SUPPLEMENTAL MATERIAL

Correcting for Bias in GPS Collar Transmission

Anticipating that GPS-collars would not produce data on 100% of expected fix times, and that failure to report data could be biased by some or all of the very covariates of interest, we performed calibration of GPS collars. Using 14 collars from animals that had died or were recaptured, we compared fixes received remotely from the satellite with fixes recorded only on the collar storage device (i.e., store-on-board). Overall, 52.6% store-on-board fixes were transmitted to the satellite and thus formed the data available from the other 20 collars for which we had only transmitted data. To account for potential biases resulting from missing fixes, we adopted a sample weighting approach (Frair et al. 2010) by estimating the probability of a successfully transmitted fix (*Pfix*) via logistic regression models (see below).

To reduce spurious effects resulting from poor GPS location accuracy, we first cleaned the data by removing all GPS location records with PDOP > 4. We further removed all GPS location records that reported elevations < 660 m (the lowest elevation in the study area, Newby and DeCesare 2020). The resulting data set consisted of 9,359 records.

We considered mixed-effects linear models in which *Pfix* was predicted from the binary response variable indicating whether the position was transmitted or not (1 if transmitted, 0 if recorded only on board the recovered collar). We entertained a suite of models with hypothesized environmental predicators including canopy cover, elevation, the cosine of aspect, slope, and topographic position index (TPI, Weiss 2001), all extracted from remote sensing data based on the GPS positions indicated by the collar. In addition, because we suspected that collar model also affected *Pfix*, we considered models in which the 4 types of GPS collars used during the study (Globalstartrack Pro, LifeCycle, SurveyGlobalstar, and LifeCyclePro500) were used as predictors. Finally, because we had only a quasi-random selection of actual collars (and animals) from which to make general inference, we adopted a mixed-model approach treating individual collars as random intercepts. We evaluated models using AIC, as well as whether all predictors in the model significantly improved fit at $\alpha = 0.05$. We considered multiple predictors in models only when correlation coefficients were < 0.5. All models were developed using program glmer with binomial error structures, and with individual collar as a random intercept. We considered all possible models consisting of up to 3 predictor variables, including 1st order interaction terms. In some cases, complex models were inestimable.

We evaluated model performance of the top model(s) using program Performance (Lüdecke et al. (2021) implemented in r 4.0.0. Additionally, we performed k-fold cross-validation with $k = 5$ and data divided into 10 bins using the glm subroutine of program kxv (Brzustowski 2005). As anticipated, *Pfix* was affected by collar type. However, in preliminary models only the Lotek LifeCyclePro500 (overall *Pfix* = 0.229) was significantly different from other collar types (overall mean *Pfix* = 0.582). Thus, collar models were recoded by whether or not they were LifeCyclePro 500 and this simplified binary factor was included as a nuisance variable in all subsequent models.

Model selection, considering only models with significant predictors, is provided in Table S2. The model with canopy closure and TPI (as well as collar model type as a nuisance variable) had almost all model weight and was ~ 24 AIC units better than the 2nd-ranking model (only canopy cover). LifeCyclePro 500 GPS collars were predicted to have a

Table S1. Adult female moose used in habitat selection analyses (minimum 100 location points per season), Cabinet-Salish study area, northwestern Montana, 2013-2022. Data indicate number of GPS points with 3rd positional dilution of precision (PDOP) < 4 (used), and number of randomly generated points within each home range (random) for each season.

	---- Winter ----		---- Summer ----	
Moose ID	used	random	used	random
113	178	1780	162	1620
119	165	1650	239	2390
120	116	1160	--	--
121	678	6780	754	7540
124	600	6000	807	8070
129	290	2900	233	2330
131	125	1250	--	--
134	185	1850	159	1590
135	397	3970	399	3990
136	555	5550	578	5780
137	181	1810	154	1540
138	584	5840	702	7020
139	248	2480	190	1900
140	149	1490	144	1440
142	440	4440	445	4450
143	502	5020	476	4760
144	433	4333	630	6300
145	454	4540	371	3711
146	502	5020	555	5550
149	476	5090	418	4181
151	189	1890	104	1040
153	280	2800	275	2749
154	309	3090	293	2930
155	320	3200	337	3370
156	178	1780	175	1750
157	412	4120	388	3880
158	169	1690	163	1630
159	312	3120	314	3140
160	314	3390	334	3339
161	--	--	190	1902
162	202	2010	195	1950
163	146	1690	182	1820
164	200	2340	261	2610
165	194	2270	206	2060
Total	10,453	104,530	10,833	108,332

Table S2. Model selection among top-ranked candidate models relating probability of a transmitted GPS fix (*Pfix*) to hypothesized environmental covariates. Abbreviations: cc = canopy cover, TPI = topographic position index, aspect = cosine of aspect. All models also included the binary variable collar model type as a nuisance parameter, and, except for the null model with no environmental covariates, included individual collar as a random intercept. The null model, shown for reference, included only collar type and included no random intercept.

	logLik	AIC	dLogLik	ΔAIC	df	weight
cc+TPI	-6783.2	13576.4	444.3	0	5	1
Cc	-6796.4	13600.8	431.1	24.4	4	<0.001
aspect+TPI	-6919.4	13848.9	308.1	272.5	5	<0.001
TPI	-6944.7	13897.4	282.8	321.0	4	<0.001
aspect	-6947.6	13903.2	279.9	326.8	4	<0.001
null	-7227.5	14459	0	882.7	2	<0.001

The top model is shown in Table S2.

Table S3. Top model relating probability of GPS fix to predictor variables.

	Estimate	SE	*z*	*P*
(Intercept)	1.1474	0.1348	8.5140	<0.0001
Canopy Closure	-0.0153	0.0009	-17.6660	<0.0001
TPI	0.0017	0.0003	5.1310	<0.0001
Collar model	-1.6919	0.2395	-7.0630	<0.0001

significantly lower probability of a fix than other collars, but interactions with both canopy cover and TPI were not significant.

Pfix was lower in areas with high canopy cover and within valleys and drainages, and higher on ridgelines and peaks. We found no evidence of overdispersion in the model (dispersion ratio = 0.997, χ^2 = 10,620, $P = 0.582$), and VIF terms for both variables were 1.01. AUC was 68.3%, and the Hosmer Lemeshow GOF χ^2 = was 8.938 (df = 8, $P = 0.348$). Approximate conditional R^2 was 0.168, and marginal R^2 was 0.128, suggesting that factors other than the environmental covariates considered (e.g., satellite angle and availability) accounted for most of the variation in fix probability. The mean Pearson correlation coefficient from k-fold cross validation (k = 5, 10 bins) was 0.988 ($P < 0.001$). Probability of fixes under the top model are illustrated in Figure S1. In RSF modelling, the reciprocal of *Pfix* was applied to each value to correct for habitat-induced biases.

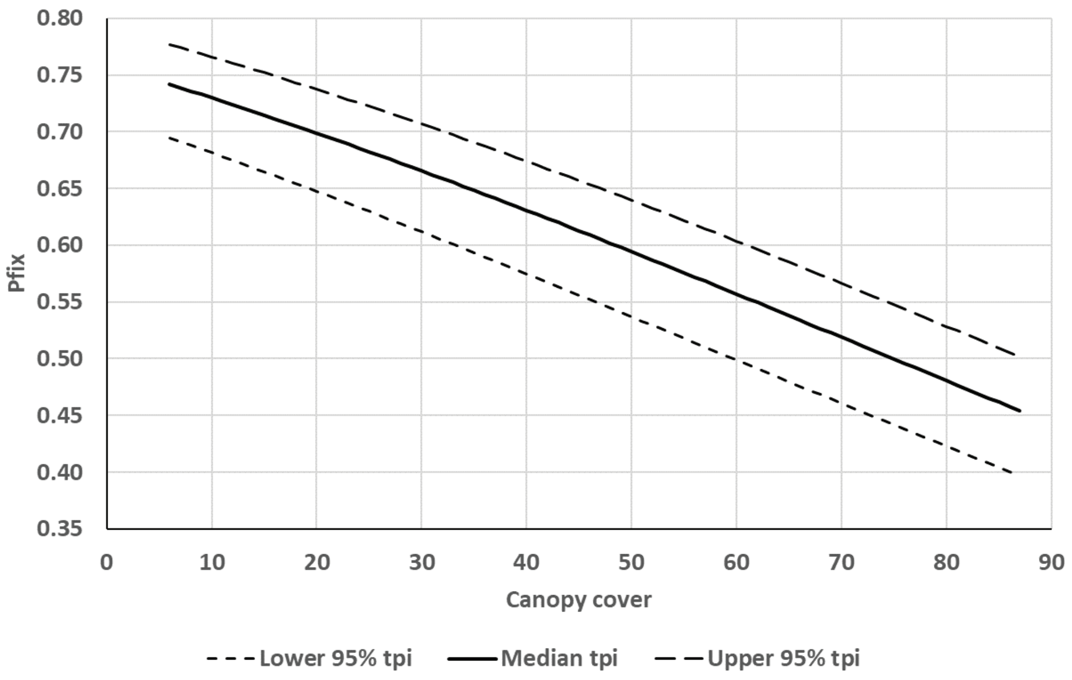

Fig. S1. Probability that a store-on-board GPS fix was transmitted and thus became part of the data set for RSF models, predicted by the top calibration model. Shown are probabilities under a range of canopy cover values, for the lower 95%, median, and upper 95% values of the topographic position index (tpi).

Table S4. Categories of vegetation type (NatureServe 2018) used at Stage 1 of the RSF analysis of Cabinet-Salish mountains moose, 2013-2022, and collapsed categories used at Stage 2 in both 2^{nd} and 3^{rd} order analyses, summer and winter. Aggregating original categories was required to increase sample sizes to the minimum necessary to avoid failures of models to converge.

Vegetation types identified by NaturServe	RSF Stage 1	Stage 2, 2nd order, winter	Stage 2, 2nd order, summer	Stage 2, 3rd order, winter	Stage 2, 3rd order, summer
Northern Rocky Mountain Dry-Mesic Montane Mixed Conifer Forest	Dry Mixed Conifer	Dry Mixed Conifer	Dry Mixed Conifer	Dry Mixed Conifer	Dry Mixed Conifer
Northern Rocky Mountain Mesic Montane Mixed Conifer Forest	Mesic Mixed Conifer	Mesic Mixed Conifer	Mesic Mixed Conifer	Mesic Mixed Conifer	Mesic Mixed Conifer
Rocky Mountain Subalpine Dry-Mesic Spruce-Fir Forest and Woodland	Spruce-Fir	Spruce-Fir	Spruce-Fir		
Rocky Mountain Subalpine Mesic-Wet Spruce-Fir Forest and Woodland					
Rocky Mountain Lodgepole Pine Forest	Lodgepole Pine	Pine	Pine	Pine	Pine
Northern Rocky Mountain Ponderosa Pine Woodland and Savanna	Ponderosa Pine				
North American Arid West Emergent Marsh	Riparian	Riparian	Riparian		Riparian
Northern Rocky Mountain Lower Montane Riparian Woodland					
Rocky Mountain Subalpine-Montane Riparian Shrubland					
Rocky Mountain Subalpine-Montane Riparian Woodland					
Northern Rocky Mountain Lower Montane Riparian Shrubland	Shrubland	Shrubland	Shrubland		
Northern Rocky Mountain Montane-Foothill Deciduous Shrubland					
Northern Rocky Mountain Avalanche Chute Shrubland					
Northern Rocky Mountain Subalpine Deciduous Shrubland					
Western Cool Temperate Developed Shrubland					
Interior Western North American Temperate Ruderal Shrubland					
Western North American Ruderal Wet Shrubland					
Northern Rocky Mountain Western Larch Savanna					
Rocky Mountain Aspen Forest and Woodland					
Northern Rocky Mountain Subalpine Woodland and Parkland					
Northern Rocky Mountain Lower Montane-Foothill-Valley Grassland					

(*Continued*)

Vegetation types identified by NaturServe	RSF Stage 1	Stage 2, 2nd order, winter	Stage 2, 2nd order, summer	Stage 2, 3rd order, winter	Stage 2, 3rd order, summer
Northern Rocky Mountain Subalpine-Upper Montane Grassland					
Rocky Mountain Subalpine-Montane Mesic Meadow					
Northern Rocky Mountain Foothill Conifer Wooded Steppe					
Rocky Mountain Alpine-Montane Wet Meadow	Steppe-Grassland		Steppe-Grassland	Non-Forested	
Interior Western North American Temperate Ruderal Grassland					
Western North American Ruderal Wet Meadow & Marsh					Non-Forested
Open Water					
Developed-Low Intensity					
Developed-Medium Intensity		Non-Forested			
Developed-High Intensity					
Developed-Roads					
North American Glacier and Ice Field					
Western Cool Temperate Urban Deciduous Forest					
Western Cool Temperate Urban Evergreen Forest	Non-Forested		Non-Forested		
Western Cool Temperate Urban Mixed Forest					
Western Cool Temperate Urban Herbaceous					
Western Cool Temperate Urban Shrubland					
Western Cool Temperate Developed Evergreen Forest					
Western Cool Temperate Developed Mixed Forest					
Western Cool Temperate Developed Herbaceous					
Western Cool Temperate Pasture and Hayland					

Table S5. Categories of timber harvest type (USFS 2023) used at Stage 1 of the RSF analysis of Cabinet-Salish mountains moose, 2013-2022, and collapsed categories used at Stage 2 in both 2nd and 3rd order analyses, summer and winter.

Harvest types identified by USFS	RSF Stage 1	Stage 2 2nd order winter	Stage 2, 2nd order summer	Stage 2, 3rd order winter	Stage 2, 3rd order summer	Functional response
Clearcut	Even-aged	Harvested (2 age classes)	Harvested (2 age classes)	Harvested	Harvested	Even-aged
Clearcut with reserve						
Seed Tree						
Commercial Thin	Intermediate					Uneven-aged
Salvage						
Selective	Selective					
Shelterwood	Shelterwood					
Liberation	Uneven-aged					
Overstory Removal						
Sanitation						
Uneven						
Unidentified	Unidentified					
Unharvested	Unharvested	Unharvested	Unharvested	Unharvested	Unharvested	Unharvested

Table S6. Names and descriptions of predictor variables used in habitat use analysis of adult female moose, Cabinet-Salish mountains, northwestern Montana. 2013-2022.

Variable name	**Interpretation and use**
Used	1 = used, 0 = random (available)
Season	Winter (January 1 through March 31) or summer (May 15 through September 15)
Weight	Available points assigned a weight of 1,000 (Muff et al 2020). Used points assigned weights using the equation that accounts for GPS acquisition bias (see Supplementary material)
Date	Date of GPS location acquisition
Time	Time of GPS location acquisition
Year	Year of GPS location acquisition
Elevation	Acquired from file “us_dem2010”
Elevation^2	As above, allowing for hypothesized parabolic relationship via 2nd-order polynomial model
Aspect	Acquired from file “us_dem2010”, transformed via cos(aspect-45)
Slope	Acquired from file “us_dem2010”
TPI	Topographic position index (Weiss 2001)
Canopy cover	Overstory canopy cover (need reference)
Canopy cover^2	As above, allowing for hypothesized parabolic relationship via 2nd-order polynomial model
Vegetation type	LANDFIRE categories, collapsed when necessary, see Supporting Material for description, from LC22_EVT_220
Harvested	Binary: 1 if harvested in past 40 years, otherwise 0
Burned	Binary: 1 if fire in past 40 years, otherwise 0; from National USFS_Final_Fire_Perimeter layer
Stand age	If recent timber harvest or fire, then current year - disturbance year; otherwise 150 (unless timber harvest “selective” or “uneven”)
Stand age^2	Square of Timber stand age, for quadratic (parabolic) relationship hypotheses
Years since harvest	If there was timber harvest, years from present (2023) to that year, otherwise assumed to be 150
Years since fire	If there was a fire, years from present (2023) to that year, otherwise assumed to be 150
Harvest type	From USFS_USA.Activity_TimberHarvest - see appendix for descriptions
Harvest type s	S stands for “short” here; categories collapsed to avoid small sample sizes and aggregate relatively similar types of stand disturbance
Harvest size	From USFS database -
Fire size	From USFS database in case size of burn turns out to matter to moose
Distance from Hwy	Derived in Arc from the highway map, in meters (highway map from another source, includes major paved roads) from Montana Primary and Secondary Roads
Distance from primary road	Derived in Arc, in 500 m categories (primary roads here are USFS system road open to traffic) National_Forest_System_Roads
Distance from water	Derived in Arc in 500 m categories (water defined here as “streams”, does not include lakes)

Table S7. Top resource selection function models using data from all animals pooled, i.e., the first of stage of the 2-stage RSF approach (Murtaugh), adult female moose, Cabinet-Salish study area, northwestern Montana, 2013-2022. Significance of predictors not shown because all are highly inflated at this, first stage, because of autocorrelation.

I. 2nd order

A. Winter

	Coefficient	Standard error
(Intercept)	-9.140	0.024
Elevation	0.126	0.050
Elevation^2	-0.196	0.047
Aspect	-0.022	0.015
Topographic Position	0.001	0.001
Mesic Mixed Conifer[a]	0.024	0.026
Nonforest[1]	-1.201	0.076
Pine[1]	-0.445	0.039
Riparian[1]	-0.123	0.068
Shrubland[1]	-0.599	0.047
Harvest (10-29)[b]: Even-aged	0.694	0.047
Harvest (10-29): Uneven-aged	0.762	0.036
Harvest (other): Even-aged	0.645	0.031
Harvest (other): Uneven-aged	0.507	0.278
Harvest size	0.002	0.001
Distance from highway	0.001	0.001
Distance from water	0.001	0.001

[a] Reference category: Dry mixed conifer
[b] Reference category: Unharvested

B. Summer (Table S7, continued)

	Coefficient	Standard error
(Intercept)	-9.481	0.021
Elevation	1.169	0.090
Elevation^2	-1.307	0.097
Aspect	0.027	0.015
Topographic Position	0.001	0.000
Harvested (10-29)[a]	0.572	0.033
Harvested (other)[a]	0.360	0.026
Harvest size	-0.045	0.013
Not vegetated[b]	-0.297	0.070
Pine^2	0.019	0.039
Riparian^2	0.472	0.066
Shrubland^2	-0.098	0.039
Spruce-Fir^2	0.109	0.053
Steppe-Grass^2	-0.265	0.069
Distance from highway	-0.001	0.012
Distance to water	0.027	0.011

[a] Reference category: Unharvested

[b] Reference category: Dry mixed conifer

II. 3rd order (Table S7, continued)

A. Winter

	Coefficient	Standard error
(Intercept)	-8.623	0.019
Canopy cover	0.146	0.037
Canopy cover^2	-0.333	0.037
Topographic index	0.003	0.000
Mesic mixed conifer[a]	0.061	0.021
Not vegetated	-1.234	0.101
Pine	-0.370	0.032
Riparian	-0.701	0.067
Shrubland	-0.308	0.033
Spruce-fir	-0.368	0.065
Steppe-Grassland	-0.070	0.049
Harvest[b]: Even-aged	0.232	0.023
Harvest: Intermediate	0.470	0.031
Harvest: Selective	0.235	0.078
Harvest: Shelterwood	0.427	0.028
Harvest: Unidentified	0.367	0.026
Harvest: Uneven	0.193	0.025
Distance from highway	0.000	0.000
Distance from water	0.000	0.000

[a] Reference category: Dry mixed conifer
[b] Reference category: Unharvested

B. Summer (Table S7, continued)

	Estimate	Standard error
(Intercept)	-9.099	0.020
Topographic Position	-0.011	0.000
Aspect	0.031	0.010
Grassland	0.126	0.068
Lodgepole	0.162	0.047
Mesic Mixed Conifer	0.128	0.019
Non-Forested	-0.270	0.067
Ponderosa Pine	-0.474	0.046
Riparian	1.097	0.028
Shrubland	0.067	0.029
Spruce-Fir	0.779	0.032
Steppe	0.314	0.069
Harvest size	-0.001	0.000
Harvest: Even-aged	0.464	0.025
Harvest: Intermediate	0.958	0.030
Harvest: Selective	0.827	0.075
Harvest: Shelterwood	1.006	0.026
Harvest: Unidentified	0.629	0.026
Harvest: Uneven	0.313	0.030
Distance from highway	0.000	0.000
Distance to water	-0.001	0.000

Table S8. Recent burns on the Cabinet-Salish study area, their characteristics, and Manly selection ratios among moose that potentially encountered them.

Fire Year	Fire(s)	Burned area (ha)	Moose winter home ranges intercepting burn	Moose summer home ranges intercepting burn	Mean selection ratio: winter	Mean selection ratio: summer
1989	Radio Tower	75	0	1	0.00	0.00
1990	Miller Ck	34	3	2	2.02	2.61
1991	Squaw Ck	384	7	6	0.95	2.40
1994	Buck Ck, Leigh Ck, McKay3	493	2	13	1.52	1.69
2001	Libby Ck	57	5	3	1.47	14.19
2015	Fisher, Midas Ck	16	5	9	0.59	0.07
2017	People’s Ck	32	1	2	1.25	>1.00[a]
2020	Swede, Lightning Pk	18	2	2	0.00	0.00

[a] Selection ratio could only be approximated because used points but no random points occurred in this burn.

Table S9. Top supported model at the 2nd-stage (Murtaugh 2010) relating percent canopy cover used to maximum daily elevation and hour-of-day, adult female moose, Cabinet-Salish study area, northwestern Montana, 2013-2022. A. Summer. B. Winter.

a. Summer

Hour-of-day	Coefficient	Standard Error	*t*	*P*
Intercept	48.200	2.410	20.000	< 0.001
0300	-0.769	0.740	-1.039	0.307
0600	2.530	1.040	2.433	0.021
0090	6.760	1.140	5.930	< 0.001
1200	7.520	1.160	6.483	< 0.001
1500	7.110	0.989	7.189	< 0.001
1800	4.190	0.891	4.703	< 0.001
2100	0.592	1.010	0.586	0.562
Maximum daily temperature	0.096	0.092	1.041	0.306

b. Winter

Hour-of-day	Coefficient	Standard Error	*t*	P
Intercept	45.100	2.480	18.185	< 0.001
0300	0.030	0.709	0.042	0.967
0600	0.364	0.561	0.649	0.521
0090	3.570	0.872	4.094	< 0.001
1200	5.720	0.814	7.027	< 0.001
1500	5.000	1.060	4.717	< 0.001
1800	1.750	0.760	2.303	0.028
2100	1.710	0.676	2.530	0.017
Maximum daily temperature	0.405	0.091	4.441	< 0.001

Notes on Figure 11 (main paper) and Table S9

At first blush, it might appear that a reason for the smooth and continuous parabolic relationships through time might be that characteristics of a location at time t+1 (e.g., 3 am) must have been highly correlated with those characteristics at time t (e.g., 6 am). Statistical problems associated with serial correlation would indeed have been problematic had the data underlying these analyses, figures, and tables come from moose equipped with GPS collars that recorded locations frequently (e.g., hourly). Indeed, a superficial look at Figure 11 would suggest that data obtained at, for example, time interval 0600-0859 came just 3 hours after data obtained at time period 0300-0559. However, as explained in the main text, about 86% of locations came from collars programmed to collect data every 13 hours, and 14% from collars programmed to collect every 23 hours. With no missing fixes, the minimum time elapsed between a fix at time t and time t+1 (3 hours later in the day) was 26 hours for the 13-hour collars (e.g., fixes at 1 am (the 0000-0259 interval) then 2 pm, then 3 am (0300-0559 interval) the following day. For collars programmed to obtain fixes every 23-hours, the minimum elapsed time between successive times t and t+1 was 20 days

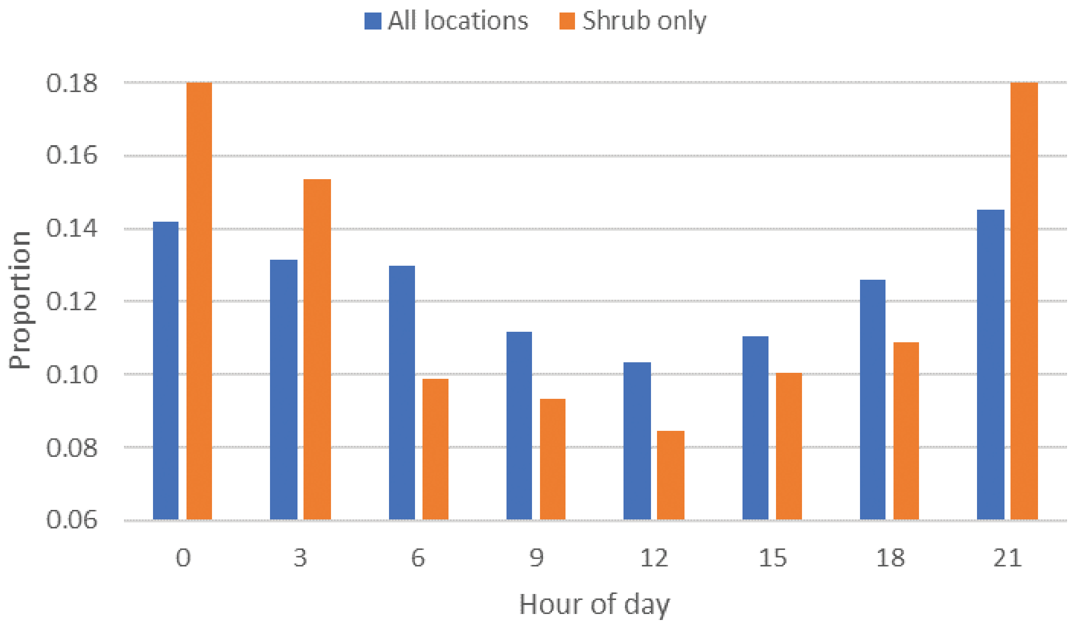

Fig. S2. The relative proportions of locations used by adult female moose in the Cabinet-Salish study area, 2013-2022 by hour of day, and the same proportions used only in shrublands by hour-of-day (both sets of histograms sum to 1.0) Note that use of proportional use of shrublands was greater than overall use during night-time hours, but less than overall during day-time hours.

(because the 23-hour schedule caused the time at which fixes were attempted to recess 1 hour each day, thus requiring 22 days (minus 2 because time periods were 3-hours long) to obtain a fix at the "next" time period. Further, because expected fixes were received at only approximately 53% of expected times, the actual time elapsed between successive fixes was considerably longer. For example, for a 13-hour collar, imagine that fix1 occurred at 1 am (interval 0-0259), and fix2 at 2 pm, (interval 1200-1459) and fix3 at 3 am (interval 0300-0559) (with fix4 at 3 pm (1500-1759 interval), and fix 5 at 4 am (0300-0559 interval). If, however, fix3 was missed, then the elapsed time between the first 2 "successive" fixes would be 52 hours (fix5 – fix1), rather than 26 hours. For these reasons, we considered the habitat characteristics at "successive" time fixes for each animal independent with no need to consider autoregressive terms in our modeling.

LITERATURE CITED (Only In Supplemental Material)

Brzustowski, J. 2005. k-fold cross-validation for present/available probability models. Free Software Foundation, Boston, Massachusetts, USA.