Designing and Monitoring the Efficacy of Functional Restoration of Linear Features for Boreal Woodland Caribou

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ABSTRACT: Oil and gas seismic lines, pipelines, forestry roads and other such linear features have encroached into boreal caribou ranges and increased the ability of predators to encounter caribou. Linear features can persist for decades within caribou ranges and habitat restoration is deemed a necessary tool to recover and stabilize dwindling caribou populations. Habitat restoration, however, has been argued an impractical mitigation due to the time and cost required for it to be effective at moderating predator-prey dynamics. We conducted a collaborative research study with the British Columbia Oil and Gas Research and Innovation Society to evaluate the functional restoration of linear features on predators and prey within a caribou range. We deployed 100 motion sensing cameras on linear features and game trails across the Parker Caribou Range in Northeast British Columbia. We continuously monitored the habitat use of humans, wolves (*Canis lupus*), black bears (*Ursus americanus*), woodland caribou (*Rangifer tarandus caribou*), and moose (*Alces alces*) for 2.5 years, both before and after habitat restoration treatments were deployed on linear features. We sampled vegetation and conducted a timed-walk to quantify the speed and ease of travel at each camera monitoring site before and after restoration. The intensity of habitat use by all four species was influenced by ease of travel and daily changes in snow depth. Restoration treatments, including a combination of soil mounding and tree felling, reduced the ease of travel and intensity of habitat use by each species. The intensity of use by wolves and caribou was greater and became concentrated on linear features that received a snow packed surface following winter snowmobiling. Our research shows that habitat restoration strategies that target travel mechanisms can be used to reduce the intensity of use by humans and predators within boreal caribou ranges. We demonstrate habitat restoration practices, ease of travel metrics and monitoring strategies that can be implemented to reduce and track the intensity of use by predators within boreal caribou ranges.

INTRODUCTION

The conservation of animal communities and the recovery of endangered species often depends on deploying effective and time-sensitive mitigation strategies. For wild animals, management often involves strategies that balance habitat restoration with human-related demands for resource and recreational access, often while controlling adverse native or non-native species interactions (e.g., predator-prey interactions). The restoration of linear features is considered essential to the recovery of boreal woodland caribou (Environment Canada 2012), but the scale and extent required is considered time and cost prohibitive (Schneider et al. 2010). More ecologically invasive and controversial management practices are being implemented to recover boreal woodland caribou in Canada. Such practices include predator (wolf) culling (e.g. Hervieux et al. 2014), maternity penning, and the proposed deployment of fenced enclosures to keep wolves away from caribou (predator exclusion areas).

We previously employed motion-triggered cameras to show that blocking seismic lines with log debris can moderate predator-prey interactions on linear features at local scales within a caribou range (Keim et al. 2019). However, it is unknown whether the intensity of predator and prey habitat use differs between natural and human footprints or whether ease of travel mitigations applied to human footprints can mitigate predator-prey interactions across broad landscapes applicable to caribou.

Herein we share our learnings from a multi-year research study aimed at implementing ease-of-travel restorations on linear features in a boreal caribou range. We demonstrate: (1) the responses of predator and prey species to differences in ease-of-travel on natural and human-caused linear features; and (2) habitat restoration practices, metrics and monitoring strategies that can be implemented to both reduce and track the intensity of use by humans and predators on linear features across boreal caribou ranges.

STUDY SYSTEM

Caribou and reindeer populations are declining globally due to the combined effects of anthropogenic landscape change and climate warming (Vors and Boyce 2009). Boreal woodland caribou populations are classified as Threatened by Canada's Species at Risk Act (Environment Canada 2012), and habitat recovery planning is underway throughout the species' range. Anthropogenic features are hypothesized to affect woodland caribou populations via two causal pathways related to predation. The first pathway is a *numerical response,* where early seral vegetation increases moose and deer (*Odocoileus* sp.) populations, subsequently increasing grey wolf populations with consequences for caribou mortality (i.e., apparent competition; Holt 1977; Seip 1992; Wittmer et al. 2005; Latham et al. 2011; Peters et al. 2013). The second pathway involves a *functional response,* where linear features increase caribou mortality by increasing the movement rate of wolves (McKenzie et al 2012) and reducing the spatial separation between travelling wolves and caribou (DeMars and Boutin 2017).

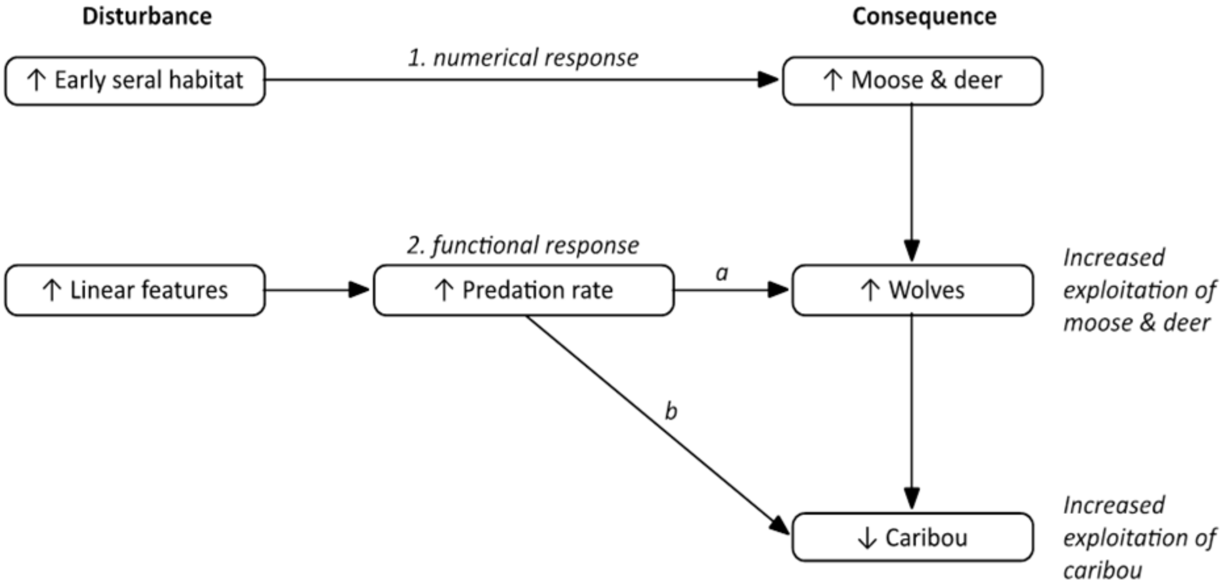

Figure 1: Hypothesized relationship between human-caused landscape disturbance and woodland caribou. Industrial development in and near caribou habitat creates early seral habitat and linear features, which are associated with different response pathways that increase predation on caribou through changes in prey populations and predator behavior.

We studied functional restoration in the Parker Caribou Range in northeast British Columbia, Canada (58° 47’ N, 123° 08’ W). The Parker Caribou Range encompasses approximately 750 km^2 and supports large mammal species including woodland caribou, gray wolves, moose, and black bears. Elk (*Cervus elaphus*), grizzly bear (*Ursus arctos*), and deer are less common but are observed intermittently. Much of the Parker Caribou Range is characterized by peat ecosystems (peatlands); however mesic forests (e.g., cottonwood, aspen, spruce and pine forests) associated with the Muskwa River and its major tributaries run through the center of the range. Ecosystems at this latitude have relatively low productivity for vegetation growth, especially within peatlands, which are the preferred habitat of boreal woodland caribou (Keim et al. 2017).

Legacy linear features developed to support oil and gas exploration, and to a lesser degree forestry, occur at an average density of 1.7 km/km^2 across the Parker Caribou Range. A government permitted, recreational snowmobiling area is found within the northeast extent of the Parker Range. Linear features are maintained to support snowmobile recreation through intermittent clearing of vegetation and mechanical grooming to pack the snow on linear features during winter. Winter snow depths varied by year between 50 and 150+ cm during our study. Snow typically arrived in October and remained through April or May. Aside from recreational snowmobiling, human activity is currently scarce to non-existent across the majority of the Parker Caribou Range.

METHODS

Camera Monitoring

Potential camera monitoring sites were randomly generated across the study area with a minimum spacing of 2.0 km. Camera monitoring sites were randomly selected (n=85) from the sampling frame and randomly assigned a sampling designation on the nearest linear feature (n=55) or game trail (n=30). The camera monitoring sites included areas that have historically been used by GPS-collared caribou and wolves (DeMars and Boutin 2014).

A series of mitigation treatments were deployed on linear features within a 9,215ha mitigation zone located in the northeast corner of the Parker Caribou Range between January and March 2017. The treatments were deployed on approximately 64 km of linear features and were designed to expedite the recovery of vegetation and reduce predator use on linear features. The treatments included combinations of soil mounding, tree felling, and tree planting (Golder 2017). In June of 2017, we established 15 additional camera monitoring sites in the mitigation zone to help evaluate treatment effects. Monitoring sites were established on linear features with treatments (n=12) and game trails (n=3). In addition, 2 of the original monitoring sites, located on linear features, were moved to maintain independence from the newly deployed treatments and camera monitoring sites.

Overall, we collected data at 102 camera monitoring sites distributed on game trails and linear features with and without mitigation treatments. Over the course of our study we monitored 58 linear features without a mitigation treatment, 12 linear features with a mitigation treatment, and 32 game trails. Twenty-five of the camera monitoring sites were located within the mitigation zone: 12 on linear features with treatments; 7 on linear features without treatments; and 7 on game trails.

Animal Observation Data

Animal monitoring mirrored the methods described in Keim et al. (2019). We deployed one PC900 HyperFire Professional Covert camera (Reconyx, Wisconsin USA) at each camera monitoring station (n=102). This camera model uses an infrared motion sensor to detect animals that cross in front of the camera, and an infrared flash that allows images to be captured during daylight, dusk, and night. We programmed each camera to collect images when triggered by animal movements in front of the camera's detection zone. When triggered, cameras recorded one image every second for 5 seconds and were immediately rearmed, insuring that all individuals were captured when moving through the detection zone. In addition, each camera was programmed to collect one daily time lapse photograph to confirm camera operation and provide information on daily snow depths and conditions at each camera monitoring site.

Each camera was installed at a height (~1 metre) to reliably capture images of wolves, moose, caribou, black bears, and humans. We limited the detection zones for recording animal use to a maximum distance of 20 m from the camera (typically less than 10 m). Cameras were positioned perpendicular or diagonal to each linear feature or game trail to capture animal and human traffic. For wider linear features, we placed cameras at locations where vegetation, topography, and feature alignments narrowed the feature widths to less than 20 m. The cameras were thus positioned to capture use across the entire linear feature or game trail.

We visually inspected each image and identified discrete animal use events. We defined an event as a discrete time-period when one or more individuals of the same species was captured by the camera. Because we were interested in quantifying intensity of use on monitoring features, we only counted animals that were observed on the linear feature or game trail being monitored at that site. Following Keim et al. (2019), we considered multiple images of a single animal that remained in front of a camera (e.g., feeding or standing) as one count event, and consider multiple individuals of the same species as a single multiple-count event (e.g., a pack of wolves). If an individual animal triggered a camera, left the monitoring station, and then returned more than 10 minutes after the last trigger, we considered these as 2 separate events. For each individual event, we recorded the species, sex, age class, time, date, and snow condition.

Camera studies may be biased when an animal is present but not recorded (i.e., detection error). We evaluated the rate of missed detections across 48,240 camera monitoring days during the winter season when we could identify missed detections by the presence of animal tracks in the snow. We visually interpreted and recorded the daily presence of animal tracks in the snow from each daily time-lapse image and contrasted the results with movement triggered photographs of humans and large mammals. The evaluation detected 4,020 humans and large mammal events and revealed 24 missed detections (0.60%). Overall, we found near-perfect rates of detection for human and large mammal species at camera monitoring sites (99.4%).

Vegetation Data

We collected vegetation data at each monitoring site to characterize ecosystem type and measure vegetation abundance. Vegetation data were collected in two, paired 4 m by 4 m plots; one plot was located on the monitoring site itself and a second control plot in the undisturbed conditions adjacent to each monitoring feature. Within each plot we visually estimated the proportion ground cover of forage types (e.g. lichens, mosses, forbs/herbs, and graminoids) and the proportion cover of shrubs and tree species.

Ease of Travel Data

We considered two metrics of movement resistance to assess the relative differences in an animal's ability to move down monitoring features. First, field staff were timed while walking a 70 m transect located on each monitoring feature (linear disturbance or wildlife game trail) and a paired, parallel transect located in the adjacent forest. We used the movement rates (km/h) as a measure of resistance (ease of travel) on each feature. Second, we collected snow depth and condition data by visually interpreting the daily time-lapse images at each monitoring site. For every day that a camera was operational, we estimated continuous snow depth (cm) data and categorical snow condition data (i.e., no snow, unpacked snow, and packed snow). Snow condition was considered packed where machines had compressed snow in front of the camera. Deep snow is known to increase the movement cost for animals (Raine 1983, Fancy and White 1987, Crête and Larivière 2003), so we considered daily snow depth as a measure of movement resistance when snow was present.

Statistical Analysis

We model the observation of an animal by a camera as events occurring in time using the counting process models described by Keim et al. (2019). We model events using a non-homogeneous Poisson process where the rate of occurrence of an event varies over time. The rate of occurrence (or, equivalently, the intensity function) can also depend on time-varying covariates. Given the duration and intent of our study we modelled the intensity function on a daily scale.

The response variable is the number of observations of a particular species on a given day, where N_{ij} denotes the number of events for the *i*-th camera and *j*-th day. We denote time-varying covariates that depend on the camera location as well as the day the data were observed as $\boldsymbol{X_{ij}}$ (e.g. snow depth). We denote covariates that vary from location to location but not temporally as $\boldsymbol{Z}_i$ (e.g., ecosystem type). Under the non-homogeneous Poisson process model, $N_{ij} \sim Poisson(l_{ij})$, we model the mean function as an additive log-linear regression model $log\lambda_{ij} = \beta_0 + f\left(\boldsymbol{X}_{ij}, \beta_1\right) + h(\boldsymbol{Z_i}, \beta_2)$ where multiple covariates are included in the functions $f(.)$ and $h(.)$. There were a substantial number of zero events in our dataset, so we used the zero inflated non-homogeneous Poisson process model (Feng and Dean 2012, Torabi 2017).

We considered covariates presumed important to the distribution of large mammal species in our study area and that were relevant to our study objectives (Appendix A). We first explored univariate relationships using a scatter or boxplot to investigate correlations and variable distributions. All covariates in the best fit models had a Pearson correlation coefficient less than 0.57 (and predominantly less than 0.01), with one exception. We found that snow depth, snow condition, and a sine transformation for day of year were correlated between 0.68 and 0.82. However, snow depths and conditions vary in both space and time and are functionally different from day of year, which is only temporally dynamic. For example, three monitoring stations can each have a different snow depth or snow condition on the same day of the year. We considered an interaction term between feature type (game trail and linear feature) and ecosystem type (peatlands, mineral soil and river valley ecosystems). We included this interaction based on our expectation that linear features would provide greater benefit when located in peatlands, because peatlands have lower average rates of ecological productivity (and hence less vegetation regrowth on linear features) than other ecosystems in the boreal forest (Keim et al. 2017).

Table 1: Covariate Definitions.

Covariate	Definition
Sine function of date	Continuous variable; transformation of Julian date reflecting a positive value of 1 in late-June and a negative value of -1 in late-December.
Cosine function of date	Continuous variable; transformation of Julian date reflecting a positive value of 1 in late-March and negative value of -1 in late-September.
Day of Study	Continuous variable for day of the study between November 8, 2015 (Day 1) and August 6, 2018 (Day 948).
Snow Condition	Discrete variable describing snow conditions at each monitoring feature / camera monitoring station. Snow conditions were determined from photographic interpretation of the captured camera images. Snow packing was typically caused by snowmobiling or winter vehicle traffic on linear features. Three possible snow conditions were described for each monitoring day: • No Snow • Snow-Packed (on linear feature) • Snow Not Packed (on linear feature)
Feature Type	Discrete variable for the feature type at each camera monitoring station: • Linear Feature without treatment (n=58) • Linear Feature with treatment (n=12) • Game trails (n=34)
Mitigation Treatment Zone	A discrete variable (yes, no) defining the areal extent wherein mitigation treatments were deployed. The mitigation treatment zone overlapped the recreational snowmobiling area within the Parker Caribou Range.
Daily counts for interacting predator and prey species	Continuous variable describing the count/day of each wildlife species detected at a camera monitoring station.
Forage and Plant Abundances	The proportion ground cover of forage and plant species measured at the location of each monitoring feature, and in the undisturbed forest adjacent to each monitoring feature. Forage species included: terrestrial forage lichens, graminoid species, forb species, shrub species and tree species.
Major River Valleys	Categorical variable for major river valleys (yes, no). Major river valleys were defined by the presence of a major river (e.g., the Muskwa River) and a break in terrain (elevation shift) that created a

	river valley zone. Major river valley ecosystems were evaluated at each monitoring site during the camera setup procedure.
Peatland Ecosystems	Categorical variable for boreal peatland soil or mineral soil ecosystems. Peatland ecosystems were evaluated at each monitoring site during the camera setup procedure.
Riparian Ecosystems	Categorical variable for riparian (yes, no) ecosystems. Riparian ecosystems were evaluated during the camera setup procedure and defined by the presence of hydrological features (streams, lakes, open water wetlands) and wetland ecological conditions.
Snow Depth	Continuous variable for the snow depth (m). Snow depths were determined from photographic interpretation of the camera images captured in each day.
Travel Speed of Feature	Continuous variable for the speed of travel (km/h), or resistance of the habitat for travel, of the feature types (game trails, linear features, treatments) at each camera monitoring location. Travel speed data was collected by measuring the amount of time (seconds) required for a human surveyor to walk a 70 m transect during the growing season.

Multi-variate models were fit using both a forward and backward model selection approach using Akaike's Information Criteria (AIC; Akaike 1973). We first employed a forward selection process where covariates were added to the count and zero-inflation sides of the model based on statistical significance and guided by biological meaningfulness. Upon completing the forward selection process, we used backwards selection to re-evaluate and remove spurious covariates.

We evaluated the goodness of fit by comparing the aggregated observed counts to the aggregated predicted counts (Keim et al. 2019). We aggregated the observed and predicted counts by 6-month periods (winter and summer season) and three primary covariates of interest to our study: feature type (game trail, linear feature, mitigation treatments), snow condition (no snow, packed snow, not packed snow), and habitat type (peatland or mineral soil ecosystems). We then square root transformed the predicted and observed counts to normalize their distributions and estimated a linear model with a zero-intercept and report the slope parameter and r-squared goodness of fit measures. Finally, we plotted the transformed counts to illustrate the goodness of fit evaluation for each species-specific model. If a model fits well, the relationship should lie along a straight line with a slope of 1 and intercept of 0, and the residuals should not exhibit a pattern.

We depict the average effect of individual covariates graphically following Avgar et al. (2017) and Keim et al. (2019). We plot the fitted values from the best fit models against a covariate of interest using a k-smooth function. We depict the smoothed relationships with a 95% confidence interval to show the average change in a model's prediction as we change one covariate (depicted on the x-axis), while averaging over the other covariates in the model according to the dataset. This approach illustrates the marginal effects of individual covariates. Finally, we measured the importance of the individual covariates in each model by calculating the AIC difference between the best fit model for each species and a model with one covariate in the best fit model removed at a time.

RESULTS

We collected animal observation data across 83,158 camera monitoring days between November 8, 2015 and August 6, 2018. Monitoring malfunctions, such as camera hardware and software issues, and vegetation or snow cover obscuring the camera lenses, resulted in 2,188 days of lost monitoring (2.6%). We visually inspected 254,122 images resulting in 1,859 humans, 749 wolf, 1,720 black bear, 1,489 moose and 2,032 woodland caribou use events. Although the study was predominantly focused on humans, wolves, black bears, moose and woodland caribou, the cameras also captured images of other large mammal species including elk, bison (*Bison bison*), grizzly bear, and deer (Figure 2).

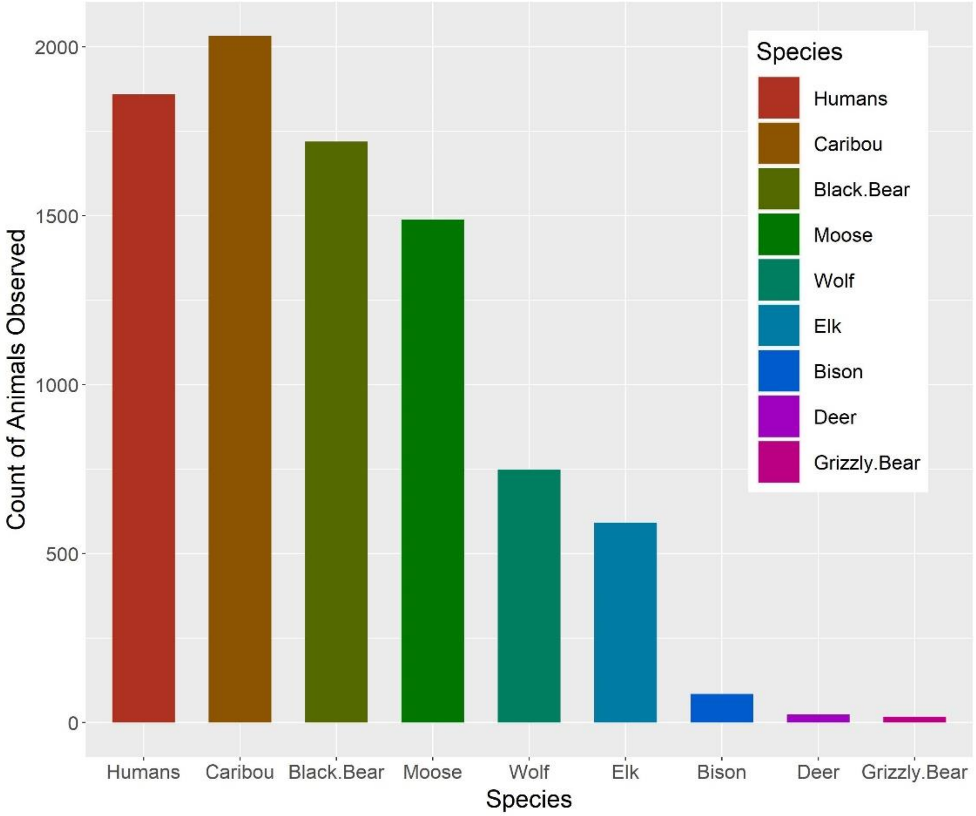

Figure 2: Count of human and animal use events recorded by motion sensor cameras between November 8, 2015 and August 6, 2018 in the Parker Caribou Range.

Parameter estimates for covariates in the best fit models are provided in Appendix A. The goodness of fit evaluations indicate that the fitted models are well calibrated with slopes near 1, multiple R-squared values greater than 0.85 (Table 2), and homogenous residuals (Appendix A).

Table 2: Goodness of fit diagnostics showing the estimated slope, standard error, and R-squared value between the aggregated counts of observed and model predicted counts at camera monitoring stations. Observed and predicted counts are square-root transformed and the intercepts are set through the origin.

Species	Slope of Relationship	Standard Error	Multiple R-Squared
Wolf	0.95	0.05	0.86
Black Bear	0.99	0.02	0.99
Caribou	0.98	0.03	0.95
Moose	0.98	0.02	0.97

Human

Human activity was clustered within the northeast portion of the Parker Caribou range, predominantly within 15 km of the community of Fort Nelson and 5 km of the Alaska Highway (Highway 97). Most monitoring cameras did not capture a single human use event (85%); 95% of human use events were captured at only 5 of the 102 monitoring sites. During our study 88% of human use events were snowmobile and all-terrain vehicles, 6% were heavy equipment, 2% were trucks, and 4% were human foot traffic. Most human use events were associated with winter season traffic (i.e., snowmobiling activities) between December and April of the calendar year (95%). Given the clear pattern of human use events in the Parker Caribou Range we did not conduct statistical analyses of the human count data.

Wolf

Most camera monitoring days had zero wolf events (n=81,943; 98%), consistent with the expectation of a zero-inflated distribution. Daily wolf counts otherwise followed a Poisson distribution with counts between 1 and 18. The best fit model for wolves (Appendix A) indicates that the intensity of wolf use was strongly related to season, joint intensities of use by moose and caribou, feature type (linear features or game trails), and ecosystem. Mean wolf counts peaked in late-fall (September to November) and were lowest during late-winter (February and March). However, this seasonal trend reversed when snow depth and condition concentrated wolf use towards linear features packed by snowmobiling activity. While the count and zero-inflation models revealed opposing directional effects for some of the habitat-based covariates (Appendix A), the overall response indicates that the intensity of use by wolves is positively related to linear features (compared to game trails, especially in peatland ecosystems), upland mineral soil ecosystems, major river valleys, and the daily count of moose events. Conditions that promote or resist travel on the motoring features contributed significantly to the intensity of use by wolves. The modelled effects overwhelmingly demonstrate that the intensity of wolf use is positively related to conditions that promote travel in the Parker Caribou Range: snow depth (negative relationship, $P < 0.0001$); snow-packing (positive relationship, $P<0.0001$); walk speed at each monitoring site (positive relationship, $P<0.0001$) and mitigation treatments (negative relationship, $P<0.0001$).

Woodland Caribou

The final model estimating caribou counts included significant parameter estimates for: seasonal effects (i.e., sine and cosine transformations on Julian day), snow depth and condition, feature type, the abundance of forage lichens, peatland and riparian ecosystems, major river valleys, the speed of walk metric and the joint daily counts of wolves (Appendix A). Mean counts of caribou peaked in late-fall (September to November) and were lowest during late-winter (February and March). However, this seasonal trend reversed when snow depth and condition concentrated caribou use towards linear features packed by snowmobiling activity.

Consistent with findings by Keim et al. (2017, 2019), the intensity of use by caribou was greater among monitoring sites located in peatland ecosystems containing greater abundances of terrestrial forages and was significantly reduced in major river valleys. The intensity of caribou use was also significantly greater on linear features compared to game trails. Overall, the modelled effects in the caribou count model reveal that the intensity of use by caribou is positively related to conditions that promote travel in the Parker Range: snow depth (negative relationship, $P<0.0001$); snow-packing (positive relationship, $P<0.0001$); walk speed at each monitoring site (positive relationship, $P<0.0001$) and mitigation treatments (negative relationship, $P<0.0001$).

The fact that season and snow packing trends are consistent among wolves and caribou suggest that the snow-packing effect of winter snowmobiling can increase the joint intensities of use by these species, and hence the encounter rates between wolves and caribou in peatland habitats. This inference is supported directly by conditional effects for caribou and wolf interactions in both the caribou ($P=0.008$) and wolf zero-inflation models ($P<0.001$). The probability of zero-inflated caribou counts was significantly reduced on days with a greater number of wolf events ($P=0.008$) and the probability of zero-inflated wolf counts was significantly reduced on days with a greater number of caribou events ($P<0.001$).

Moose

The final model estimating moose counts included significant parameter estimates for: seasonal effects (i.e., sine and cosine transformations on Julian day), snow depth and condition, feature type, the abundance of *Populus* forage species, the presence of peatland ecosystems and major river valleys, mitigation treatments, the speed of walk metric and the joint daily counts of wolves and black bear (Appendix A).

The intensity of use by moose was markedly greater among monitoring sites located in major river valleys and upland mineral soil ecosystems containing greater abundances of willow and *Populus* browse. The intensity of use by moose was positively related to conditions that promote travel: winter snow depth (negative relationship, $P<0.0001$); snow-packing (positive relationship, $P<0.04$); walk speed at each monitoring site (positive relationship, $P<0.0001$) and mitigation treatments (negative relationship, $P<0.02$). For moose, the ease of travel mechanism may be conditional upon other environmental conditions, such as browse availability, which is greater within major river valleys. The mean counts of moose peaked in the summer months (June to September) and were lowest during winter (November to April). This seasonal trend was largely correlated with snow effects during our study (negatively correlated).

Black Bear

Our cameras did not record any black bear events between the end of October and the second week of April of each calendar year. We presume this period overlaps the denning (hibernating) period for black bears and therefore evaluated intensity of use from the third week of April to the end of October. The final model estimating black bear counts included significant parameter estimates for: seasonal effects (i.e., sine and cosine transformations on Julian day), snow depth, feature type, mitigation treatments, the presence of peatland ecosystems and major river valleys, the speed of walk metric and the joint daily counts of moose and wolves (Appendix A).

Consistent with moose and wolves, the intensity of use by black bears was markedly greater among monitoring sites located in major river valleys and upland mineral soil ecosystems. Within major river valleys, the intensity of use by black bears was greater on game trails compared to linear features, while outside of the major river valleys the intensity of use was greater on linear features relative to game trails. This effect may have resulted, in-part, because ecological conditions within major river valleys are more productive and the natural recovery of vegetation on linear features makes them more difficult to traverse. This is supported by our finding that the intensity of use by black bears was correlated with conditions that promote ease of travel: the walk-speed measure (positive relationship, $P<0.0001$), snow depth (negative relationship, $P<0.0001$), and the mitigation treatments (negative relationship, $P=0.004$). Overall, the mean counts of black bears peaked in mid-summer (June and July) and were lowest during spring and fall (April and October) nearer the denning period.

Joint-Species Relationships

All species evaluated, except for caribou, exhibited higher intensities of use in mineral soil ecosystems compared to peatlands (Figure 3). Within peatlands, all species used linear features at higher rates than game trails (Figure 3). The intensities of use by wolves, moose, and black bears in peatland ecosystems is markedly increased by the presence of linear features. These relationships indicate that reducing the influences of linear features in peatland ecosystems has potential to reduce the spatial overlap between caribou and the other three species (wolf, moose, and black bear).

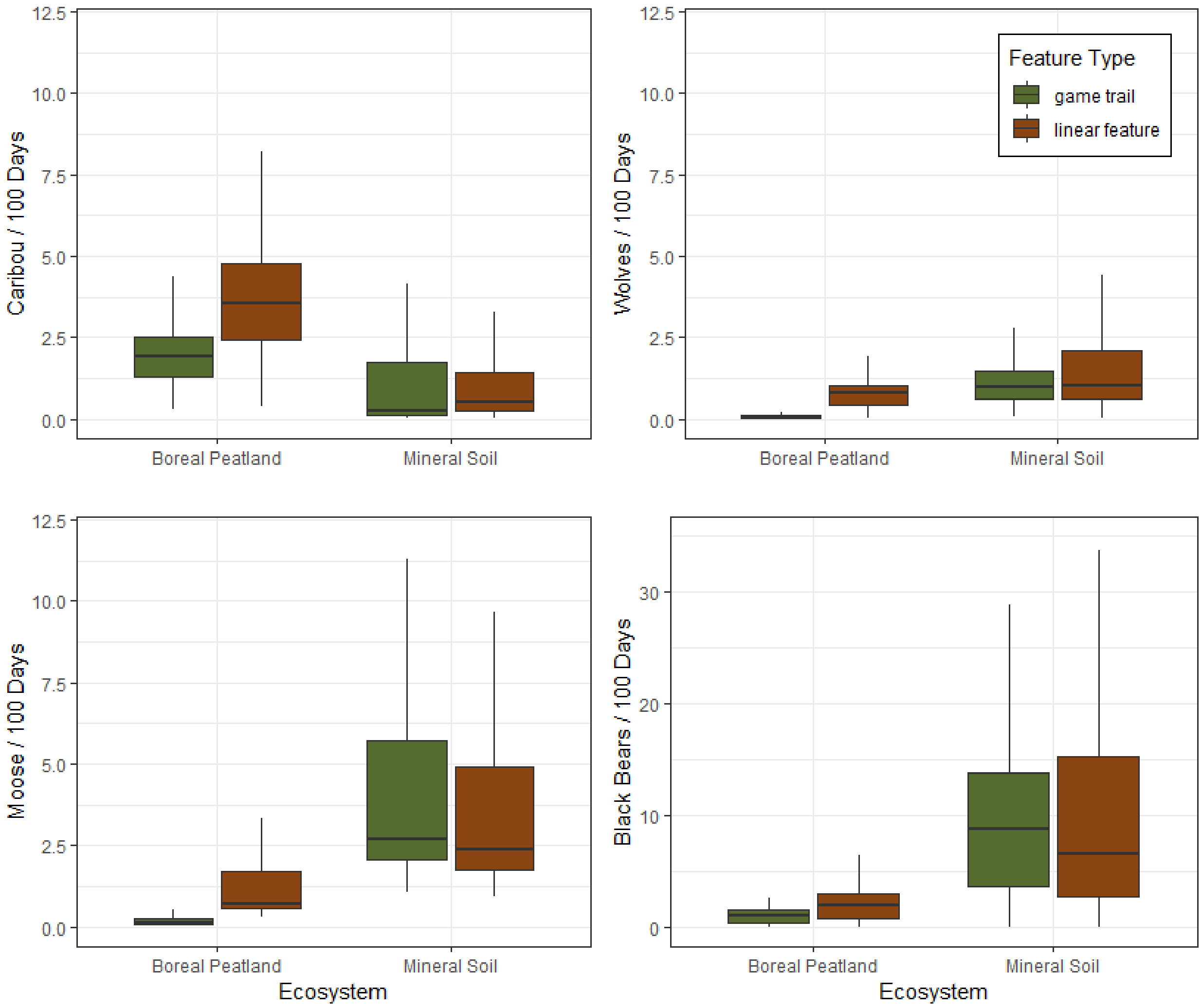

Figure 3: Relationship between the estimated daily intensity of animal use and the ecosystem type at each motion sensor camera monitoring location. The estimated daily intensity of animal use is scaled-up to 100 camera monitoring days.

Ease of Travel Mechanisms

Ease of travel mechanisms (e.g., speed of travel, snow depth, mitigation treatments and snow packing) were positively correlated with the intensity of use by all four species evaluated. The best fit models indicate that speed of travel influenced the intensity of use by all four species irrespective of ecosystem and feature type (Figure 4). While the conditional effect of the speed of travel mechanism was linear for caribou, the marginal effect shows the mean intensity of use by caribou stabilizes at approximately 3.5 km/h (Figure 4). We surmise that the slope stabilizes because caribou primarily use peatland habitats and were infrequently observed on features that promote faster travel (i.e., mineral soil ecosystems).

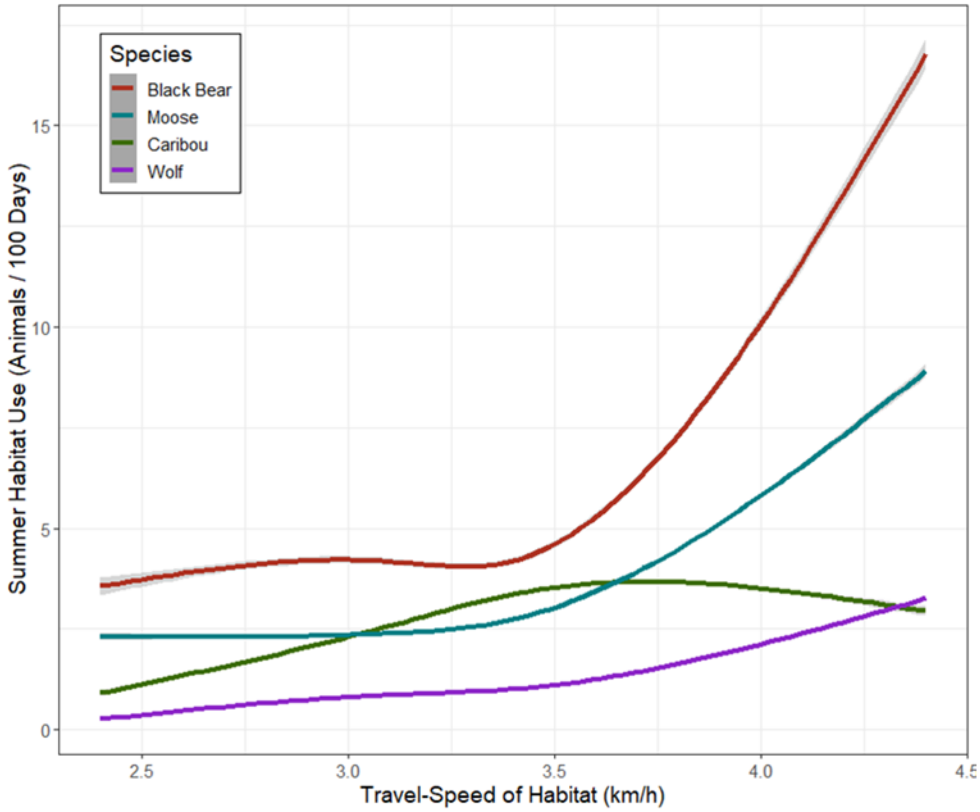

Figure 4: Marginal effect of travel speed (km/h) on the estimated daily intensity of animal use measured at each motion sensor camera monitoring location. The estimated daily intensity of animal use is scaled-up to 100 camera monitoring days and the plot was derived by limiting the dataset to snow-free monitoring days.

During winter, snow depth reduced intensity of use by all four species (Figure 5). Intensity of use by caribou, wolves, and black bears declined over the range of snow depths observed within our study. Moose were relatively insensitive to snow depth; however, moose use declined where snow depths exceeded 65 to 80 cm.

The species-specific effects snow-packing caused by snowmobiles mirrored the snow depth results. Snowmobiling reduced snow depths and created a packed snow surface that can make winter travel easier under most snow conditions. The intensity of use in peatland ecosystems by both wolves and caribou was markedly greater on linear features whose snow was packed. The impact of snowmobiling can accordingly increase the joint intensities of use and, hence, encounter rates between wolves and caribou in peatland habitats.

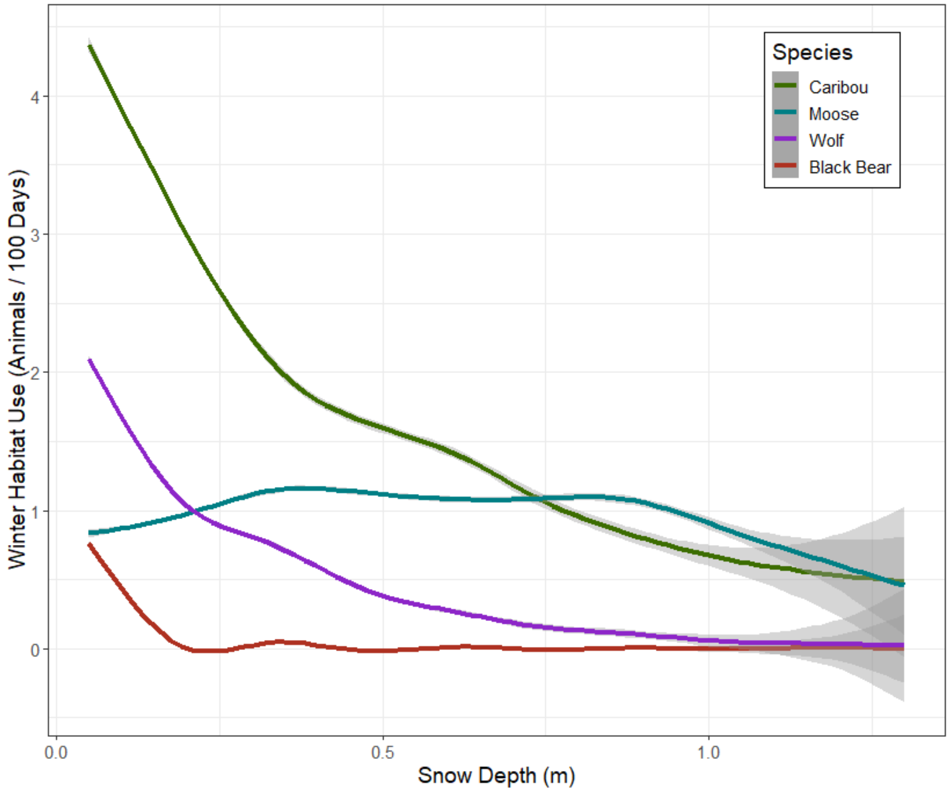

Figure 5: Marginal effect of daily snow depths (m) on the estimated daily intensity of animal use observed at each motion sensor camera monitoring location. The estimated daily intensity of animal use is scaled-up to 100 camera monitoring days and the plot was derived by limiting the data to monitoring days with presence of snow.

Treatment Effects in Peatland Ecosystems

The benefit of traveling on a game trail or linear feature depends, in-part, on ease of travel in the adjacent ecosystem. Our data show that using a game trail or linear feature is more beneficial in locations where the mean travel speed is slower in the adjacent ecosystem (Figure 6). Field data also indicate that linear features are more beneficial than game trails in peatland ecosystems, and suggests that deployed treatments should, on average, mitigate the benefit of linear features to a level approximately equivalent to game trails (Figure 6). Timed-walk measurements were conducted by a field biologist; however, based on species' consistent response to travel mechanisms (see above) we expect these measurements reflect species-specific responses.

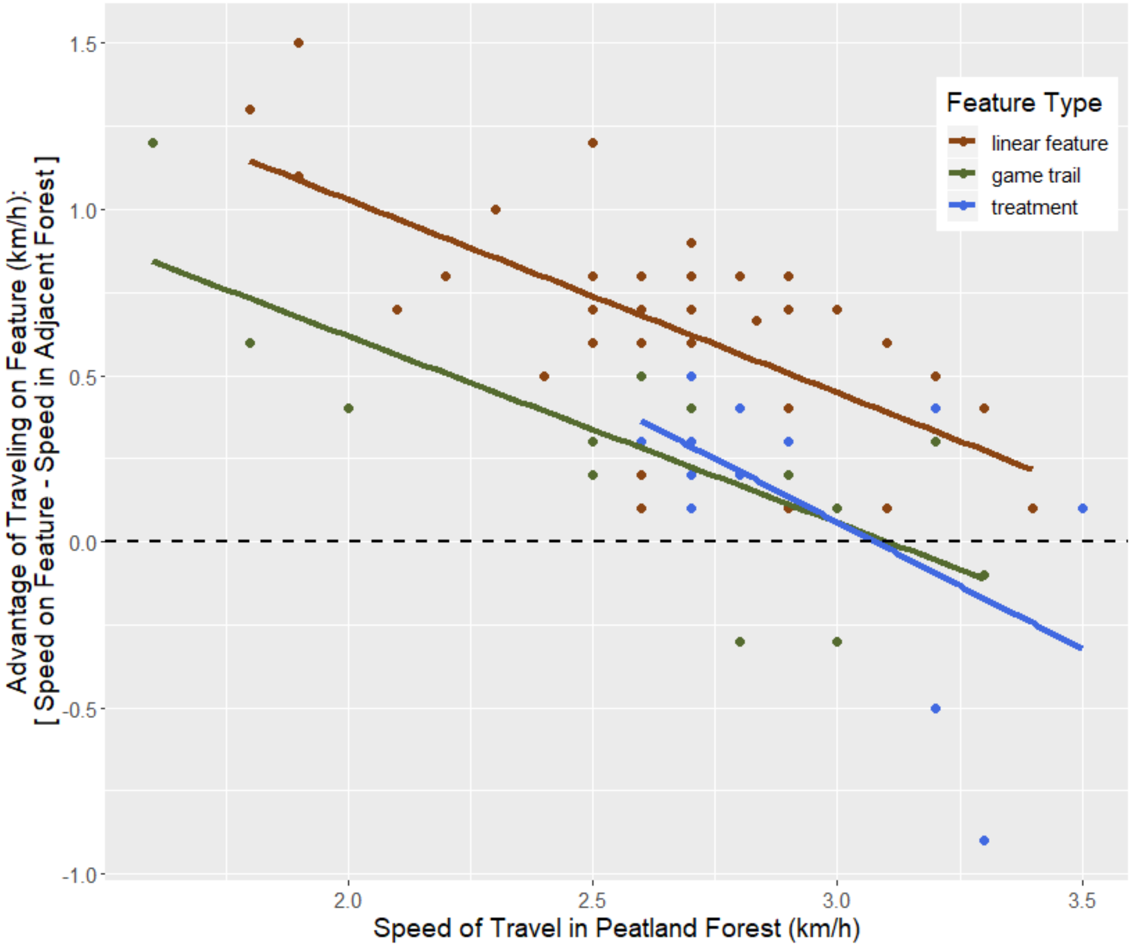

Figure 6: The advantage of travel (km/h) on game trails and linear features with, and without, mitigation treatments relative to the speed of travel in natural peatland conditions. Speed of travel was measured by conducting timed walks on matched and paired transects. The dashed line (y-intercept of 0) indicates a travel benefit of zero and results when the speed of travel on the monitoring feature and in the adjacent forest are identical.

Statistical models show that mitigation treatments reduced the intensity of use by all four large mammal species evaluated (Appendix A). In peatland ecosystems, mitigation treatments reduced intensity of use on linear features to a rate near or approaching the mean intensity of use measured on game trails (Figure 7). From June 2017 to 2018, the rate of use by humans and large mammals on linear features without treatments was greater than on linear features with treatments (Table 3). The rates of use by wolves and caribou were 4.65 and 3.12 times greater, respectively, on untreated linear features relative to treated linear features during the post-treatment monitoring period (Table 3).

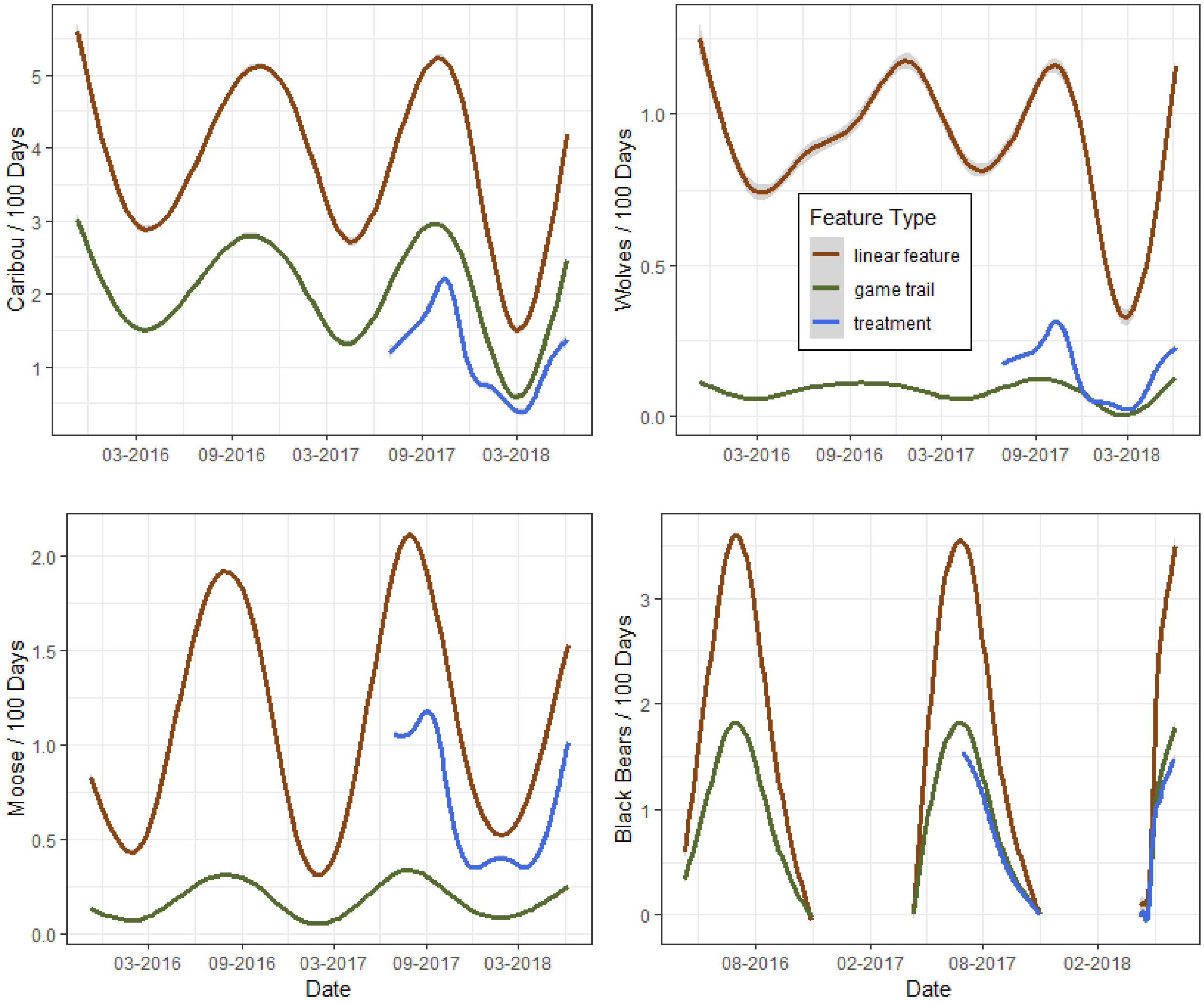

Figure 6: Marginal effect of date on the estimated intensity of animal use by caribou, wolves, moose, and black bear on game trails and linear features with and without mitigation treatments. The estimated daily intensity of animal use is scaled-up to 100 camera monitoring days and the plot was derived by limiting the data to within peatland ecosystems.

Table 3: Human and animal events recorded on linear features with and without mitigation treatments in peatland ecosystems within the Parker Caribou Range. Event data are limited to the post-treatment period between June 2017 and 2018.

Species	Peatland: Linear Features without Treatments (Events / 100 Monitoring Days)	Peatland: Linear Features with Treatments (Events / 100 Monitoring Days)	Ratio (Untreated Rate: Treated Rate)
Humans	390 (2.86)	48 (0.11)	25.34
Wolf	161 (1.18)	9 (0.25)	4.65
Caribou	577 (4.22)	26 (1.35)	3.12
Moose	147 (1.08)	14 (0.72)	1.47
Black Bear	126 (0.92)	4 (0.39)	2.33

DISCUSSION

Management strategies that reduce ease of travel on linear features, such as tree felling and soil mounding restorations or restricting snowmobiling, can markedly reduced the intensity of use by humans and predators within peatland ecosystems. Peatland ecosystems are the critical and preferred habitats used by woodland caribou (Wasser et al. 2011; DeMars and Boutin 2017; Keim et al. 2017, 2019). Habitat treatments deployed on linear features to reduce ease of travel within or approaching peatland ecosystems can thus reduce the encounter rates between predators and woodland caribou. Other management strategies to recover caribou, including wolf culling and fenced enclosures within caribou ranges similarly aim to reduce predator-caribou encounters and thus caribou predation (Hervieux et al. 2014, Cornwall 2016). Our results show that habitat restoration treatments can be applied as an alternative mitigation strategy to wolf culling and fenced enclosures in boreal caribou ranges. There is no doubt that habitat restoration is less ecologically invasive and controversial than the culling of wild animals or the development of fenced enclosures across natural landscapes. We recommend that mitigations to reduce the ease-of-travel on linear features be explored more broadly as a conservation strategy across boreal caribou ranges.

The amount of anthropogenic linear developments within individual caribou ranges is correlated with caribou population declines. The restoration of linear features has accordingly been identified as an important criterion for the recovery of the species (Environment Canada 2012); however, restoring linear features within caribou ranges is not trivial. Boreal peatlands have low ecological productivity (Keim et al. 2017) and habitats can require decades to recover following human disturbance (Van Rensen et al. 2015). The cost and time required to restore caribou habitats is largely impractical across broad landscapes (Schneider et al. 2010), particularly given the rate of caribou population declines relative to the time required for habitat recovery. In light of this challenge, we believe that restoration practices that target ease-of-travel mechanisms are a valuable, and possibly critical, interim strategy while boreal caribou ranges slowly recover.

Like other habitat restoration works conducted in boreal peatlands, the restoration treatments deployed in the Parker Caribou Range employed wheeled and tracked machinery. Given the organic soil conditions in peatland ecosystems, such works must be conducted during winter when the ground is frozen and can support heavy machinery. However, felling or hinging trees into linear features could be conducted at much lower cost using trained fellers on foot without a seasonal constraint. As our study demonstrated, a timed walk survey could be simultaneously conducted to rapidly assess the efficacy of such treatments to reduce the ease-of-travel by humans and predators in peatlands.

Keim et al. (2019) demonstrated that winter oil exploration programs conducted within boreal caribou ranges increase and concentrate the intensity of use by wolves and caribou by creating packed snow conditions. We found that even snowmobiling can increase ease-of-travel and concentrate the intensity of use by humans, predators and caribou in peatland ecosystems during winter. We suggest that recreational snowmobiling could be promoted on linear features located outside of the peatland ecosystems, where caribou are less plentiful, as another mitigation strategy. Our study suggests that such a strategy would draw predators away from caribou and increase their presence within the habitats that are most heavily used by alternate-prey species. Hence, such as strategy would dually serve to reduce predator encounters with caribou and increase their encounters with expanding deer and moose populations to more broadly manage the wildlife community (Wasser et al. 2011). Moreover, our data indicate that winter traffic (e.g., snowmobiling) also facilitates predator travel during the summer. This result is reasonable as snowmobile traffic can maintain linear features as travel corridors by suppressing vegetation regrowth and compacting the soil substrates on linear features. Understanding the relationship between linear features, traffic, and vegetation growth has important implications for ecological recovery and wildlife use (Dickie et al. 2017, Finnegan et al. 2018).

Finally, we suggest that both camera monitoring and timed-walk surveys could have important implications for habitat conservation planning for caribou. Habitat restoration is being recommended over large areas of caribou range, but with limited resources. Identifying and prioritizing treatment areas that are likely to generate the greatest benefit for caribou is essential. Monitoring the intensity of habitat use by caribou and other large mammals (predators and prey) over large areas is feasible using motion-triggered cameras (Keim et al. 2019), and the data can indicate where habitat mitigations are mostly likely to reduce caribou predation risk. In addition, motion sensor cameras can provide pre- and post-treatment monitoring data to gauge the success of restoration efforts. Similarly, timed-walk surveys can be used to quickly assess ease of travel conditions for large mammals and provide site-level information to guide the locations and types of treatments required. Together these techniques provide important feedback for managers to directly address ecological mechanisms implicated in caribou population declines.

ACKNOWLEDGEMENTS

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Appendix A: Statistical Models, Parameter Estimates, and Diagnostic Plots

```
Wolf Zero-Inflated Poisson Model:

Count model coefficients (poisson with log link):
                              Estimate Std. Error z value Pr(>|z|)
(Intercept)                    1.56601    0.18697   8.376  < 2e-16 ***
scale(sine day)               -0.58538    0.09590  -6.104 1.03e-09 ***
scale(cosine day)             -0.30496    0.04980  -6.124 9.15e-10 ***
scale(date)                    0.29957    0.05353   5.596 2.19e-08 ***
Riparian(Yes)                 -0.90295    0.16938  -5.331 9.78e-08 ***
RiverV(Yes)                   -1.35958    0.22530  -6.035 1.59e-09 ***
Snow.Condition(Packed)        -0.97821    0.24952  -3.920 8.84e-05 ***
Snow.Condition(Unpacked)      -0.43790    0.17910  -2.445 0.014485 *
sqrt(Moose Count)              0.55850    0.14329   3.898 9.71e-05 ***
featuretype(linear feature)   -0.53392    0.14785  -3.611 0.000305 ***
Treatment(Yes)                -1.39555    0.38073  -3.665 0.000247 ***

Zero-inflation model coefficients (binomial with logit link):
                                          Estimate Std. Error z value Pr(>|z|)
(Intercept)                               8.82438    0.60197  14.659  < 2e-16 ***
scale(cosine day)                        -0.25162    0.06292  -3.999 6.36e-05 ***
scale(sine day)                          -0.27922    0.13209  -2.114 0.034526 *
scale(date)                               0.25441    0.06651   3.825 0.000131 ***
RiverV(Yes)                              -0.43072    0.21005  -2.051 0.040309 *
Featuretype(linear feature)              -2.59522    0.58764  -4.416 1.00e-05 ***
Peatland(No)                             -3.23191    0.60016  -5.385 7.24e-08 ***
Snow.Condition(Packed)                   -1.95721    0.31003  -6.313 2.74e-10 ***
Snow.Condition(Unpacked)                 -0.58283    0.24900  -2.341 0.019247 *
scale(snowdepth)                          0.93772    0.15529   6.039 1.55e-09 ***
scale(travel speed)                      -0.22409    0.05429  -4.128 3.66e-05 ***
sqrt(Caribou Count)                      -0.64957    0.19655  -3.305 0.000950 ***
featuretype(linear feature):Peatland(No)  2.26002    0.60710   3.723 0.000197 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
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Caribou Zero-Inflated Poisson Model:

Count model coefficients (poisson with log link):

                           Estimate Std. Error z value Pr(>|z|)

(Intercept)                1.45949    0.61789   2.362 0.018174 *

scale(sine day)           -0.41625    0.05771  -7.212 5.50e-13 ***

scale(cosine day)         -0.13978    0.02782  -5.023 5.08e-07 ***

sqrt(speed of travel)     -0.84338    0.34228  -2.464 0.013741 *

ftype(linear feature)      0.30290    0.07443   4.069 4.71e-05 ***

ftype(treatment)           0.25490    0.19486   1.308 0.190826

Peatland(No)               0.34247    0.09415   3.637 0.000275 ***

Snow.Condition(Packed)     0.50876    0.16635   3.058 0.002226 **

Snow.Condition(Unpacked)   0.50775    0.11152   4.553 5.29e-06 ***


Zero-inflation model coefficients (binomial with logit link):

                          Estimate Std. Error z value Pr(>|z|)

(Intercept)               9.50877    0.72639  13.090  < 2e-16 ***

scale(sine day)          -0.19574    0.06465  -3.028  0.00246 **

sqrt(lichen cover)       -0.05172    0.01173  -4.411 1.03e-05 ***

Peatland(No)              2.09965    0.24453   8.586  < 2e-16 ***

RiverV(Yes)               0.86379    0.29615   2.917  0.00354 **

Riparian(Yes)            -1.60548    0.25705  -6.246 4.22e-10 ***

sqrt(snowdepth)           2.06193    0.21382   9.643  < 2e-16 ***

sqrt(speed of travel)    -3.39659    0.40821  -8.321  < 2e-16 ***

ftype(linear feature)     0.02106    0.09658   0.218  0.82740

ftype(treatment)          0.99914    0.25399   3.934 8.36e-05 ***

sqrt(Wolf Count)         -0.53510    0.20153  -2.655  0.00793 **

---

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Moose Zero-Inflated Poisson Model:

Count model coefficients (poisson with log link):

                             Estimate Std. Error z value Pr(>|z|)

(Intercept)                  -0.41577    0.09089  -4.574 4.77e-06 ***

scale(sine day)              -0.23225    0.04873  -4.766 1.88e-06 ***

scale(cosine day)            -0.11634    0.03458  -3.365 0.000767 ***

scale(date)                  -0.13374    0.05273  -2.536 0.011201 *

featuretype(linear feature)  -0.22481    0.11048  -2.035 0.041873 *

sqrt(populous cover)          0.29597    0.09251   3.199 0.001378 **

RiverV(Yes)                   0.23331    0.08277   2.819 0.004822 **


Zero-inflation model coefficients (binomial with logit link):

                                         Estimate Std. Error z value Pr(>|z|)

(Intercept)                              5.85252    0.27268  21.463  < 2e-16 ***

scale(sine day)                          -0.67287    0.09777  -6.882 5.90e-12 ***

sqrt(snowdepth)                           0.28728    0.39401   0.729  0.46592

scale(date)                               -0.16296    0.05515  -2.955  0.00313 **

featuretype(linear feature)               -1.98061    0.26633  -7.437 1.03e-13 ***

Peatland(No)                              -2.91875    0.25351 -11.514  < 2e-16 ***

sqrt(populous cover)                      0.18083    0.08691   2.081  0.03747 *

Snow.Condition(Packed)                    0.76360    0.36925   2.068  0.03864 *

Snow.Condition(Unpacked)                  0.69556    0.24550   2.833  0.00461 **

Treatment(Yes)                            0.57269    0.24331   2.354  0.01859 *

scale(speed of travel)                    -0.12332    0.03020  -4.083 4.45e-05 ***

sqrt(Black.Bear Count)                    -0.40465    0.12446  -3.251  0.00115 **

sqrt(Wolf count)                          -0.58267    0.19029  -3.062  0.00220 **

scale(sine day):sqrt(snowdepth)           1.20781    0.24292   4.972 6.63e-07 ***

featuretype(linear feature):Peatland(no)  1.90157    0.26430   7.195 6.26e-13 ***

---

Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

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```
Black Bear Zero-Inflated Poisson Model:

Count model coefficients (poisson with log link):

                                      Estimate Std. Error z value Pr(>|z|)

(Intercept)                           -1.85512    0.20885  -8.883  < 2e-16 ***

Peatland(No)                           1.01014    0.17570   5.749 8.96e-09 ***

Featuretype(linear feature)            0.27939    0.16059   1.740 0.081899 .

RiverV(Yes)                            0.71427    0.16152   4.422 9.77e-06 ***

scale(Speed of Travel)                 0.10370    0.02535   4.090 4.31e-05 ***

sqrt(Moose Count)                      -0.39601    0.18937  -2.091 0.036511 *

Treatment(Yes)                         -0.80925    0.28294  -2.860 0.004235 **

Featuretype(linear feature):River(Yes) -1.01971    0.29131  -3.500 0.000464 ***


Zero-inflation model coefficients (binomial with logit link):

                                       Estimate Std. Error z value Pr(>|z|)

(Intercept)                            3.25106    0.24047  13.520  < 2e-16 ***

scale(cosine day)                      -0.44180    0.04098 -10.780  < 2e-16 ***

scale(sine day)                        -0.64137    0.04680 -13.705  < 2e-16 ***

Peatland(No)                           -0.91447    0.19484  -4.694 2.68e-06 ***

RiverV(Yes)                            0.14187    0.18811   0.754  0.45071

Featuretype(linear feature)            -0.36216    0.18522  -1.955  0.05055 .

scale(snowdepth)                       1.41488    0.23763   5.954 2.61e-09 ***

sqrt(Wolf Count)                       -0.60564    0.26147  -2.316  0.02054 *

sqrt(Moose Count)                      -0.91844    0.31314  -2.933  0.00336 **

River(Yes):featuretype(linear feature)  0.77828    0.32640   2.384  0.01711 *

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Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```
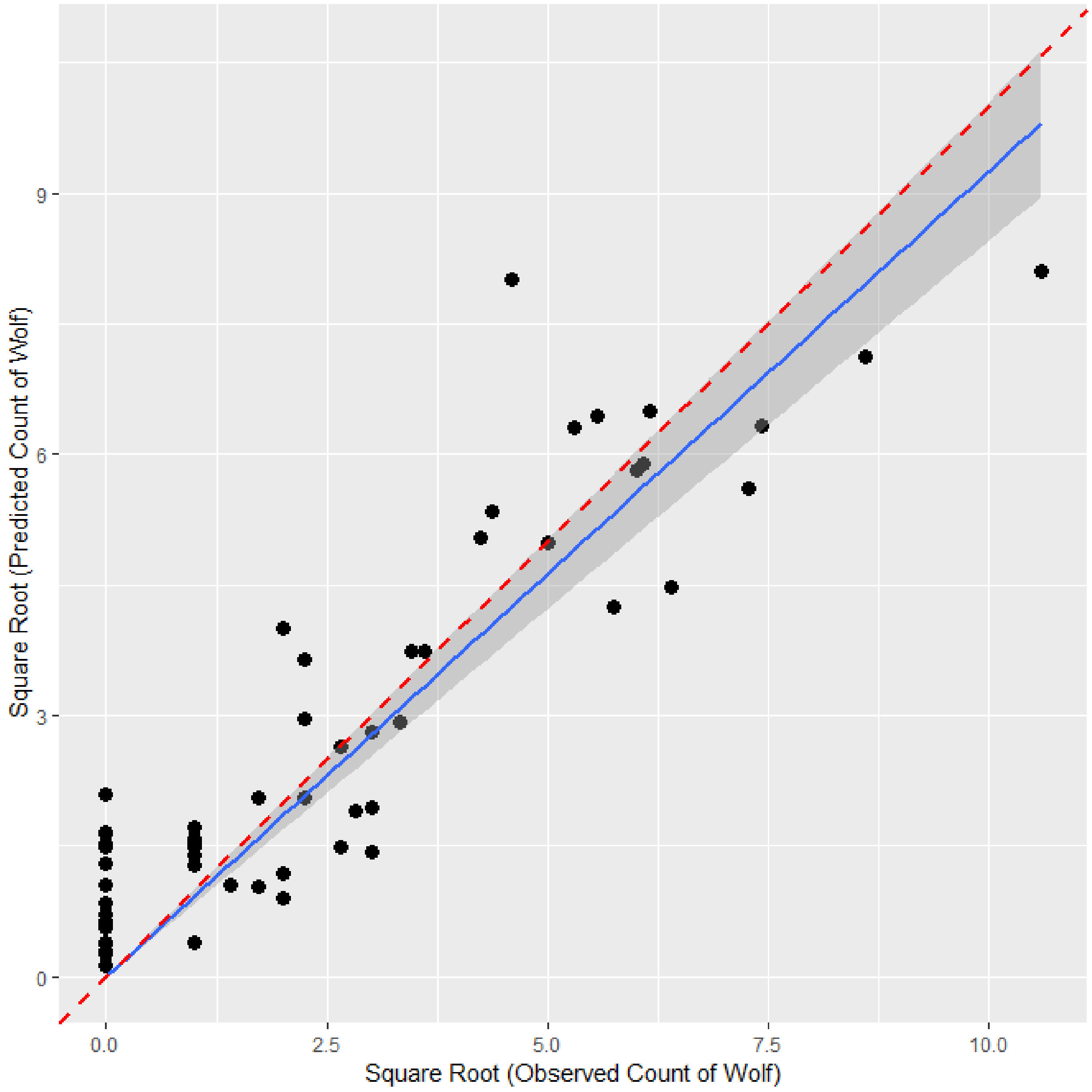
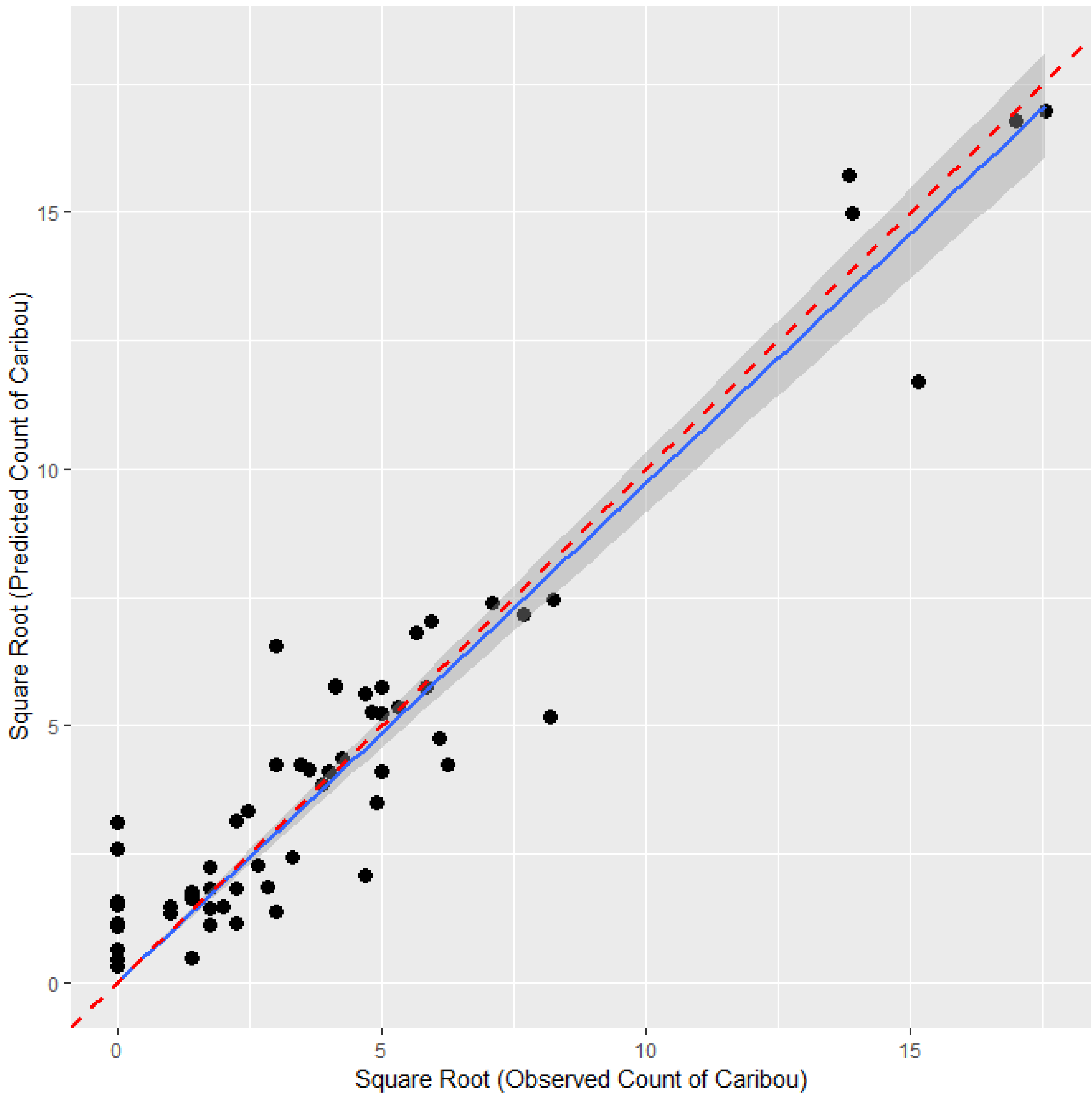
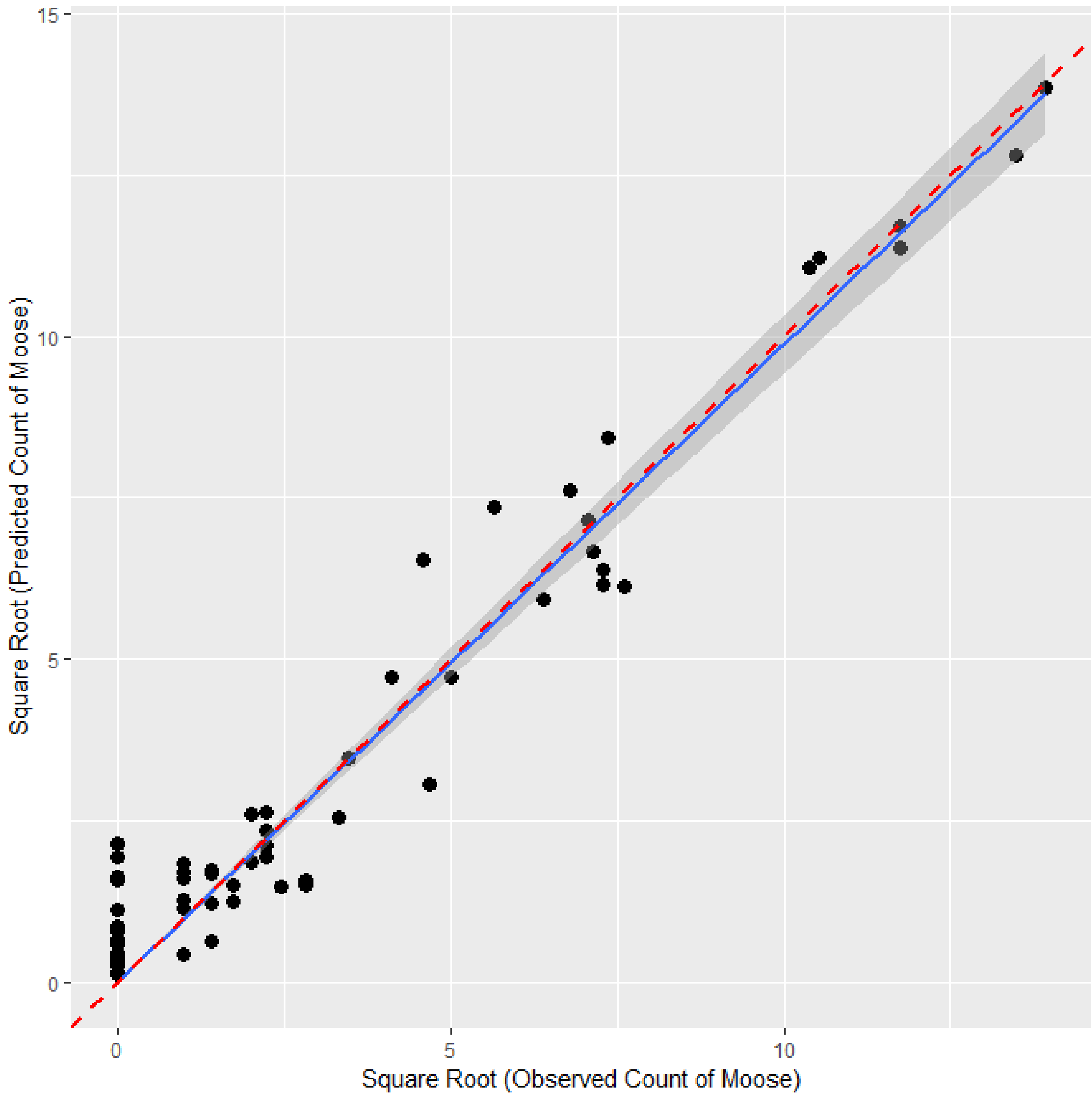
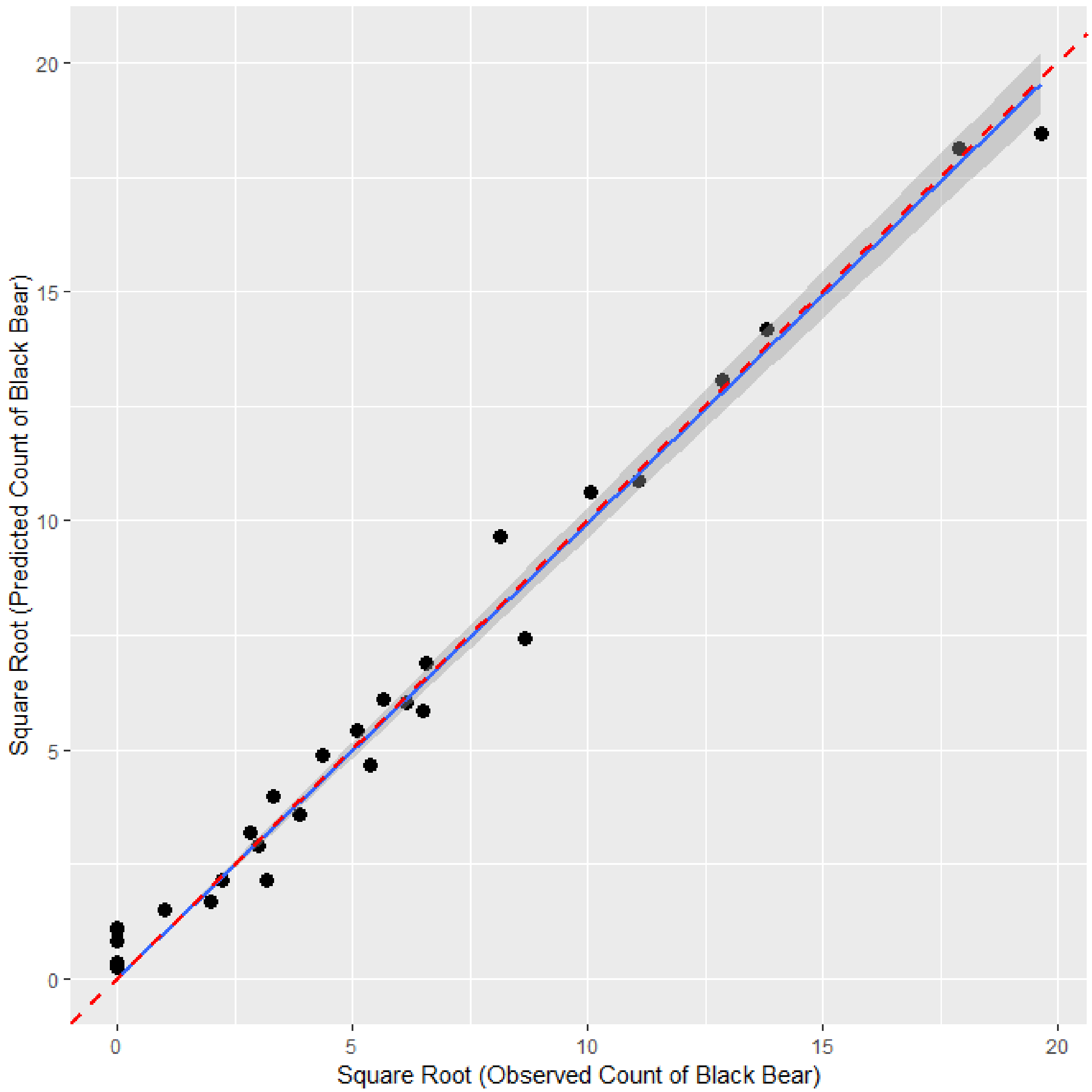

Goodness of Fit Diagnostic Plots:




Square Root (Predicted Count of Caribou)
0
5
10
15
0
5
10
15
Square Root (Observed Count of Caribou)


15
10
5
0
0
5
10
Square Root (Predicted Count of Moose)
Square Root (Observed Count of Moose)



Goodness of fit diagnostic Figures: plots depict the model predicted counts versus observed counts given the wolf, woodland caribou, moose and black bear zero-inflated count model estimates. Predicted and observed counts are square root transformed. The blue line depicts the linear relationship between the predicted and observed counts with an intercept set through the origin; a 95% confidence interval is depicted as a shaded, grey envelope. The red-dashed line depicts a line with slope of 1 and intercept of 0.