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Calving Area Selection by Boreal Caribou in Northeast British Columbia
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FORWARD

This report is an update of selected analyses contained within the following report:

DeMars, C.A. & Boutin, S. (2014). Assessing spatial factors affecting predation risk to boreal caribou calves: implications for management. Final report prepared for the Science, Community and Environmental Knowledge fund, Victoria, BC. 157p.

EXECUTIVE SUMMARY

The boreal ecotype of woodland caribou (*Rangifer tarandus caribou*) is federally listed as *Threatened* and *Red-listed* in British Columbia due to direct and indirect effects of landscape disturbance within caribou range. Habitat protection and restoration have been identified as key management strategies for stabilizing and recovering caribou populations. Most caribou ranges, however, occur in landscapes managed for multiple uses, which may necessitate that areas within ranges be prioritized for conservation actions. Effectively prioritizing areas requires identifying habitats with high influence on a species' population dynamics. For boreal caribou, calving areas may be one such habitat because high rates of calf mortality – particularly during the neonate (≤4 weeks old) period – have been a contributing factor to population declines.

To evaluate caribou habitat requirements during the calving season, we initiated a three-year research project in 2011 and a primary output was a spatially-explicit model of calving area selection. In this report, we used recently acquired GPS data to update the DeMars & Boutin (2014) model with a particular focus on improving predictive performance. Using a similar analytical framework, the updated model showed improved prediction compared to the previous iteration and, importantly, had good predictive performance within the Chinchaga range, allowing for the development of the first predictive map for this range. Inferences on female selection of calving areas were similar those of the previous model. In general, females selected landscapes comprised of high proportions of fens and treed bog and within these landscapes avoided aquatic features and areas of natural and anthropogenic disturbance. The addition of interaction terms in the updated model also highlighted female selection of fens that were likely transitional between nutrient-poor and nutrient-rich fens. Maintaining and improving predictive performance over time will require periodic model updates, which will necessitate sustaining a sample of GPS radio-collared caribou with fix rates that are sufficiently fine-scale to effectively predict calving events and neonate survival.

TABLE OF CONTENTS

LIST OF TABLES (EXCLUDES APPENDICES)

LIST OF FIGURES (EXCLUDES APPENDICES)

INTRODUCTION

A fundamental strategy in wildlife conservation is identifying and protecting a species' habitat (Kerr & Deguise 2004). This strategy, however, is challenging in landscapes managed for multiple uses because competing social and economic interests often dictate that not all habitat can be protected (Schneider *et al.* 2012). In such landscapes, areas targeted for conservation need to be prioritized (Moilanen *et al.* 2005). Effectively prioritizing multi-use landscapes for conservation requires identifying habitats that have high influence on the population dynamics of the species of interest.

Throughout its distribution, the boreal ecotype of woodland caribou occurs in landscapes managed for multiple uses. Within boreal caribou ranges, direct and indirect impacts from landscape disturbance have contributed to population declines in many herds (Sorensen *et al.* 2008; Hervieux *et al.* 2013), leading to this ecotype being *Red-listed* in British Columbia and federally listed as *Threatened* under the *Species at Risk Act* (Environment Canada 2008). Stabilizing and recovering caribou populations will require protecting and conserving caribou habitat within these multi-use landscapes (Environment Canada 2012). Because a primary demographic driver of population declines has been low rates of calf survival (DeCesare *et al.* 2012a; Hervieux *et al.* 2013), identifying calving habitat will be necessary to effectively prioritize areas for restoration and/or protection.

In 2011, we initiated a three-year research project in northeast British Columbia to evaluate caribou and predator spatial dynamics during the calving season. Primary objectives of the project were to identify key attributes of caribou calving habitat and develop a predictive model of calving area selection (DeMars & Boutin 2014). Calving areas were defined as those areas used by females with neonate calves (≤ 4 weeks old). Model outputs suggested that females selected calving areas in landscapes with a high proportion of nutrient-poor fen and within these landscapes females avoided rivers, lakes and anthropogenic disturbance. Outside of these general trends, however, females demonstrated considerable variation in calving area selection, which affected the predictive performance of the model. Model prediction may have been further affected by small per-range sample sizes.

In this report, we update the DeMars & Boutin (2014) model of calving area selection by using recently collected GPS location data from radio-collared female caribou in northeast BC. Our primary objectives were to improve the predictive performance of the DeMars & Boutin (2014) model, develop spatially explicit predictions (i.e. maps) of calving areas for all six boreal caribou ranges in British Columbia, and further evaluate caribou response to natural and anthropogenic features during the calving season.

METHODS

CARIBOU SPATIAL DATA

We used spatial data from 56 reproductive-aged female boreal caribou fitted with Iridium satellite GPS collars (Advanced Telemetry Systems; model #2110E). Individual females were captured by net-gunning from a helicopter during the winter months (January – March) of 2011 (*n* = 25), 2012 (*n* = 2) and 2013 (*n* = 29). Captured females were distributed among all six recognized boreal caribou ranges in northeast BC – Calendar (*n* = 7), Chinchaga (*n* = 7), Maxhamish (*n* = 14), Parker (*n* = 7), Prophet (*n* = 9), and Snake-Sahtaneh (*n* = 10) – as well as in an area north of the community of Fort Nelson (*n* = 2). All capture and handling procedures followed approved governmental and institutional animal care protocols (BC RIC

1998; BC Wildlife Act Permits FJ12-76949 and FJ12-80090; University of Alberta Animal Use protocol # 748/02/13).

For animals captured in 2011 and 2012, radio-collars were programmed to acquire one GPS location (or fix) every two hours during calving (April 15 – July 15) and once per day otherwise. Collars deployed between December 2012 and March 2013 were programmed for a fix rate of every four hours during the calving season and every eight hours otherwise. Twenty females had functioning radio-collars through the 2014 calving season (i.e. beyond July 15, 2014). Although radio-collar deployment on caribou continued in 2014 and 2015, we could not use data from five animals in 2014 or any 2015 data as the fix rates of these collars were too coarse (i.e. 2 locations per day) to reliably identify calving locations (see below).

DATA SCREENING

For all analyses, we used GPS location data confined to the calving season (April 15 – July 15) and we applied the following procedures to screen the raw data for potential errors. First, we removed all locations with low positional accuracy, defined here as two-dimensional GPS locations (or fixes) with dilution of precision values > 5 (Lewis *et al.* 2007). Next, we used the methods of Bjørneraas *et al.* (2010) to exclude outlying locations that were beyond the range of possible caribou movement. We then calculated per collar fix rates and excluded three individuals in 2012 and three individuals in 2014 that had fix rates < 50%. After these procedures, the mean per collar fix rates during the calving season were 98% (range: 93 – 100) for 2011, 98% (95 – 100) for 2012, 87% (68 – 96) for 2013 and 87% (68 – 96) for 2014.

PREDICTING PARTURITION AND NEONATE SURVIVAL

With our focus on female selection of calving areas, we further restricted our analyses to those GPS locations where a female caribou was accompanied by a neonate calf (hereafter, calving locations). We identified calving locations using the movement-based methods (MBMs) of DeMars *et al.* (2013). These methods predict the calving status of females (parturient vs. barren) and the survival status of neonate calves and further yield estimates of parturition date and calf loss date, where appropriate. The population-based MBM derives estimates of calving status and neonate survival using *a priori* thresholds of three-day average movement rates (m/hr). We used the same thresholds as DeMars et al. (2013), predicting a female to have calved when three-day average movement rates dropped below 15.3 m/hr and a calf to have died when rates exceeded 178.6 m/hr. We also used the individual-based MBM to estimate calf survival. This method predicts calf loss by evaluating for an abrupt change – or break point – in the distribution of step lengths (the distance between successive GPS locations) of an individual female post-calving. Akaike's Information Criterion (AIC) is used to discriminate between movement models with and without a breakpoint.

For data spanning 2011 to 2013, MBM predictions were corroborated by aerial survey data (DeMars & Boutin 2014). If model predictions differed, we used the prediction which matched the status (e.g. calf presence / absence) on aerial survey. In one instance, we truncated the post-calving data to the date the calf was last observed as the predicted date of calf loss fell before the aerial survey, which was conducted prior to four weeks post-calving. For five animals in 2013 and all 2014 data, we relied solely on MBM predictions to identify calving locations. If model predictions of calving status differed (n = 5), we used the predictions of the population-based MBM due to its higher accuracy in identifying calving events (DeMars *et al.* 2013). If model predictions of calf survival differed (*n* = 8), we visually inspected the raw movement data and evaluated AIC scores for individual-based MBMs of calf status. If AIC scores of calf survival and calf loss differed by > 2 AIC units, we used the status assigned by the individual-based MBM due to its higher accuracy in predicting survival state. If AIC scores of calf status models differed by ≤ 2 AIC units – indicating a virtual tie between models (Burnham & Anderson 2002) – we used the status that matched the prediction of the population-based MBM.

Following our screening procedures, our final data set consisted of 43 female caribou predicted to have calved at least once during the four-year study period. Eighteen females calved in two years, resulting in 61 caribou-calving seasons (caribou-calving seasons by range: Calendar = 6, Chinchaga = 5, Maxhamish = 20, Parker = 7, Prophet =12, Snake-Sahtaneh = 11). Because our objective was to assess how females selected calving areas within caribou range, this final data set excludes two animals that calved north of Fort Nelson in areas outside of current range boundaries and 2014 data from one Chinchaga female that calved in Alberta.

CALVING AREA SELECTION: GENERAL FRAMEWORK

We evaluated calving area selection by female caribou using resource selection functions (RSFs; Manly *et al.* 2002), a modelling framework that compares the distribution of environmental attributes associated with GPS (or "used") locations to the distribution of environmental attributes associated with random (or "available") locations that are generated within the spatial scale of interest (Johnson *et al.* 2006). Modelled environmental attributes – or resources – include biotic (e.g. vegetative cover) and abiotic conditions (e.g. slope) thought to influence a species presence in a defined area.

We estimated RSFs at a second-order scale (*sensu* Johnson 1980; Fig.1), which compares calving areas to random areas within a herd's range. This scale likely reflects the primary selective decision of female caribou as many individuals undertake long distance, migratory-type movements just prior to calving, indicating that selection is occurring at large spatial scales (Schaefer *et al.* 2000; Faille *et al.* 2010). Moreover, this scale of selection is likely more informative for guiding landscape-level management strategies that are necessary for conserving wide-ranging species like caribou (Courtois *et al.* 2004; Boyce 2006).

Note that in this update, we specified the actual GPS locations of females with calves as the "used" locations whereas RSF analyses contained in DeMars & Boutin (2014) specified used locations as random points generated within the estimated calving area, delineated by an 80% utilization distribution. Both approaches will yield similar insights into calving area selection; however, the use of the GPS locations may yield more precise estimates of the actual resources (30-m pixel scale) used by female caribou with calves (resources defined at a 30-m pixel scale).

We characterized availability similar to DeMars & Boutin (2014), using random points sampled within a herd's range. Because insufficient sampling of availability can lead to biased estimates of resource selection (Northrup *et al.* 2013; Benson 2013), we conducted a sensitivity analysis to determine the number of random points needed to adequately characterize availability (Appendix A). Using data from the Snake-Sahtaneh herd, we performed repeated RSF analyses, plotting parameter estimates of land cover covariates against the number of random points used (range: 200 – 20,000). Based on this analysis, parameter estimates stabilized at 5000 random points and we used this number in all subsequent analyses.

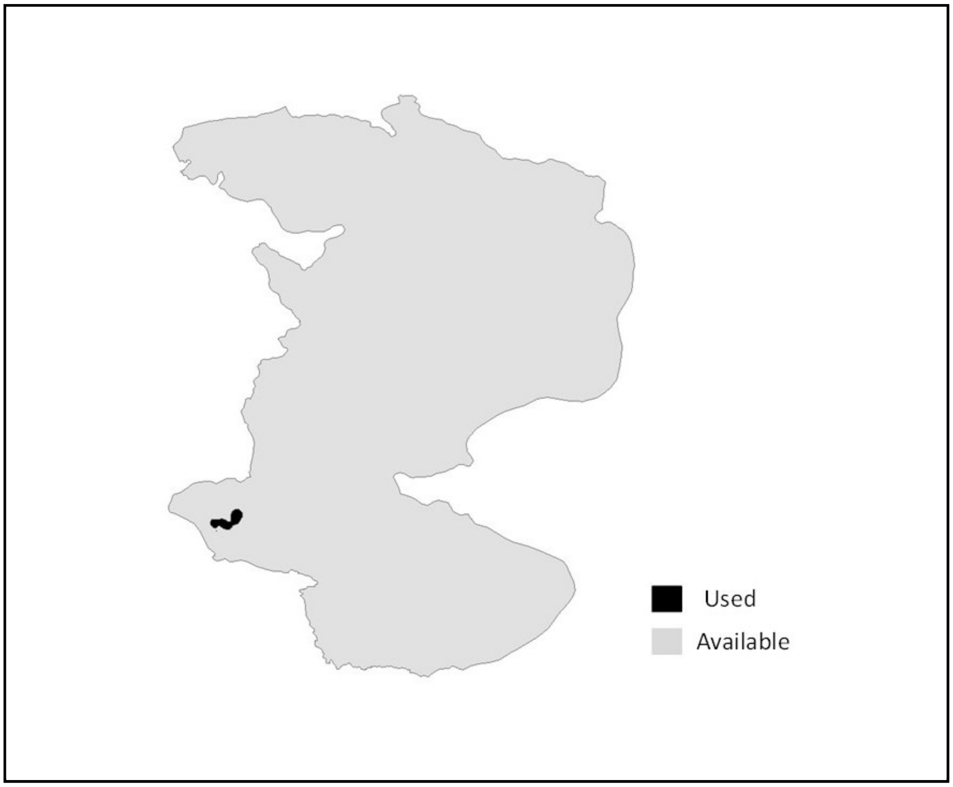

Figure 1: Second-order selection of calving areas by female boreal caribou in northeast British Columbia. The black dots indicate GPS locations of a female with a neonate calf. Attributes of these GPS locations are compared to attributes of random locations generated within a herd's range (here, the Snake-Sahtaneh range shown in grey).

ENVIRONMENTAL VARIABLES

To model female selection of calving areas, we used the same suite of environmental variables as described in DeMars & Boutin (2014; see Appendix B). This suite included variables describing land cover type, normalized difference vegetation index (NDVI), slope, natural features (lakes, rivers and forest fires) and anthropogenic disturbance. Prior to RSF model development, we conducted exploratory analyses comparing the mean value of each environmental attribute associated with the GPS locations of each caribou to the mean values associated with random points sampled within each range (Appendix C).

Land cover type was characterized by Enhanced Wetlands Classification (EWC) GIS data (30-m pixel resolution) developed by Ducks Unlimited Canada, which we collapsed into eight categories that were biologically meaningful to caribou (Table 1). We considered caribou response to land cover at two scales: a fine-scale (30-m pixel) representing the land cover type at the used or random location; and a landscape-level scale representing the proportion of each land cover in a 1500-m radius surrounding each used and random location (hereafter, landscape context). This latter scale is the same scale used in RSF analyses by DeMars & Boutin (2014). All landscape context variables were arcsine transformed as most demonstrated a right-skewed distribution.

Table 1: Classification of land cover types used to model resource selection by boreal caribou in northeastern BC. Land cover types were developed from Ducks Unlimited Enhanced Wetlands Classification data clipped to the study area (DU 2010).

Land cover	EWC Class	Description
Treed bog	Treed bog, Open bog, Shrubby bog	Black spruce and *Spaghnum* moss dominated bogs with no hydrodynamic flow. Areal coverage: ~20%
Nutrient poor fen	Graminoid poor fen, Shrubby poor fen, Treed poor fen	Low nutrient peatland soils influenced by groundwater flows. Treed poor fens dominate, comprised of black spruce, tamarack and bog birch (25-60% tree cover). Areal coverage: ~22%
Nutrient rich fen	Graminoid rich fen, Shrubby rich fen, Treed rich fen	Low nutrient peatland soils influenced by groundwater flows. Shrubby fens dominate, comprised of bog birch, willow and alder. Areal coverage: ~5%
Conifer swamp	Conifer swamp	Tree cover >60% dominated by black or white spruce. Occur on peatland or mineral soils. Areal coverage: ~9%
Deciduous swamp	Shrub swamp, Hardwood swamp	Mineral soils with pools of water often present. At least 25% of tree cover is deciduous (paper birch and balsam poplar). Areal coverage: ~12%
Upland conifer	Upland conifer	Mineral soils with tree cover >25%. Dominant tree species: black spruce, white spruce and pine. Areal coverage: ~9%
Upland deciduous	Upland deciduous	Mineral soils with tree cover >25% and >25% deciduous trees Dominant tree species: aspen and paper birch. Areal coverage: ~17%
Other	Upland other, Cloud shadow, Anthropogenic, Burn, Aquatic	Uplands: mineral soils with tree cover <25%. Anthropogenic: urban areas, houses, roads and cut blocks. Burns: recent burns where vegetation is limited or covered by burn Aquatic: includes a continuum of aquatic classes from low turbidity lakes to emergent marshes where aquatic vegetation is >20% of the cover. Total areal coverage: ~6% (Cloud shadow <0.5%)

We modelled NDVI, which can be considered an index of forage productivity (Gustine *et al.* 2006; Suzuki *et al.* 2011), following DeMars & Boutin (2014). For each year (2011 – 2014), we obtained NDVI data (250-m pixel resolution) spanning the calving season (April 15 – July 15) from the U.S. National Aeronautics and Space Administration MODIS database. The NDVI data is derived from MODIS images taken over a 16-day window. We used the nearest-neighbour interpolation algorithm within ArcGIS (version 10.3.1.4959; Esri, Inc., Redlands, CA, USA) to rescale the NDVI data to match the resolution of the land cover data (30-m pixel resolution). We then calculated an average NDVI value for each pixel during each calving season.

We calculated slope in a GIS framework using a digital elevation model obtained from BC Terrain Resources Information Management data. For rivers, lakes, major roads and forestry data (fires, cut blocks, and forestry roads), we used data sets from the BC Geographic Data Discovery Service. We combined cut blocks and forest fires < 50 years old to create a unified variable describing early seral vegetation, which has been shown to be important in caribou habitat modelling (Sorensen *et al.* 2008; Hins *et al.* 2009). For well sites, pipelines, seismic lines (1996 to present) and petroleum development roads, we accessed data sets from the BC Oil and Gas Commission. We also used linear feature data from BC Terrain Resources Information Management, specifically a shapefile representing all linear features visible on the landscape, regardless of type or age, from 1992 aerial photos. To create a parsimonious data set describing linear features for the study area, we merged all major roads, forestry roads, petroleum development roads, and seismic lines into one file then integrated the resulting data set at a scale of 10-m to eliminate redundancies among the original data sets.

We evaluated caribou response to natural and anthropogenic features using measures similar to those described in DeMars & Boutin (2014). For assessing caribou response to rivers, lakes, early seral vegetation and well sites, we used distance-to measures, which compare the relative proximities of caribou and random locations to a given feature. For linear features, we assessed line density in a 400-m radius. All disturbance variables (e.g. distance to early seral vegetation, linear feature density, etc.) were estimated on a yearly basis to account for annual changes in these features. With our focus on calving, we estimated disturbance variables up to April 15 of a given year. These year-specific variables were then matched to caribou GPS locations of the same year (i.e. 2014 calving locations were matched to disturbance variables calculated up to April 15, 2014). To account for yearly changes in the availability of disturbance variables, we also drew year-specific sets of random locations.

STATISTICAL ANALYSES

To predict female selection of calving areas, we estimated RSFs using generalized linear mixed effect models (GLMMs; Gillies *et al.* 2006; Zuur *et al.* 2009), which account for the hierarchical structure inherent in GPS location data and unequal sample sizes among individual caribou. In all GLMMs, we assigned individual caribou-year as a random grouping effect (i.e. a random intercept). This formulation of caribou-year accounts for yearly differences in calving area selection for individuals calving in more than one season. GLMMs therefore took the form

$$ln\left[\frac{\pi(y_i=1)}{1-\pi(y_i=1)}\right] = \beta_0 + \beta_1 x_{1ij} + \ldots + \beta_n x_{nij} + \gamma_{0j} \qquad \text{(Gillies } et\ al. \text{ 2006)}$$

where the left-hand side of the equation is the logit transformation for location y_i, β_0 is the fixed-effect intercept, β_n is the fixed-effect coefficient for each explanatory covariate x_n, and γ_{0j} is the random intercept for caribou-year *j*. The fixed-effect coefficients yield inferences on how a typical caribou selects resources and can be interpreted within the classic use-availability design of

$$\omega(x_i) = \exp(\beta_1 x_1 + \beta_2 x_2 + \ldots \beta_n x_n) \qquad \text{(Manly } et\ al. \text{ 2002)}$$

where $\omega(x_i)$ is the relative selection value of a resource unit (or pixel) in category *i* as a function of the explanatory covariates (x_n) and their estimated coefficients (β_n).

For our initial analyses, we specified the fixed-effects component of the model as

Land cover (pixel) + landscape context + slope + NDVI + river + lake + early seral + well site + line density

Within this model structure, none of the explanatory variables were found to be significantly correlated (variance inflation factors < 2; Zuur, Ieno & Elphick 2010). To better compare relative effect sizes, we standardized all variables before model fitting. For land cover and landscape context, we set treed bog as the reference category. Note that this model specification results in a ranking of land cover types and landscape contexts; thus, inferences on selection of a given land cover or landscape context are relative to treed bog.

From this base model, we further considered whether quadratics or exponential decay transformations of distance-to variables improved model performance as measured by AIC. For exponential decay transformations, we followed Nielsen *et al.* (2009), using a decay of $e^{-\alpha d}$ where *d* is the distance to the landscape feature and α is the shape parameter. We set α to 0.002 which erodes the effect of a feature to where distances > 1500-m essentially have a similar and limited effect. We also considered whether interaction terms improved model performance. Because previous analyses suggested caribou select fens – and to a lesser extent upland conifer – for calving (DeMars & Boutin 2014), we considered fine-scale interactions (i.e. pixel scale) of fens and upland conifer with NDVI as well as larger-scale interactions (i.e. landscape context) of fens and upland conifer with line density.

We used the random-intercept GLMMs for developing predictive maps of calving areas. While this formulation is useful for discriminating whether a particular location will be selected by a female caribou during calving, variance estimates from such models do not reflect variation in selection among individual caribou because the GPS and random locations are considered the sample units (Schielzeth & Forstmeier 2009). To explicitly assess variation among individual caribou, DeMars & Boutin (2014) used random-slope GLMMs where a suite of explanatory variables were specified as random coefficients. This formulation yields individual-specific parameter estimates for these variables and variance estimates calculated across individual caribou. Here, we used an alternative but similar approach to assess variation in selection among individual caribou-years. We estimated two-stage RSF models where RSF models are first estimated for each individual caribou-year using logistic regression then population-level parameter estimates for each covariate are calculated by averaging estimates across all caribou-years (Glenn *et al.* 2004; Fieberg *et al.* 2010). To account for differences in the precision of parameter estimates among caribou-years, population means were calculated by weighting individual parameter estimates by the inverse of their variance (Murtaugh 2007). To facilitate averaging across caribou-years and for comparing results with those in DeMars & Boutin (2014), we did not consider quadratic or interaction terms for two-stage RSF models.

A primary drawback to two-stage approaches is that some individuals may have perfect or near perfect avoidance of certain covariates, creating boundary issues that may cause inflated parameter estimates. Such estimates may have undue influence on population means, even after inverse-variance weighting. Therefore, to more explicitly evaluate variation among caribou, for each covariate we present the population mean, the median, and the number of individual caribou-years showing selection (i.e. a positive parameter estimate).

Model Validation

We assessed the predictive performance of the top random-intercept GLMM using *k*-fold cross-validation (Boyce *et al.* 2002). To do so, we randomly partitioned the data by individual caribou-year into five folds (or subsets), using four folds for model training then testing model prediction on the GPS locations from the withheld caribou-years. For each test, we used the fixed-effects output from the training data to predict values for both the random locations generated within each range and the withheld GPS locations. We partitioned the predicted values of the range random points into deciles (i.e. 10 ordinal bins containing an equal number of random points) then assessed model prediction by comparing the proportional frequency of predicted values for the withheld GPS locations falling within a bin to bin rank using Spearman's correlation coefficient (r_S; DeCesare *et al.* 2012). We repeated this process 30 times and calculated the mean r_S with higher $\bar{r}_S$ values indicating better predictive performance. [Note: we also assessed the predictive performance of two-stage RSF models but predictive power was lower than GLMMs and their validation results are not shown here.]

We used a similar process to further quantify the relative selective value of predicted calving areas and to assess predictive performance among herd ranges. Using parameter estimates from the top model and all data, we predicted values for the range random points, partitioned these into decile bins then assessed the correlation (r_S) between bin rank and the frequency of predicted values for all caribou GPS locations within each bin. We also computed the selection ratio for each bin, defined as the proportion of GPS locations falling within a bin divided by the bin's proportion of random points. Ratios > 1 indicate areas that are relatively selected (i.e. where caribou use exceeds random expectation) while ratios < 1 indicate areas that are relatively avoided. To evaluate range-specific performance, we repeated this process with the following two modifications. First, we used only range-specific GPS locations and calculated a range-specific r_S where the number of random points per RSF decile bin used random points across all ranges (i.e. per RSF bin availability was calculated across ranges). Second, we used only range-specific GPS locations and calculated a range-specific r_S where only range-specific random points determined relative availability per RSF bin. This latter modification allowed for availability to change among ranges, which resulted in RSF bins to no longer be classified as deciles (i.e. the proportion of random points falling within an RSF bin varied). Moreover, it allowed for an assessment of the relative availability of each RSF bin within each range.

All statistical analyses were performed in R, version 3.1.2 (R Core Team 2014) and we used the 'lme4' package (Bates *et al*. 2013) to estimate RSFs.

RESULTS

The top GLMM model for explaining female selection of calving areas included interactions of NDVI with poor fens and rich fens as well as linear feature density interacting with landscape context variables describing the proportion of nutrient-poor fens, nutrient-rich fens and upland conifer (Table 2). This model was 1991 AIC units lower than a model without interactions. In general, the model indicates that caribou GPS locations were disproportionately situated in treed bogs, poor fens and rich fens and within landscapes having higher proportions of treed bogs, fens, and conifer swamps. Caribou GPS locations were also disproportionately situated in areas with shallow slope, low densities of linear features and with slightly higher NDVI values. In terms of proximity to natural and anthropogenic features, the spatial distribution of caribou locations was best explained by exponential decay variables for lakes and well sites and quadratic variables for rivers and early seral vegetation. Parameter estimates for these variables indicate that caribou locations were relatively further away from lakes and well sites while they were situated intermediate in distance from rivers and early seral vegetation.

The interaction between NDVI and fens indicates that caribou locations were disproportionately situated in poor fens with higher NDVI values and rich fens with low NDVI values (Figs. 2-3). This finding suggests that a relatively high proportion of caribou locations occurred in what might be considered the transition zone between poor and rich fens.

The interaction between linear feature density and landscape context variables depended on the type of land cover considered. With poor fens, RSF values increased with increasing line density when the proportion of poor fens increased by approximately one standard deviation above mean values (Fig. 4). This relationship, however, reversed when the proportion of poor fens was below this threshold, with increasing line density then discounting RSF values. With rich fens, increasing line density discounted RSF values regardless of the proportion of rich fen although this relationship was more pronounced at higher proportions of rich fen (Fig. 5). With upland conifer, increasing line density discounted RSF values when the proportion of upland conifer was above mean values and this relationship strengthened as the proportion of upland conifer increased (Fig. 6). Below mean upland conifer values, increasing line density had minimal effect.

The two-stage RSF model yielded similar inferences to the random-intercept GLMM but also highlighted the high variation among female caribou in selecting calving areas (Table 3). In general, females avoided deciduous forests at a fine-scale and selected landscapes with a high proportion of poor fens and, to a lesser extent, rich fens and upland conifer. Females also selected calving areas with shallow slopes and low line densities. Proximity to natural and anthropogenic features was more variable, particularly in terms of the number of females showing selection or avoidance of a specific feature.

MODEL VALIDATION

The top GLMM had good predictive performance as evaluated by *k*-fold cross-validation ($\bar{r}_S$= 0.83). When considering model fit using all data, the proportional frequency of caribou GPS locations correlated highly with RSF bin rank (r_S = 0.98) and caribou showed disproportional use of RSF bins ranked ≥ 6 (Table 4, Appendix D). Predictive performance varied among ranges. When availability is scaled across ranges, only Prophet had low predictive performance (r_S = 0.35), primarily due to a lack of caribou locations in the top two RSF bins (Table 5). When availability was specifically scaled to each range, predictive performance in three of the six ranges remained high (Chinchaga, Maxhamish, and

Parker, all $r_S \geq 0.77$; Table 6). Lower performance in the other three ranges again seemed to be driven by a lack of caribou locations in the top two RSF bins.

Table 2: Fixed-effect parameter estimates (β) and standard errors (SE) from the top RSF model for explaining calving area selection by female boreal caribou in northeast British Columbia. Note that inferences on selection of land cover types (30-m scale) and land cover proportions (1.5 km scale) are in reference to treed bog.

Variable	β	SE
Intercept	-3.72	0.10
Poor Fen (30-m)	-0.03	0.03
Rich Fen (30-m)	0.00	0.05
Conifer Swamp (30-m)	-0.49	0.04
Deciduous Swamp (30-m)	-0.70	0.05
Upland Conifer (30-m)	-1.28	0.07
Upland Deciduous (30-m)	-1.88	0.09
Other (30-m)	-1.29	0.12
Proportion of Poor Fen (1.5-km)	0.09	0.02
Proportion of Rich Fen (1.5-km)	0.34	0.01
Proportion of Conifer Swamp (1.5-km)	0.01	0.01
Proportion of Deciduous Swamp (1.5-km)	-0.25	0.01
Proportion of Upland Conifer (1.5-km)	-0.11	0.02
Proportion of Upland Deciduous (1.5-km)	-0.83	0.02
Proportion of Other (1.5-km)	-0.35	0.02
Slope	-0.15	0.01
NDVI (30-m)	0.12	0.02
NDVI * Poor Fen (30-m)	0.11	0.03
NDVI * Rich Fen (30-m)	-0.24	0.05
Distance to River	0.48	0.01
(Distance to River)^2	-0.14	0.01
Distance to Lake (exponential decay)	0.09	0.01
Distance to Early Seral	-0.36	0.02
(Distance to Early Seral)^2	-0.30	0.01
Distance to Well (exponential decay)	0.31	0.02
Linear Feature Density (400-m)	-0.31	0.02
Proportion of Poor Fen * Linear Feature Density	0.12	0.01
Proportion of Rich Fen * Linear Feature Density	-0.03	0.01
Proportion of Upland Conifer * Linear Feature Density	-0.68	0.02

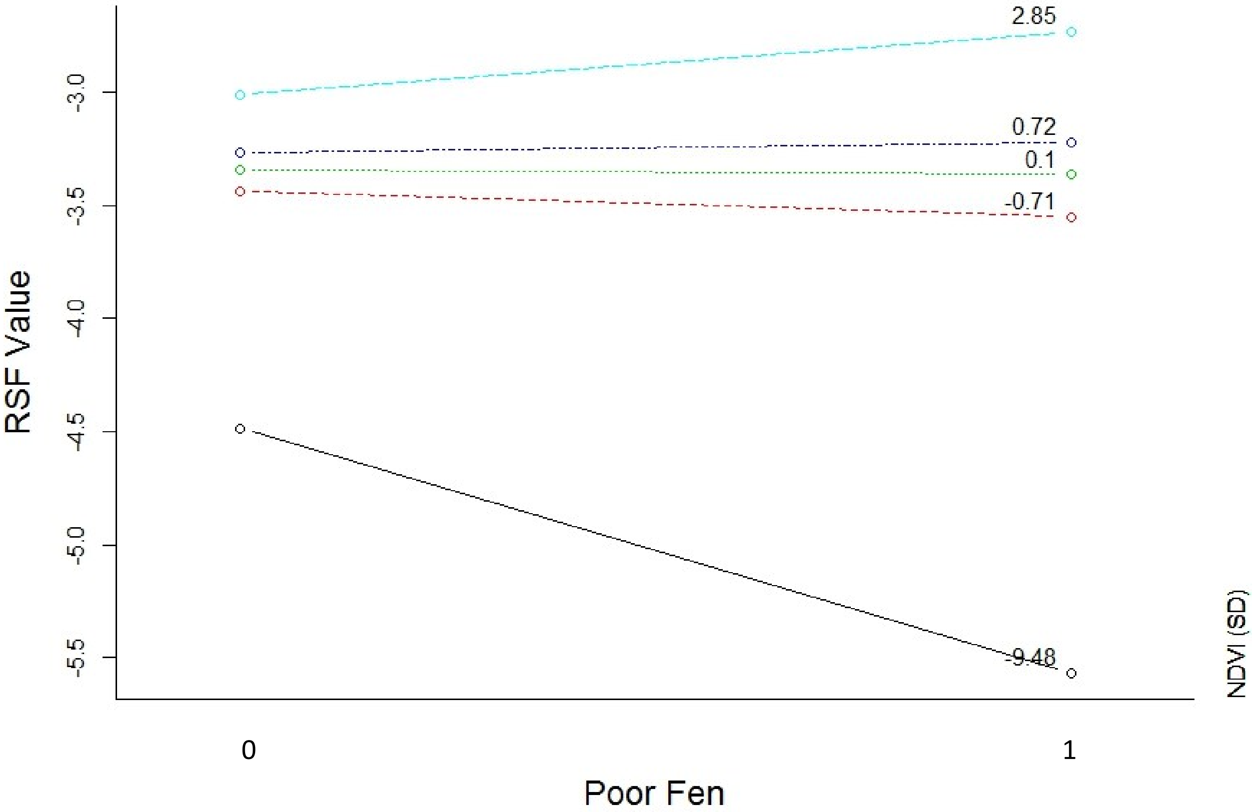

Figure 2: The interacting effects of nutrient-poor fens (30-m scale) and normalized difference vegetation index (NDVI) on selection of calving areas by female boreal caribou in northeast British Columbia. Note that NDVI data are presented in standardized form (mean NDVI = 6367 units; sd = 672) and each colored line represents the relationship between nutrient-poor fens and the RSF value when NDVI is *x* deviations away from the mean.

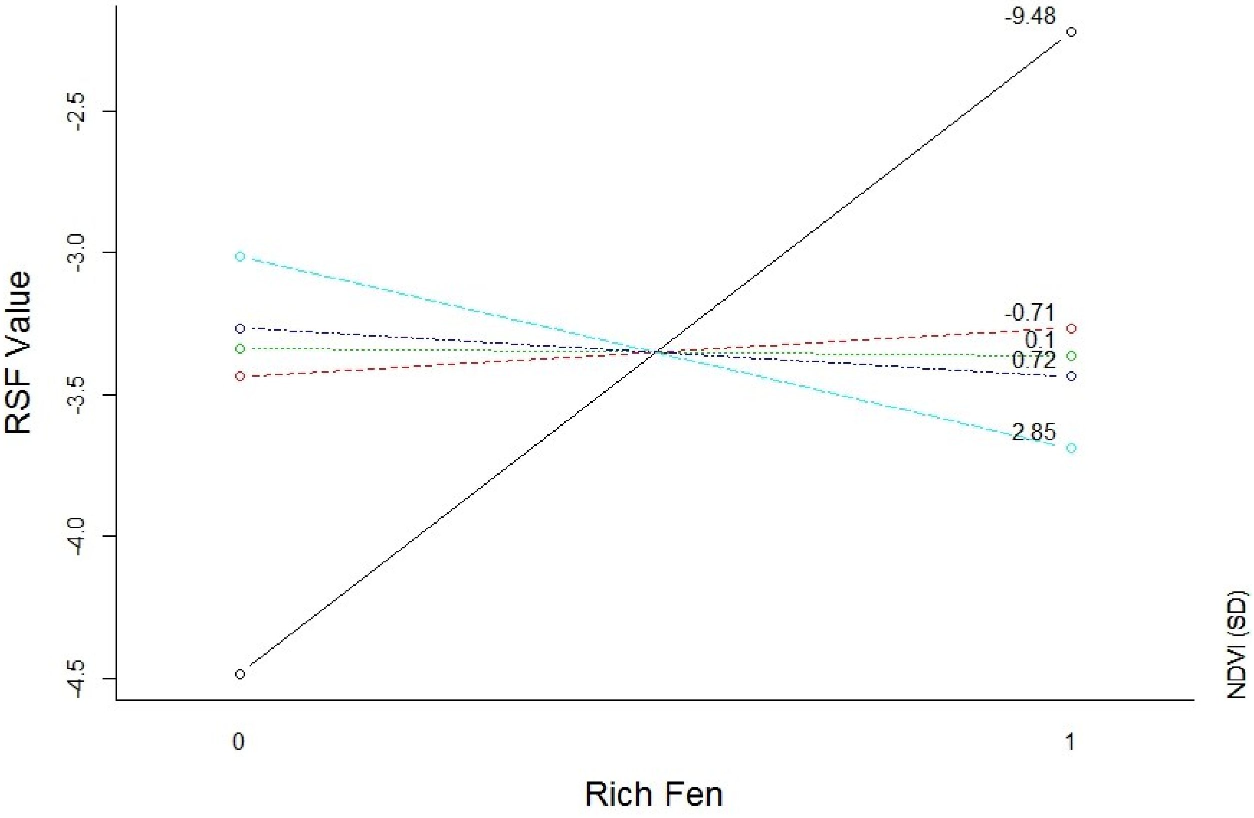

Figure 3: The interacting effects of nutrient-rich fens (30-m scale) and normalized difference vegetation index (NDVI) on selection of calving areas by female boreal caribou in northeast British Columbia. Note that NDVI data are presented in standardized form (mean NDVI = 6367 units; sd = 672) and each colored line represents the relationship between nutrient-rich fens and the RSF value when NDVI is *x* deviations away from the mean.

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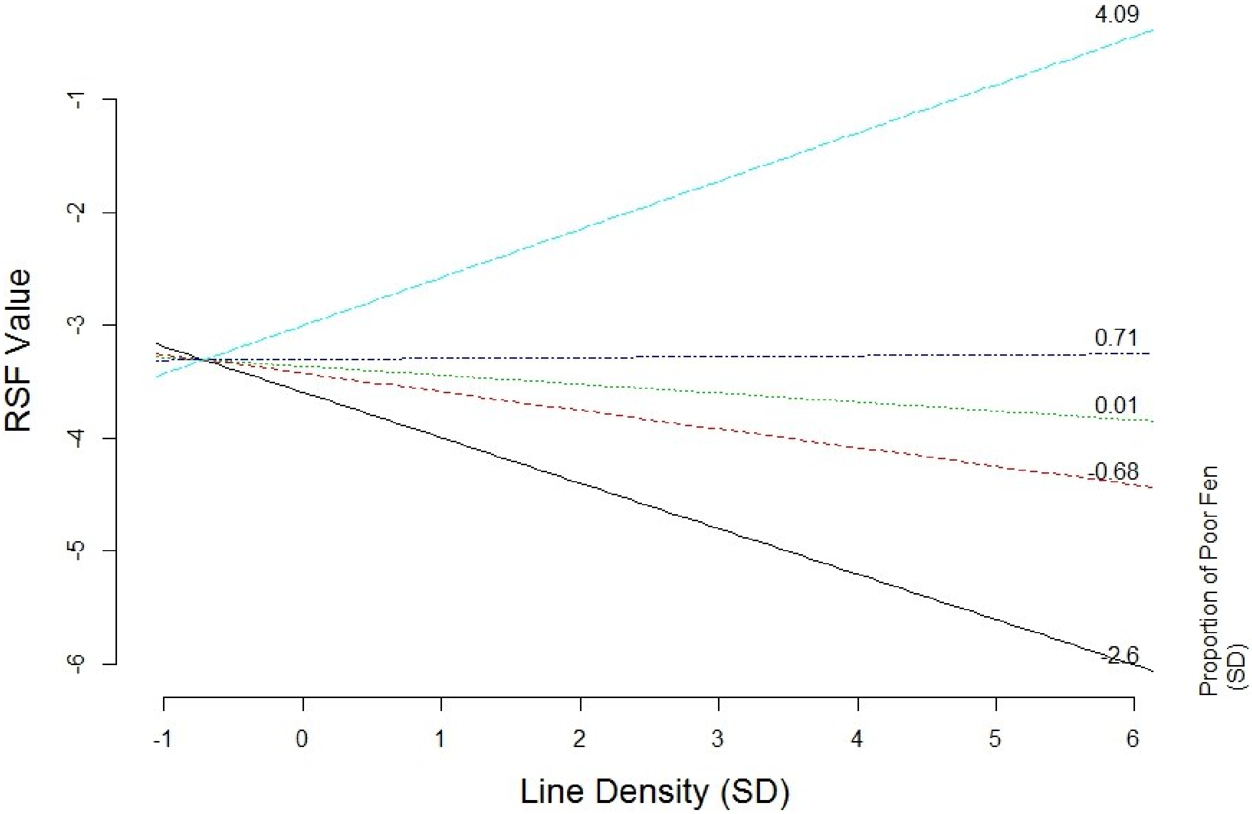

Figure 4: The interacting effects of linear feature density (400-m radius) and the proportion of poor fens in the landscape (1.5-km radius) on selection of calving areas by female boreal caribou in northeast British Columbia. Note that the data are presented in standardized form and that proportion of poor fen has been arcsine transformed to correct for skewness (line density mean = 3.54 km/km^2, sd =3.63; prop. of poor fen mean = 0.51, sd = 0.20). Each colored line represents the relationship between line density and the RSF value when the proportion of poor fen is *x* deviations away from the mean.

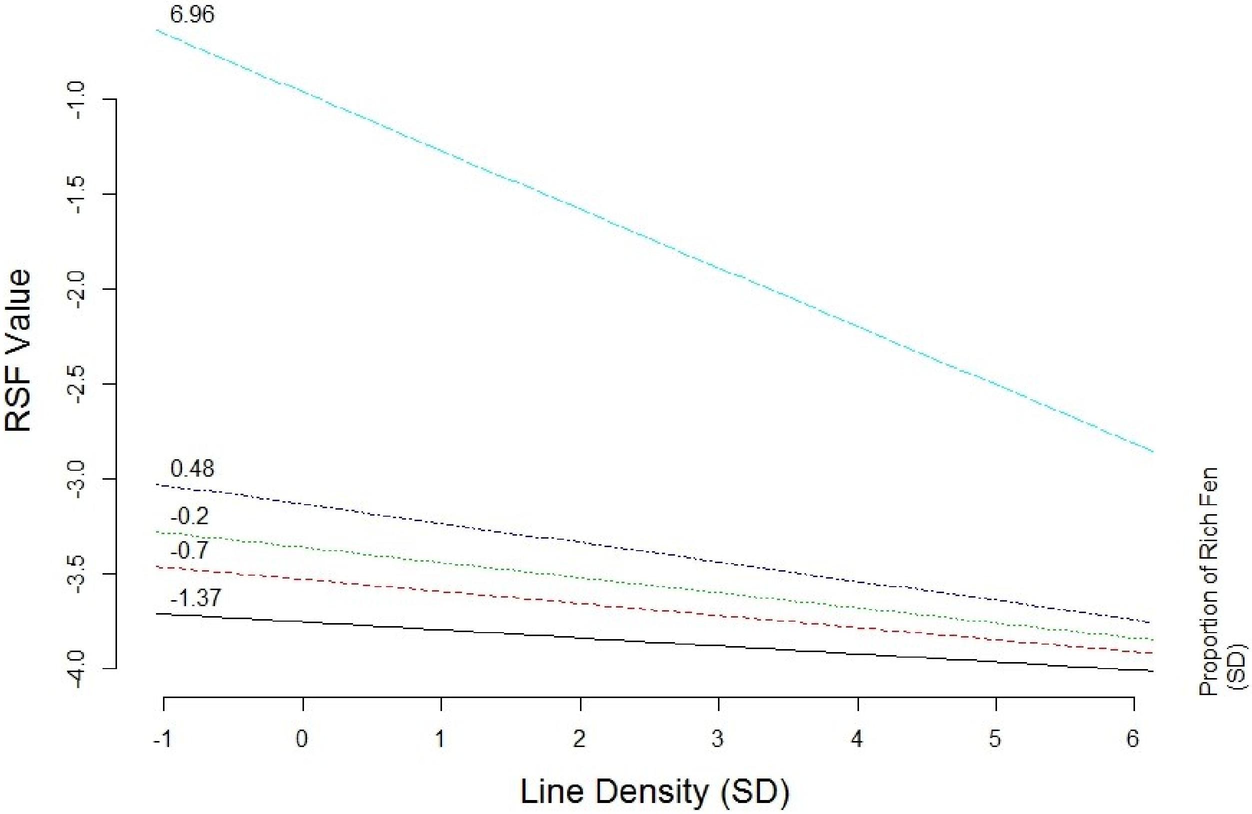

Figure 5: The interacting effects of linear feature density (400-m radius) and the proportion of rich fens in the landscape (1.5-km radius) on selection of calving areas by female boreal caribou in northeast British Columbia. Note that the data are presented in standardized form and that proportion of rich fens has been arcsine transformed to correct for skewness (line density mean = 3.54 km/km2, sd =3.63; prop. of rich fen mean = 0.14, sd = 0.12). Each colored line represents the relationship between line density and the RSF value when the proportion of rich fen is *x* deviations away from the mean.

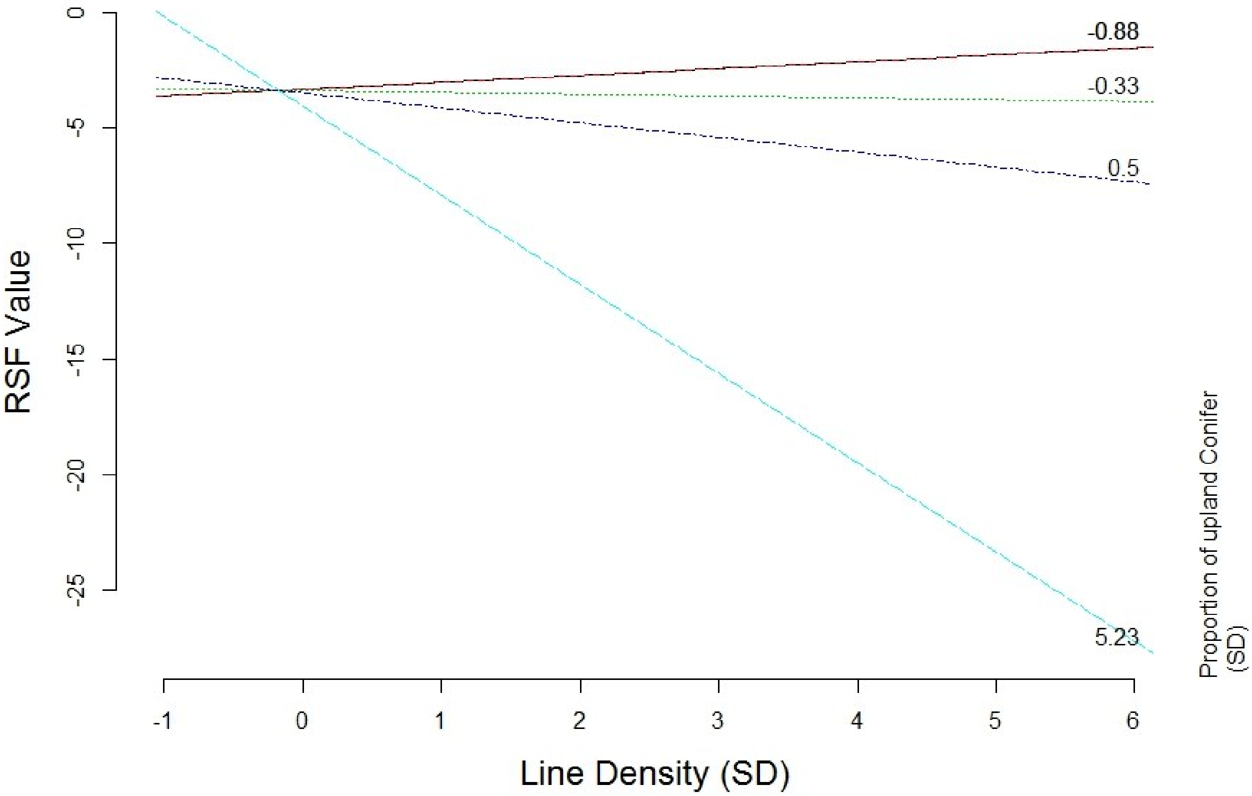

Figure 6: The interacting effects of linear feature density (400-m radius) and the proportion of upland conifer in the landscape (1.5-km radius) on selection of calving areas by female boreal caribou in northeast British Columbia. Note that the data are presented in standardized form and that proportion of upland conifer has been arcsine transformed to correct for skewness (line density mean = 3.54 km/km2, sd =3.63; prop. of upland conifer mean = 0.19 sd = 0.21). Each colored line represents the relationship between line density and the RSF value when the proportion of upland conifer is *x* deviations away from the mean.

Table 3: Population-level parameter estimates (β) and the number of caribou-years showing selection (i.e. β > 0) from two-stage RSF models for explaining calving area selection by female boreal caribou in northeast British Columbia. 95% confidence intervals (CI) for the mean are also shown. Note that inferences on selection of land cover types (30-m scale) and land cover proportions (1.5 km scale) are in reference to treed bog.

Variable	No. of Caribou-Years (*n* = 61) with Positive β	Mean β	95% CI	Median β
Poor Fen (30-m)	27	-0.29	-0.52, -0.05	-0.25
Rich Fen (30-m)	29	0.86	0.28, 1.51	1.12
Conifer Swamp (30-m)	25	-0.65	-0.98, -0.32	-0.33
Deciduous Swamp (30-m)	21*	-0.50	-0.86, -0.13	-0.51
Upland Conifer (30-m)	29	-0.33	-0.78, 0.18	-0.17
Upland Deciduous (30-m)	18*	-1.04	-1.48, -0.56	-0.79
Other (30-m)	33	0.70	0.03, 1.5	0.24
Proportion of Poor Fen (1-km)	39*	0.69	0.22, 1.12	1.00
Proportion of Rich Fen (1-km)	35	0.40	0.03, 0.72	0.52
Proportion of Conifer Swamp (1-km)	28	0.29	-0.11, 0.6	-0.43
Proportion of Deciduous Swamp (1-km)	32	0.35	0.06, 0.64	0.00
Proportion of Upland Conifer (1-km)	34	0.49	0.15, 0.88	0.64
Proportion of Upland Deciduous (1-km)	24	-0.45	-0.85, -0.11	-0.92
Proportion of Other (1-km)	21*	-0.25	-0.6, 0.04	-0.25
Slope	22*	-0.13	-0.26, -0.02	-0.25
NDVI (30-m)	34	-0.12	-0.35, 0.15	-0.08
Distance to River	30	0.13	-0.26, 0.5	0.46
Distance to Lake	25	0.11	-0.22, 0.4	-0.01
Distance to Early Seral	23	-0.64	-1.18, -0.1	-0.61
Distance to Well	30	0.14	-0.21, 0.52	0.11
Linear Feature Density (400-m)	21*	-0.09	-0.44, 0.24	-0.52

* Indicates the number of caribou-years with a positive coefficient differs from random expectation (*p*-value < 0.05 from binomial exact test)

Table 4: Performance of the top RSF model for predicting calving areas of female boreal caribou in northeast British Columbia. The selection ratio is the proportion of caribou GPS locations within an RSF bin divided by the bin's proportion of available points. Spearman's correlation coefficient comparing RSF bin rank to the selection ratio was 0.98.

RSF Bin	Min. Bin Value	Max. Bin Value	No. of Caribou GPS Locations	No. of Available Points	Selection Ratio
1	0.0000	0.0005	82	30498	0.07
2	0.0005	0.0014	393	30501	0.35
3	0.0014	0.0030	670	30501	0.60
4	0.0030	0.0055	853	30498	0.76
5	0.0055	0.0091	1133	30502	1.01
6	0.0091	0.0145	1267	30500	1.13
7	0.0145	0.0225	1329	30497	1.18
8	0.0225	0.0355	1617	30497	1.44
9	0.0355	0.0627	2020	30505	1.80
10	0.0627	1.0000	1868	30501	1.66

Table 5: Performance by range of the top RSF model for predicting calving areas of female boreal caribou in northeast British Columbia. RSF prediction is assessed using Spearman's correlation coefficients (r_S) which correlate RSF bin rank to the selection ratio. Higher values of r_S represent better predictive power. Here, the selection ratio is calculated as the proportion of range-specific caribou GPS locations falling with a particular RSF bin divided by the proportion of available locations within that bin. The proportion of available points per bin is calculated across ranges.

Range	r_S	RSF Bin	Caribou GPS Locations	Proportion of GPS Locations	Selection Ratio
Parker	0.96	1	1	< 0.01	0.01
		2	27	0.02	0.20
		3	43	0.03	0.31
		4	122	0.09	0.89
		5	70	0.05	0.51
		6	81	0.06	0.59
		7	130	0.09	0.94
		8	222	0.16	1.61
		9	313	0.23	2.27
		10	368	0.27	2.67
Prophet	0.35	1	51	0.02	0.20
		2	56	0.02	0.22
		3	222	0.09	0.87
		4	181	0.07	0.71
		5	356	0.14	1.40
		6	586	0.23	2.31
		7	448	0.18	1.76
		8	434	0.17	1.71
		9	132	0.05	0.52
		10	76	0.03	0.30
Maxhamish	0.98	1	11	< 0.01	0.03
		2	172	0.04	0.42
		3	288	0.07	0.70
		4	302	0.07	0.73
		5	421	0.10	1.02
		6	399	0.10	0.97
		7	494	0.12	1.20
		8	556	0.14	1.35
		9	769	0.19	1.87
		10	706	0.17	1.71
Snake	0.93	1	5	< 0.01	0.02

Range	r_S	RSF Bin	Caribou GPS Locations	Proportion of GPS Locations	Selection Ratio
		2	18	0.01	0.09
		3	76	0.04	0.37
		4	166	0.08	0.81
		5	254	0.12	1.24
		6	166	0.08	0.81
		7	171	0.08	0.83
		8	255	0.12	1.24
		9	541	0.26	2.64
		10	399	0.19	1.95
Calendar	0.79	1	0	0.00	0.00
		2	2	0.00	0.03
		3	40	0.06	0.57
		4	100	0.14	1.43
		5	21	0.03	0.30
		6	63	0.09	0.90
		7	96	0.14	1.37
		8	103	0.15	1.47
		9	177	0.25	2.53
		10	98	0.14	1.40
Chinchaga	0.83	1	13	0.03	0.29
		2	20	0.05	0.45
		3	10	0.02	0.23
		4	29	0.07	0.65
		5	42	0.09	0.95
		6	43	0.10	0.97
		7	16	0.04	0.36
		8	45	0.10	1.01
		9	74	0.17	1.67
		10	152	0.34	3.42

Table 6: Range-specific performance of the top RSF mode, scaled by range area, for predicting calving areas of female boreal caribou in northeast British Columbia. RSF prediction is assessed using Spearman's correlation coefficients (r_S) which correlate RSF bin rank to the selection ratio. Higher values of r_S represent better predictive power. Here, the selection ratio is calculated as the proportion of range-specific caribou GPS locations falling with a particular RSF bin divided by the proportion of range-specific available locations within that bin.

Range	r_S	RSF Bin	Caribou GPS Locations	Proportion of GPS Locations	Available Locations	Proportion of Available Locations	Selection Ratio
Parker	0.87	1	24	0.02	3220	0.09	0.19
		2	49	0.04	5415	0.15	0.23
		3	86	0.06	5030	0.14	0.43
		4	131	0.10	4083	0.12	0.82
		5	129	0.09	3895	0.11	0.84
		6	186	0.14	2999	0.09	1.58
		7	224	0.16	2652	0.08	2.15
		8	222	0.16	2276	0.07	2.48
		9	228	0.17	2608	0.07	2.22
		10	98	0.07	2822	0.08	0.88
Prophet	-0.09	1	168	0.07	5614	0.09	0.71
		2	168	0.07	5591	0.09	0.71
		3	121	0.05	5988	0.10	0.48
		4	232	0.09	6022	0.10	0.91
		5	407	0.16	6316	0.11	1.52
		6	491	0.19	5900	0.10	1.96
		7	421	0.17	6286	0.10	1.58
		8	338	0.13	6049	0.10	1.32
		9	81	0.03	6334	0.11	0.30
		10	115	0.05	5900	0.10	0.46
Maxhamish	0.83	1	32	0.01	14116	0.14	0.06
		2	180	0.04	12728	0.13	0.34
		3	421	0.10	11453	0.11	0.89
		4	381	0.09	11373	0.11	0.81
		5	313	0.08	10456	0.10	0.73
		6	577	0.14	9816	0.10	1.43
		7	625	0.15	8639	0.09	1.76
		8	575	0.14	7928	0.08	1.76
		9	685	0.17	6805	0.07	2.44
		10	329	0.08	6686	0.07	1.19
Snake	0.13	1	15	0.01	2699	0.05	0.15

Range	r_S	RSF Bin	Caribou GPS Locations	Proportion of GPS Locations	Available Locations	Proportion of Available Locations	Selection Ratio
		2	75	0.04	3274	0.06	0.61
		3	153	0.07	3804	0.07	1.08
		4	333	0.16	4576	0.08	1.95
		5	242	0.12	5444	0.10	1.19
		6	240	0.12	6670	0.12	0.96
		7	305	0.15	6885	0.13	1.19
		8	281	0.14	7564	0.14	1.00
		9	321	0.16	7302	0.13	1.18
		10	86	0.04	6782	0.12	0.34
Calendar	-0.14	1	0	0.00	316	0.01	0.00
		2	13	0.02	914	0.03	0.61
		3	106	0.15	1730	0.06	2.63
		4	112	0.16	1942	0.06	2.47
		5	69	0.10	2446	0.08	1.21
		6	72	0.10	3160	0.11	0.98
		7	120	0.17	4208	0.14	1.22
		8	128	0.18	4912	0.16	1.12
		9	69	0.10	5492	0.18	0.54
		10	11	0.02	4880	0.16	0.10
Chinchaga	0.77	1	28	0.06	4533	0.18	0.35
		2	19	0.04	2579	0.10	0.41
		3	12	0.03	2496	0.10	0.27
		4	54	0.12	2502	0.10	1.22
		5	23	0.05	1945	0.08	0.67
		6	40	0.09	1955	0.08	1.15
		7	50	0.11	1827	0.07	1.54
		8	71	0.16	1768	0.07	2.26
		9	32	0.07	1964	0.08	0.92
		10	115	0.26	3431	0.14	1.89

DISCUSSION

Developing accurate, spatially explicit predictions of habitat use is a fundamental objective of wildlife management (Guisan *et al.* 2013). To improve the performance of the DeMars & Boutin (2014) model for predicting selection of calving areas by female boreal caribou, we incorporated additional GPS location data and evaluated for quadratic and interacting relationships among environmental covariates. This model formulation improved predictive performance under *k*-fold cross-validation ($\bar{r}_S$ = 0.83 versus $\bar{r}_S$= 0.79) and had high relative fit when considering all the data (r_S = 0.98). Importantly, the current model had good predictive performance when considering Chinchaga caribou (r_S = 0.83) whereas the DeMars & Boutin (2014) had relatively poor performance (r_S = -0.25). This improved prediction allowed development of the first map of predicted calving areas for the Chinchaga range (Appendix D).

Predictive performance varied somewhat by range (Tables 5-6) and this variation may have been partially driven by per-range sample sizes of radio-collared caribou. Prediction for the Maxhamish range, which had the highest number of caribou-years (*n* = 20), remained relatively good independent of how RSF bin values were scaled, indicating the relatively high influence of this range on model formulation. Conversely, ranges with smaller sample sizes were more sensitive to scaling of RSF bins. This sensitivity was primarily driven by a lack of caribou GPS locations in the top RSF bins and less by the relative availability of these bins within individual ranges. The lack of GPS locations in the top bins should not be interpreted as avoidance of these areas by female caribou; rather, it is likely an artefact of sampling variation. Female boreal caribou are known to use a "spacing out" strategy at calving to reduce predation risk (Bergerud & Page 1987; DeMars *et al*. 2016). This dispersion strategy likely results in females using calving areas that necessarily vary in their relative suitability, as evidenced by GPS locations occurring in all RSF bins. Thus, having small sample sizes per range may result in samples that are not representative of the variation of calving areas used by females in a particular range. Note that we attempted to further improve predictive performance by developing range-specific models but these models generally performed worse on *k*-fold cross-validation than the across-ranges model (unpublished data; results not shown), a finding again likely influenced by small per-range sample sizes.

Female responses to environmental attributes when selecting calving areas were similar to those documented in DeMars & Boutin (2014). In general, females selected landscapes with high proportions of fen and within these landscapes used sites characterized by fens and treed bog. The interaction of fens with NDVI at the site-level, however, suggests fine-scale selection by caribou below the broader classification of land covers represented by the Ducks Unlimited Canada EWC data. Females appeared to be selecting nutrient-poor fens with relatively high NDVI values and nutrient-rich fens with relatively low NDVI values. If the transition from poor fens to rich fens indicates a continuum of primary productivity, then caribou seemed to select fens with intermediate levels of productivity. This fine-scale selection likely is indicative of the forage – predation risk trade-off faced by calving caribou: that is, selecting fens that have adequate forage to meet lactation demands (Parker *et al.* 2009), but not overly productive (i.e. rich fens with high NDVI values) where use by alternate prey (e.g. moose [*Alces alces*] and beaver [*Castor canadensis*]) and predators (wolves [*Canis lupus*] and black bears [*Ursus americanus*]) may be high.

Beyond the selection of fens, maternal females generally showed selective responses consistent with predation averse behaviours. Females highly avoided forests with a deciduous component at both fine and landscape scales, likely due to the increased predation risk associated with these land cover types

(McLoughlin *et al.* 2005). Females also avoided lakeshores, perhaps because these areas are selected by predators and the hydrogeomorphology of northeast BC lakes provide limited escape terrain (DeMars & Boutin 2014). Similarly, females avoided being near rivers, well sites and early vegetation, all features that have been shown to be selected by alternate prey and predators (Proulx & Kariz 2005; Latham *et al.* 2011; DeMars & Boutin 2014).

Caribou response to linear feature density was more variable. In general, females seemed to avoid areas of high line densities (Tables 1, 3) but the addition of interaction terms with land cover proportions suggests that the response to line density is not strong or consistent. In rich fen and upland conifer landscapes, calving locations were disproportionately situated in areas of low line densities. This relationship, however, did not hold in poor fen landscapes where caribou locations were disproportionately situated in areas with relatively high line density. Given that linear features are a relatively new phenomenon from an evolutionary perspective, it is perhaps unsurprising that caribou response to line density is weak and variable (Sih 2013). Moreover, it is perhaps unrealistic to consider that animals could perceive changes in the density of features that individually have a relatively small and narrow extent (cf. cut blocks or recent forest fires).

MODEL LIMITATIONS

We evaluated calving area selection by female boreal caribou using a generalized mixed-effects modelling approach to estimate resource selection functions. RSFs yield the relative probability that a resource unit will be selected and do not infer the absolute probability of occurrence in a given area (Lele *et al.* 2013). More specifically, our model – and the resulting predictive map – do not represent the absolute probability that a female caribou will occur at a given location during the calving season; rather, the map should be viewed as a continuum of relative habitat suitability for caribou at calving. We further note the following limitations to our modelling approach:

1. Even in areas with apparent high suitability, the actual probability of caribou occurrence will be relatively low because boreal caribou normally occur at low densities throughout their range (e.g. ~ 3 caribou / 100 km^2).
2. Female caribou show considerable individual variation in how they select calving areas (Table 3) and as a consequence caribou can – and probably do – occur in areas with relatively low suitability. This idea is supported by the presence of caribou calving locations in RSF bins with values < 5 in all caribou ranges (Tables 4-6).
3. An increase in habitat suitability does not necessarily equate to an increase in the probability of calf survival. Other factors, such as the number of predators and disease, can influence calf survival in addition to habitat suitability (DeMars & Boutin 2014).
4. Our model does not yield inferences on the spatial requirements of caribou during calving. Females use space to distance themselves from predators and other ungulate species during calving (Bergerud & Page 1987; DeMars *et al*. 2016) and therefore space likely interacts with habitat to influence predation risk. The amount of space – or the areal extent of habitat with high suitability – required by females to effectively reduce predation risk is not currently known.

FUTURE CONSIDERATIONS

Species distribution models like RSFs are useful for predicting a species' space use in a targeted area over a given time period but their predictive performance is known to diminish through space and time (Beyer *et al.* 2010; Matthiopoulos *et al.* 2011). Declines in predictive performance may be particularly evident in rapidly changing landscapes and when animals show a functional response in selection due to changing resource availability. This potential change in predictive performance, combined with the above mentioned issues related to small per-range sample sizes, suggests that management strategies designed to improve calving conditions for boreal caribou in northeast BC may require periodic updating of the RSF model. Such analyses, however, will require maintaining a sample of GPS radio-collared caribou programmed with fix rates that will allow effective prediction of calving events and neonate survival (e.g. every 4 hours) to isolate calving locations.

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APPENDIX A: RANDOM POINT SENSITIVITY ANALYSIS

We evaluated calving area selection by female boreal caribou using resource selection functions (RSFs). These functions entailed a comparison between environmental attributes associated with caribou GPS locations and those associated with random locations sampled within caribou range. To determine the number of random points needed to adequately characterize availability at the range scale, we conducted sensitivity analyses by performing univariate RSFs and assessing when the parameter estimate stabilized for each environmental variable (Fig. A.1). These analyses suggested that parameter estimates stabilized after 5000 random points were sampled within each range.

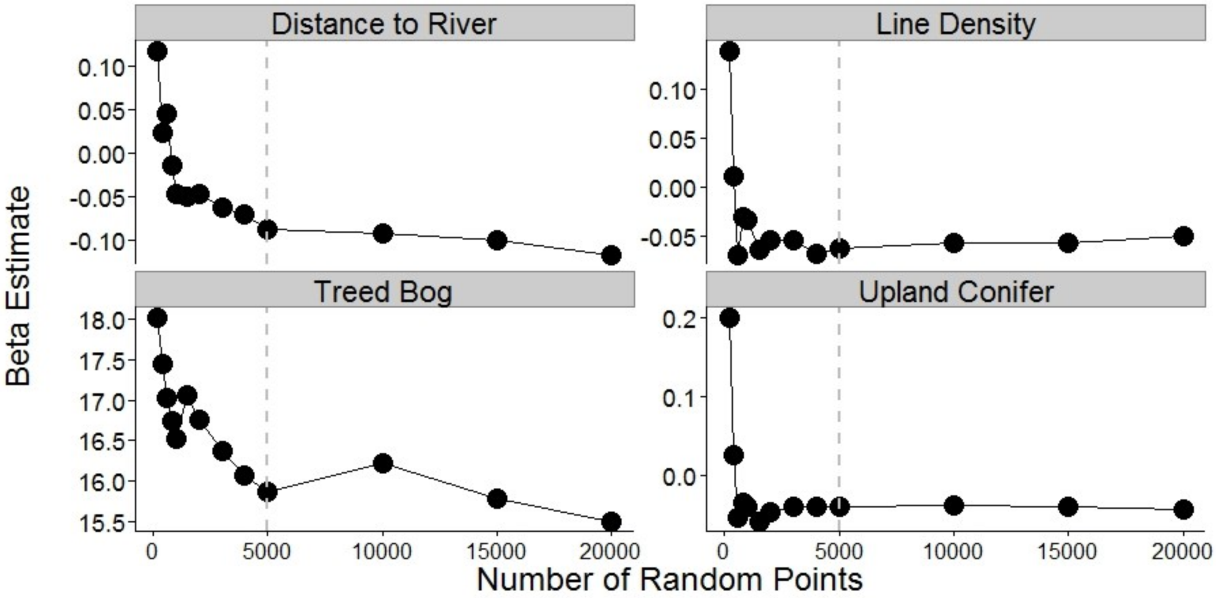


Figure A.1: Sensitivity analyses to determine the number of random points needed to adequately characterize availability of each environmental variable at the caribou range scale. Parameter (beta) estimates from univariate resource selection functions stabilized when 5000 random points were used (vertical gray dashed line).

APPENDIX B: GIS DATA SOURCES

Table B.1: List of GIS data sources used to model resource selection functions evaluating calving area selection by female boreal caribou in northeast British Columbia.

Variable	Source	Access Information
Land Cover	Ducks Unlimited Canada	Ducks Unlimited Canada 100, 17958 106 Ave, Edmonton, AB T5S 1V4
Forest Structure	Vegetation Resource Inventory, BC Ministry of Forests, Lands and Natural Resource Operations	https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=47574&recordSet=ISO19115
Rivers, Lakes	Digital Baseline Mapping, BC Integrated Land Management Bureau, Geographic Data Discovery Service	https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=3679&recordSet=ISO19115
Forest Fire History	Fire Perimeters – Historical, , BC Integrated Land Management Bureau (ILMB), Geographic Data Discovery Service	http://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=57060&recordSet=ISO19115
Cut Blocks	Forest Tenure Cut Block Polygons, BC Ministry of Forests, Lands and Natural Resource Operations	https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=50580&recordSet=ISO19115
Pipelines	BC Oil and Gas Commission	ftp://www.bcogc.ca/outgoing/OGC_Data/Pipelines/
OGC Seismic Lines	BC Oil and Gas Commission	ftp://www.bcogc.ca/outgoing/OGC_Data/Geophysical/
Major Roads	Digital Baseline Mapping, BC ILMB, Geographic Data Discovery Service	https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=3679&recordSet=ISO19115
Forestry Roads	Forest Tenure As-Built Roads, BCGOV FOR Resource Tenures and Engineering	https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=45694&recordSet=ISO19115
Other Secondary Roads	BC Oil and Gas Commission	ftp://www.bcogc.ca/outgoing/OGC_Data/Roads/
Well Sites	BC Oil and Gas Commission	ftp://www.bcogc.ca/outgoing/OGC_Data/Wells/
TRIM Lines	TRIM miscellaneous annotation, BC Integrated Land Management Bureau, Geographic Data Discovery Service	https://apps.gov.bc.ca/pub/geometadata/metadataDetail.do?recordUID=4105&recordSet=ISO19115
NDVI	U.S. National Aeronautics and Space Administration MODIS database	http://modis.gsfc.nasa.gov/data/dataprod/dataproducts.php?MOD_NUMBER=13

APPENDIX C: UNIVARIATE ANALYSES OF USE VERSUS AVAILABILITY

Prior to RSF model development, we conducted univariate analyses comparing the mean values of environmental variables (or resources) associated with GPS locations of each female caribou to the mean values associated with random points sampled within each caribou range (*n* = 6; Figs. C.1 – C.23). GPS locations were restricted to those locations where a female was accompanied by a neonate calf (≤ 4 weeks old). See *Environmental Variables* and Table 1 in the main text for descriptions of each variable.

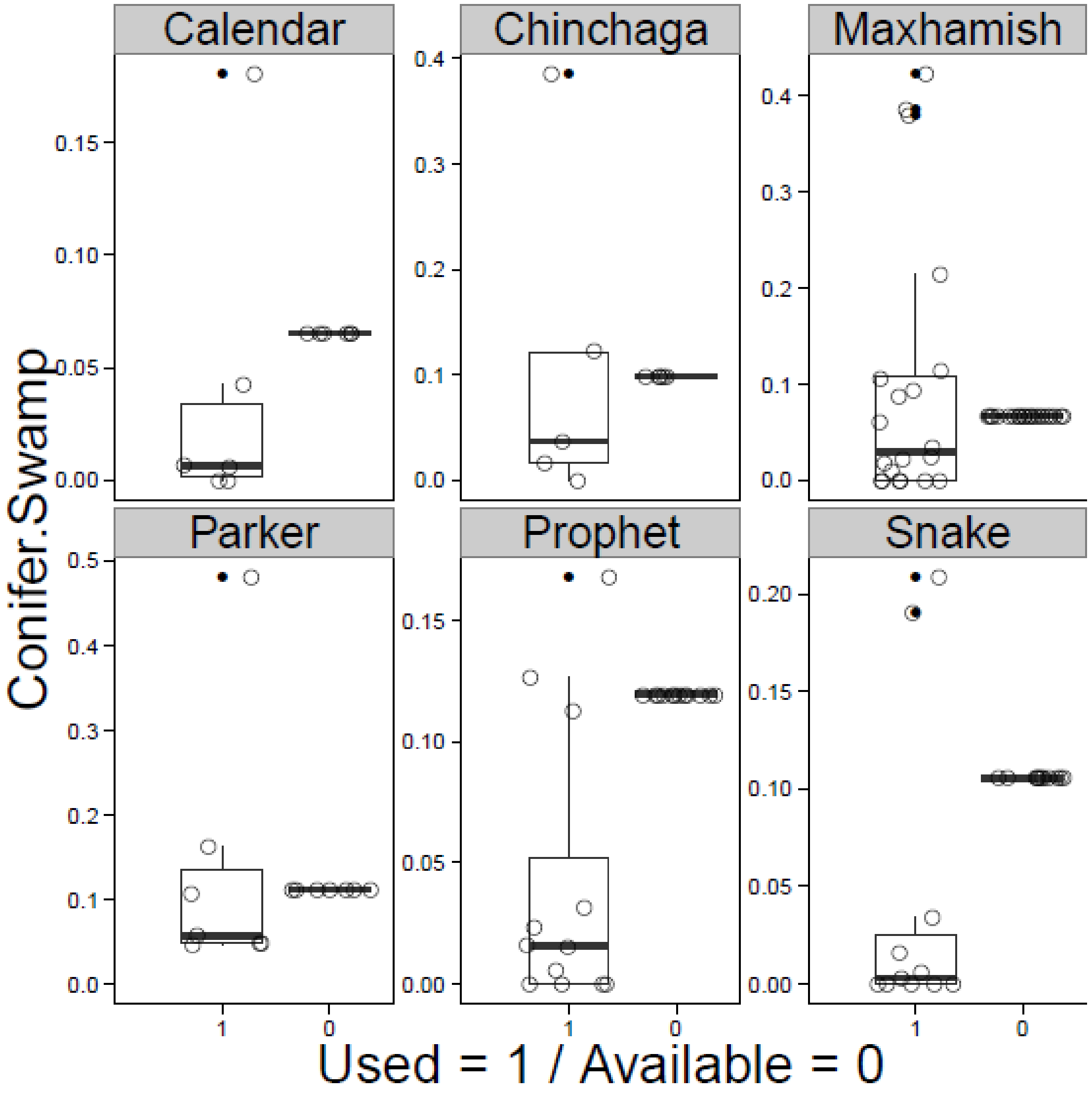


Figure C.1: Mean percentages of GPS locations (“used” locations) within conifer swamp (30-m pixel scale) for each caribou compared to the mean percentages of conifer swamp within caribou range (“available”). Note the differing scales of the y-axis in each plot.

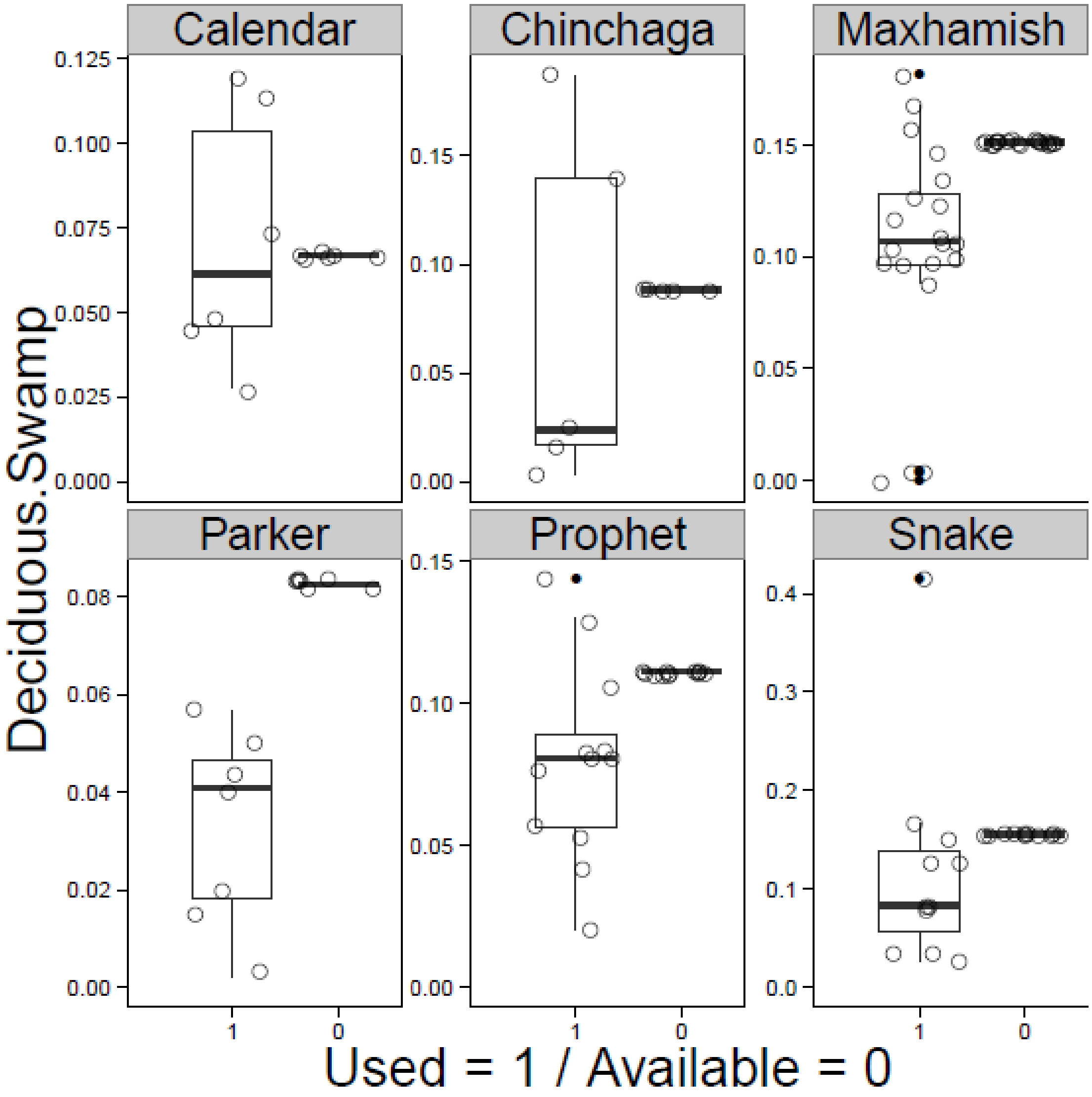


Figure C.2: Mean percentages of GPS locations ("used" locations) within deciduous swamp (30-m pixel scale) for each caribou compared to the mean percentages of deciduous swamp within caribou range ("available"). Note the differing scales of the y-axis in each plot.

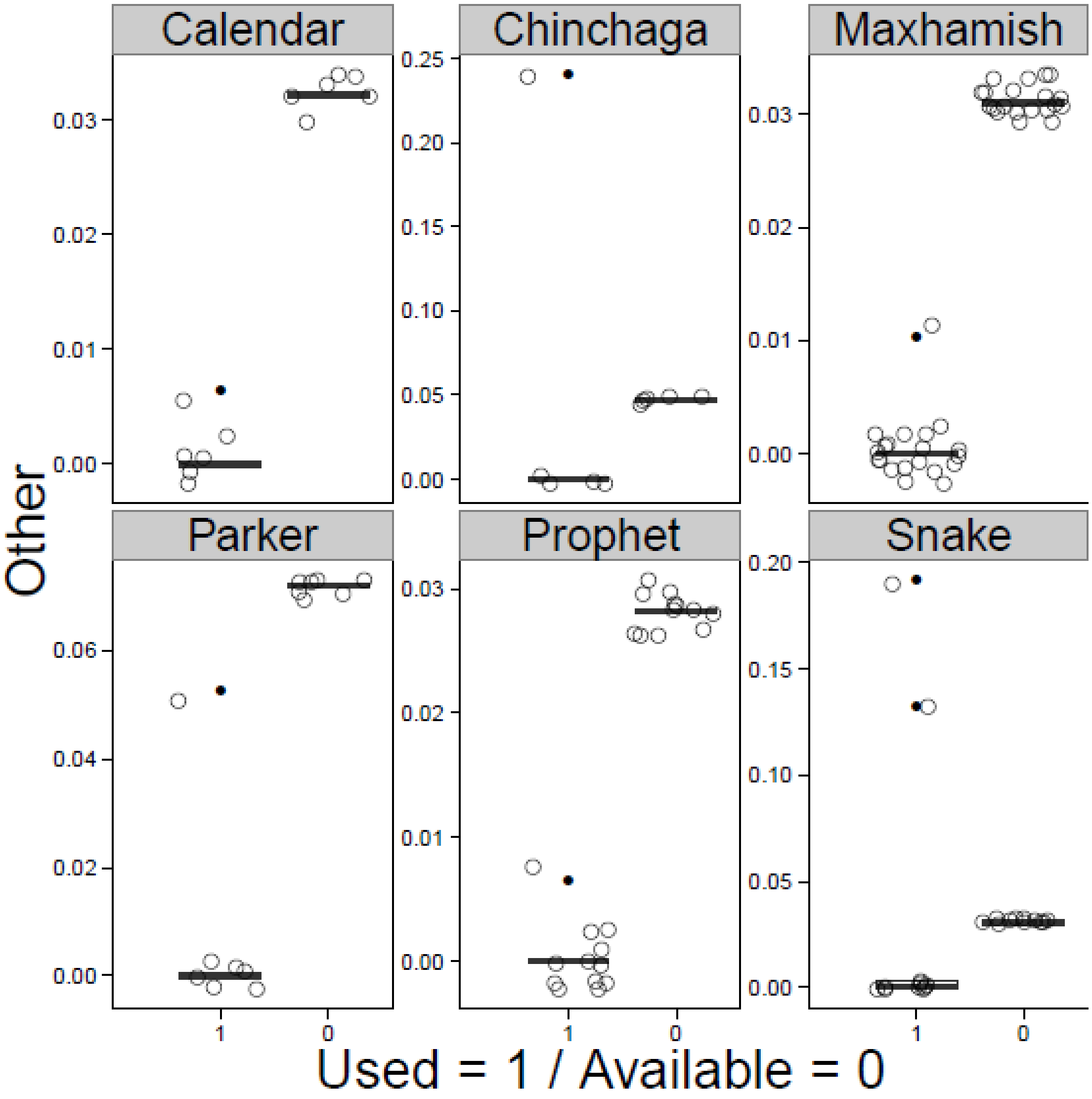


Figure C.3: Mean percentages of GPS locations ("used" locations) within the land cover class "other" (30-m pixel scale) for each caribou compared to the mean percentages of "other" within caribou range ("available"). Other" includes recent forest fires, anthropogenic disturbance and aquatic areas. Note the differing scales of the y-axis in each plot.

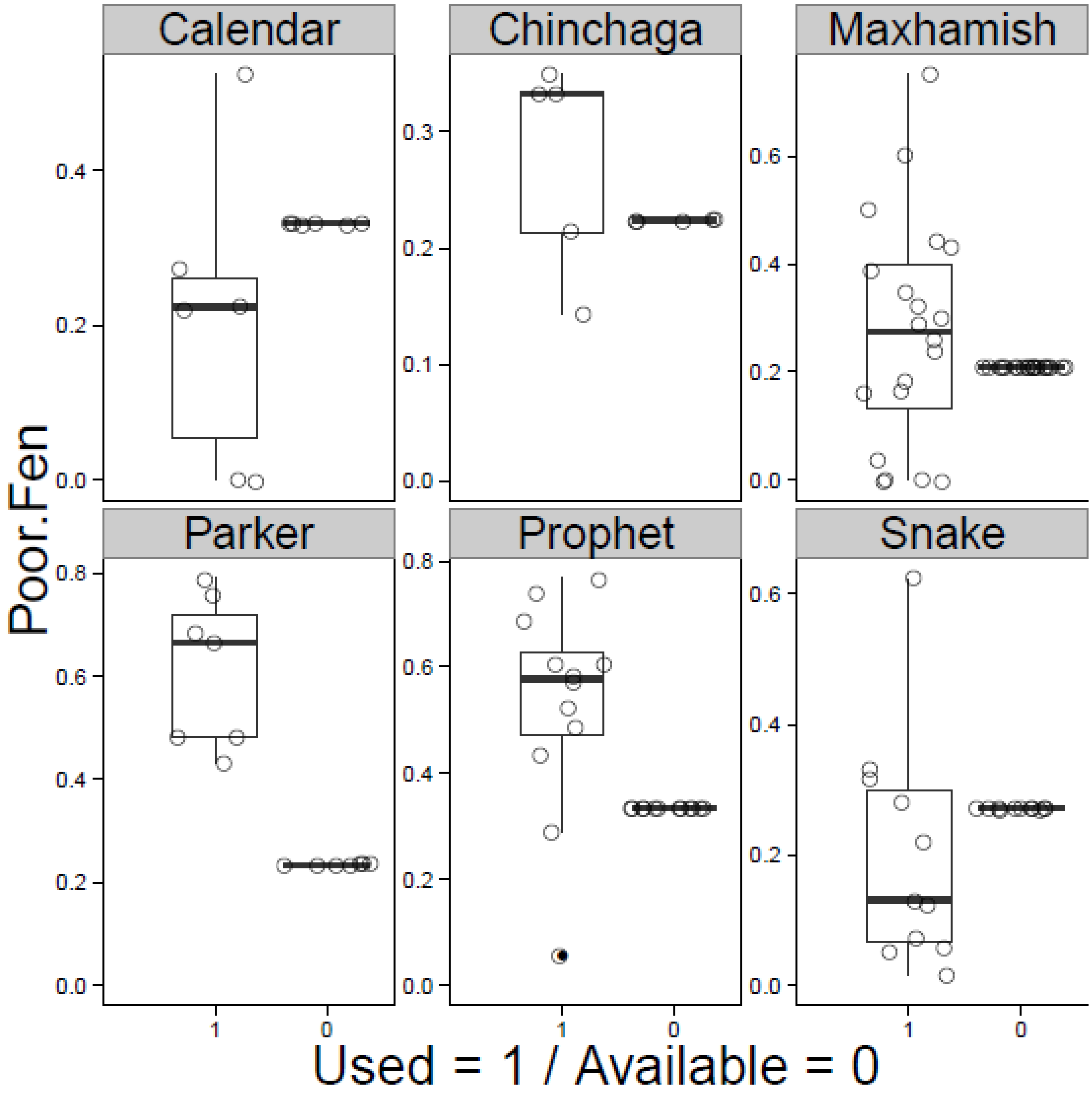


Figure C.4: Mean percentages of GPS locations ("used" locations) within nutrient-poor fen (30-m pixel scale) for each caribou compared to the mean percentages of nutrient-poor fen within caribou range ("available"). Note the differing scales of the y-axis in each plot.

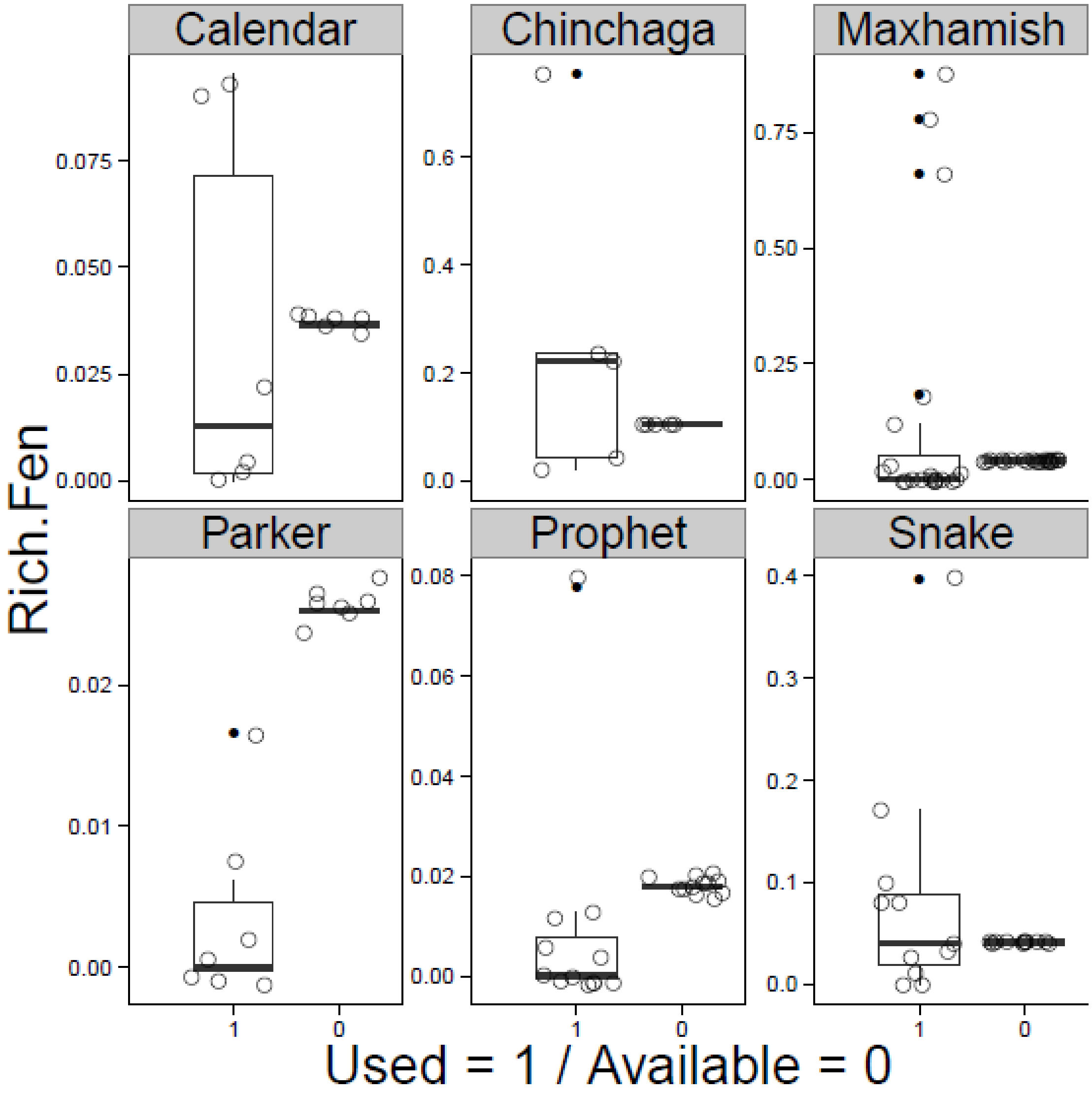


Figure C.5: Mean percentages of GPS locations ("used" locations) within nutrient-rich fen (30-m pixel scale) for each caribou compared to the mean percentages of nutrient-rich fen within caribou range ("available"). Note the differing scales of the y-axis in each plot.

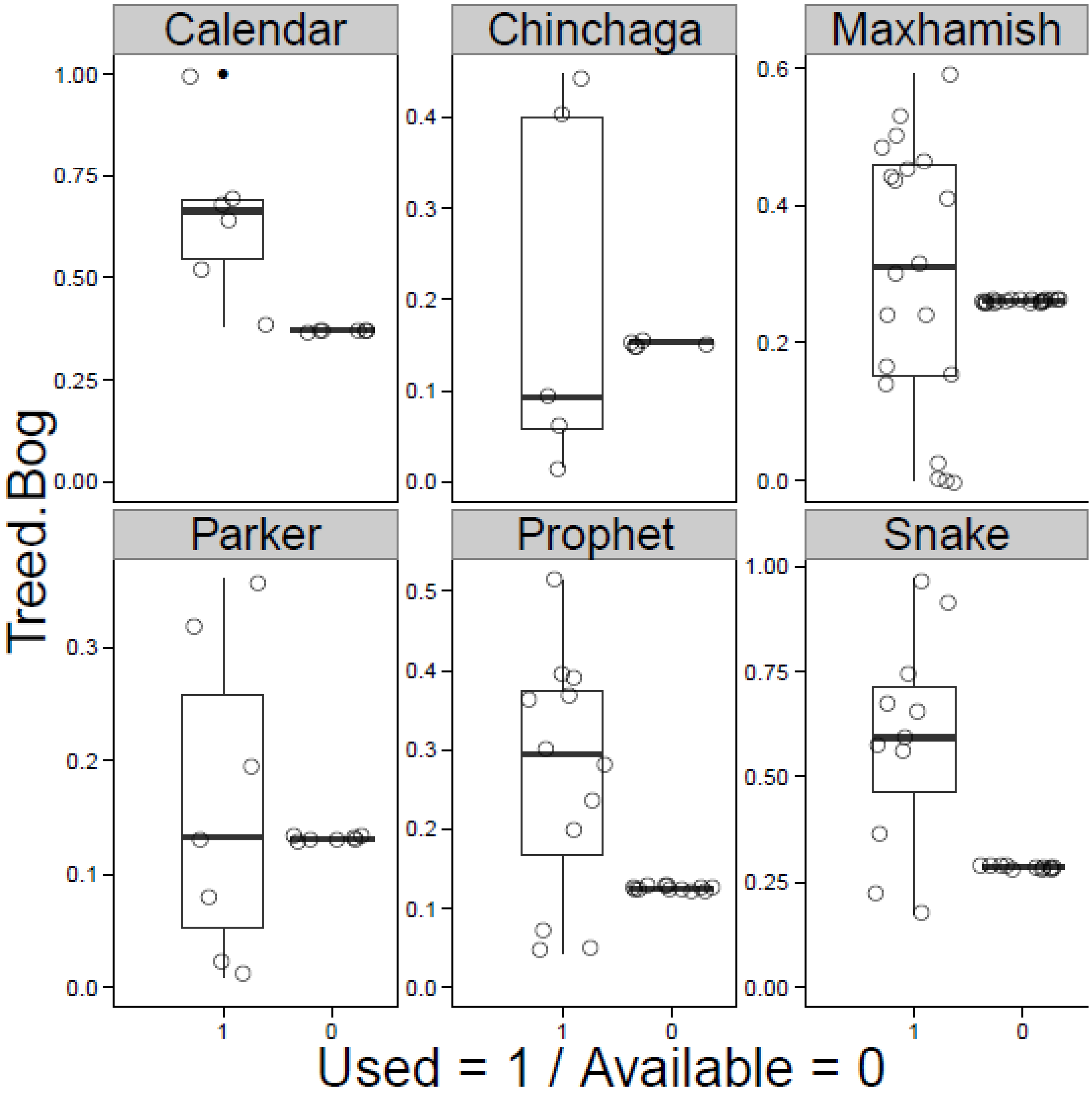


Figure C.6: Mean percentages of GPS locations ("used" locations) within treed bog (30-m pixel scale) for each caribou compared to the mean percentages of treed bog within caribou range ("available"). Note the differing scales of the y-axis in each plot.

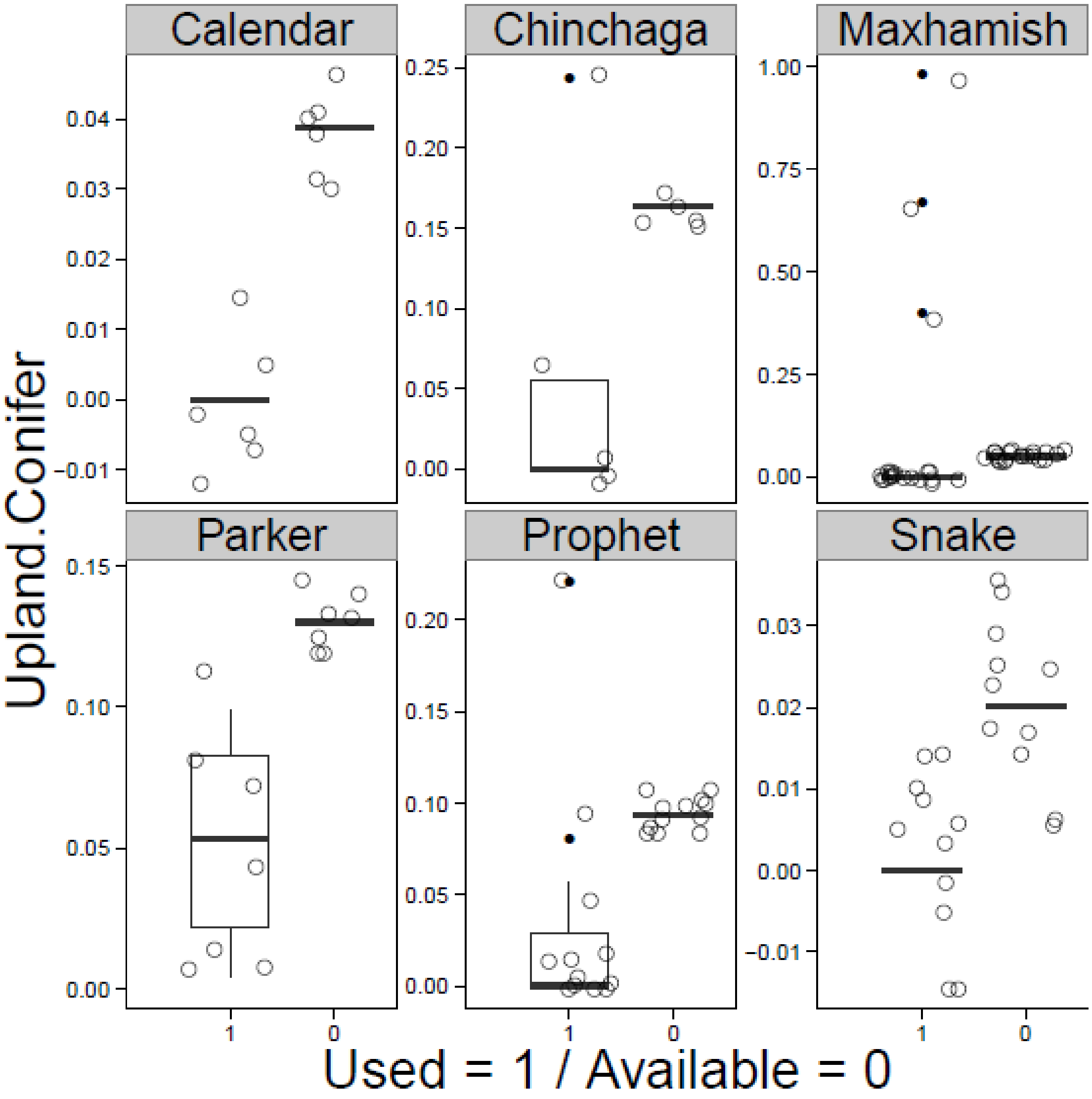


Figure C.7: Mean percentages of GPS locations ("used" locations) within upland conifer forest (30-m pixel scale) for each caribou compared to the mean percentages of upland conifer forest within caribou range ("available"). Note the differing scales of the y-axis in each plot.

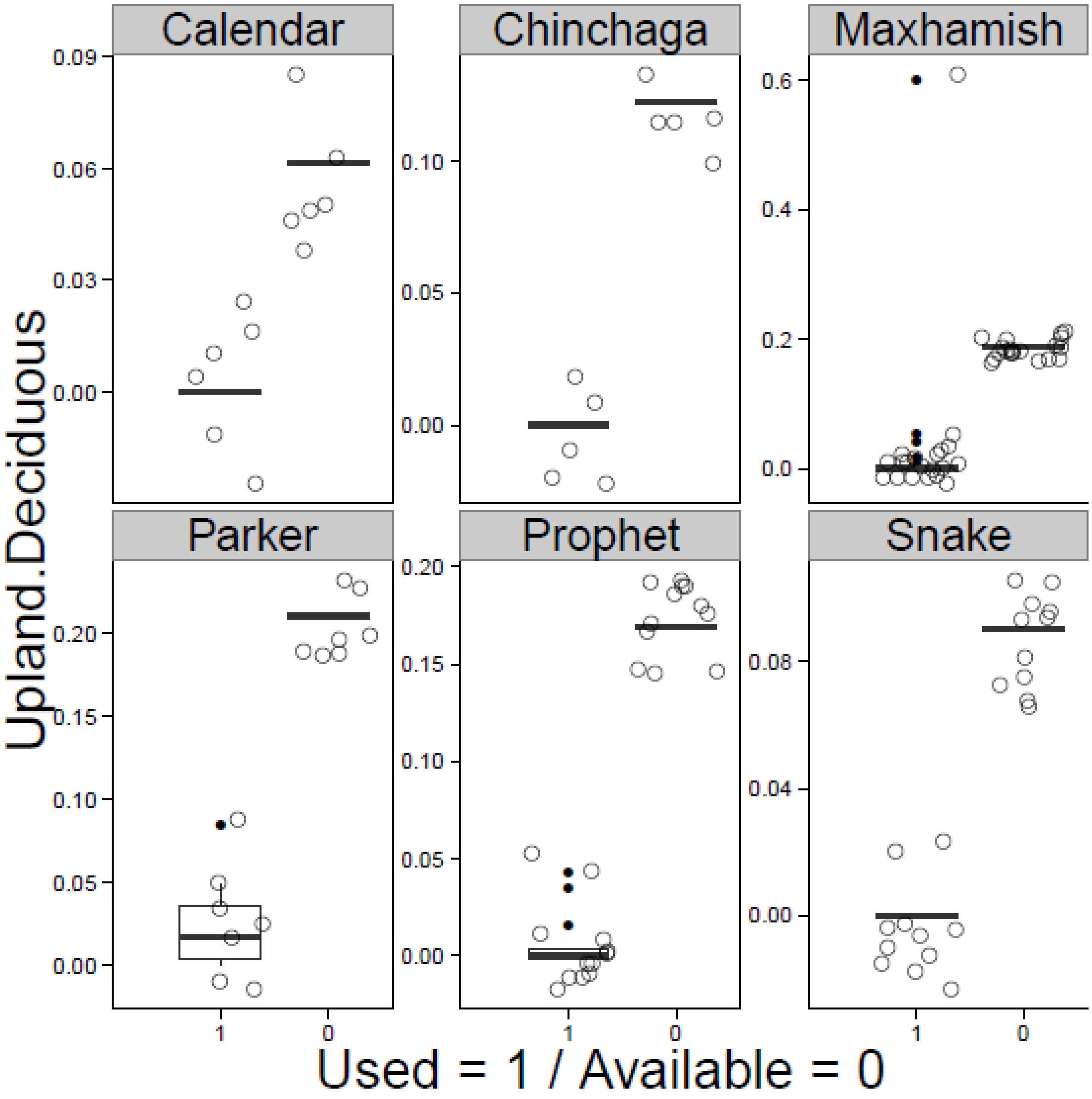


Figure C.8: Mean percentages of GPS locations ("used" locations) within upland deciduous forest (30-m pixel scale) for each caribou compared to the mean percentages of upland deciduous forest within caribou range ("available"). Note the differing scales of the y-axis in each plot.

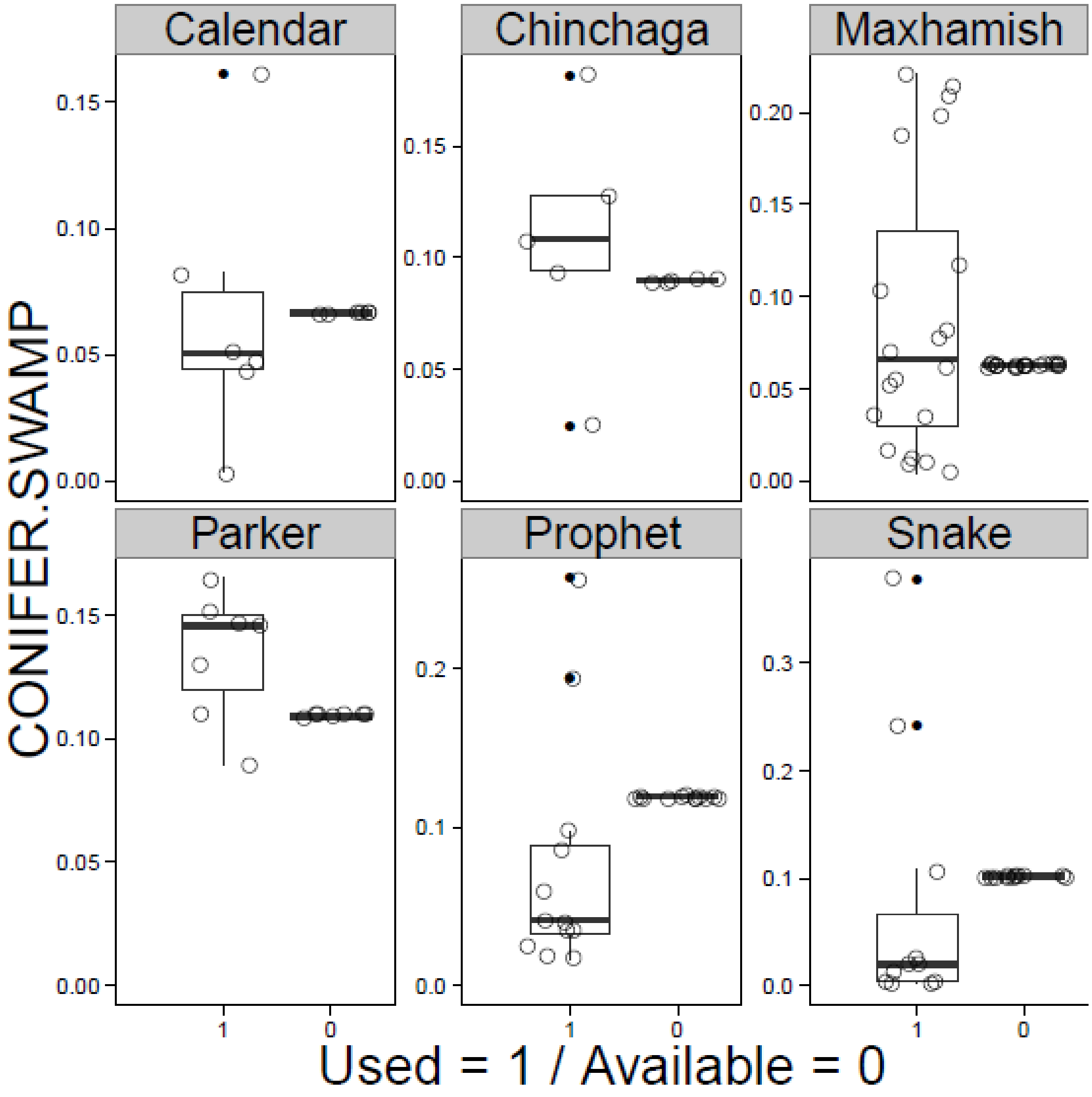


Figure C.9: Mean proportions of conifer swamp (1.5 km radius) surrounding GPS locations ("used" locations) of each caribou compared to the mean proportions within caribou range ("available"). Note the differing scales of the y-axis in each plot.

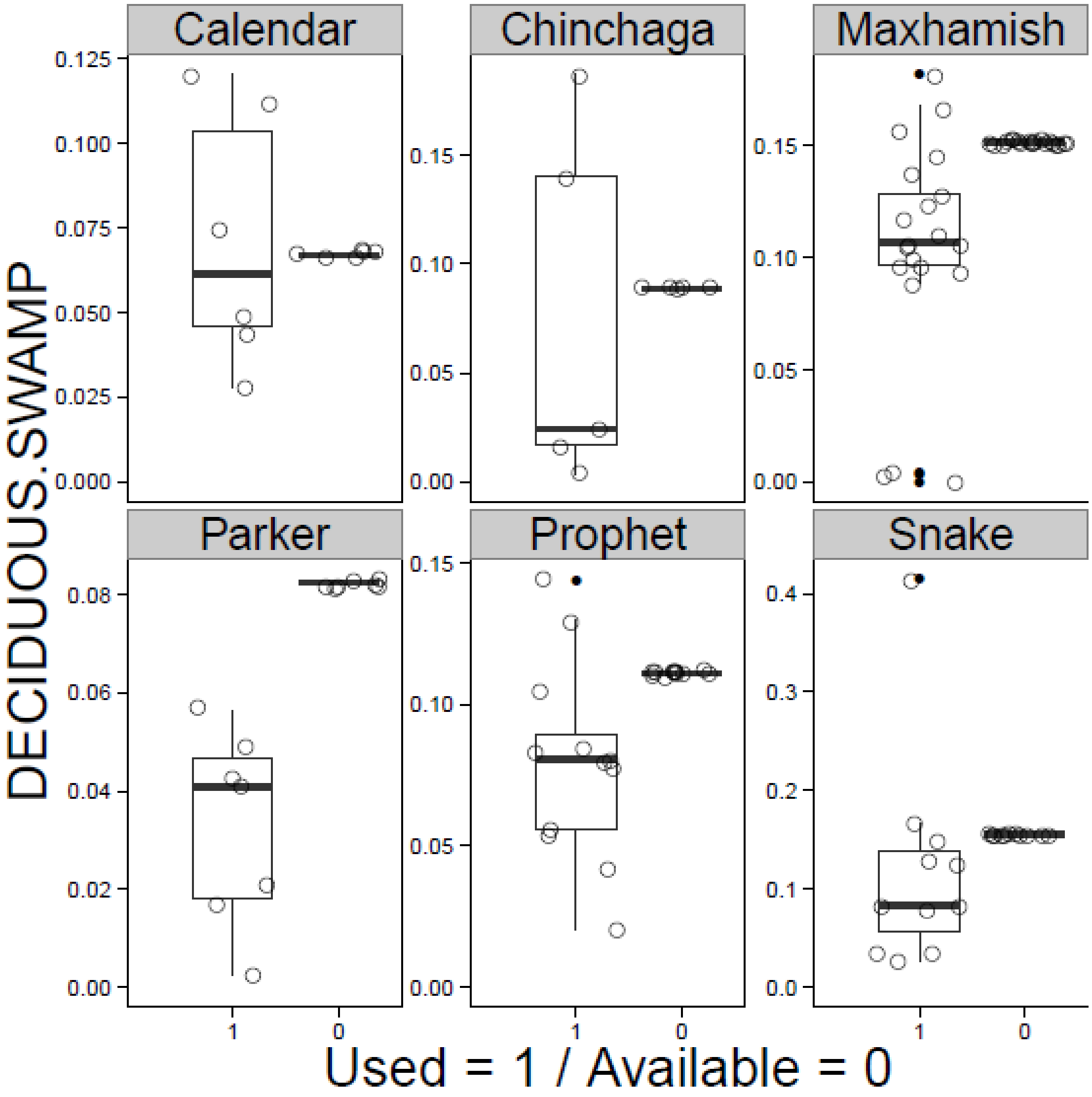


Figure C.10: Mean proportions of deciduous swamp (1.5 km radius) surrounding GPS locations ("used" locations) of each caribou compared to the mean proportions within caribou range ("available"). Note the differing scales of the y-axis in each plot.

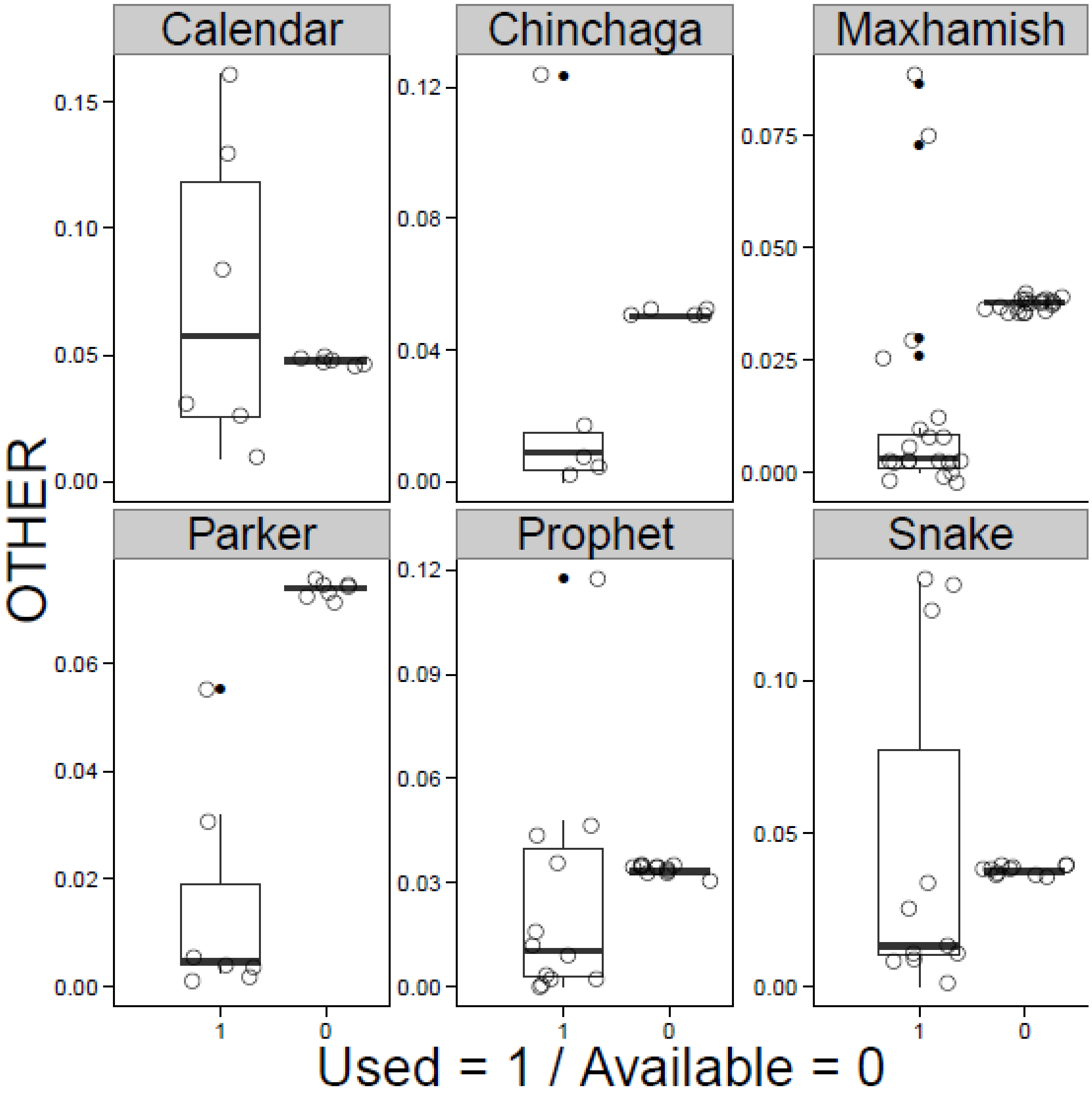


Figure C.11: Mean proportions of the land cover “other” (1.5 km radius) surrounding GPS locations (“used” locations) of each caribou compared to the mean proportions within caribou range (“available”). “Other” includes recent forest fires, anthropogenic disturbance and aquatic areas. Note the differing scales of the y-axis in each plot.

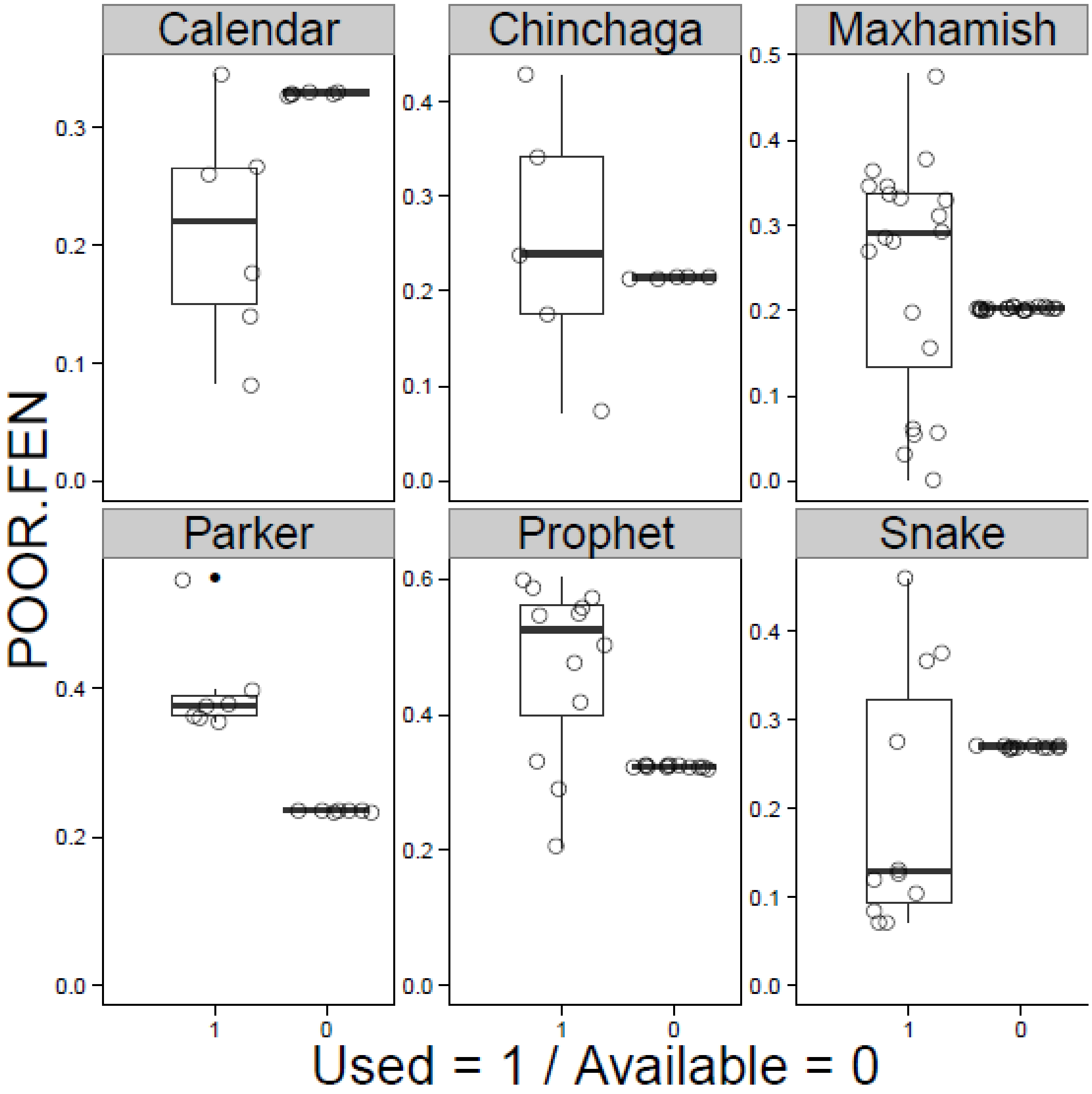


Figure C.12: Mean proportions of nutrient-poor fen (1.5 km radius) surrounding GPS locations ("used" locations) of each caribou compared to the mean proportions within caribou range ("available"). Note the differing scales of the y-axis in each plot.

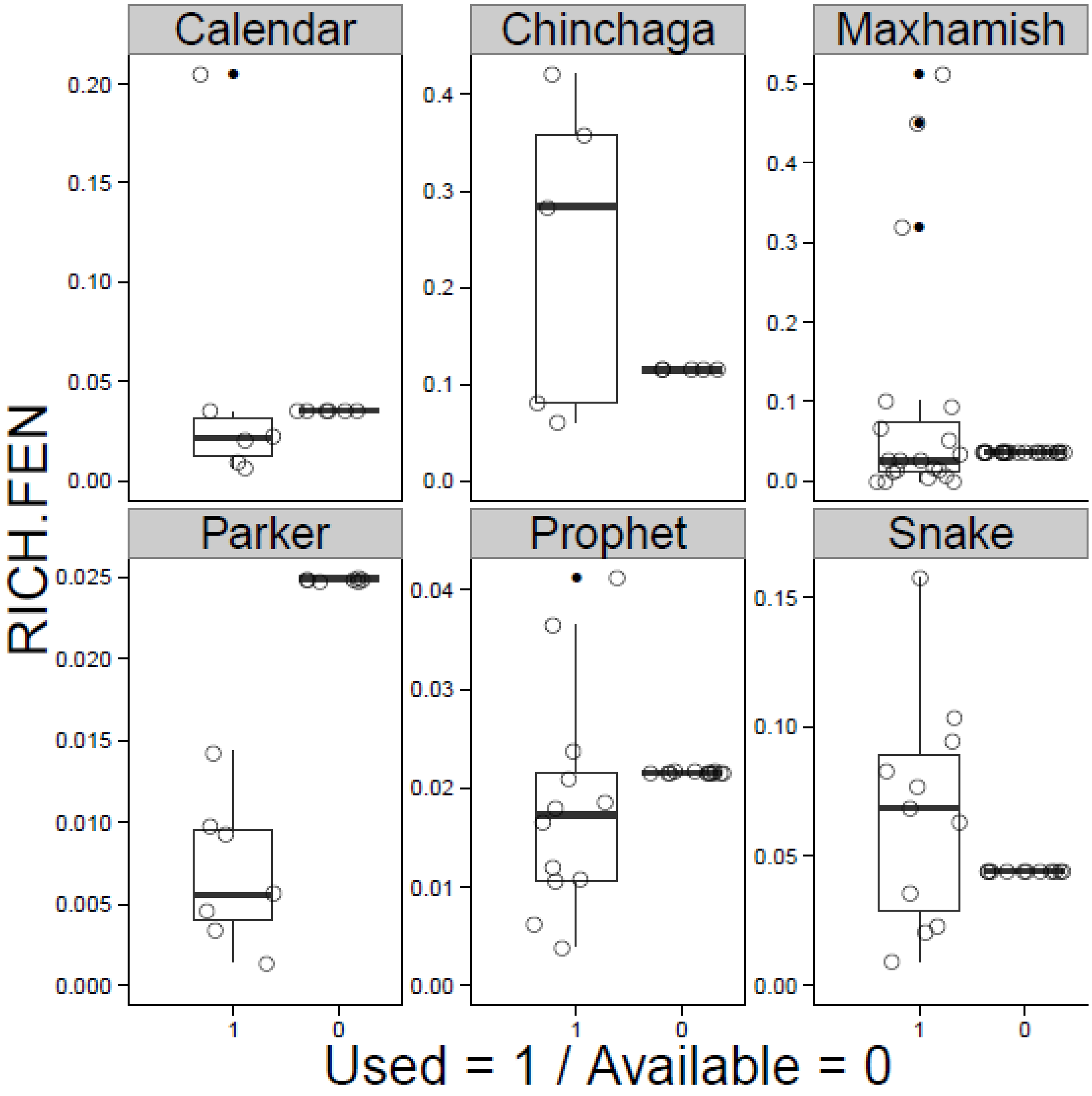


Figure C.13: Mean proportions of nutrient-rich fen (1.5 km radius) surrounding GPS locations ("used" locations) of each caribou compared to the mean proportions within caribou range ("available"). Note the differing scales of the y-axis in each plot.

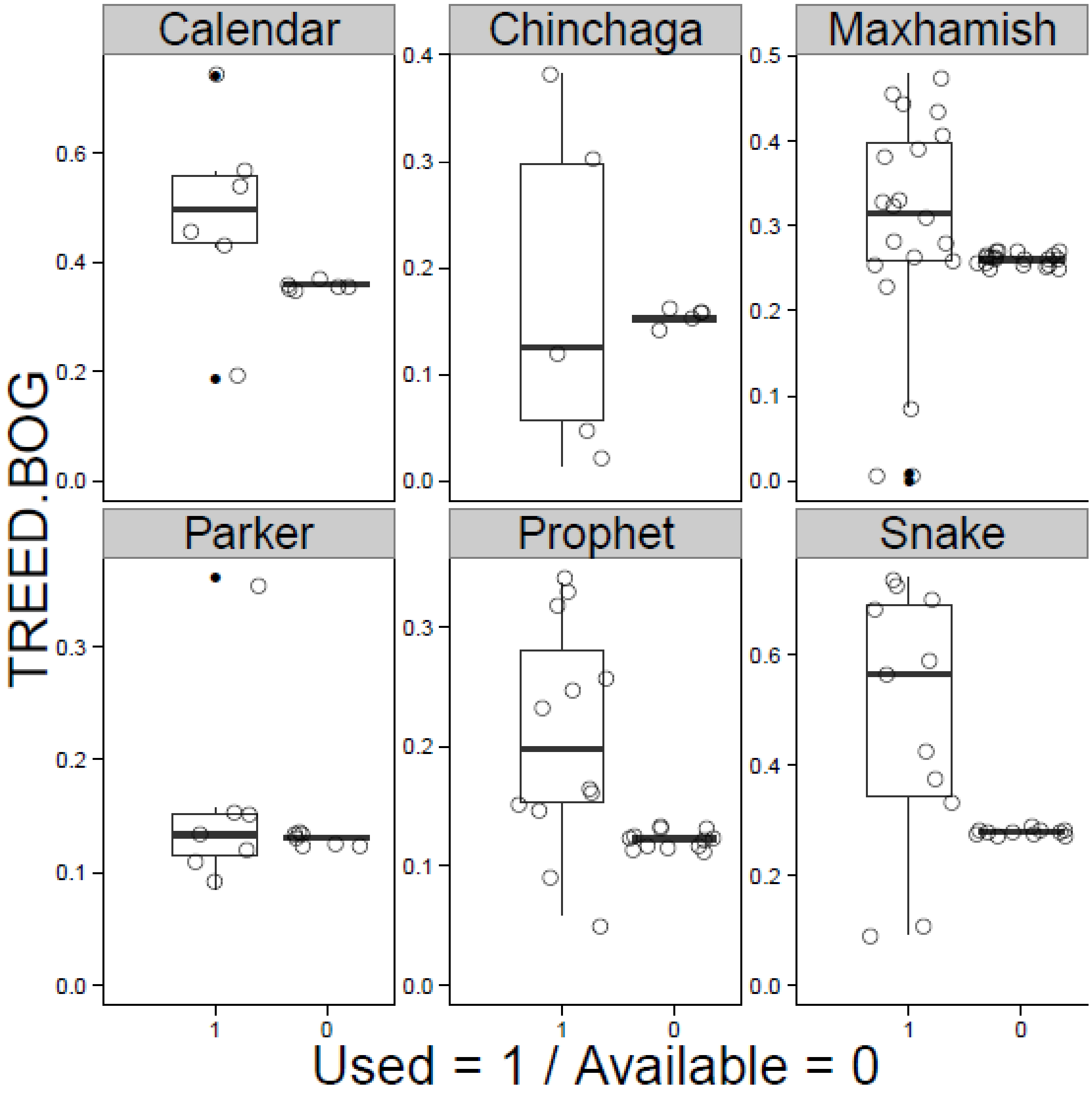


Figure C.14: Mean proportions of treed bog (1.5 km radius) surrounding GPS locations ("used" locations) of each caribou compared to the mean proportions within caribou range ("available"). Note the differing scales of the y-axis in each plot.

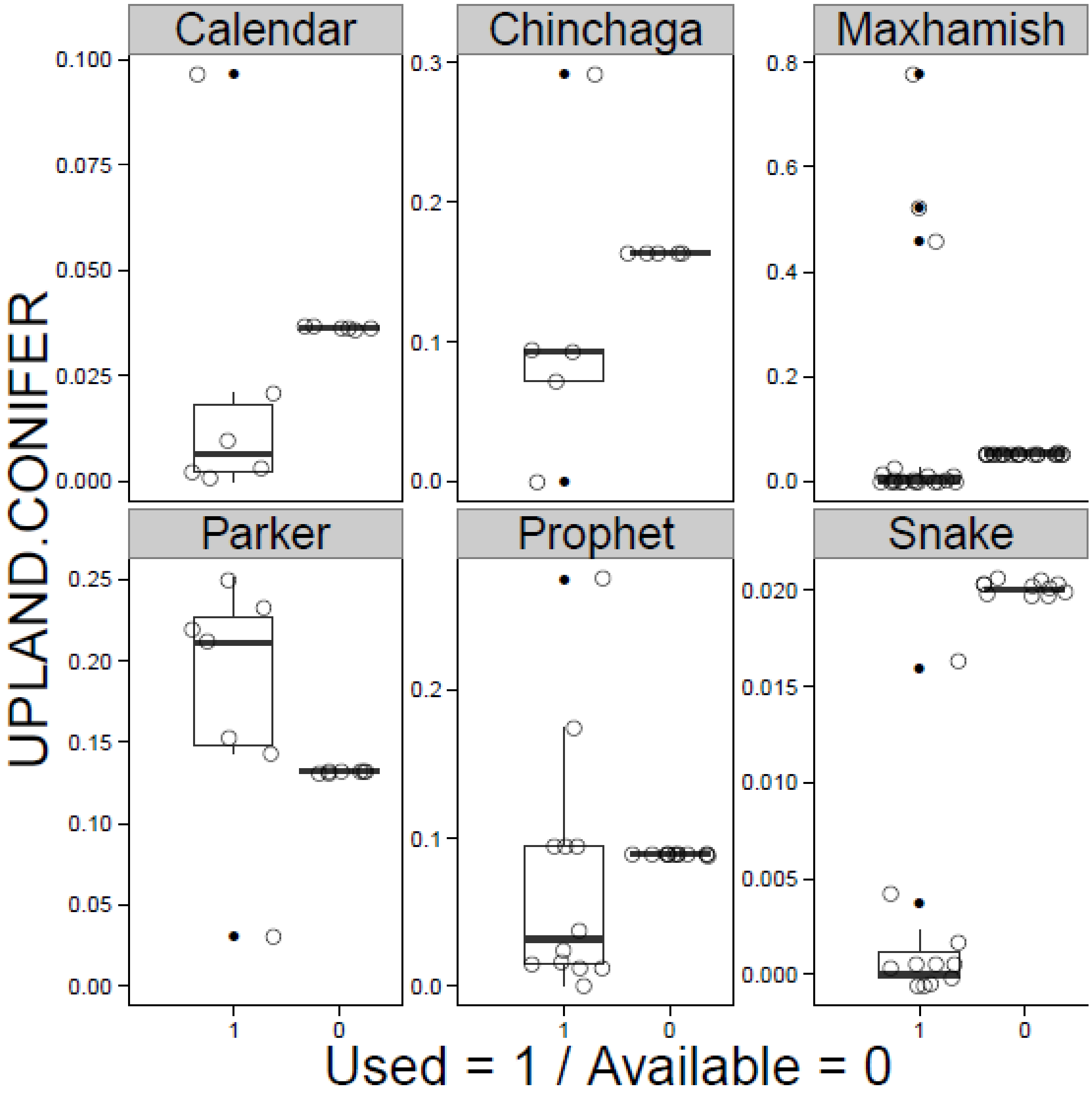


Figure C.15: Mean proportions of upland conifer forest (1.5 km radius) surrounding GPS locations ("used" locations) of each caribou compared to the mean proportions within caribou range ("available"). Note the differing scales of the y-axis in each plot.

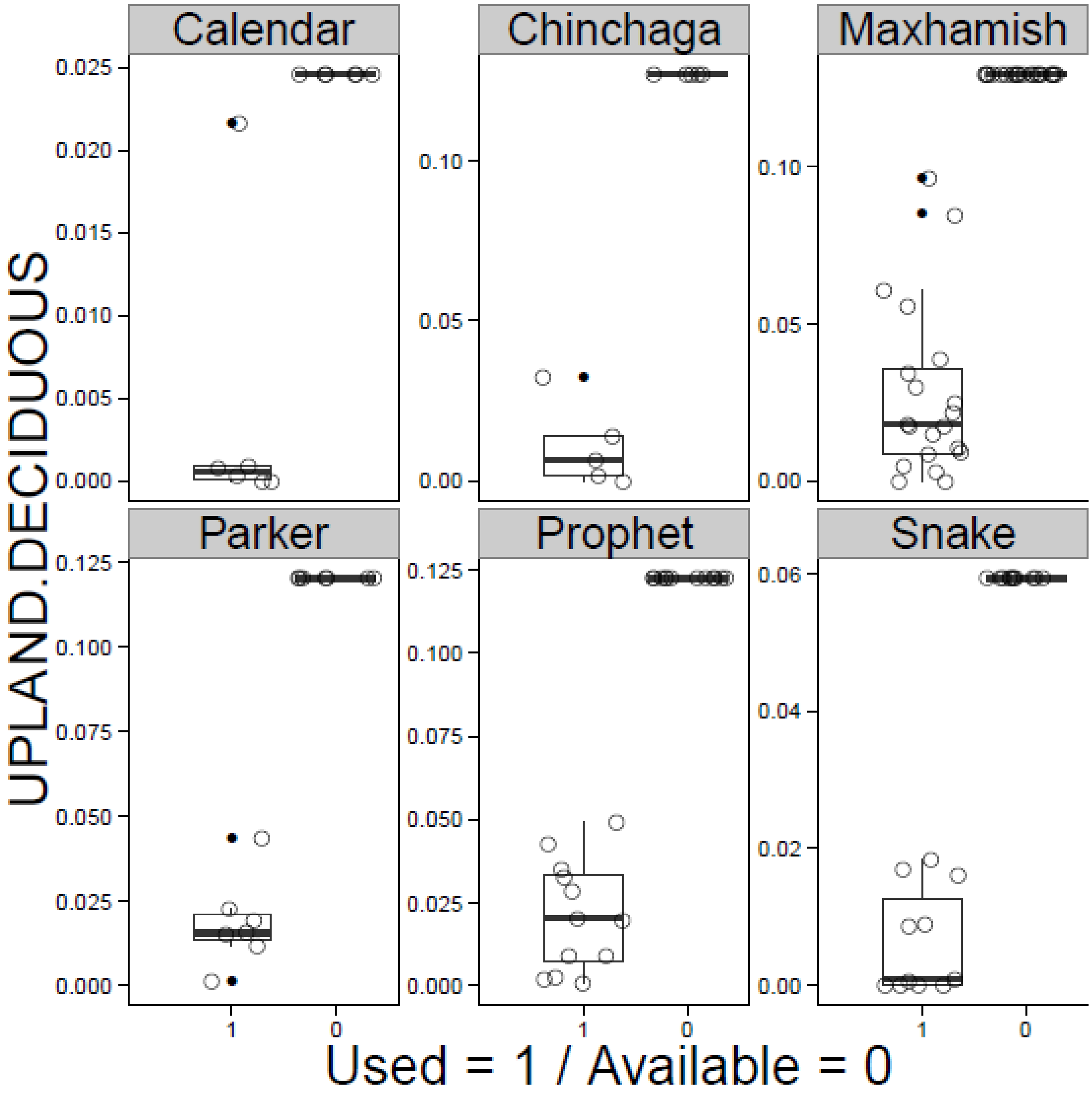


Figure C.16: Mean proportions of upland deciduous forest (1.5 km radius) surrounding GPS locations ("used" locations) of each caribou compared to the mean proportions within caribou range ("available"). Note the differing scales of the y-axis in each plot.

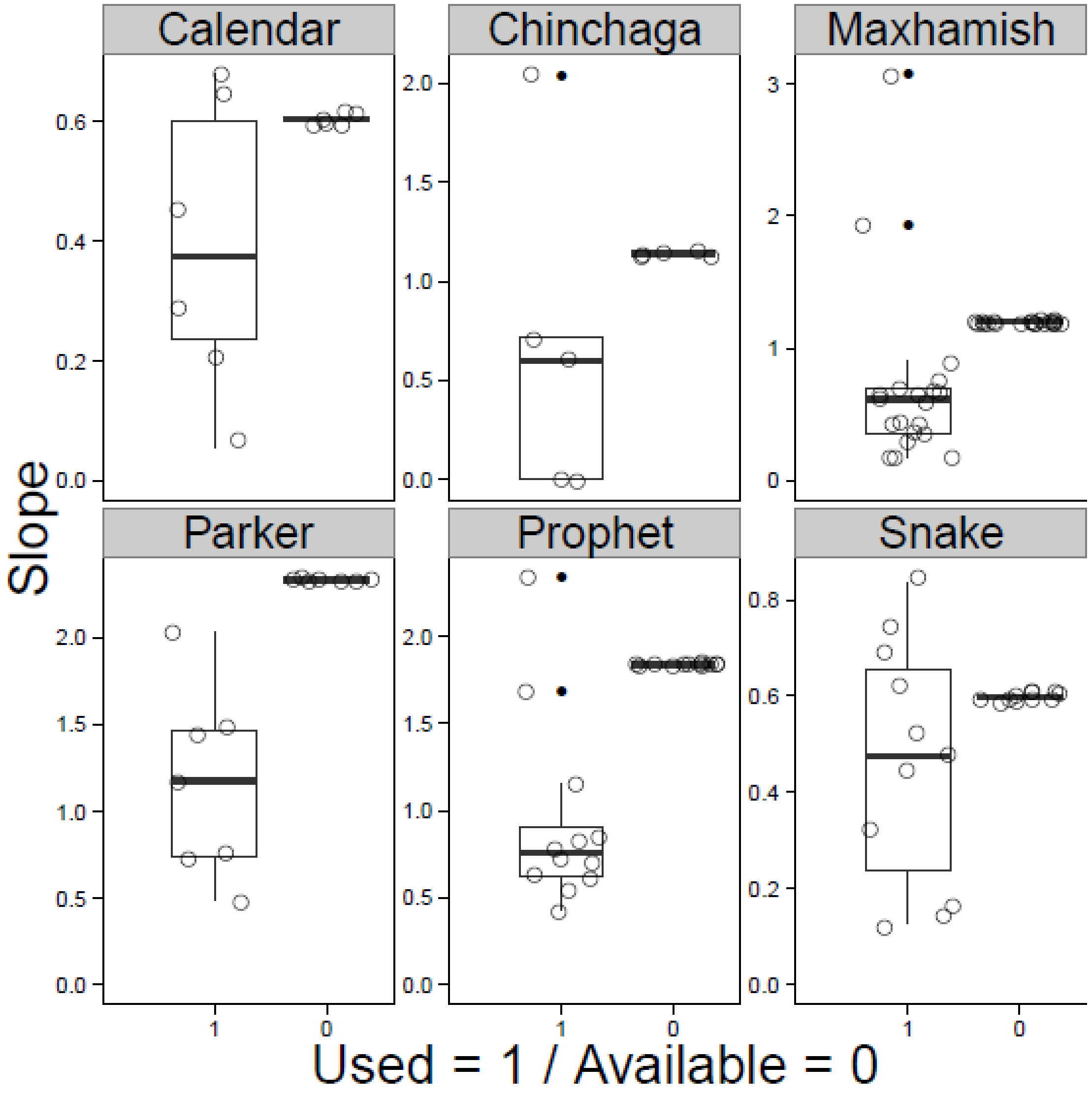


Figure C.17: Mean values of slope associated with GPS locations ("used" locations) of each caribou compared to the mean values within caribou range ("available"). Note the differing scales of the y-axis in each plot.

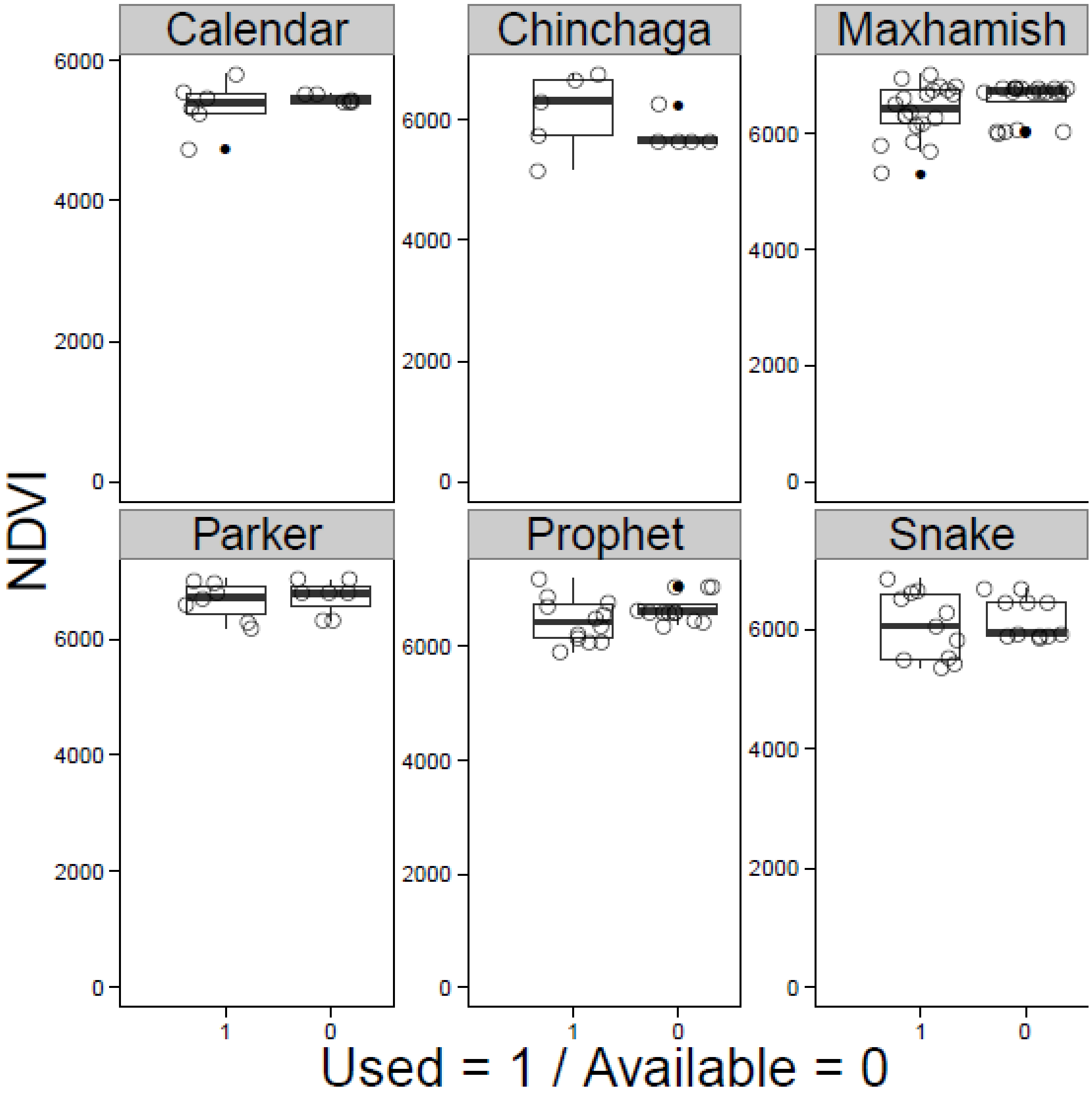


Figure C.18: Mean values of normalized difference vegetation index (NDVI) associated with GPS locations ("used" locations) of each caribou compared to the mean values within caribou range ("available"). Note the differing scales of the y-axis in each plot.

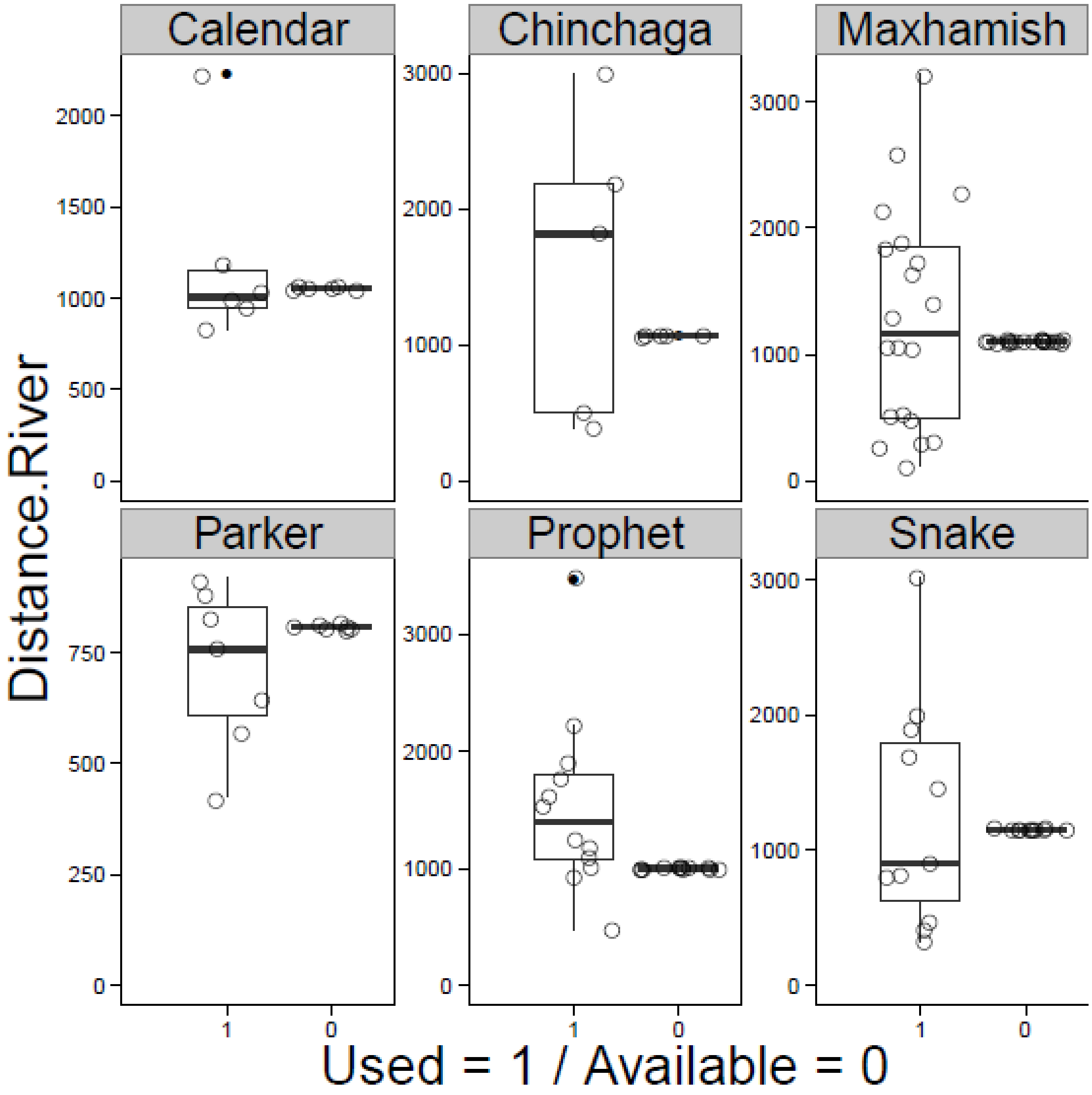


Figure C.19: Mean distances to the nearest river associated with GPS locations ("used" locations) of each caribou compared to the mean values within caribou range ("available"). Note the differing scales of the y-axis in each plot.

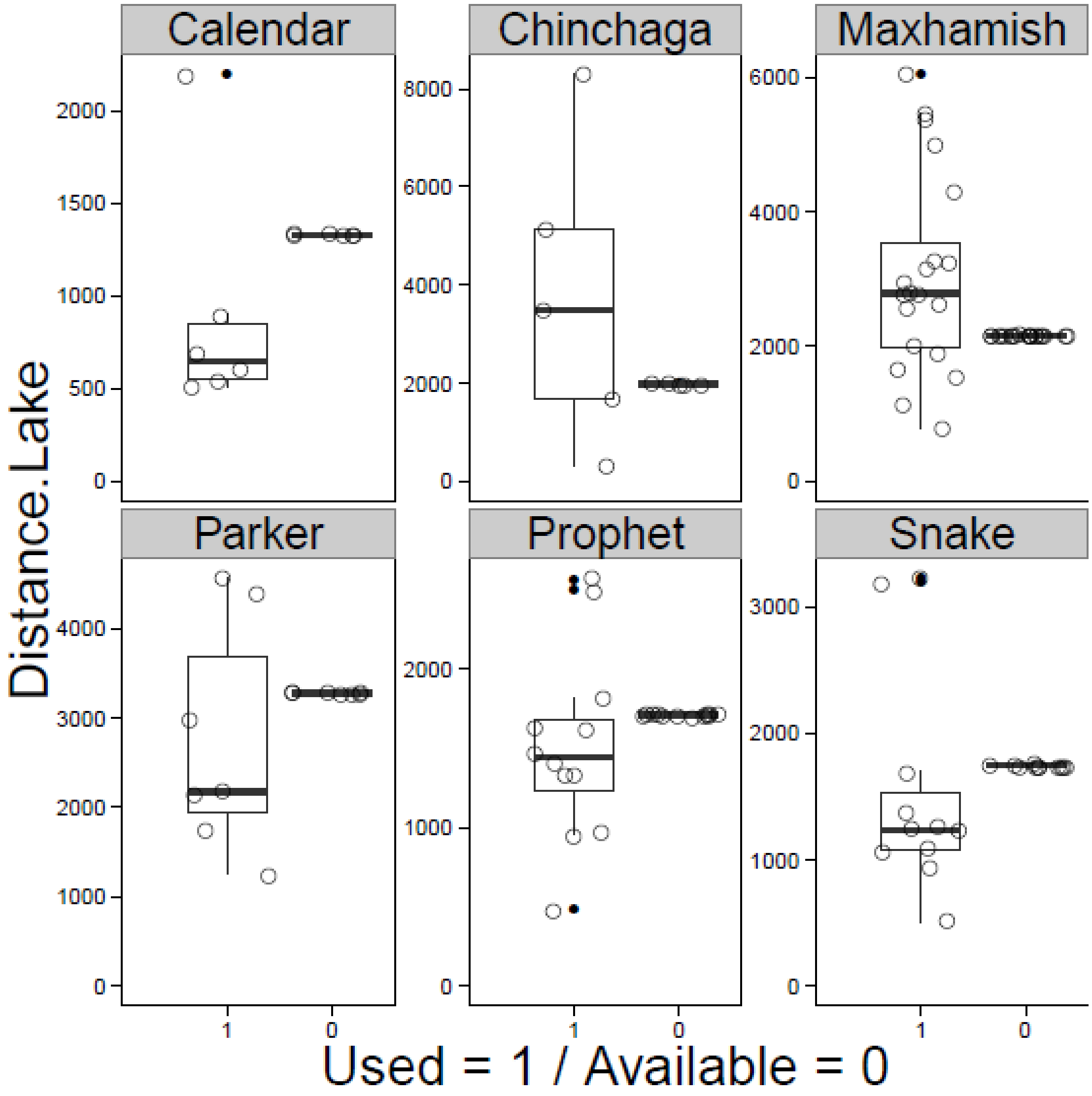


Figure C.20: Mean distances to the nearest lake associated with GPS locations ("used" locations) of each caribou compared to the mean values within caribou range ("available"). Note the differing scales of the y-axis in each plot.

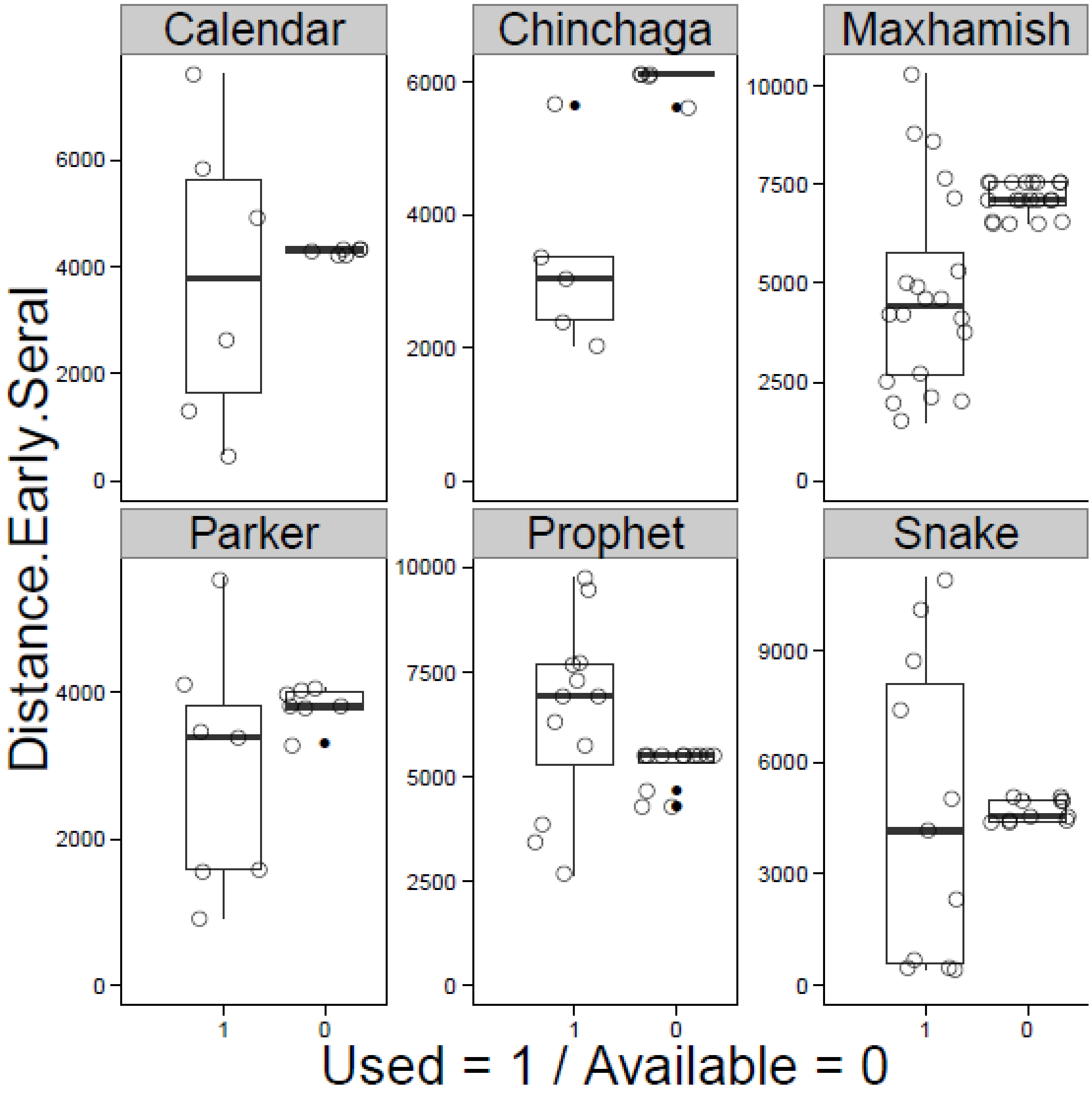


Figure C.21: Mean distances to the nearest early seral vegetation associated with GPS locations ("used" locations) of each caribou compared to the mean values within caribou range ("available"). Early seral vegetation was defined as forest fires or cut blocks ≤ 50 years old. Note the differing scales of the y-axis in each plot.

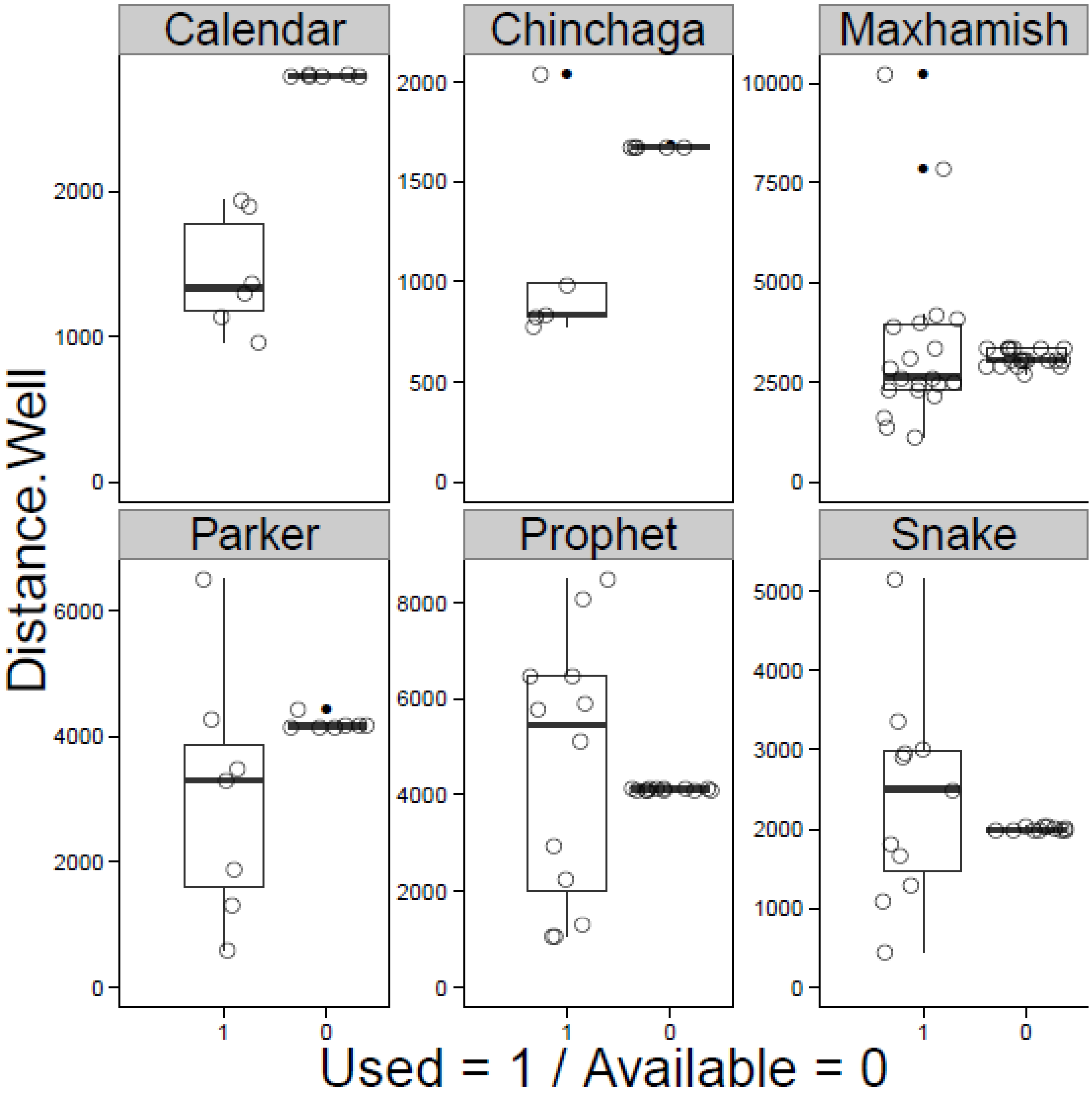


Figure C.22: Mean distances to the nearest well site associated with GPS locations ("used" locations) of each caribou compared to the mean values within caribou range ("available"). Note the differing scales of the y-axis in each plot.

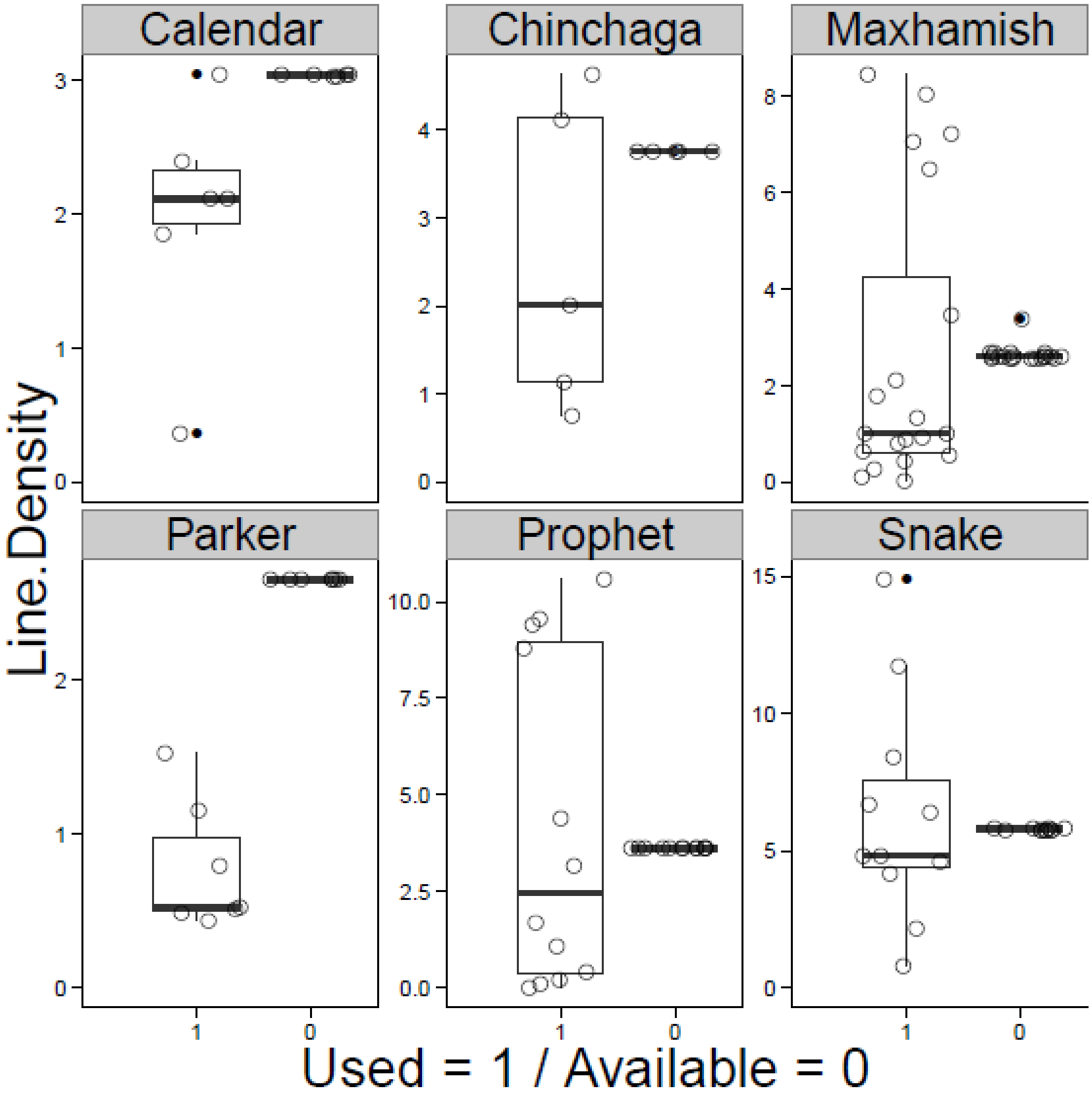
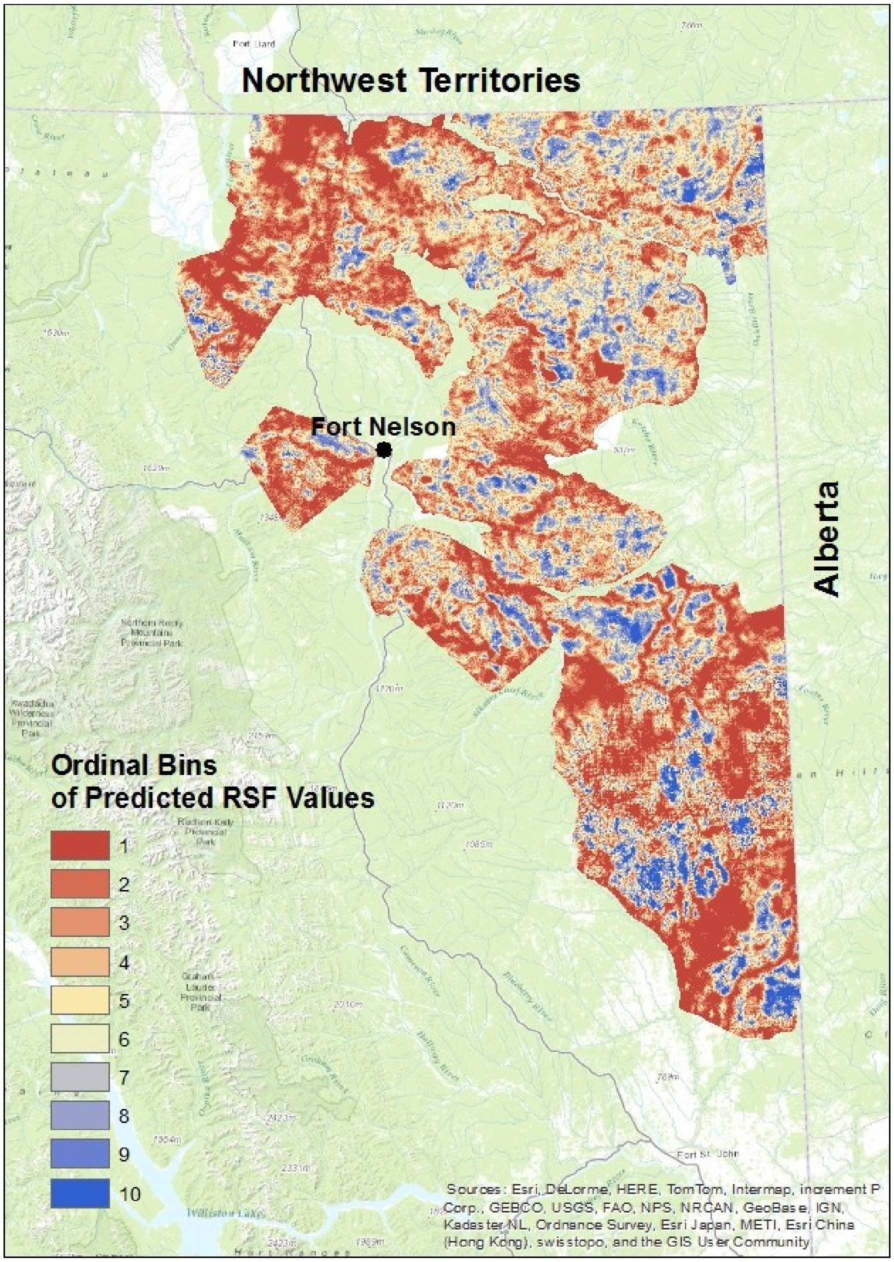


Figure C.23: Mean densities of linear features (400-m radius) surrounding GPS locations (“used” locations) of each caribou compared to the mean values within caribou range (“available”). Linear features include seismic lines, pipe lines, and roads. Note the differing scales of the y-axis in each plot.

APPENDIX D: PREDICTED CALVING AREAS FOR BOREAL CARIBOU IN NORTHEAST BRITISH COLUMBIA

We used the top resource selection function to develop spatially explicit predictions of calving area selection by female boreal caribou in northeast British Columbia (Fig. D.1). Predictions were restricted to areas within caribou ranges.



Sources: Esri, DeLorme, HERE, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, and the GIS User Community

Figure D.1: Spatially explicit predictions of calving area selection by female boreal caribou in northeast British Columbia. Females showed disproportionate use of areas with RSF bin values ≥ 6.