roads and trails than to the nearest wooded swamp (430 ± 6 m; t -test, $t_{4544} = 16.5$, $p < 0.01$), but not the nearest shrub swamp (299 ± 3 m; t -test, $t_{4544} = -0.5$, $p = 0.6$) (Fig. 2.2).

Based on a comparison of linear mixed-effects models with sex and season as fixed effects and individual as a random effect, two models were considered to have substantial support ($\Delta AIC < 2$; Table 2.1). In the first model, distance to the nearest road

or trail covaried by sex, such that female lynx tended to be closer to roads and trails than males by approximately 110 m ($\beta_{\text{Females}} = -110.6$, SE = 71.4). However, given a large amount of variance, the 95% confidence interval for this difference in distance to nearest road feature among females overlaps zero (-250.5 m - 29.4 m) indicating that the effect of sex on proximity to roads and trails may not be significant. This lack of difference between males and females may be driven largely by one male (Lynx 6) that tended to be closer to roads and trails than other male lynx (Fig. 2.3). In fact, approximately 26% of total variance in distance to the nearest road or trail was explained by differences between individual animals (Table 2.2). Thus, the second most parsimonious model included only individual differences in distance to the nearest road feature (Tables 2.1 and 2.2). However, we could not select between these two models, as they had similar support. We did not detect an effect of season on distance to nearest road feature, as the models including season as a covariate did not have support based on ΔAIC estimates. To test whether Lynx 6 was, in fact, influencing the lack of difference in distance to nearest road or trail between males and females, we removed this individual from the data and repeated our model selection process. Without this male lynx, one linear mixed effect model was supported, and this model included sex as a fixed effect and individual as a random effect (i.e. Distance to roads/trails \sim sex + [1| individual]). According to this model, females were closer to roads and trails by approximately 171 m ($\beta_{\text{Females}} = -171.0$, SE = 42.7), but again, approximately 16% of variance in distance to nearest road feature was explained by differences among individual lynx.

Proximity to Roads and Trails for Actual versus Random Locations

When compared to random locations within the seasonal 95% kernel home range, actual lynx locations were, on average 64 ± 18 m closer to roads and trails than random locations for 59% ($n = 10$) of seasonal home ranges. For 18% ($n = 3$) of seasonal home ranges, actual lynx locations were, on average, 19 ± 6 m farther from roads and trails than random locations, and for the remaining 23% ($n = 4$) of seasonal home ranges, the mean distance to the nearest road or trail for actual locations did not differ from the mean distance for random locations. Given the minor differences in distance to the nearest road feature between actual and random locations, these differences may be more statistically than biologically meaningful. There appear to be no patterns based on sex, season or relative geographic location of the seasonal home range, however, distance to the nearest road feature for random locations varied among individual lynx (Fig 2.4).

A second test comparing actual GPS locations and random locations within the home range examined the frequency with which locations were closer to road features than random expectation. We tested whether lynx occurred close to roads and trails more frequently than would be expected at random by comparing the percent of actual lynx locations and random locations within each home range that were within 5 m, 10 m, 25 m and 50 m of a road or trail. When compared to a 1:1 line indicating neither a preference nor aversion to road features, lynx within several seasonal home ranges were slightly closer to roads and trails than expected, and this tendency to be closer to road features occurred up to 50 m from the nearest road or trail (Fig. 2.5).

Lynx did not appear to be selecting for or avoiding roads and trails when we compared the cumulative frequency distribution of distance to the nearest road feature for actual lynx locations and random locations within the home range (Fig. 2.6). For most lynx, the cumulative frequency distributions for actual GPS locations and random locations followed a similar trajectory. The simplest interpretation of this pattern is that lynx were not selecting for areas closer to or further from roads and trails than if they were moving at random around the home range. However, for two individuals (Lynx 6, male and Lynx 24, female) the cumulative frequency distribution of actual locations followed a steeper trajectory than that for random locations, indicating that these individuals were closer to the nearest road feature than if they were occurring randomly within the home range. Thus, these two lynx may have been preferentially using areas near road infrastructure.

Locations on Roads and Trails

There were 135 lynx locations on roads and trails (3.0% of locations; approximately 0.09 locations/day). The proportion of locations on road features was similar for female ($n = 72$; 3.2%; 0.09 locations/day) and male lynx ($n = 63$; 2.8%; 0.09 locations/day). More summer-fall and denning season locations (4.9% and 4.4%, respectively) were recorded on roads and trails than winter locations (2.3%). There were 9 instances (males, $n = 5$; females, $n = 4$) of two consecutive locations on a road or trail, 6 of which were recorded during winter.

Movement Rates within the Home Range

Two models were considered to have substantial support ($\Delta AIC < 2$), when we compared linear mixed-effects models for movement rate with sex and season as fixed effects and individual as a random effect (Table 2.3). In the most parsimonious model, movement rates between locations separated by 6 hrs were slower among females by approximately 85 m/hr ($\beta_{\text{Females}} = -84.6$, SE = 26.5), as well as slower in winter by 22 m/hr ($\beta_{\text{Winter}} = -22.2$, SE = 9.6; Table 2.4). However, because the 95% confidence interval for difference in movement rate bounds zero, we did not detect a significant difference in movement rate between summer-fall and denning season locations (-38.4 m/hr – 8.3 m/hr). As this model indicated that sex and season were covariates of movement rate, only 14.5% of variance in these data was explained by differences among individual lynx (Table 2.4; Fig. 2.7). Given the lack of difference in movement rate between summer-fall and denning season locations, the second model with support included only sex as a covariate of movement rate, and again indicated that females moved at slower rates over a 6 hr interval than males ($\beta_{\text{Females}} = -84.9$, SE = 27.2; Table 2.4). However, these differences in movement rate between males and females were small, and thus may not necessarily have biological significance.

For the 9 instances of consecutive locations on a road or trail, the mean movement rate of 227 m/hr was faster than the mean movement rate for consecutive locations not on a road or trail (170 m/hr; $n = 4,519$). Mean movement rate for consecutive locations on road features was 201 m/hr for males ($n = 5$) and 259 m/hr for females ($n = 4$). This rate was faster than the movement rate for consecutive locations not on road features for

females (124 m/hr), but was similar to the movement rate for consecutive locations not on a road or trail for males (215 m/hr).

Home Range Area and Road and Trail Density

Home range area varied among individual lynx and between male and female lynx (Table 2.5). Home range area based on 6 hr GPS radiocollar locations was larger for male lynx ($139 \pm 56 \text{ km}^2$) than female lynx ($35 \pm 11 \text{ km}^2$; Wilcoxon Rank Sum Test, $W = 63, p < 0.05$). One male (Lynx 12) had a larger home range than other males, and also had a part of his home range in the BWCAW. When this male was excluded, the difference in home range area between male ($84 \pm 12 \text{ km}^2$) and female lynx ($35 \pm 11 \text{ km}^2$) was still statistically significant (Wilcoxon Rank Sum Test, $W = 54, p < 0.05$). Furthermore, after excluding this individual, the pattern suggested that home range area for male and female lynx combined was largest in winter ($62 \pm 12 \text{ km}^2$), followed by the denning season ($50 \pm 26 \text{ km}^2$), and summer-fall ($48 \pm 28 \text{ km}^2$). However, these differences were not statistically significant (ANOVA, $F_{2,13} = 0.4, p = 0.7$), likely because of the small sample size, especially the lack of summer-fall home ranges for male lynx.

Road density was similar among seasonal home ranges, individuals, seasons and sexes (Table 2.5). Road density was similar for male ($1.3 \pm 0.1 \text{ km/km}^2$) and female ($1.4 \pm 0.1 \text{ km/km}^2$) home ranges (Wilcoxon Rank Sum Test, $W = 26, p = 0.4$) and did not differ between winter ($1.4 \pm 0.1 \text{ km/km}^2$), summer-fall ($1.3 \pm 0.2 \text{ km/km}^2$) or denning season ($1.4 \pm 0.2 \text{ km/km}^2$) home ranges (ANOVA, $F_{2,14} = 0.1, p = 0.9$).

Linear regression indicated a negative relationship between distance to nearest road feature and road and trail density within seasonal home ranges (Fig. 2.8; $p < 0.01$). This relationship was nearly identical for random locations within the seasonal home range ($p < 0.01$). While mean movement rate appeared to decrease with increasing density of road features, road and trail density was not significantly correlated with movement rate (between locations separated by 6 hrs) within seasonal home ranges (Fig. 2.9; $p = 0.2$).

Crossing of Roads and Trails

The movement paths of the 7 study lynx intersected or crossed roads and trails 3 ± 0.4 times/day. The rate with which lynx crossed roads or trails varied by both individual lynx and sex. Male lynx crossed roads and trails (4 ± 0.1 intersections/day) more than female lynx (2 ± 0.3 intersections/day), but this difference was not statistically significant due to individual variation (Wilcoxon Rank Sum Test, $W = 12$, $p = 0.1$). Daily intersections with roads and trails was not correlated with road and trail density within the home range (Linear Regression, $\beta = 0.48$, $t_5 = 0.31$, $R^2 = 0.02$, $p = 0.8$).

We examined the percent of road and trail crossings comprised of different road surface types (Table 2.6). Road features made of asphalt, improved native material and native material comprised the largest percent of roads and trails crossed for most animals. For Lynx 2 and Lynx 6 crushed aggregate or gravel road features also represented a large percent of roads and trails crossed, and trails designated for snowmobile use comprised a large proportion of road features crossed for Lynx 2, Lynx 6 and Lynx 14. Roads and trails crossed by Lynx 12 were predominantly features made of improved native material

or native material. This was expected because parts of the home range of Lynx 12 were in the roadless BWCAW (Fig 2.1). Thus, the home range of this lynx had a slightly lower road density than other home ranges, and included predominantly portage and non-mechanized vehicle trails (Tables 2.5 and 2.6).

DISCUSSION

At the home range scale in Minnesota, distance to roads and trails for Canada lynx locations was similar to the distance to roads and trails for random locations, suggesting that lynx were not preferentially using or avoiding road features within the home range. However, lynx tended to be closer to road features than random expectation for locations < 50 m from a road or trail. Thus, in areas close to road infrastructure, lynx may have been selecting for roads and trails. In our study area in Minnesota, lynx were an average of 300 m from roads and trails within their home range, with about 60% of home range locations occurring within 300 m of a road or trail. Furthermore, proximity to road features within home ranges did not appear to be affected by sex or season, but was instead explained by variability among individuals. Lynx in Minnesota also occur near roads when dispersing. During long-distance movements outside of their home ranges, lynx were even closer to roads and trails, preferentially using roads or road corridors, and occurring an average of 177 m from the nearest road feature (Moen et al. 2010).

Human-lynx interactions are more likely near roads and trails, but the effect of road features on Canada lynx changes with the scale of observation and by geographic location. In Maine and British Columbia, lynx selected against roads and road edges within home ranges (Apps 2000; Fuller et al. 2007). Lynx presence was lower as road density increased at the southern edge of the lynx range in Alberta (Bayne et al. 2008). Among home ranges in our study area, road density was relatively uniform (despite a nearly 100km² difference in home range area between males and females; Burdett et al. 2007), as it was across the study area (Moen et al. 2010). Ubiquitous road density is the result of road and trail management at the scale of Lynx Analysis Units (LAUs) (i.e. areas roughly approximating an annual lynx home range) across the Superior National Forest (Ruediger et al. 2000). Such uniform road and trail density within our study area may at least partially explain the lack of differentiation between actual lynx locations and random locations in terms of distance to road features, as well as decreasing distance to road features with increasing road density.

The differential reaction of individual Canada lynx to roads and trails, as well as differential reactions at various geographic locales or landscape scales may occur because road use represents a trade-off between exposure to risk (i.e. the mortality risk associated with human activities, as well as interspecific interactions) and the potential for increased movement or foraging efficiency. Use of road features could benefit lynx by reducing energetic expenditure during movement between preferred use areas and by increasing opportunities for foraging. We found that movement

rates were marginally slower in winter, suggesting seasonal differences in foraging time or strategy, or impediments to movement when snow is present. Though based on a small number of locations, mean movement rate was approximately 60 m/hr faster for consecutive locations on roads and trails than those not on a road or trail, suggesting a small improvement in travel efficiency on roads. Though the sample size was limited, most consecutive locations on a road or trail occurred during winter. Thus, roads may improve movement capabilities, particularly during snow cover. However, contrary to expectation, movement rates within the home range tended to decrease with increasing road and trail density. During long-distance movements, movement rates of lynx were faster in the roadless BWCAW than the roaded portions of the Superior National Forest (Moen et al. 2010). This suggests that lynx were not using roads solely to increase travel speed, and may have been slowed by other factors. Prey abundance, human activities, and encounters with competitors may contribute to slower movement rates on roads and trails, but we could not determine which was responsible for the observed differences in movement rates with existing data.

There is some support for prey abundance reducing lynx movement rates on roads. Snowshoe hare occur along roads and trails where browse and understory cover are abundant, and are also subject to high rates of predation along roads (Pietz and Tester 1983; Sievert and Keith 1985). In Ontario, snowshoe hare track distributions were dependent on distance from anthropogenic corridors, including roads and ditches, with hares appearing more abundant at least 10-30 m from such

corridors (Davey 1997). Thus, prey abundance and encounters with prey along roads may explain the occurrence lynx near roads and trails, as well as why lynx tended to have slower movement rates in areas with higher road and trail densities.

The proximity to roads and trails, occurrences on roads and trails, and crossing of roads and trails indicate that lynx could also be subject to the mortality risks associated with roads during movements and activities inside the home range, as well as during extra-territorial movements. In northeastern Minnesota, nearly half of recorded lynx mortalities were caused by human activities (Moen et al. 2008). However, the proportion of asphalt roads crossed by lynx also indicated that at least some individuals frequently used highways and other roads with potentially high volumes of traffic without mortality. Vehicle collisions negatively affect survival and serve as a major source of mortality for other carnivore species, especially larger species with low reproductive rates and high mobility, which may increase their vulnerability to the risks of roads (Snow et al. 2011; Bateman and Fleming 2012; Rytwinski and Fahrig 2012). The effect of traffic volume requires further study to quantify its effects on lynx road use and lynx survival in the study area.

Reducing mortality risk for Canada lynx would benefit recovery efforts for the species, but may not be as simple as urging land managers to limit access to roads and trails frequented by lynx. An implicit assumption is that mortality rates are higher closer to roads (*e.g.* Bayne et al. 2008). If true, we should attempt to determine the amount of time that lynx spend near roads and trails to assess the amount of time a lynx is potentially vulnerable to human-caused mortality due to incidental shooting,

trapping or vehicle collisions. Results from this study of Canada lynx in the Superior National Forest indicate that the proportion of locations near roads and trails was greater than expected. Within home ranges, about 3% of lynx locations were on or within 5 m of a road or trail, and about 9% of locations were within 25 m of a road or trail. Assuming that GPS locations are a representative sample of lynx locations, a lynx would be within 5 m of a road or trail about 45 minutes each day, and within 25 m of a road or trail approximately 2.25 hours each day. However, we have not demonstrated that mortality risk is increased due to the time lynx spend near roads/trails. Additional research is required to evaluate the distance of influence for human activities and thus human-caused mortality, as well as the risks associated with a lynx being close to a road or trail. For example, the mortality database currently being maintained by the U.S. Fish and Wildlife Service could be used to identify characteristics of roads (i.e., traffic volume) where lynx have died from direct and incidental take. It is also critical that we evaluate traffic volume in relation to road use by lynx, as well as the relationship between traffic volume and lynx-vehicle collisions within the home range, as mortality due to vehicle accidents may affect the long-term sustainability of the Minnesota lynx population. Finally, we recommend examining road use at smaller geographic and temporal scales, including within the core home range and for locations separated by a shorter interval than the 6 hr interval used here (e.g., 0.5 hr and 1 hr), to better understand the interaction among road density, road use by humans, road use by lynx, and risk of mortality.

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Table 2.1. Ranking of linear mixed-effects models based on Akaike’s Information Criterion (AIC) for distance to the nearest road or trail (m) within the seasonal 95% kernel home ranges of 7 Canada lynx (4M, 3F) monitored with GPS radiotelemetry from 2003-2009 in northeastern Minnesota. Both sex and season (i.e. winter, denning and summer-fall) were included as fixed effects and individual lynx was included as a random effect. Models marked with an asterisk (*) were considered to have support.

Model	df	ΔAIC	Deviance
sex + (1 individual)	4	0*	63558.1
intercept + (1 individual)	3	0.07*	63560.2
sex + season + (1 individual)	6	2.79	63556.9
season + (1 individual)	5	2.89	63559.0

Table 2.2. Model output for the two supported linear mixed-effects models of distance to the nearest road or trail (m) within the seasonal 95% kernel home ranges of 7 Canada lynx (4M, 3F) monitored with GPS radiotelemetry from 2003-2009. In the first model (a) sex was included as fixed effect and individual was included as a random effect, and in the second model (b) only individual was included as a random effect. Models were ranked based on Akaike's Information Criterion (AIC).

(a)

Model: Distance ~ sex + (1| Individual)

<i>Random Effects</i>	Variance	Standard Deviation	
Intercept (Individual)	8537	92.4	
Residual	68871	262.4	
<i>Fixed Effects</i>	Estimate (m)	Standard Error	95% Confidence Interval
Intercept (Distance to roads/trails)	371.4	46.9	279.5 – 463.3
Sex (Female)	-110.6	71.4	-250.5 – 29.4

(b)

Model: Distance ~ Intercept + (1| Individual)

<i>Random Effects</i>	Variance	Standard Deviation	
Intercept (Individual)	11523	107.3	
Residual	68872	262.4	
<i>Fixed Effects</i>	Estimate (m)	Standard Error	95% Confidence Interval
Intercept (Distance to roads/trails)	324.0	41.0	243.7 – 404.3

Table 2.3. Ranking of linear mixed-effects models for movement rate (m/hr) between location attempts separated by 6 hrs within the seasonal 95% kernel home ranges of 7 Canada lynx (4M, 3F) monitored with GPS radiotelemetry from 2003-2009 in northeastern Minnesota. Rankings are based on Akaike’s Information Criterion (AIC). Both sex and season (i.e. winter, denning and summer-fall) were included as fixed effects and individual lynx was included as a random effect. Models marked with an asterisk (*) were considered to have support.

Model	df	ΔAIC	Deviance
sex + season + (1 individual)	6	0*	60533.9
sex + (1 individual)	4	1.39*	60539.3
season + (1 individual)	5	4.44	60540.4
intercept + (1 individual)	3	5.55	60545.5

Table 2.4. Model output for the two supported linear mixed-effects models of movement rate (m/hr) within the seasonal 95% kernel home ranges of 7 Canada lynx (4M, 3F) monitored with GPS radiotelemetry from 2003-2009. In the first model (a) sex and season (i.e. winter, denning, and summer-fall) were included as fixed effects and individual was included as a random effect, and in the second model (b) sex was included as a fixed effect and individual was included as a random effect. Models were ranked based on Akaike’s Information Criterion (AIC).

(a)

Model: Movement Rate ~ sex + season + (1| Individual)

<i>Random Effects</i>	Variance	Standard Deviation	
Intercept (Individual)	1078	32.8	
Residual	37299	193.1	
<i>Fixed Effects</i>	Estimate (m/hr)	Standard Error	95% Confidence Interval
Intercept (Movement Rate)	228.9	18.6	192.5 – 265.4
Sex (Female)	-84.9	26.5	-136.8 – -33.0
Season (Summer-fall)	-15.1	11.9	-38.4 – 8.3
Season (Winter)	-22.2	9.6	-41.0 – -3.4

(b)

Model: Movement Rate ~ sex + (1| Individual)

<i>Random Effects</i>	Variance	Standard Deviation	
Intercept (Individual)	1165	34.1	
Residual	37339	193.2	
<i>Fixed Effects</i>	Estimate (m/hr)	Standard Error	95% Confidence Interval
Intercept (Movement Rate)	213.5	18.0	178.3 – 248.8
Sex (Female)	-84.9	27.2	-138.2 – -31.5

Table 2.5. Mean home range area (km²) (\pm standard error, SE) and mean road and trail density (km/km²) (\pm SE) for 17 seasonal 95% kernel home ranges of 4 male and 3 female Canada lynx (number of seasonal home ranges per individual is shown in parentheses) monitored with GPS radiotelemetry from 2003-2009 in northeastern Minnesota. Mean home range area and mean road and trail density are included for male and female lynx, and overall for all 7 individuals.

	Mean Home Range Area (km²)	Mean Road and Trail Density (km/km²)
<i>Lynx 02 (n = 3)</i>	95.7 (\pm 18.3)	1.29 (\pm 0.12)
<i>Lynx 05 (n = 2)</i>	57.9 (\pm 29.4)	1.04 (\pm 0.02)
<i>Lynx 06 (n = 2)</i>	93.4 (\pm 2.4)	1.87 (\pm 0.11)
<i>Lynx 12 (n = 1)</i>	522.4	1.04
<i>All Male Lynx</i>	139.0 (\pm 55.7)	1.34 (\pm 0.13)
<i>Lynx 07 (n = 5)</i>	23.9 (\pm 8.0)	1.64 (\pm 0.12)
<i>Lynx 14 (n = 2)</i>	10.1 (\pm 3.8)	1.10 (\pm 0.03)
<i>Lynx 24 (n = 2)</i>	85.6 (\pm 17.1)	1.19 (\pm 0.05)
<i>All Female Lynx</i>	34.5 (\pm 11.1)	1.42 (\pm 0.11)
ALL LYNX	83.7 (\pm 29.0)	1.38 (\pm 0.08)

Table 2.6. Percent of roads and trails crossed within the seasonal 95% kernel home ranges of 7 Canada lynx (4M, 3F) monitored via GPS radiotelemetry in northeastern Minnesota from 2003-2009 for different U.S. Forest Service road surface type designations. Includes number of roads and trails crossed, duration of time lynx was radiocollared (days), and roads and trails crossed per day. Roads and trails with surfaces designated for portage, hiking and cross-country skiing were not included here because they lack motorized vehicle traffic.

	Percent of Road and Trail Crossings (%)						
	<i>Male Lynx</i>				<i>Female Lynx</i>		
	Lynx 02	Lynx 05	Lynx 06	Lynx 12	Lynx 07	Lynx 14	Lynx 24
Asphalt	19	19	11	9	40	37	2
Crushed Aggregate or Gravel	13	2	23	4	6	3	9
Frozen Soil	0	1	0	1	1	0	1
Improved Native Material	7	32	8	24	9	6	35
Native Material	28	27	24	46	11	30	37
Snowmobile Trail	32	0	26	6	0	23	0
<i>Surface Type Not Specified</i>	1	19	3	9	34	0	16
Number of Road and Trail Crossings	1167	815	841	140	1132	219	289
Duration of Observation (Days)	272	221	200	35	511	148	115
Road and Trail Crossings/Day	4.3	3.7	4.2	4.0	2.2	1.5	2.5

Figure 2.1. Distribution of 17 seasonal home ranges (95% fixed-kernel) for 7 GPS radiocollared Canada lynx (4M, 3 F) monitored in northeastern Minnesota from 2003-2009. The Superior National Forest and roadless Boundary Waters Canoe Area and Wilderness (BWCAW) are highlighted, as is the network of roads, trails and railroads in Cook, Lake and St. Louis counties.

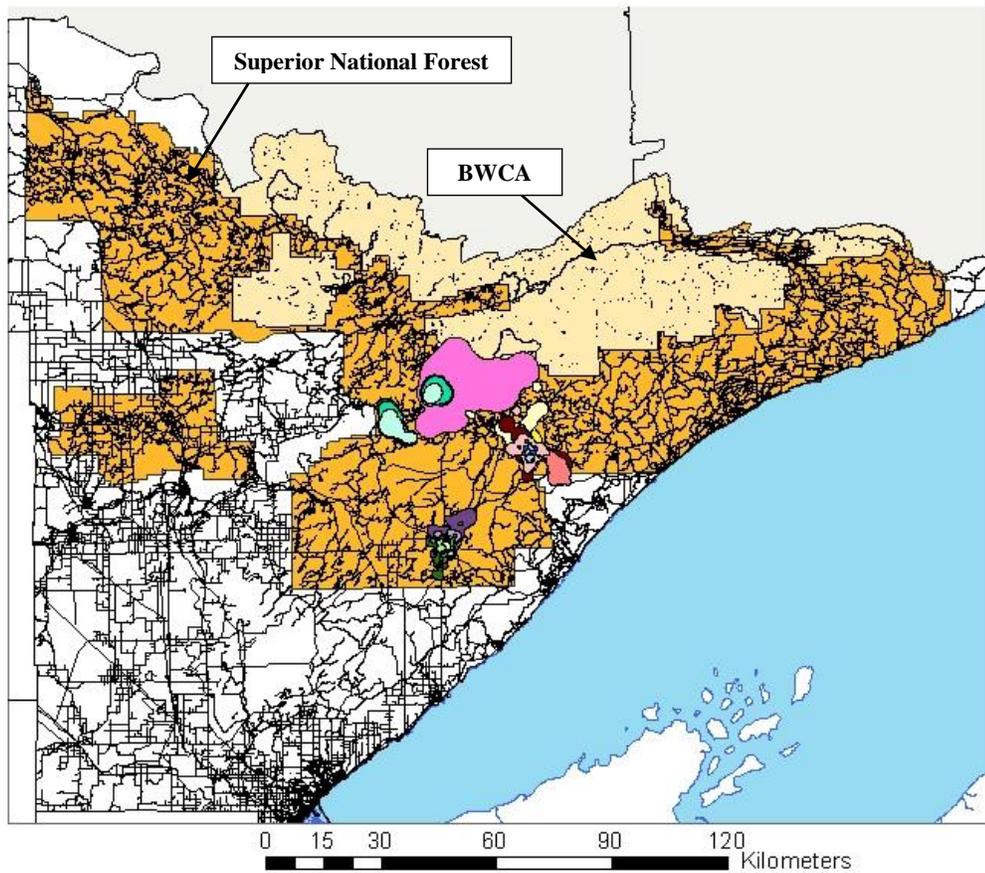


Figure 2.2. Box plot of distance (m) to the nearest road or trail, stream, lake or river, shrub swamp and wooded swamp within the seasonal 95% kernel home ranges of 7 Canada lynx (4M, 3 F) monitored with GPS radiotelemetry in northeastern Minnesota from 2003-2009. Asterisks indicate a significant difference in proximity when compared to distance to roads or trails.

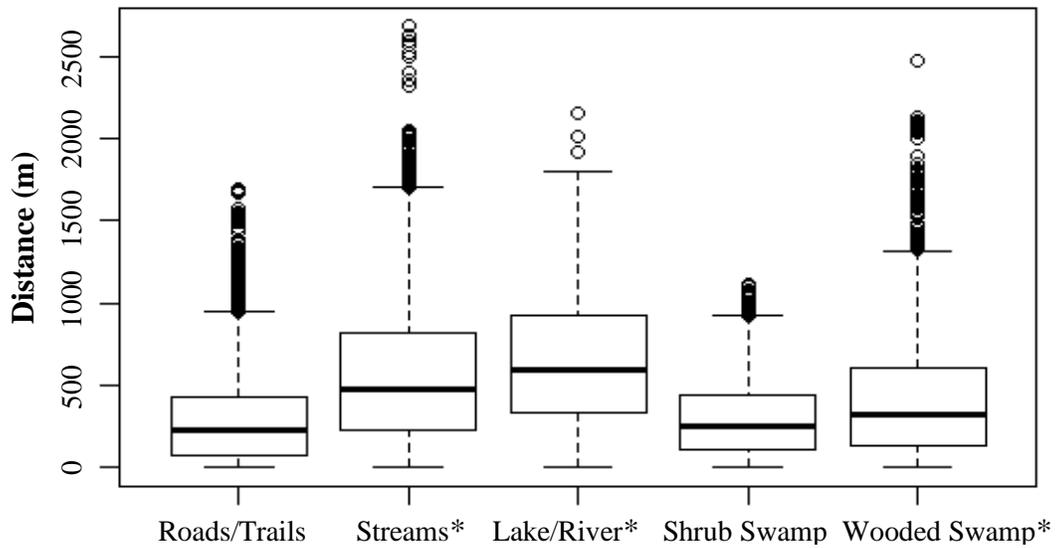


Figure 2.3. Box plot of distance (m) to the nearest road or trail within the seasonal home ranges (95% kernel) of 4 male (white) and 3 female (gray) Canada lynx monitored with GPS radiotelemetry in northeastern Minnesota from 2003-2009.

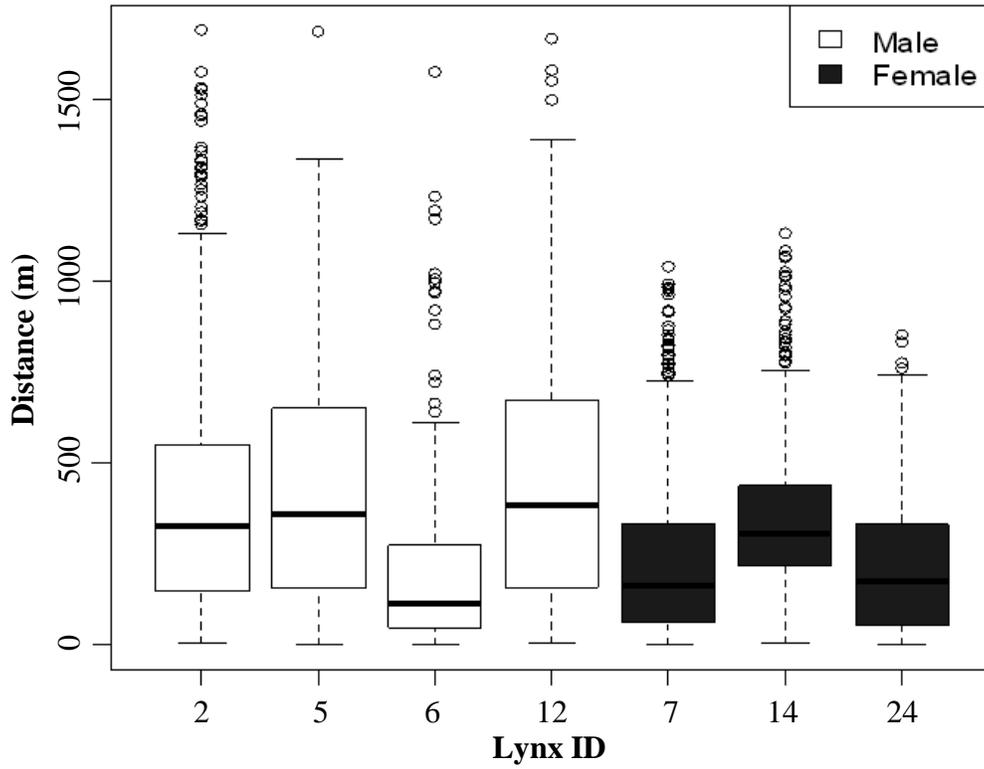


Figure 2.4. Box plot of distance (m) to the nearest road or trail for all random location replicates within the seasonal home ranges (95% kernel) of 4 male (white) and 3 female (gray) Canada lynx monitored with GPS radiotelemetry in northeastern Minnesota from 2003-2009.

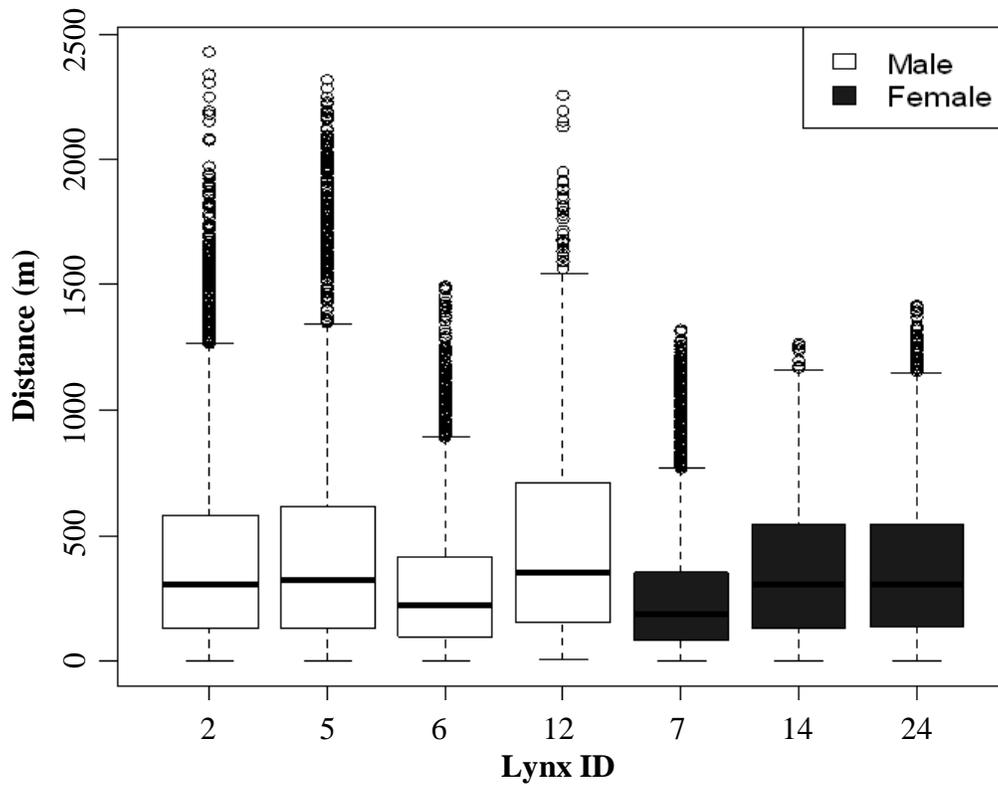


Figure 2.5. Comparison of the percent of locations (collected via GPS radiotelemetry from 2003-2009) within 5 m, 10 m, 25 m and 50 m of a road or trail for Canada lynx locations and random locations within 17 seasonal home ranges (95% kernel) in northeastern Minnesota. Home ranges belonging to female lynx ($n = 3$) are indicated with a gray circle (\bullet) and home ranges of male lynx ($n = 4$) are indicated with a black diamond (\blacklozenge). A 1:1 relationship between actual locations and random locations indicates neither preference nor avoidance of roads and trails, while points above the 1:1 line indicate avoidance of roads and trails, and points below the 1:1 line indicate a preference for roads and trails. Note the change in scale for locations within 50 m of a road or trail.

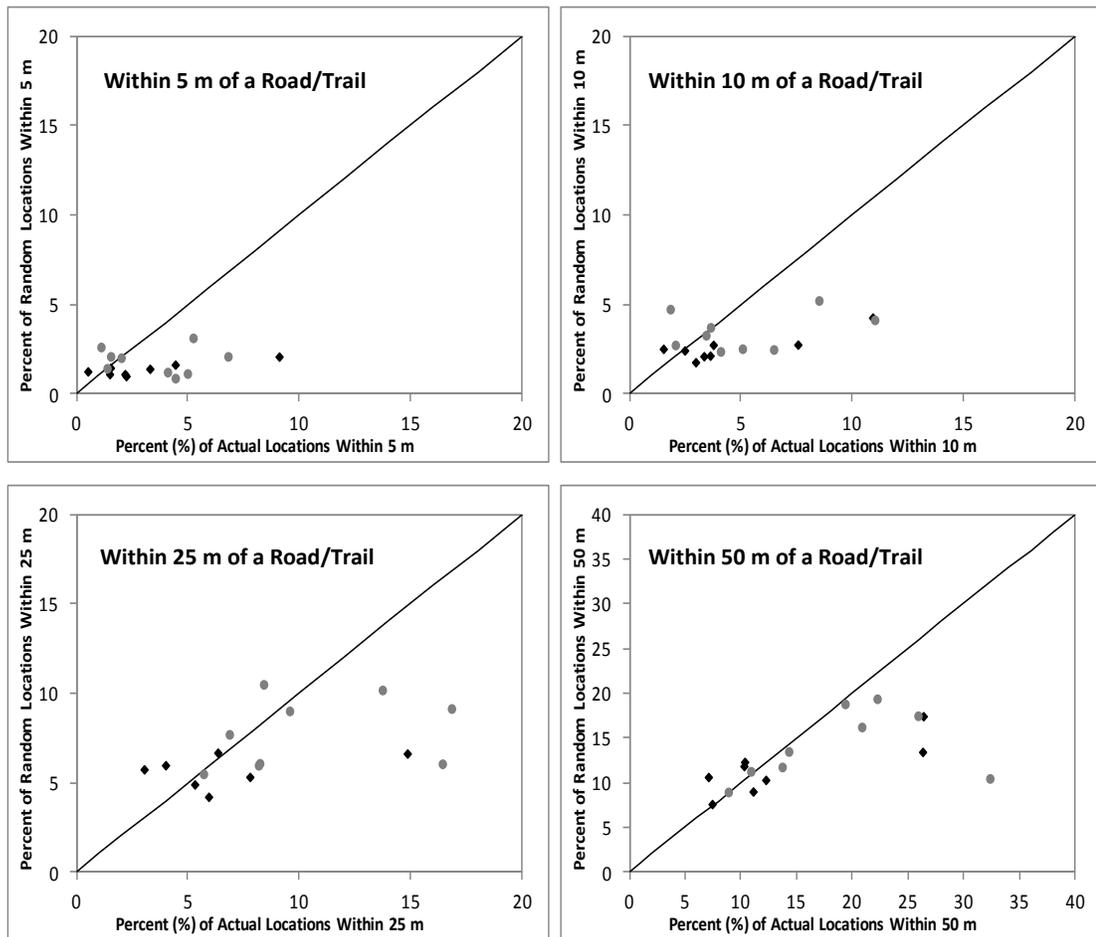
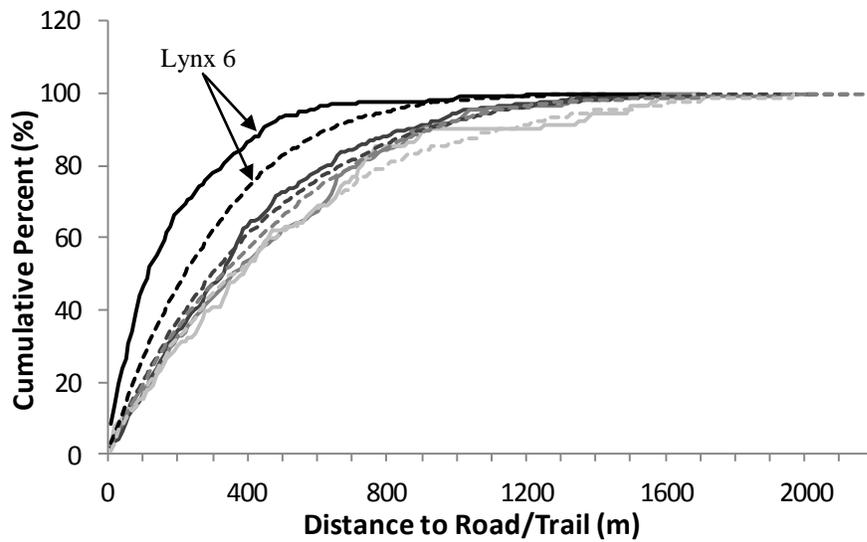


Figure 2.6. Cumulative frequency distribution of distance to the nearest road or trail (m) for lynx locations and random locations within the seasonal 95% kernel home ranges of 7 Canada lynx monitored with GPS radiotelemetry from 2003-2009 in northeastern Minnesota. Solid lines represent actual locations for each lynx, while dashed lines represent the mean of 10 random replicates for each individual separated by (a) male lynx (n = 4) and (b) female lynx (n = 3).

(a)



(b)

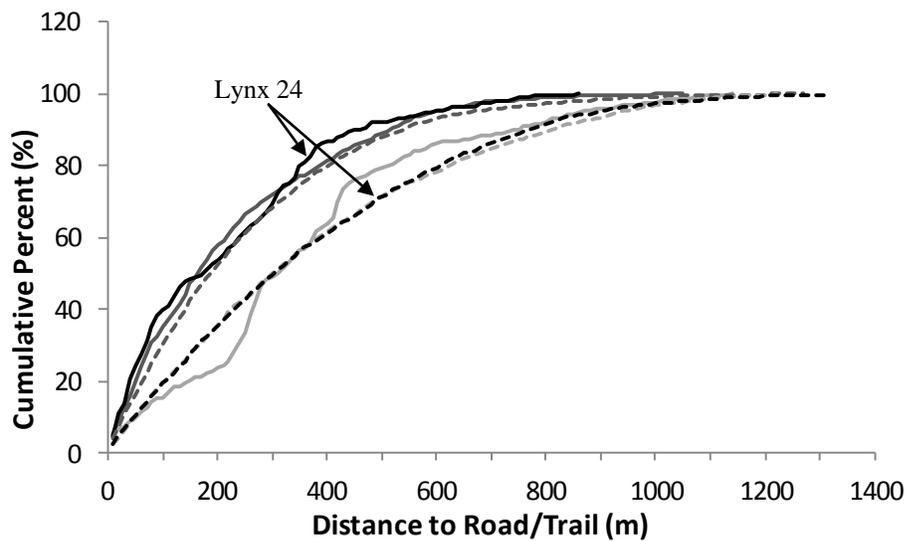


Figure 2.7. Box plot of movement rate (m/hr) between locations separated by 6 hrs within the seasonal 95% kernel home ranges of male (white, n = 4) and female (gray, n= 3) Canada lynx monitored by GPS radiotelemetry in northeastern Minnesota from 2003-2009.

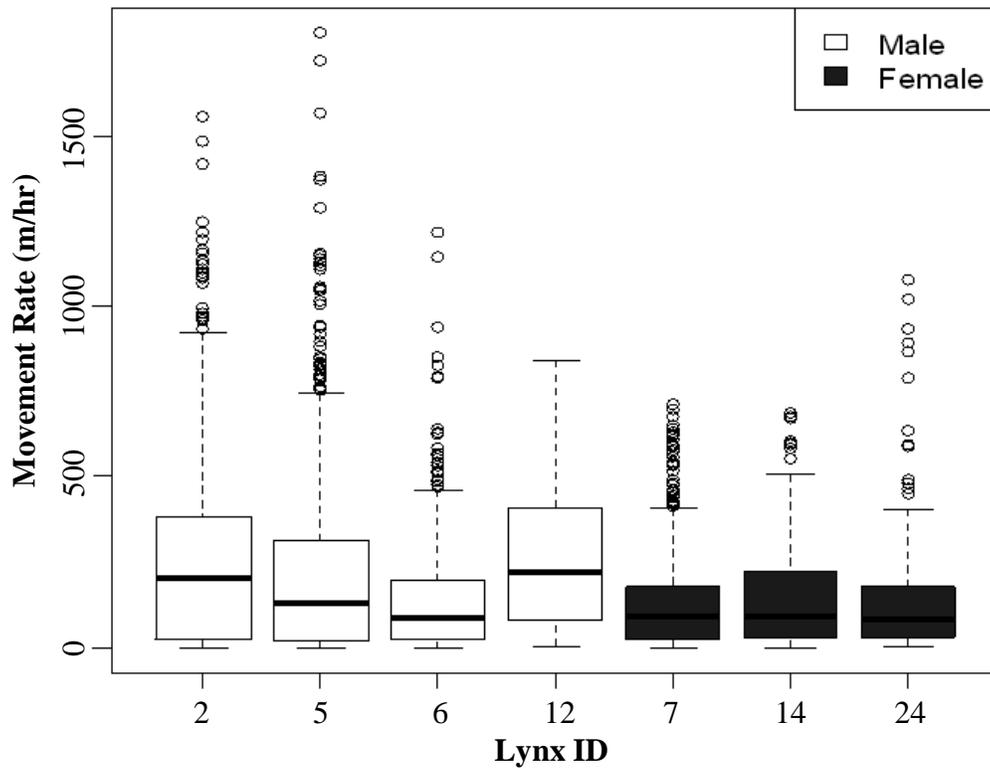


Figure 2.8. Linear regression of road and trail density (km/km^2) and mean distance to the nearest road and trail (m) for actual locations (\blacklozenge , solid line) and random locations (\times , dashed line) for 7 Canada lynx (4M, 3F) monitored via GPS radiotelemetry from 2003-2009 in northeastern Minnesota. For actual lynx locations, each record represents one of 17 seasonal 95% kernel home ranges. For random locations, each record represents the mean of 10 replicates within each home range.

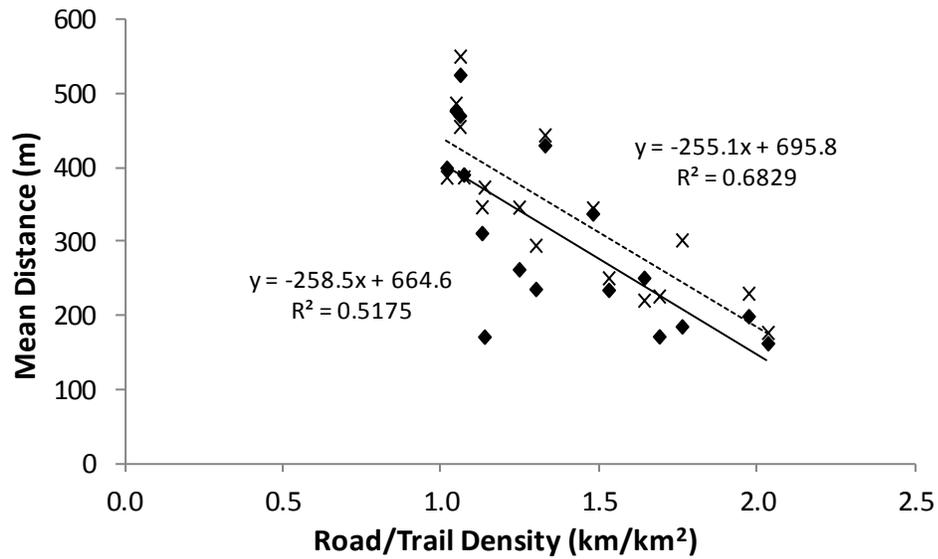
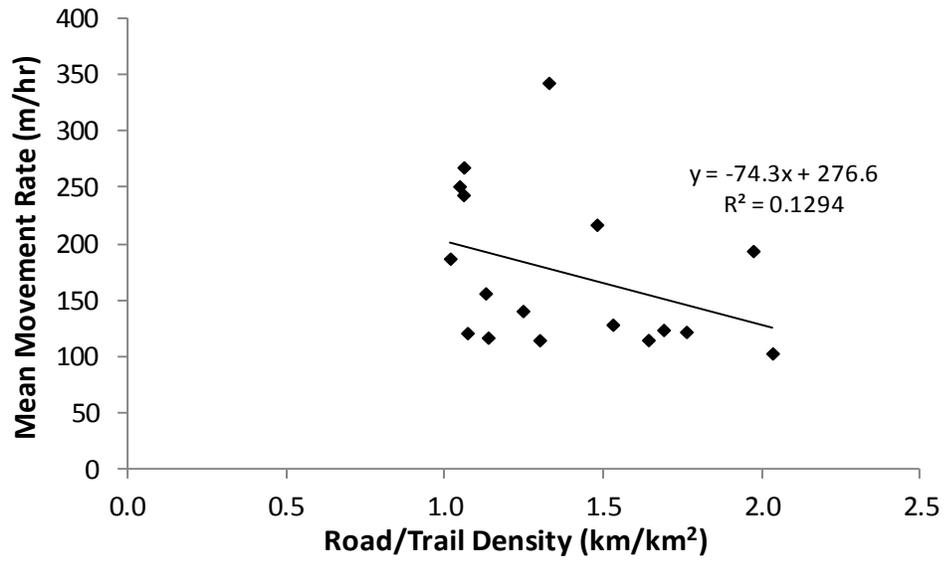


Figure 2.9. Linear regression of road and trail density (km/km^2) and mean movement rate (m/hr) within 17 seasonal home ranges (95% kernel) of 7 Canada lynx (4M, 3F) monitored with GPS radiotelemetry from 2003-2009 in northeastern Minnesota.



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