Seasonal Habitat Selection by Boreal Caribou in Northeast British Columbia

Predictive Mapping Methodology and Results

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Overview

This document describes the methods used to develop predictive maps of seasonal habitat selection by female boreal caribou in northeast British Columbia. Maps were developed for three seasons: Summer (15 July – 14 September), Rut / Fall (15 September – 30 November), and Winter (1 December – 15 April). A map of predicted calving areas, which was developed in 2015, is also available (DeMars & Boutin 2015).

Methods

Caribou Spatial Data

Maps of seasonal habitat selection used spatial data from 172 reproductive-aged female boreal caribou fitted with GPS collars. Individual females were distributed among all five recognized caribou ranges in northeast BC (Calendar: *n* = 20; Chinchaga: *n* = 44; West Side Fort Nelson: *n* = 30; Maxhamish: *n* = 38; Snake-Sahtaneh: *n* = 40) and were monitored for various intervals between 2011 – 2017. The interval of GPS location acquisition (i.e., fix rate) varied among radio-collars, ranging from once per day to every eight hours.

Data Screening

Prior to analyses, the following procedures were used to screen the raw data for potential errors. First, all locations with low positional accuracy were removed (two-dimensional GPS locations (or fixes) with dilution of precision values > 5; Lewis et al. 2007). Next, outlying locations that were beyond the range of possible caribou movement were removed using the methods of Bjørneraas et al. (2010). These procedures censored < 0.4% of the data. Individual caribou data sets were then analyzed to determine fix rates. Based on this information, a regular sampling interval was specified for each individual data set by removing GPS locations that fell outside of the normal sampling interval, a procedure necessitated by some collars having periods of aberrant fix acquisition. Per collar rates of fix success for each season were then calculated and only caribou-seasons with fix success rates ≥ 90% were retained for subsequent analyses as low rates of fix success can bias inferences on habitat selection (Frair et al. 2010). For each season-specific analysis, individuals with < 30 days of monitoring time were also excluded.

After these screening procedures, the final data set consisted of 133 caribou (Calendar: *n* = 19; Chinchaga: *n* = 28; West Side Fort Nelson: *n* = 22; Maxhamish: *n* = 33; Snake-Sahtaneh: *n* = 31). Among the three seasons, winter analyses used data from 120 caribou (*n* = 197 caribou-seasons), summer analyses used data from 38 caribou (*n* = 61 caribou-seasons), and fall used data from 85 caribou (*n* = 147 caribou-seasons).

Seasonal Resource Selection: General Framework

Habitat selection by female caribou was evaluated 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. RSFs were estimated at a second-order scale (*sensu* Johnson 1980; Fig.1), which compared caribou GPS locations to random locations sampled within a herd's range. Based on sensitivity analyses in DeMars and Boutin (2015), 5000 random points were sampled within each range to adequately characterize resource availability.

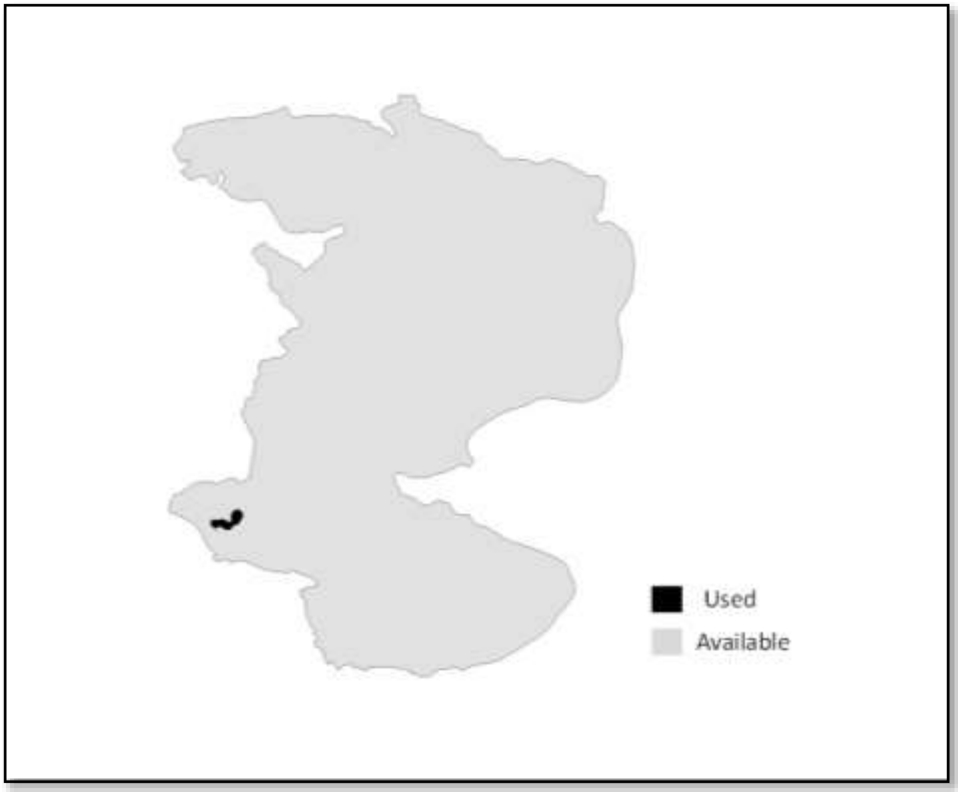

Figure 1: Second-order resource selection by female boreal caribou in northeast British Columbia. The black dots indicate GPS locations of a female within a given season. Attributes of these GPS locations are compared to attributes of random locations generated within a herd's range (here, the Snake-Sahtaneh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

Environmental Variables

Seasonal habitat selection was modelled using the same suite of environmental variables as described in DeMars and Boutin (2014, 2015). This suite included variables describing land cover type, normalized difference vegetation index (NDVI), slope, natural features (lakes, rivers and forest fires) and anthropogenic disturbance. Land cover type was characterized by Enhanced Wetlands Classification (EWC) GIS data (30-m pixel resolution) developed by Ducks Unlimited Canada, which was collapsed into eight categories that were biologically meaningful to caribou (Table 1). Caribou response to land cover was assessed 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 1-km radius surrounding each used and random location (hereafter, landscape context).

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.

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: ~22%
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: ~25%
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: ~6%
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: ~8%
Upland deciduous	Upland deciduous	Mineral soils with tree cover >25% and >25% deciduous trees Dominant tree species: aspen and paper birch. Areal coverage: ~14%
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: ~5% (Cloud shadow <0.5%)

In ungulate studies, NDVI is considered an index of forage productivity (Gustine et al. 2006; Pettorelli et al. 2007; Suzuki et al. 2011). NDVI data were obtained from the U.S. National Aeronautics and Space Administration MODIS database. These data (250-m pixel resolution) were derived from MODIS images taken over a 16-day window. Data were obtained for each year (2011 – 2017) and an average NDVI value was calculated for each pixel during each summer and fall season (NDVI was not considered for winter analyses). The 'nearest-neighbour' interpolation algorithm within ArcGIS (version 10.6.1; Esri, Inc., Redlands, CA, USA) was used to rescale the NDVI data to match the resolution of the land cover data (30-m pixel resolution).

Slope was calculated in a GIS framework using a digital elevation model obtained from BC Terrain Resources Information Management data. To model rivers, lakes, major roads and forest-related impacts (fires, cut blocks, and forestry roads), data sets were obtained from the BC Geographic Data Discovery Service. Cut blocks and forest fires < 50 years old were combined 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). Impacts from well sites, pipelines, seismic lines (1996 to present) and petroleum development roads were modelled using data sets from the BC Oil and Gas Commission. Linear feature data were also obtained 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, all major roads, forestry roads, petroleum development roads, and seismic lines were merged into one file then integrated at a scale of 10-m to eliminate redundancies among the original data sets.

Caribou response to natural and anthropogenic features was evaluated using measures similar to those described in DeMars & Boutin (2014). For assessing caribou response to rivers, lakes, early seral vegetation and well sites, distance-to measures were used. These measures compare the relative proximities of caribou and random locations to a given feature. For linear features, two measures were considered: distance-to and 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. These year-specific variables were then matched to caribou GPS locations of the same year and season (i.e. 2014 summer locations were matched to disturbance variables calculated up to 15 July 2014). Year-specific sets of random locations were also sampled to account for yearly changes in the availability of disturbance variables.

Statistical Analyses

For all seasonal analyses, RSFs were estimated 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, individual caribou-year was assigned as a random grouping effect (i.e. a random intercept). This formulation of caribou-year accounts for yearly differences in resource selection. GLMMs therefore took the form

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

where the left-hand side of the equation is the logit transformation for location y_i (binary response: 1 = caribou GPS location; 0 = random location), 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

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

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 summer and fall RSFs, 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

For the winter, NDVI was excluded from the model structure. To better compare relative effect sizes, all variables were standardized before model fitting. For fine-scale land-cover, upland conifer was set as the reference category. Note that this model specification results in a ranking of land-cover types; thus, inferences on selection of a given land-cover are relative to upland conifer. For landscape context, univariate RSFs were conducted to determine the land-cover proportions (1-km radius) that had the most explanatory power, as defined by Akaike's Information Criterion (AIC) values. The top two variables describing land-cover proportions—the proportion of treed bog and the proportion of upland deciduous—were retained for final modelling.

Within this base model, exponential decay transformations of distance-to variables were considered to improve model performance, as measured by comparing AIC values from univariate RSFs fit to transformed and untransformed variables (the variable-type with the lowest AIC values was retained for final modelling). Following Nielsen et al. (2009), these transformations used a decay of $e^{-\alpha d}$ where *d* is the distance to the landscape feature and α is the shape parameter. The shape parameter was set to 0.002, which erodes the effect of a feature to where distances > 1500-m essentially have a similar and limited effect. For linear features, a similar approach was used to compare the predictive performance of line density versus distance-to measures. In all final seasonal models, two interaction terms were considered that evaluated how caribou responded to forage availability and linear features within landscapes with high proportions of treed bog, which previous univariate analyses found to be the landscape context variable with the highest selection value. These interactions therefore took the form of

*Proportion of treed bog * NDVI (summer and fall only)*

*proportion of treed bog * top linear feature variable*

Model Validation

Model performance was assessed using *k*-fold cross-validation (Boyce et al. 2002). In this process, the data were first randomly partitioned by individual caribou-year into five folds (or subsets). Four of these folds were used for model training then model prediction was tested on the GPS locations from the withheld caribou-years. For each test, the fixed-effects output from the training data was used to predict values for both the random locations generated within each range and the withheld GPS locations. The predicted values of the range random points were then partitioned into deciles (i.e. 10 ordinal bins containing an equal number of random points) and model prediction was assessed 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). This process was repeated five times to calculate a mean r_S with higher $\bar{r}_s$ values indicating better predictive performance.

For each seasonal RSF, selection ratios were calculated to determine RSF values that were relatively selected by caribou. These ratios were calculated by partitioning predicted values for range random points into deciles to create ten RSF bins then determining the proportion of predicted values for caribou GPS locations occurring within each bin. Selection ratios were therefore calculated as

$$\frac{No. GPS\ Locations\ Bin_i \ / \ \sum_{n=1}^{10} No. GPS\ Locations\ Bin_i}{No. Available\ Locations\ Bin_i \ / \ \sum_{n=1}^{10} No. Available\ Locations\ Bin_i}$$

All statistical analyses were performed in R, version 3.5.1 (R Core Team 2018) and the 'glmmTMB' package (Brooks *et al*. 2017) was used to estimate RSFs.

RESULTS

Across all seasonal models, land-cover variables had the strongest effect sizes (Table 2). At a fine-scale, upland conifer and conifer swamp were the top-ranked land-covers in summer whereas bogs and fens were the top-ranked land-covers in fall and winter. Across all seasons, landscapes with high proportions of upland deciduous forest were avoided while those with high proportions of treed bog were selected. Caribou also consistently selected for areas with low slope.

Compared to land-cover, caribou responded less strongly to natural and anthropogenic features. In summer and fall, caribou were generally farther away from lakes and rivers than expected but this avoidance behaviour was weaker in winter. Anthropogenic features had weak and variable effects on caribou habitat selection. In summer, caribou were farther away from early seral forests and wells than expected but were closer to these features in fall and winter. For linear features, line density had higher predictive performance than distance-to measures, yet across all seasons line density had minimal influence on caribou habitat selection. NDVI also had limited influence on caribou habitat selection.

All seasonal models demonstrated excellent predictive performance ($\bar{r}_s$ > 0.97). For all seasons, caribou selected for RSF bin values ≥ 8 (Table 3).

Table 2: Parameter estimates (β) and their standard errors (SE) from resource selection functions estimated to assess seasonal habitat selection by female boreal caribou in northeast British Columbia.

	Season								
	Summer (*n* = 61 caribou-seasons)			Fall (*n* = 147 caribou-seasons)			Winter (*n* = 197 caribou-seasons)		
Variable	β	SE	*p*	β	SE	*p*	β	SE	*p*
Treed bog	-0.56	0.09	<0.001	0.84	0.06	<0.001	0.97	0.04	<0.001
Poor fen	-0.56	0.09	<0.001	0.45	0.06	<0.001	0.49	0.04	<0.001
Rich fen	-1.00	0.12	<0.001	0.89	0.07	<0.001	0.50	0.05	<0.001
Conifer swamp	-0.46	0.10	<0.001	-0.29	0.07	<0.001	0.10	0.05	0.054
Deciduous swamp	-1.36	0.11	<0.001	-0.09	0.07	0.204	-0.20	0.05	<0.001
Upland deciduous	-0.76	0.14	<0.001	-0.42	0.11	<0.001	-0.84	0.09	<0.001
Other	-1.79	0.21	<0.001	0.95	0.07	<0.001	0.42	0.05	<0.001
Prop. Treed bog (1-km)	0.43	0.02	<0.001	0.43	0.01	<0.001	0.63	0.01	<0.001
NDVI	0.07	0.04	0.042	0.11	0.01	<0.001	-	-	-
Linear feature density (400-m)	0.00	0.02	0.973	0.09	0.01	<0.001	0.05	0.01	<0.001
Prop. Upland deciduous	-1.58	0.07	<0.001	-1.72	0.04	<0.001	-1.34	0.02	<0.001
Slope	-0.28	0.05	<0.001	-0.37	0.02	<0.001	-0.14	0.01	<0.001
Distance to lake	-	-	-	0.08	0.01	<0.001	0.05	0.01	<0.001
Distance to lake (exp. decay)	0.14	0.02	<0.001	-	-	-	-	-	-
Distance to river (exp. decay)	0.20	0.02	<0.001	0.23	0.01	<0.001	-0.03	0.01	<0.001
Distance to early seral	-	-	-	-0.14	0.01	<0.001	-0.21	0.01	<0.001
Distance to early seral (exp. decay)	0.11	0.02	<0.001	-	-	-	-	-	-
Distance to well	-	-	-	-0.42	0.01	<0.001	-0.24	0.01	<0.001
Distance to well (exp. decay)	0.10	0.02	<0.001	-	-	-	-	-	-
Prop. Treed bog * NDVI	0.01	0.03	0.632	-0.04	0.01	<0.001	-	-	-
Prop. Treed bog * Linear feature density	0.07	0.01	<0.001	-0.04	0.01	<0.001	-0.12	0.01	<0.001

Table 3: Mapped bin values from seasonal resource selection functions (RSFs), the number of caribou GPS locations and random (or available) locations occurring within each bin, and the estimated selection ratio for each bin. Selection ratios in bold indicate bins that are that are selected by female boreal caribou within a given season (i.e., ratios > 1.0).

	RSF Bin	Min. Value	Max. Value	No. of GPS Locations	No. of Available Locations	Selection Ratio
Summer	1	0.00000	0.00053	1	30496	0.00
	2	0.00053	0.00203	28	30498	0.08
	3	0.00203	0.00529	48	30503	0.13
	4	0.00529	0.01109	82	30498	0.22
	5	0.01109	0.01944	121	30494	0.33
	6	0.01944	0.03035	206	30508	0.56
	7	0.03035	0.04486	362	30501	0.98
	8	0.04486	0.06551	554	30499	**1.50**
	9	0.06551	0.10126	873	30496	**2.37**
	10	0.10126	1.00000	1412	30504	**3.83**
Fall	1	0.00000	0.00032	27	73495	0.02
	2	0.00032	0.00192	110	73502	0.07
	3	0.00192	0.00628	246	73497	0.15
	4	0.00628	0.01400	331	73497	0.20
	5	0.01400	0.02513	435	73498	0.27
	6	0.02513	0.04150	771	73496	0.47
	7	0.04150	0.06383	1280	73497	0.79
	8	0.06383	0.09845	2178	73495	**1.34**
	9	0.09845	0.16839	3747	73505	**2.30**
	10	0.16839	1.00000	7132	73500	**4.39**
Winter	1	0.00000	0.00039	36	98490	0.01
	2	0.00039	0.00191	191	98502	0.06
	3	0.00191	0.00553	414	98495	0.12
	4	0.00553	0.01084	752	98487	0.22
	5	0.01084	0.01742	1397	98504	0.41
	6	0.01742	0.02567	1975	98503	0.58
	7	0.02567	0.03788	2787	98479	0.82
	8	0.03788	0.05940	3868	98514	**1.14**
	9	0.05940	0.11083	6350	98474	**1.87**
	10	0.11083	1.00000	16186	98521	**4.77**

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Appendix A: GIS Data Sources

Table A.1: List of GIS data sources used to model resource selection functions evaluating seasonal habitat 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
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