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Modeling large-scale winter recreation terrain selection with implications for recreation management and wildlife

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A B S T R A C T

Winter recreation is a rapidly growing activity, and advances in technology make it possible for increasing numbers of people to access remote backcountry terrain. Increased winter recreation may lead to more frequent conflict between recreationists, as well as greater potential disturbance to wildlife. To better understand the environmental characteristics favored by winter recreationists, and thus predict areas of potential conflict or disturbance, we modeled terrain selection of motorized and non motorized recreationists, including snowmobile, backcountry ski, and snowmobile assisted hybrid ski. We used sports recorder Global Positioning System (GPS) devices carried by recreationists at two study areas in Colorado, USA, (Vail Pass and the San Juan Mountains), to record detailed tracks of each recreation type. For each recreation activity, we modeled selection of remotely sensed environmental characteristics, including topography, vegetation, climate, and road access. We then created spatial maps depicting areas that recreation activities were predicted to select and combined these maps to show areas of potential ecological disturbance or interpersonal conflict between motorized and non motorized activities. Model results indicate that motorized and non motorized activities select different environmental character istics, while still exhibiting some similarities, such as selection for ease of access, reflected in proximity to highways and densities of open forest roads. Areas predicted to have only motorized recreation were more likely to occur further from highways, with greater forest road densities, lower canopy cover, and smoother, less steep terrain, while areas with only non motorized recreation were closer to highways, with lower forest road densities, more canopy cover and steeper terrain. Our work provides spatially detailed insights into terrain characteristics favored by recreationists, allowing managers to maintain winter recreation opportunities while reducing interpersonal conflict or ecological impacts to sensitive wildlife.

1. Introduction

The ecological impact of human recreation on the landscape is a rapidly growing concern for land use managers, as centers of hu man population spread out into previously sparsely populated areas (Theobald, 2004). Winter recreation, including backcountry and downhill skiing, snowshoeing, and snowmobiling, is a popular use of public lands, as well as a primary economic driver to com munities throughout the western United States (Bowker et al., 2012). Technological advances in motorized winter recreation, such as heliskiing, snow biking, more powerful snowmobiles, and snowmobile assisted (hybrid) skiing, means that recreationists access increasingly remote areas. With greater numbers of recrea tionists seeking their own recreation experience on a shared landscape, ecological impacts of recreation as well as encounters between non motorized and motorized recreationists are likely to increase (Gramann, 1982; Manning & Valliere, 2001).

Increases in the number of people using a recreation area or in

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the spatial extent of recreation can have negative ecological consequences, such as increased disturbance to wildlife. For instance, large scale displacement of animal populations to areas of poorer habitat has been demonstrated in moose (*Alces alces*) due to disturbance from snowmobiles (Harris, Nielson, Rinaldi, & Lohuis, 2014) and mountain goats (*Oreamnos americanus*) due to the presence of ski areas (Richard & Côté, 2016). The challenge of managing recreation to both allow human use of public lands while also conserving ecosystems is intensified by a lack of detailed knowledge of the spatial and environmental characteristics of human recreation.

In addition to ecological implications, increased recreation also has the potential to exacerbate conflict or safety issues between different recreation user groups (Miller, Vaske, Squires, Olson, & Roberts, 2016; Thapa & Graefe, 2004; Vaske, Carothers, Donnelly, & Baird, 2000). Interpersonal conflict, in which direct or indirect contact between different types of recreationists aggravates users (Jacob & Schreyer, 1980; Vaske, Needham, & Cline Jr., 2007), is likely to depend on the environmental preferences of each type of activity, and the degree to which these preferences overlap. Vaske, Donnelly, Wittmann, and Laidlaw (1995) found low interpersonal conflict between hunters and non hunters in a Colorado study due to their natural separation by topography, as well as management regulations that prevented interaction. To predict areas more likely to engender interpersonal conflict among recreation types, a better understanding of the terrain characteristics favored by different types of recreationists is needed (Kliskey, 2000; Snyder, Whitmore, Schneider, & Becker, 2008).

Most recreation studies rely heavily on the recreationist to self report details about his/her movements and interactions with other recreationists (Brown & Raymond, 2014; D'Antonio et al., 2010; Tomczyk, 2011). This provides neither an objective nor complete depiction of the spatial and temporal movement patterns of a recreationist through a landscape (Cole & Daniel, 2003; Hallo, Manning, Valliere, & Budruck, 2004). In addition, self reported interactions or conflicts with other users may be unconsciously biased by user perception, which may differ from realized interpersonal conflict. For instance, hikers in New Zealand who did not encounter mountain bikers had a more negative opinion of them than those that did (Cessford, 2003). A difference in perception versus realization of conflict could lead to inappropriate management practices in an attempt to reduce conflict where none exists. One way to overcome these methodological issues is to use Global Positioning System (GPS) devices to collect high resolution spatial data, which can provide an objective depiction of recreationist movements (Beeco & Brown, 2013; Hallo et al., 2012; Lai, Li, Chan, & Kwong, 2007) and interactions.

We use GPS locations collected by recreationists in two locations in western Colorado, USA to model landscape level recreation patterns. Like many areas in western USA, western Colorado is experiencing rapidly growing winter recreation on public lands, and also has a number of sensitive wildlife species that may be negatively affected by increasing recreation, including threatened Canada lynx (*Lynx canadensis*). We apply resource selection functions (RSFs) and step selection functions (SSFs) to quantify the importance of a given set of environmental covariates to each recreation activity, as well as to provide a spatial depiction of predicted areas of use (Boyce, Vernier, Nielsen, & Schmiegelow, 2002; Manly, McDonald, Thomas, McDonald, & Erickson, 2002). Both types of models are frequently used in wildlife studies to quantify habitat selection, which is characterized by the environmental conditions at sites used by individuals compared to those same conditions at a set of randomly available locations (Manly et al., 2002). Here we use RSFs and SSFs in a novel way: to determine which environmental characteristics are selected by people taking part in different recreation activities. We quantify selection over the entire recreation study area using RSF models, and employ SSFs to determine selection at a finer scale, as each recreationist moves through the landscape.

The goals of our research were to: 1) use GPS technology to measure movement characteristics of motorized (snowmobile, hybrid ski) and non motorized (backcountry ski), winter recreationists 2) use spatially explicit models to predict environmental characteristics and spatial landscapes likely sought by winter recreationists, and 3) use these modeled understandings to determine characteristics of potential interpersonal conflict or ecological impact. Results from our analyses can be used to identify areas selected by different recreation activities to inform management decisions on recreation zoning or education programs to limit interpersonal conflict or reduce wildlife disturbance.

2. Methods

2.1. Study area

Our study area consisted of two broad locations in the Colorado Rocky Mountains, USA (Fig. 1). The Vail Pass site covers an area in the northern Sawatch and Mosquito Ranges, southern Gore Range and western Front Range (approximate centroid coordinates 106.30° W, 39.45°N) near the towns of Vail, Leadville, and Frisco, CO. Data were collected on public lands administered by the White River National Forest and the San Isabel National Forest. The San Juan site covers a large area in southwest Colorado in the San Juan mountain range near the towns of Silverton and Telluride (approximate centroid 107.88°W, 37.82°N). Data were collected on public lands administered by the San Juan National Forest, the Uncompahgre National Forest, and the Bureau of Land Management. Both sites experienced winter recreation between the end of December and early April in the sub alpine and alpine zones with elevations between 2380 m and 4340 m and annual snowfall typically between 380 cm and 1000 cm (National Weather Service, 2017). Both sites had some level of recreation zoning, where motorized recreation was prohibited in certain designated areas.

The sites differed in terms of terrain and accessibility. Recreation in the Vail Pass site was largely influenced by proximity to major population centers, which are within a 1–2 h drive. Winter recreation was concentrated along Interstate 70 between Copper Mountain and Vail, CO in the fee operated Vail Pass Winter Recreation Area (VPWRA) managed by the White River National Forest, as well as along Highway 6 over Loveland pass (non motorized use only). Motorized recreation was heavily concentrated along a network of 50 miles of established groomed routes in the VPWRA. Non motorized access to backcountry huts in the VPWRA also attract recreation to the area. The VPWRA sees roughly 35,000 fee paying visitors per winter season, of whom approximately 11,000 are hut visitors (U.S.D.A. Forest Service, 2015). Hybrid use has increased sharply on the VPWRA, where backcountry skiers and snowboarders use snowmobiles or snow coaches to access terrain that would otherwise be inaccessible in a single day trip. The majority of data collected was motorized or hybrid use in the Vail Pass site.

Winter recreation in the San Juan site was more dispersed, with a greater number of access portals spread over a larger spatial extent than Vail. Access was highly dependent on the network of maintained roads, especially along U.S. Highway 550 and C.O. Highway 145 (see Fig. 1A), and there was no recreation fee area. The San Juan site was more isolated from major population centers (none within 2–3 h drive). While the majority of winter recreation in the Vail Pass study site was concentrated in fewer than 10 access portals, recreation in the San Juan site occurred from over 50 access portals, and included over 250 km of established groomed routes. Due to steep terrain, motorized recreation in the San Juan site was more concentrated compared to non motorized recreation. Taken together, the two study sites effectively capture the spectrum of winter recreation in the Colorado Rocky Mountains and thus pro vide a broad sample of recreation terrain in western Colorado.

2.2. Data collection

From January to March of 2010–2013, we stationed technicians at recreation access portals to distribute GPS units (Qstarz Inter national Co., Ltd., model BT Q1300, Position accuracy < 10 m). Technicians sampled recreationists by walking through a parking area and selecting every 4th vehicle (Vail Pass) or driving between access portals and approaching recreationists still at their vehicle (San Juans). For the latter approach, technicians began driving be tween access portals at approximately 10:00 h, and checked all known access portals (~50 portals) for recreationists at least once per day; technicians spent between 15 min and 1 h at each location, depending on the number of recreationists present, and did not vary the order in which they checked sites. Technicians gave a brief explanation of the project goals, informed recreationists that no personally identifiable information would be collected, and offered a map of the track made by the recreationist as an incentive for carrying the GPS unit. Participants then dropped the GPS unit into a collection bin at the end of the day, or returned it by mail. Tech nicians recorded the type of recreation activity engaged in and number of people in the group. If > 1 person was in the group, only one GPS unit was given to the group as a whole. While technicians did not sample the same people multiple times per day, it is possible that some recreationists carried a GPS unit more than once during the study. Given the large number (>35,000) of recrea tionists in our study areas, however, we do not believe that this happened frequently and thus assume independence of recreation tracks, which we define as a single user's, or group of users', daily travel pattern. We recorded snowmobile, backcountry ski or snowboard (hereafter backcountry ski), and hybrid recreation. Snowmobile included any motorized use, including snow cats and motorized bikes. Hybrid use occurred when skiers or snowboarders were transported by a snowmobile or snow cat, usually to a peak or ridge, and then skied down the slope.

We visually screened all recorded recreation tracks for erro neous points using ArcGIS (Environmental Systems Research Institute 2011, ArcGIS Desktop: Release 10. Redlands, CA). When screening data, we deleted points that were in areas where recre ation was not taking place, such as in parking lots or on highways, as well as outliers that were obviously erroneous based on large distances between a given point and the points directly before and after it. Additionally, points were more prone to error immediately after GPS units were turned on, as the units searched for sufficient satellites to collect data; we closely examined the start of each recreation track and removed all inaccurate points until the loca tions visually became more consistent (Beeco & Hallo, 2014). For analysis, we divided the GPS points recorded by snowmobilers into those that occurred on groomed routes and those that took place in non groomed areas (henceforth on and off trail, respectively) and hybrid GPS points into ski (non motorized) and snowmobile (motorized) segments, since we expected terrain selection to differ between these categories. We used road and trail GIS layers pro vided by the U. S. Forest Service (White River NF, Uncompahgre NF, San Juan NF travel management GIS layer) and considered snow mobile tracks < 15 m to either side of a road or trail as "on trail" and points > than 15 m as "off trail" to account for spatial resolution of GPS data. We classified motorized hybrid data when the average speed was greater than or equal to 30 miles per hour (48 km/h) and the track was gaining elevation, or the point fell within 15 m of a trail, and non motorized hybrid data otherwise.

GPS location data were recorded at 5 s intervals; if GPS units remained stationary, however, no location was collected until the device detected movement. Since recreation activities occurred at different speeds, this resulted in locations that ranged from 1 m to 40 m apart. To best assess conflict potential between recreation activities, we standardized spatial scales by sub sampling recrea tion activities at approximately 140 m between points (20 s interval for snowmobiles, 25 s for hybrid snowmobiles, 60 s for hybrid skiers, 120 s for backcountry skiers). This represented a fine scale perception distance at which both motorized and non motorized recreationists might make movement decisions. We also used magnetic and infra red trail counters as an independent assess ment of recreation intensity and distribution throughout our study areas to verify the efficacy of our GPS sampling. Trail counters recorded the number of people passing by constricted trail seg ments used by various recreation activities. We visually compared the counts from trail counters to GPS recreation tracks to locate any areas that had recreation but were not being adequately sampled by GPS methods, and adjusted our sampling efforts accordingly. We also used trail counters to identify intense periods of use during the day and week to better inform our sampling effort. We summarized trail counter data to mean counter hits per day of week and hour of day at each study area.

2.3. Environmental variables

We considered 12 environmental covariates as potential pre dictors of recreation selection. Covariates were chosen based on factors that we believed were important to recreationists: topog raphy, vegetation, climate, and access (Table 1). To account for the possibility that recreationists might consider these environmental covariates at different spatial scales when making land use de cisions, we considered all variables at four spatial scales. We used ArcGIS to calculate the average of each covariate within 125 m, 500 m, 1250 m, and 2500 m radii, chosen to span both small and large scale movements based on observed recreation travel dis tances. We standardized all covariates by subtracting the mean and dividing by the standard deviation to allow direct comparison be tween estimated model coefficients and for ease of model fitting.

2.4. Statistical analyses

To measure movement characteristics of recreation tracks, we calculated the total number of points recorded for each track, the total distance covered, the average movement speed, the length of time spent moving, and the minimum and maximum elevation reached along each track. We calculated the time and distance between two consecutive GPS points and used these to calculate average movement speed and length of time spent moving. We considered a point to be 'moving' if the speed was greater than 1 km/h. Total distance covered was calculated by summing the distance between consecutive GPS points. We used a digital elevation model (DEM; USGS National Elevation dataset) to deter mine difference between the points in each track with the mini mum and maximum elevation. Once these characteristics were calculated for each track, they were summarized by taking the median over all tracks within each recreation activity. To summa rize the environmental conditions that were available to each recreation type, as well as the conditions that each recreation type actually used (as compared to what they select, which is measured below and may differ from use), we also calculated the mean of all 'used' and 'available' points for each recreation activity for each of the 12 environmental covariates.

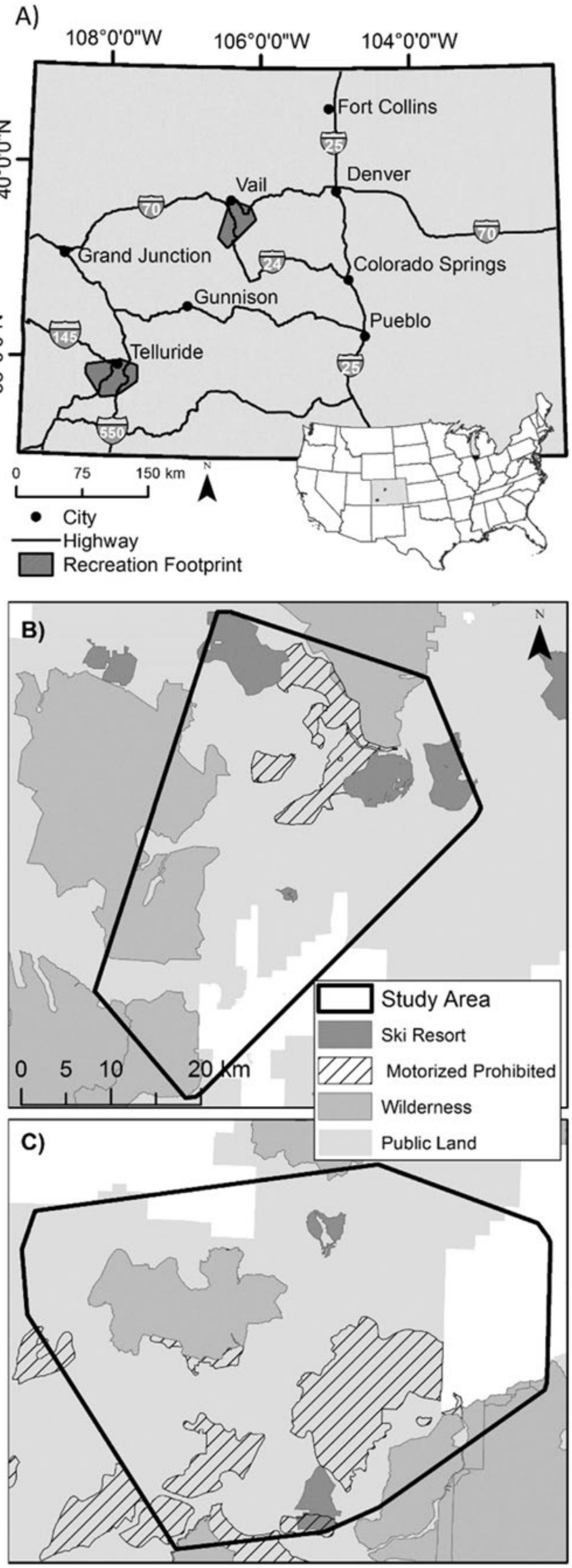

Fig. 1. Spatial extent of recreation used in this study at two locations in western CO, USA: the more northerly Vail Pass and the southerly San Juan Mountains (A); inset shows the position of Colorado within the USA. Panels B and C show areas that were closed to motorized recreation (gray wilderness areas and horizontally striped zoned areas) within the Vail (B) and San Juan (C) study areas.

We used both resource selection function (RSF) and step selection function (SSF) models to characterize environmental selection of snowmobiles, hybrid skiers, and backcountry skiers. Both RSF and SSF functions compare environmental characteristics at actual GPS locations ('used' locations) to those same characteristics at locations randomly selected across a study area ('available' locations); environmental characteristics that are used disproportionately more than what is available are said to be selected. The area considered as available in the models was defined as a minimum convex polygon around all recreation locations at each study site (Fig. 1); this insured that inferences made from each model would be comparable for all recreation types. Within this boundary, we removed privately owned land not available to recreationists. For motorized models only, we also removed areas administratively closed to motorized recreation, such as wilderness or designated non motorized areas (Fig. 1B&C).

We used a general linear mixed effects model with a logit link function (logistic regression; Hosmer, Lemeshow, & Sturdivant, 2013) and individual recreation track ID as a random intercept to control for non independence between points within a single track (Gillies et al., 2006) to estimate separate relative probability RSFs for backcountry ski, hybrid ski, hybrid snowmobile, snowmobile on trail, and snowmobile off trail recreation activities. We randomly generated 'available' points within the available areas defined above for a given recreation activity at a ratio of 1 'used' point to 5 'available' points so that available environmental characteristics were adequately sampled. Correlations among covariates within small (125 m and 500 m radii) and large (1250 m and 2500 m radii) spatial scales were often high. Thus, we initially fit univariate models with only one covariate at a given scale at a time to discard any covariates with poorer fit than a null model based on Akaike Information Criteria (AIC; Akaike, 1974), and to select one large and one small spatial scale per covariate. We included quadratic forms of covariates to investigate non linear relationships if supported by AIC. We then used the selected covariates to construct all subsets of candidate models for multivariate analysis using the 'lme4' (Bates, Maechler, Bolker, & Walker, 2014) and 'MuMIn' packages (Barton, 2015) in R (R Core Team, 2015); covariates correlated at $|r| > 0.6$ were not allowed in the same model. We ranked multivariate models using AIC.

The SSF models that evaluated fine scale selection by winter recreationists used conditional logistic regression to estimate relative probability of selection (Fortin et al., 2005; Thurfjell, Ciuti, & Boyce, 2014). At each 'used' GPS location, we compared 5 'available' GPS locations that were selected based on the known distribution of step lengths (straight line distance from one GPS point to the next) and turn angles estimated from actual recreation data. Thus, each used point was compared directly to a set of available points that the recreationist could have chosen as they moved from point A to point B on a track. We used the same covariates as in the RSF, but limited scales to only 125 m and 250 m since the purpose of the SSF model was to evaluate selection decisions at a fine scale as recreationists traverse landscapes. Variable selection and model fitting were performed as in the RSF models, except that models were fitted using the R package 'survival' (Therneau, 2015) to estimate conditional regression models.

To provide managers with a map that could be used to inform management decisions on recreation zoning or to identify areas selected by different recreation activities, we created maps of predicted relative probability of selection for each recreation type across western Colorado within an elevation zone delineated by

Table 1
Variable names, native resolution, source and description for all covariates used to model selection of environmental characteristics by recreationists in Colorado, USA.

Name	Resolution	Source	Description
Highway	Vector/ 30 m	Colorado Department of Transportation Online Transportation Information System	Euclidean distance to nearest highway (m)
Elevation	30 m	United States Geological Survey National Elevation Dataset	Elevation (m)
Canopy	30 m	National Land Cover Database (2011) Tree Canopy (Homer et al., 2015)	Percent tree canopy cover
Evergreen	30 m	National Land Cover Database (2011) Land Cover (Homer et al., 2015)	Percent conifer forest
North	30 m	ArcGIS Aspect Tool, Cosine transformation	Index of north-facing aspect
Precipitation	800 m	PRISM 1980 2010 Precipitation normals	Average annual precipitation (mm)
Slope	30 m	ArcGIS Slope Tool	Slope in degrees
Temperature	800 m	PRISM 1980 2010 Mean temperature normals	Mean annual temperature (°C)
Roughness	30 m	DEM Surface Tools (Jenness, 2013)	Index of terrain variability; 3D area divided by 2D area
TPI	30 m	Land Facet Corridor Tools (Jenness, Brost, & Beier, 2013)	Topographic position index, measure of landscape concavity or convexity
Road Density	Vector/ 30 m	National Forest travel management road layer, including only forest roads, not highways	Non-drivable forest roads that can be used as travel corridors; length of road per unit area, varying scales
Forest Edge	30 m	National Land Cover Database 2011 Landcover Type: Deciduous, Evergreen, and Mixed Forest (Homer et al., 2015)	Index of forest connectivity; length of forest/non-forest edge per unit area, varying scales

minimum and maximum elevation from all recreation data combined. We used the top performing RSF model from each recreation type to predict relative probability of selection based on the environmental covariates across western Colorado. The used available study design employed here produces a relative probability of selection since the number of sampled available points is arbitrary (Keating & Cherry, 2004). Thus, we used the equation

$$w(x) \quad \frac{\exp(\beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k)}{(1 + \exp(\beta_1 x_1 + \beta_2 x_2 + \ldots + \beta_k x_k))}$$

where β is an estimated model coefficient and x is the value of k covariates, to estimate relative probability of selection rescaled from 0 to 1 (Manly et al., 2002).

2.5. Recreation overlap analysis

To determine what environmental conditions are present at areas of predicted spatial overlap between motorized and non motorized forms of recreation, and thus what conditions may favor conflict between user groups, we performed the following analysis. We first created a binary depiction of each recreation type from each continuous relative probability surface generated above based on the maximum sum of sensitivity (true positives) and specificity (true negatives; Freeman & Moisen, 2008). This threshold optimizes the number of 'used' recreation locations correctly assigned into 'recreation area' and the number of 'available' locations correctly assigned into 'non recreation area'. We then used the binary surfaces to identify areas of motorized activities only (snowmobile and hybrid snowmobile), non motorized activities only (backcountry ski and hybrid ski), and areas with both motorized and non motorized recreation. To generate a summary of environmental characteristics at these areas of predicted overlap compared to areas with only one predicted type of recreation, we averaged each of our 12 environmental variables (Table 1) across each of these areas. We also determined the degree to which each predicted continuous surface was similar to the others, using a Pearson correlation, to determine which types of recreation were more likely to select similar environmental characteristics.

2.6. Model validation

We used 5 fold cross validation to determine goodness of model fit. Recreation tracks were split into 5 equal sized groups, the model was re estimated on 4 of the groups and used to predict the RSF values of the withheld 5th group; each group was withheld in turn. We predicted RSF values at all 'available' locations and binned these values into 10 quantiles. Predictions from 'used' locations were then grouped based on these quantiles, and the number of predicted used locations in each quantile was counted. We compared the predicted count of used locations to the quantile rank using a Spearman rank correlation (Boyce et al., 2002). Good model fit is indicated by a strong correlation between predicted values and quantile number. In addition, for RSF models, we performed a second independent validation using 100,000 withheld GPS points from each recreation type. The RSF value was predicted at each of these withheld points and then binned according to Boyce et al. (2002).

3. Results

3.1. Recreation summary

In January to March of 2010–2013, we recorded 2143 recreation tracks. We collected an average of 1306 (SD 435) GPS points per track (Table 2; Fig. 2). The most tracks in our dataset came from backcountry skiing or snowboarding (52%), followed by snowmobile (32%). Snowmobiles traveling on trails or groomed routes traveled the fastest, with a median speed of 30.6 km/h, while backcountry ski was slowest, at a median 4.3 km/h (Table 3). Hybrid recreationists traveled greatest distances, with median track length 41.0 km, while back country skiers traveled shortest, 5.2 km. Within hybrid recreation tracks, approximately 4.8 km, or 12% of total distance, was spent skiing. Snowmobiles averaged 35.2 km tracks, of which a median 4.9 km (approximately 13%) were spent off trail (Table 3). The duration of trips was similar among hybrid, backcountry skiers, and snowmobiles, at approximately 4 h. Of this time, each recreation type also spent approximately 2.5 h in active movement. Snowmobilers had the biggest change from minimum

Table 2
Summary of the number of tracks collected for each winter recreation activity in Colorado, 2010 2013. The total number of GPS points originally recorded at 5 s intervals, as well as the average and standard deviation of GPS points per track, are given.

Recreation Mode	# Tracks	Total # of points	Mean pts/track	SD
Snowmobile	686	889,674	1297	827
Hybrid	346	604,223	1746	1203
Backcountry Ski	1111	973,163	876	921
Total	2143	2,467,060	1306	435

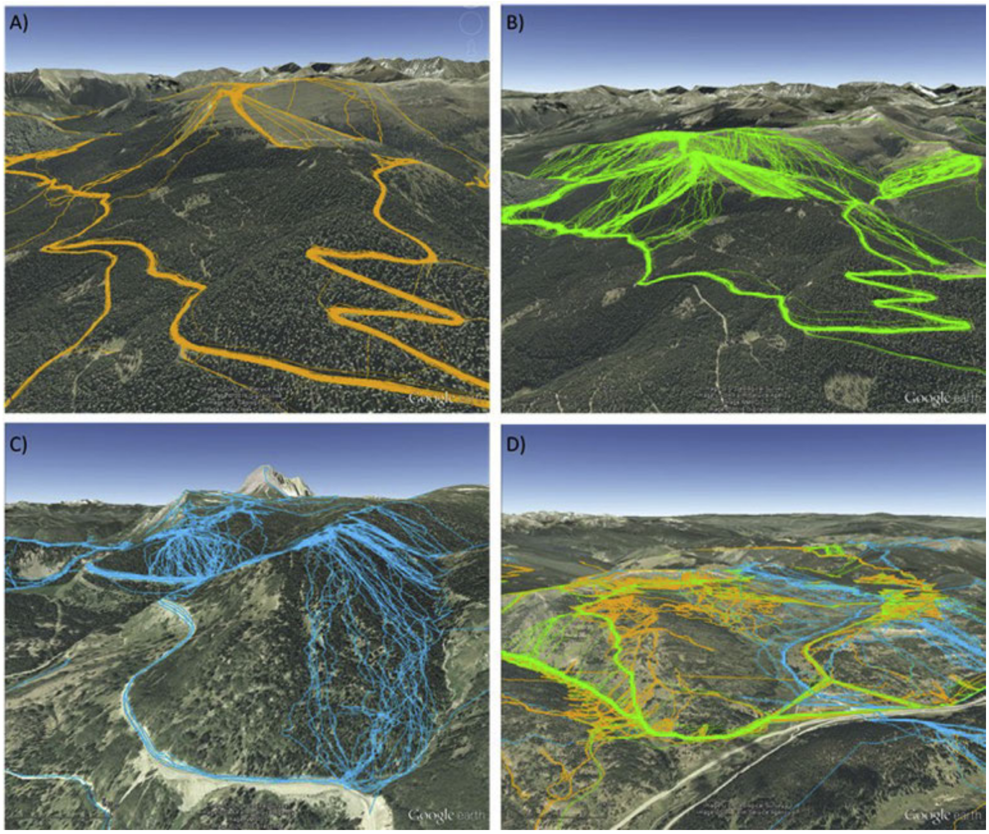

Fig. 2. Examples of recreation tracks recorded with GPS units during the study in western Colorado, 2010 2013. Panel A) snowmobile tracks primarily on trails in the Vail study area, B) hybrid skiing in the Vail study area; thick lines near the bottom of the picture show snowmobile travel, while thinner dispersed lines further back show skiing, C) backcountry ski recreation in the San Juans study area, and D) a combination of all three recreation types at the Vail study area, showing areas of overlap as well areas used primarily by one recreation type. Image credit: Google, DigitalGlobe.

Table 3
Median movement characteristics for all snowmobiles (Snmb), snowmobiles on trails (Snmb on-tr), snowmobiles off trails (Snmb off-tr), all hybrid (Hybrid), hybrid snowmobile (Hyb snmb), hybrid ski (Hyb ski), and backcountry ski (BC ski) recreation types studied in western CO, 2010 2013. The median and bootstrapped 95% lower confidence interval (LCI) and upper confidence interval (UCI) for movement speed (km/hr), total track distance (km), time spent actively moving (hr), total recorded trip time (hr), and total elevation change (m) is given.

		Snmb	Snmb on-tr	Snmb off-tr	Hybrid	Hybr snmb	Hyb ski	BC ski
Movement Speed (km/h)	Median	24.5	30.6	22.4	27.6	28.3	14.0	4.3
	95% LCI	24.0	29.7	21.9	26.8	27.6	13.0	4.2
	95% UCI	25.2	31.4	22.9	28.4	28.8	14.8	4.4
Track Distance (km)	Median	35.2	33.2	4.9	41.0	35.5	4.8	5.2
	95% LCI	32.9	31.3	4.1	38.4	33.6	4.4	5.0
	95% UCI	37.0	35.2	5.6	44.1	37.3	5.5	5.4
Active move time (hr)	Median	2.4	1.8	0.4	2.5	2.6	0.7	2.0
	95% LCI	2.3	1.7	0.4	2.2	2.3	0.6	1.9
	95% UCI	2.5	1.9	0.5	2.7	2.8	0.7	2.1
Total trip time (hr)	Median	3.8	2.5	0.7	4.6	3.5	1.0	3.6
	95% LCI	3.6	2.4	0.6	4.3	3.5	0.9	3.5
	95% UCI	4.0	2.6	0.8	4.8	3.7	1.1	3.8
Total Elevation Change (m)	Median	660.0	557.0	321.5	498.0	490.0	375.0	382.0
	95% LCI	557.0	538.0	293.0	489.0	482.0	369.0	371.0
	95% UCI	715.0	643.0	345.0	516.0	501.5	386.0	395.0

to maximum elevation within tracks, with a median difference of 660 m. Back country ski had the least elevation change, of 382 m (Table 3).

Based on the mean of used GPS points, the covariates that indexed distance to highway, road density, percent canopy cover, and slope showed the greatest differences between winter recreation types (Appendix A: Table A.1, Fig A.1). Hybrid skiers used areas that were farthest from highways (as averaged over all used GPS points; 4.61 km), followed by hybrid snowmobiles (4.05 km); snowmobiles on trail (3.41 km) and off trail (3.38 km) were next and did not differ from each other, and backcountry skiers remained nearest to major roads (2.46 km; Appendix A: Table A.1). On trail snowmobiles and hybrid snowmobiles used areas with greater forest road density (1.19 km/km^2 and 0.92 km/km^2, respectively), while off trail snowmobiles and backcountry skiers used the least (0.65 km/km^2 and 0.62 km/km^2, respectively;

Appendix A: Table A.1). Snowmobilers both on and off trail had the greatest mean percent canopy cover at used GPS locations (37.88% and 35.25%, respectively), followed by hybrid snowmobiles (33.88%) and backcountry skiers (31.26%). Backcountry skiers and hybrid skiers used steeper slopes than other recreationists (18.31° and 17.26°, respectively), while off trail snowmobiles used the shallowest (14.7°; Appendix A: Table A.1, Fig A.1).

We deployed 140 trail counters at 95 locations over both study areas from 2010 to 2013. Trail counters confirmed higher concen trated levels of use in the Vail area than in the more dispersed San Juan Mountains, with average seasonal counts approximately 5 times greater (average Vail 2010–2011: 73,967; average San Juans 2011–2013: 14,994 counter hits per year). Counter data also indi cated greater recreation intensity during weekends (Saturday and Sunday, Vail: 55.9, SD 84.1; San Juans: 25.0, SD 34.9 counter hits per day) then during weekdays (Vail: 33.0, SD 46.6; San Juans: 13.2, SD 20.6 counter hits per day), a pattern consistent across study areas (Fig. 3). Hourly counts indicated virtually no recreation took place after dark: 96% of trail counter hits occurred between 0800 and 1700 h. Peak use occurred between 1000 and 1500 h, with an average of 5.3 (SD 11.1) hits per hour during this time in Vail Pass and 2.3 (SD 5.5) hits per hour in the San Juans (Fig. 3).

3.2. Reponses of winter recreationists to environmental features

Top performing RSF models for all winter recreation activities indicated the importance of topography, access, and climate when making landscape scale selection choices. All top models were >Δ4

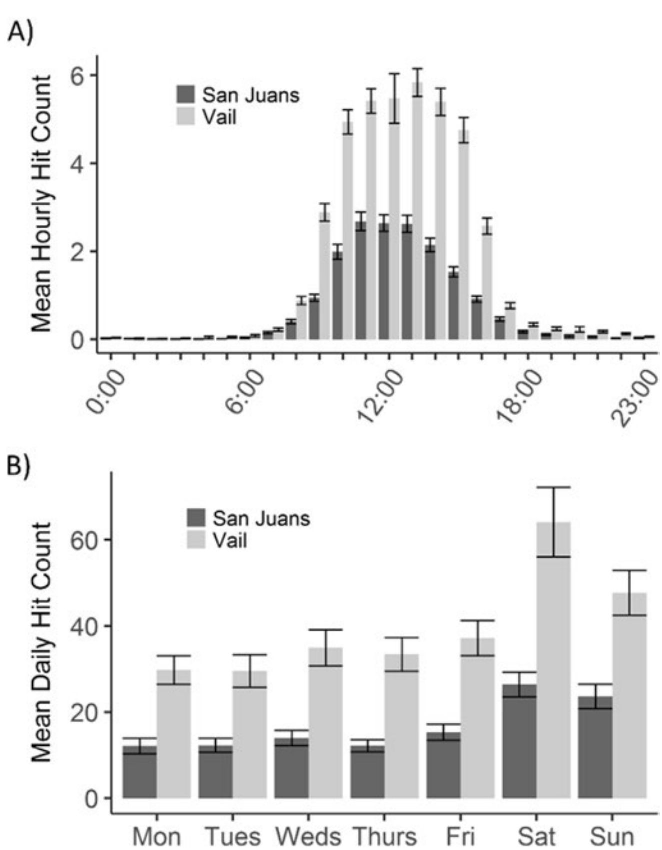

Fig. 3. Mean hourly (A) and daily (B) count of recreationists from 140 magnetic and infrared trail counters deployed in Vail Pass (light gray) and San Juan (dark gray) study areas, western CO, USA.

AIC better than the next performing model (Appendix B: Tables B.1 B.5). Based on coefficient confidence interval overlap with 0, all parameters in the top model for each recreation type were signif icant predictors of selection (except canopy cover for hybrid snowmobiles and backcountry ski, which did overlap 0). For brevity, we mention the top three contributing covariates for each model here, based on the strength of standardized beta coefficients, but all contributing covariates are presented in Table 4. Snowmo biles on trails selected areas that had greater forest road density, moderate annual precipitation, and lower terrain variability (Table 4; Fig. 4). Off trail snowmobiles selected moderate levels of snow, shallow slopes, and higher elevation (Table 4). Hybrid rec reationists selected shallow slopes, intermediate distances from highways, and greater annual precipitation while on snowmobiles (Table 4), and moderate north facing slopes with greater precipi tation while on skis (Table 4; Fig. 4). Backcountry skiers selected areas that were closer to highways, had greater annual precipita tion, and higher forest road density (Table 4; Fig. 4). Maps of pre dicted probabilities of landscape selection generated from top performing RSF models for each type of recreation across western Colorado are shown in Appendix C: Figs C.1 C.5.

At a fine scale, winter recreationists were sensitive to access, topography and vegetation when making movement decisions, again as determined by the size of standardized coefficients in top performing SSF models. There was some SSF model uncertainty, with between one and four models within >Δ4 AIC of the top performing model (Appendix D: Tables D.1 D.5). However, models within >Δ4 AIC differed from the top performing model by only one term, indicating that the extra parameters were non informative, and thus we took the top ranked, most parsimo nious, model. All parameters in the top model for each recreation type were significant predictors of selection, based on coefficient confidence interval overlap with 0; for brevity, we mention the top three contributing covariates for each model here, but all contrib uting covariates are presented in Table 5. Snowmobiles, while on trails, selected movement paths with moderate forest road density, moderate canopy cover, and higher elevation, while off trail, they selected movement paths closer to the highway with moderate canopy cover and low terrain variability (Table 5). Hybrid recrea tionists, while snowmobiling, selected movement paths with moderate canopy cover, greater annual precipitation, and greater distances from highways, while on skis they selected warmer temperatures and greater annual precipitation, and avoided level terrain (Table 5). Backcountry skiers selectively moved through areas that were intermediate distances from highways, at middle elevations, and with greater forest road density (Table 5).

3.3. Recreation overlap

The minimum and maximum elevation from all recreation points combined was 2300 m–4250 m; thus, we created predicted binary surfaces of winter recreation within this zone across western Colorado, a total area of 3123 km^2. Using the binary motorized and non motorized recreation maps we predicted that at least one type of recreation would occur on 590 km^2 (18.9%). In areas with at least one type of recreation, motorized only was predicted to occur on 35.2%, non motorized recreation on 27.3%, and both activities were predicted to occur on 37.5% of this area (Fig. 5). Areas predicted to have both types of recreation were characterized by closer prox imity to highways, high forest road density, high elevation, greater annual precipitation, and patchier forest, as well as intermediate levels of canopy cover, slope, TPI, and roughness, as compared to motorized or non motorized only areas (Fig. 6). Winter recrea tionists with highest potential conflict based on predicted selection probabilities were backcountry skiers and hybrid skiers, with a

Table 4
Model coefficients and standard errors, as well as the scale of the covariate (m), from general linear mixed models (resource selection functions) of landscape-scale recreation terrain selection in western CO, USA; variance of the random effect (individual track) is also given. All covariates (except canopy cover for hybrid snowmobile and backcountry ski) were significant predictors of recreation selection, based on confidence interval overlap with 0. A superscript 2 indicates covariates that were fitted as a quadratic function.

Covariate	Snowmobile On-Trail			Snowmobile Off-Trail			Hybrid Snowmobile			Hybrid Ski			Backcountry Ski		
	Scale	β	SE	Scale	β	SE	Scale	β	SE	Scale	β	SE	Scale	β	SE
Highway	2500	−0.87	0.01	2500	−0.85	0.02	1250	1.11	0.02	1250	1.25	0.06	2500	−1.73	0.02
Highway^2							1250	−1.72	0.02	1250	−1.26	0.05			
Elevation				125	1.57	0.03									
Elevation^2				125	−0.11	0.02									
Forest Edge	125	0.16	0.01	2500	0.46	0.02	125	−0.13	0.01	2500	0.64	0.05	2500	0.64	0.01
Canopy	125	−0.5	0.01	2500	1.49	0.02	2500	−0.02	0.02	125	−0.96	0.04	2500	−0.02	0.02
Canopy^2	125	0.05	0.01	2500	−0.29	0.02	2500	−0.55	0.01				2500	−0.16	0.01
Evergreen	2500	0.32	0.01	125	−0.68	0.02	125	−1.29	0.01				500	0.08	0.01
Evergreen^2	2500	−0.65	0.01	125	−0.65	0.02							500	−0.49	0.01
North	500	−0.12	0.01	2500	0.34	0.02	2500	−1.2	0.02	2500	−2.12	0.13	500	−0.16	0.01
Precipitation		1.22	0.01		2.36	0.03		1.32	0.01		1.82	0.06		1.12	0.02
Precipitation^2		−0.47	0.01		−0.61	0.02									
Road Density	125	1.84	0.01	125	0.35	0.01	125	1.03	0.01	1250	1.15	0.04	125	0.9	0.01
Slope	1250	−0.79	0.01	125	−1.6	0.02	1250	−1.97	0.01	125	1.96	0.08			
Slope^2	1250	−0.27	0.01							125	−2.22	0.07			
Roughness	500	−0.9	0.01	2500	−0.87	0.02	2500	−1.01	0.02	2500	−0.53	0.04	125	−0.74	0.01
Temperature		0.29	0.01					0.18	0.02		−0.22	0.07		−0.78	0.02
Temperature^2								−0.95	0.01		−1.28	0.05		−0.62	0.01
TPI	500	−0.54	0.01	500	−0.58	0.02	2500	−0.3	0.01	2500	−0.11	0.04	125	0.14	0.01
Random effect		0.5	0.71		2.16	1.47		0.79	0.89		1.16	1.08		0.72	0.85

Table 5
Coefficients and standard errors from conditional logistic regression (step selection function) models of fine-scale recreation terrain selection in western CO, USA. All covariates were significant predictors of recreation selection, based on confidence interval overlap with 0. A superscript 2 indicates covariates that were fitted as a quadratic function.

Covariate	Snmb On-Trail		Snmb Off-Trail		Hybrid Snmb		Hybrid Ski		Backcountry Ski	
	β	SE	β	SE	β	SE	β	SE	β	SE
Highway			−0.53	0.17	0.49	0.06			−0.64	0.07
Highway ^{2}									0.13	0.03
Elevation	0.38	0.05	0.28	0.09					−0.59	0.05
Elevation^2									−0.22	0.02
Forest Edge	0.02	0.01	0.05	0.01	−0.23	0.01	−0.09	0.02	0.06	0.02
Canopy	−0.40	0.01	−0.39	0.02	−0.68	0.01	0.08	0.03	0.21	0.03
Canopy^2	−0.10	0.01	−0.20	0.01	−0.28	0.01	−0.32	0.03	−0.24	0.02
Evergreen									−0.18	0.01
Evergreen^2									−0.10	0.01
North	0.01	0.00	−0.03	0.01	0.12	0.01	0.14	0.03		
Precipitation					0.50	0.07	1.01	0.18		
Road Density	0.77	0.01	0.24	0.01	0.34	0.01	−0.08	0.04	0.37	0.01
Road Density^2	−0.13	0.00			−0.04	0.00				
Slope	−0.08	0.03	−0.14	0.04	−0.37	0.02	−0.27	0.05		
Roughness	−0.26	0.01	−0.31	0.01	−0.48	0.01	−0.45	0.03	−0.31	0.01
Roughness^2					0.04	0.00	0.13	0.01		
Temperature					−0.34	0.04	1.87	0.09		
TPI	−0.23	0.01	−0.23	0.02	0.03	0.01	−0.49	0.03	0.08	0.01
TPI^2					0.31	0.01	0.23	0.02	0.07	0.01

Pearson correlation coefficient of 0.25. Recreationists with the least potential conflict were hybrid snowmobiling and off trail snow mobiles with a correlation of 0.07 (Appendix E).

3.4. Validation

Cross validation indicated excellent RSF model fit for all recre ation types, with Spearman rank correlations of 0.98 for off trail snowmobile, on trail snowmobile, hybrid ski, and hybrid snow mobile, and 1.0 for backcountry ski. Our independent validation of withheld points also indicated strong model performance, with Spearman rank correlations of 0.99 for off trail snowmobile, 1.0 for on trail snowmobile, 0.95 for hybrid ski, 0.99 for hybrid snowmo bile, and 1.0 for backcountry ski. Good predictive ability is indicated when independent recreation data have high predicted RSF values and Spearman correlations are closer to 1.

4. Discussion

This study provides a measure of winter recreation at a spatial scale and magnitude of data collection which has not, to our knowledge, been previously accomplished in the literature. We recorded approximately 2100 unique GPS tracks of recreationists and demonstrated the efficacy of resource selection models to better understand winter recreation. Our analysis is unique in its application of a modeled understanding of environmental selection to winter recreation, using the actual locations of recreationists rather than metrics inferred by surveys, parking lot counts, or track evidence. We found differences in modeled terrain selection be tween motorized and non motorized forms of recreation: areas predicted to be selected only by motorized users were farther from highways, with greater forest road densities, more open canopy, and shallower slopes, while areas predicted to be used only by non

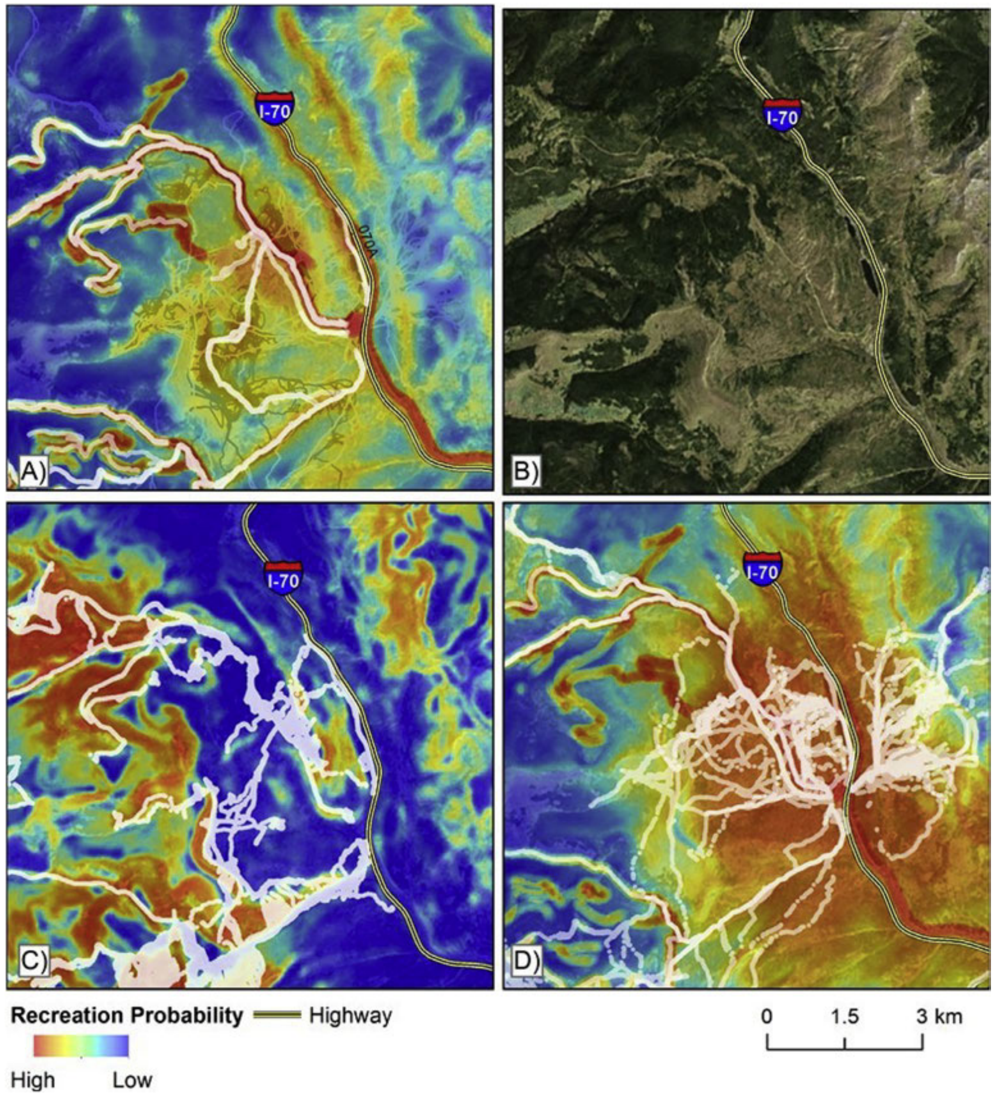

Fig. 4. Example of spatial predictions from top-performing RSF recreation models at the Vail study area in Colorado, USA. Warm colors indicate greater probability of selection by each recreation type; white tracks are actual GPS locations from recreationists. All panels show same spatial extent in the area of Vail Pass Winter Recreation Area; panel A is on-trail snowmobile, B shows an aerial image of the actual terrain, C is hybrid ski, and D is backcountry ski. Image credit: Esri software. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

motorized users tended to be closer to highways, in denser canopy cover, with more terrain variability and steeper slopes (Fig. 6). These results can help identify areas where interpersonal recreation conflict between different user groups is likely to occur as well as ecologically sensitive areas that may be more susceptible to disturbance from a given type of recreation.

4.1. Environmental characteristics of recreation

Few studies have similarly examined the land use patterns of winter recreationists. Braunisch, Patthey, and Arlettaz (2011) used snow track data and found a preference by skiers for smooth terrain, though the study was conducted only on areas near ski resorts and ski lifts in Switzerland. In a study using surveys in British Columbia, Canada, Kliskey (2000) found preferences of snowmobilers for low canopy closure and less steep slopes. Rupf et al. (2011) sampled 303 individuals with GPS data loggers and found a tendency for skiers and snowboarders to be peak oriented, although their study was focused on wildlife and not recreation.

While we found differences in the selection of environmental characteristics for each type of recreation, in general, certain environmental characteristics were consistently important to all types of winter recreation at a landscape scale. Access to recreation areas was important to both motorized and non motorized recreationists; snowmobilers and skiers selected areas that were close to highways and all recreation types selected greater density of forest roads, indicating the importance of accessibility over other environmental characteristics.

A key finding from this study is the importance of roads to all types of winter recreation. The presence of paved highways enables recreationists to quickly reach areas open to recreation, while the presence of forest roads allows them to permeate forested back country areas more easily. Recreation is predicted to increase with increases in the extent of highways or the density and extent of forest roads, supporting the idea that recreation is an emergent property of roads on the landscape. Westcott and Andrew (2015) similarly showed that road proximity was one of the most important predictors when modeling the environmental associations of

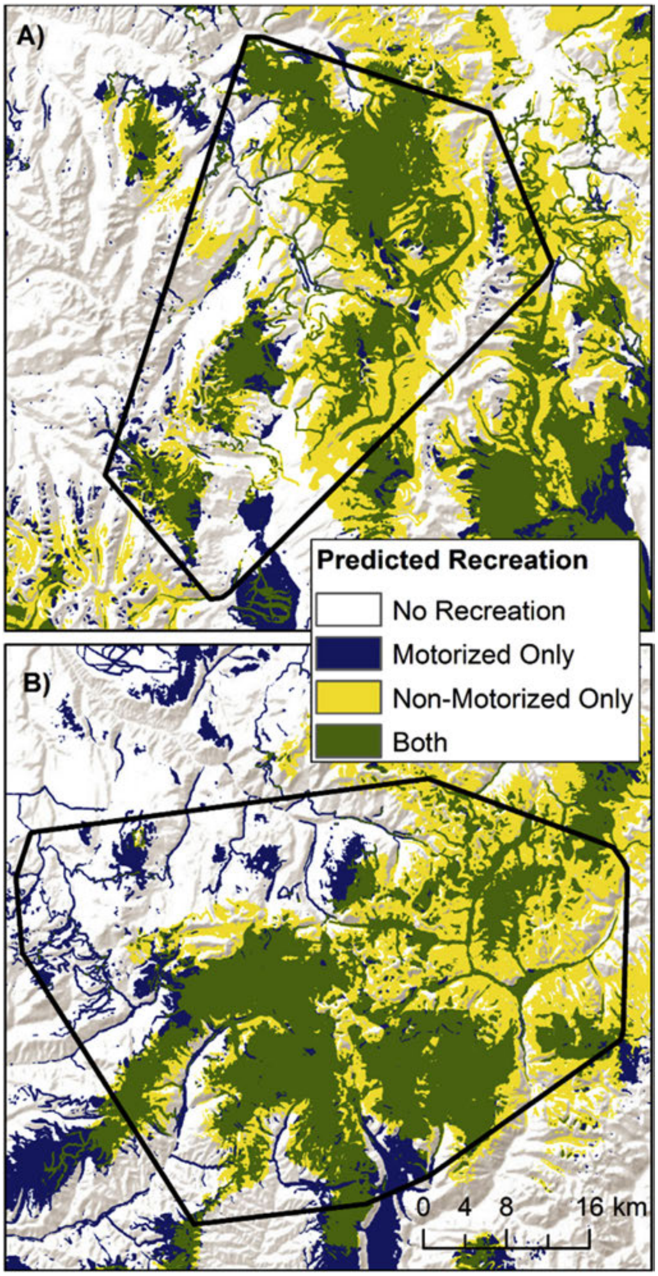

Fig. 5. The distribution of predicted areas of potential overlap between motorized and non-motorized recreation activities within the Vail (A) and San Juan (B) study areas (thick black line denotes study area boundary). Green indicates areas predicted to be selected by both types of recreation, yellow is non-motorized only, and blue indicates motorized recreation. Background image credit: Esri software. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

off road vehicle recreation. Indeed, the preferences of recreationists for certain environmental characteristics may be outweighed in practice by accessibility, with areas considered less suitable receiving more actual use due to the presence of ample parking areas and road access (Beeco, Hallo, & Brownlee, 2014; Brabyn & Sutton, 2013). Our models showed that areas greater than 11 km from a highway were predicted to have virtually no recreation at all, while areas predicted to have the highest recreation use, both motorized and non motorized, were nearest highways. This has implications for forest and recreation management, since recreationists are likely to use forest roads to access the back country even if these roads are closed to vehicles (Havlick, 2002). Through the creation of forest roads, whether through logging operations, as part of fire reduction or suppression activities, or for access to human developments, recreation is likely to show a corresponding increase as well.

Differences in the results of the RSF and SSF models provide information on the importance of environmental characteristics to recreationists when first selecting where to recreate, and then deciding how to move through the landscape once there. Topographic features, such as low to moderate slope, low terrain variability, and selection for drainages (except for skiers who selected ridges), were consistent predictors of recreation selection at a landscape scale, while vegetation characteristics were generally not among the top contributing covariates. Fine scale movement models, conversely, were most strongly influenced by access and vegetation characteristics, and were more variable between different types of recreation. A stronger response to vegetation covariates at a small scale suggests that recreationists select areas in which to recreate at a hierarchical scale, with road access and large topographic features dictating an initial area selection, and finer scale features such as forest density determining where to move within this area. The greater influence of vegetation at a small spatial scale may be related to the differences in movement speed and maneuverability of the different recreation types, since non motorized recreationists may be better able to safely move through dense trees, while motorized recreationists may select open areas for play and fast travel.

Temporally, recreationists exhibited clear patterns of use with respect to time of day and day of the week. Nearly all recreation occurred during daylight hours, and dropped off to almost nothing after dark. Recreation was also markedly higher on weekends, particularly Saturdays, as compared to the rest of the week (Fig. 3). Thus, the ecological impact of winter recreation may decrease for species that are crepuscular or nocturnal, which will be active in times when little or no recreation is present. Similarly, weekdays may have a lower ecological impact than weekends, so that if management were undertaken to reduce or cap the number of users in an area, it may only need implementation during weekends.

4.2. Conflict and ecological implications

The predictions from our landscape scale selection models made possible a spatially resolute depiction of areas which motorized and non motorized recreation were likely to select, and thus where interpersonal conflict may be more likely (Miller, 2016; Vaske et al., 2000). In a related survey study focused only on the Vail Pass area, Miller et al. (2016) found greater interpersonal conflict in areas of shared use. Managers often employ spatial or temporal closures of areas to motorized or non motorized activities in an attempt to limit shared use and minimize conflict (Albritton & Stein, 2011; Leung & Marion, 1999). This is often an asymmetrical solution, however, with non motorized users reporting increased satisfaction while motorized users are dissatisfied with increased restrictions (Jackson, Haider, & Elliot, 2003). Our model indicates that while zoning is a useful tool in some areas, it may be unnecessary in others. The environmental characteristics at areas predicted to have both types of recreation tended to differ from areas with either type alone (Fig. 6). Areas of overlap were closer to roads, had moderate slopes, and were in areas of patchier or more fragmented forest. This pattern may result from the use by both motorized and non motorized recreation of areas that are logistically necessary but not preferred, such as areas near parking lots and large groomed travel corridors. Thus, managers may be able to limit zoning to

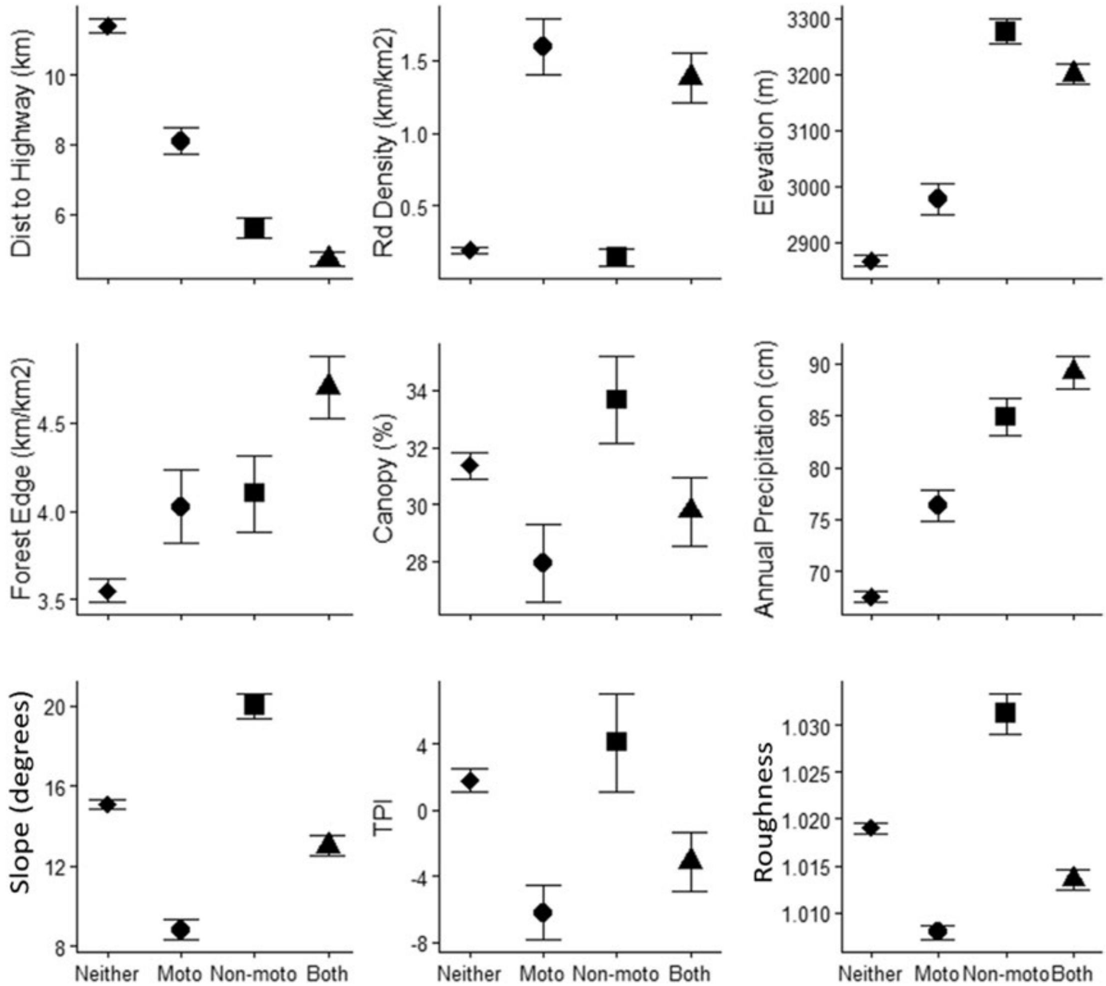

Fig. 6. Mean of environmental characteristics summarized in areas predicted across western Colorado to be selected by either motorized (Moto, circle) or non-motorized (Non-moto, square) winter recreation only, or both (triangle) or neither (diamond).

these areas of forced co occurrence, while allowing recreationists more liberty outside these areas, where terrain selection should diverge.

Outside of overlap areas, motorized and non motorized forms of recreation show distinct separation in many environmental traits. Motorized recreationists tend to select drainages with low slope and low terrain variability, in lower elevation areas with more open canopy and less precipitation. This suite of characteristics probably favors fast, long distance movements, which our results show are characteristic of snowmobiles. Non motorized recreationists, alternatively, select ridges with steeper slope and greater terrain variability, at higher elevations and with less open canopy and more snow (Fig. 6), traits consistent with skiing down steep, treed slopes. Differences in environmental characteristics used by each recreation type may provide useful guidelines on determining whether to zone certain areas for motorized or non motorized use only, while still providing each type of recreation the environ mental characteristics they prefer. Areas of steep slope, for instance, may be set aside for backcountry skiers or hybrid skiers with little effect to snowmobilers, since they prefer more flat terrain.

Modeled areas of overlap also have implications for conflict between recreation and species of conservation concern. Motorized winter recreation creates increased noise and engine emissions which can negatively impact wildlife (Shively et al., 2008; Zielinski, Slauson, & Bowles, 2008), while non motorized forms may displace wildlife (Krebs, Lofroth, & Parfitt, 2007; Reimers, Eftestøl, & Colman, 2003) or contribute to habitat loss through the construc tion of recreation infrastructure (Sato, Wood, & Lindenmayer, 2013). Wildlife may also respond differently to motorized versus non motorized types of winter recreation (Larson, Reed, Merenlender, & Crooks, 2016); Reimers et al. (2003) found that reindeer (*Rangifer tarandus tarandus*) detected snowmobiles sooner than skiers, but responded to skiers by moving greater distances than from snowmobiles, and Seip, Johnson, and Watts (2007) found threatened woodland caribou strongly avoided motorized snow mobile recreation over huge areas. The spatial depiction of relative recreation probability (Appendix C: Figs C.1 C.5) generated by our models provides detailed maps which can be used to determine the likelihood of motorized or non motorized forms of recreation in a given area. The use of a modeled RSF allows managers to consider the relative probability of a specific type of recreation co occurring with a given species, and thus will allow decisions to be tailored for species that differ in sensitivity to different types of recreation.

5. Conclusions

The sharp increase in the extent and popularity of winter rec reation presents a challenge to land managers responsible for multiple use lands (Bowker et al., 2012), with associated concern as to its impact on wildlife and the environment (Arlettaz et al., 2015;

Braunisch et al., 2011; Patthey, Wirthner, Signorell, & Arlettaz, 2008). Thus, managers face multiple challenges of reducing impacts to the environment and wildlife while also minimizing interpersonal conflict and still providing winter recreation opportunities. One way in which the likelihood of interpersonal conflict may be minimized is to reduce the time that motorized and non motorized users are funneled into a single shared use access area or travel corridor, since our results show that the conditions that motorized and non motorized users select are fairly distinct, and thus recreationists may self select areas that reduce co occurrence between the two types. Alternatively, if active zoning is required to separate users to reduce conflict or for safety, the conditions that each recreation type favors should be considered. Our results underscore the importance of road and road access management in affecting the spatial footprint of winter recreation. Decisions about the placement or density of roads need careful assessment as they can influence the movements of winter recreationists relative to wildlife or each other. Management practices that lower tree density and increase forest patchiness will also influence motorized and non motorized recreation at fine spatial scales.

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Appendix A. Table A.1

The mean and 95% confidence intervals of all used and available GPS points for each environmental covariate (see Table 1 in manuscript for more covariate information) at the 2500 m scale used to model winter recreation selection in western Colorado, USA, from 2010 to 2013. Summaries for each winter recreation activity, on trail snowmobile (Snmb On Tr), off trail snowmobile (Snmb Off Tr), snowmobile segments of snowmobile assisted hybrid skiing (Hybrid Snmb), ski segments of snowmobile assisted hybrid skiing (Hybrid Ski), and back country ski or snow board (Ski), are provided to allow comparison between recreation types within a given covariate.

Covariate	Activity	Used Points		Available Points	
		Mean	95% CI	Mean	95% CI
Distance to Highway (km)	Snmb On-Tr	3.41	3.19 3.62	4.35	4.05 4.65
	Snmb Off-Tr	3.38	3.19 3.57	4.37	4.07 4.67
	Hybrid Snmb	4.05	3.9 4.21	3.59	3.28 3.9
	Hybrid Ski	4.61	4.48 4.74	3.58	3.27 3.89
	Ski	2.46	2.35 2.56	4.95	4.7 5.19
Elevation (m)	Snmb On-Tr	3208.27	3190.77 3225.77	3246.61	3222.78 3270.45
	Snmb Off-Tr	3395.73	3383.01 3408.45	3246.23	3222.29 3270.18
	Hybrid Snmb	3408.50	3399.38 3417.61	3278.60	3254.29 3302.91
	Hybrid Ski	3425.94	3417.01 3434.86	3279.75	3255.34 3304.17
	Ski	3375.08	3366.35 3383.82	3298.73	3282.91 3314.55
Forest Edge (km/km^2)	Snmb On-Tr	3.77	3.68 3.86	3.22	3.13 3.32
	Snmb Off-Tr	4.11	4.03 4.18	3.22	3.13 3.32
	Hybrid Snmb	3.57	3.47 3.66	3.26	3.14 3.38
	Hybrid Ski	3.35	3.28 3.43	3.26	3.14 3.39
	Ski/Board	3.98	3.92 4.04	3.16	3.09 3.23
Percent Canopy Cover	Snmb On-Tr	37.88	37.17 38.58	34.12	33.15 35.09
	Snmb Off-Tr	35.25	34.58 35.92	34.03	33.06 35
	Hybrid Snmb	33.88	32.99 34.78	36.34	35.11 37.58
	Hybrid Ski	32.48	31.51 33.44	36.31	35.08 37.54
	Ski/Board	31.26	30.7 31.83	33.50	32.75 34.25
Percent Evergreen Forest	Snmb On-Tr	51.54	50.23 52.85	46.92	45.12 48.73
	Snmb Off-Tr	51.08	49.82 52.35	46.73	44.92 48.53
	Hybrid Snmb	50.84	49.61 52.07	53.33	51.03 55.63
	Hybrid Ski	51.31	49.97 52.66	53.30	51 55.6
	Ski/Board	44.58	43.56 45.59	46.01	44.63 47.39
Average Annual Precipitation (mm)	Snmb On-Tr	82.77	81.75 83.8	79.00	77.44 80.56
	Snmb Off-Tr	90.49	89.58 91.4	79.18	77.61 80.75
	Hybrid Snmb	84.65	83.84 85.46	71.93	70.4 73.45
	Hybrid Ski	84.94	84.04 85.84	71.98	70.45 73.5
	Ski/Board	90.17	89.14 91.21	84.04	82.77 85.3
Forest Road Density (km/km^2)	Snmb On-Tr	1.19	1.12 1.26	0.52	0.47 0.58
	Snmb Off-Tr	0.65	0.6 0.71	0.52	0.47 0.58
	Hybrid Snmb	0.92	0.87 0.97	0.63	0.59 0.67
	Hybrid Ski	0.91	0.86 0.95	0.63	0.59 0.67
	Ski/Board	0.62	0.6 0.65	0.54	0.5 0.57
Slope (degrees)	Snmb On-Tr	15.97	15.67 16.27	18.00	17.56 18.45
	Snmb Off-Tr	14.70	14.46 14.95	18.03	17.58 18.48
	Hybrid Snmb	16.28	15.99 16.57	16.71	16.22 17.2

(continued on next page)

(*continued*)

Covariate	Activity	Used Points		Available Points	
		Mean	95% CI	Mean	95% CI
	Hybrid Ski	17.26	16.99 17.53	16.74	16.25 17.23
	Ski/Board	18.31	17.98 18.64	18.88	18.54 19.22
Roughness[a]	Snmb On-Tr	1.003	1.002 1.003	1.004	1.004 1.004
	Snmb Off-Tr	1.001	1.001 1.002	1.004	1.004 1.004
	Hybrid Snmb	1.001	1.001 1.002	1.003	1.003 1.004
	Hybrid Ski	1.002	1.002 1.002	1.003	1.003 1.004
	Ski/Board	1.003	1.003 1.003	1.004	1.004 1.005
Mean Annual Temperature (^{o}C)	Snmb On-Tr	1.59	1.5 1.68	1.25	1.13 1.36
	Snmb Off-Tr	0.69	0.61 0.77	1.25	1.13 1.37
	Hybrid Snmb	0.48	0.4 0.55	0.93	0.79 1.07
	Hybrid Ski	0.29	0.21 0.36	0.92	0.78 1.06
	Ski/Board	1.06	1.01 1.11	1.20	1.11 1.3
Topographic Position Index (TPI[b])	Snmb On-Tr	−50.08	−60.07 −40.09	−9.44	−20.55 1.67
	Snmb Off-Tr	28.52	21.27 35.78	−9.83	−20.97 1.32
	Hybrid Snmb	11.94	−1.89 25.76	−10.32	−23.97 3.33
	Hybrid Ski	63.15	49.91 76.39	−9.54	−23.21 4.13
	Ski/Board	−18.06	−27.13 −8.99	1.11	−7.98 10.2

[a] Higher values represent greater terrain variability.
[b] Negative values indicate drainages, positive indicate ridges.

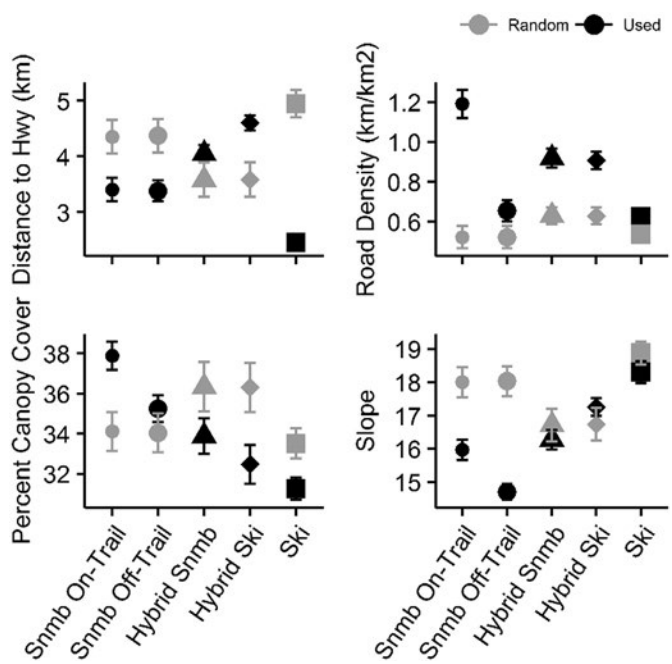

Fig A.1. Mean and 95% CI summaries of environmental characteristics at used and random locations of each recreation activity at both study areas in Colorado, USA. Plots shown are distance to highway (km), road density (km/km^2), percent canopy closure (%), and slope (degrees).

Appendix B. Model selection results showing the top 10 models from resource selection functions (RSF) for each recreation type studied in western Colorado, USA from 2010 to 2013.

Table B.1
Model selection table for on-trail snowmobile RSF models showing habitat selection of winter recreationists driving snowmobiles on trails. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript '2'. Further information on environmental covariates is given in Table 1 of the manuscript.

Model covariates	K	AIC	Δ AIC	AIC Wt	LL
$Highway_{2500} + ForestEdge_{125} + Canopy_{125} + Canopy^2_{125} + Evergreen_{2500} + Evergreen^2_{2500} + North_{500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + Temp + TPI_{500}$	17	212,588.3	0	1	−106277
$Highway_{2500} + ForestEdge_{125} + Canopy_{125} + Evergreen_{2500} + Evergreen^2_{2500} + North_{500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + Temp + TPI_{500}$	16	212,617.5	29.19	0	−106293
$Highway_{2500} + ForestEdge_{125} + Canopy_{125} + Canopy^2_{125} + Evergreen_{2500} + Evergreen^2_{2500} + North_{2500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + Temp + TPI_{500}$	17	212,749.7	161.46	0	−106358
$Highway_{2500} + ForestEdge_{125} + Canopy_{125} + Evergreen_{2500} + Evergreen^2_{2500} + North_{2500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + Temp + TPI_{500}$	16	212,762.1	173.85	0	−106365
$Highway_{2500} + ForestEdge_{125} + Canopy_{125} + Canopy^2_{125} + Evergreen_{2500} + Evergreen^2_{2500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + Temp + TPI_{500}$	16	212,877.4	289.12	0	−106423
$Highway_{2500} + ForestEdge_{125} + Canopy_{125} + Evergreen_{2500} + Evergreen^2_{2500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + Temp + TPI_{500}$	15	212,889.9	301.58	0	−106430
$Highway_{2500} + Elevation_{2500} + Elevation^2_{2500} + ForestEdge_{125} + Canopy_{125} + Canopy^2_{125} + Evergreen_{2500} + Evergreen^2_{2500} + North_{500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + TPI_{500}$	18	213,091.4	503.11	0	−106528
$Highway_{2500} + Elevation_{2500} + Elevation^2_{2500} + ForestEdge_{125} + Canopy_{125} + Evergreen_{2500} + Evergreen^2_{2500} + North_{500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + TPI_{500}$	17	213,110.5	522.24	0	−106538
$Highway_{2500} + Canopy_{125} + Canopy^2_{125} + Evergreen_{2500} + Evergreen^2_{2500} + North_{500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + Temp + TPI_{500}$	16	213,128.7	540.46	0	−106548
$Highway_{2500} + ForestEdge_{2500} + Canopy_{125} + Canopy^2_{125} + Evergreen_{2500} + Evergreen^2_{2500} + North_{500} + Precip + Precip^2 + RdDensity_{125} + Slope_{1250} + Slope^2_{1250} + Roughness_{500} + Temp + TPI_{500}$	17	213,131.1	542.83	0	−106549

Table B.2
Model selection table for off-trail snowmobile RSF models showing habitat selection of winter recreationists driving snowmobiles on off-trail play areas. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript '2'. Further information on environmental covariates is given in Table 1 of the manuscript.

Model Covariates	K	AIC	Δ AIC	AIC Wt	LL
$Highway_{2500} + Elevation_{125} + Elevation^2_{125} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + North_{2500} + Precip + Precip^2 + RdDensity_{125} + Slope_{125} + Roughness_{2500} + TPI_{500}$	17	52,437.11	0	1	−26201.6
$Highway_{2500} + Elevation_{125} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + North_{2500} + Precip + Precip^2 + RdDensity_{125} + Slope_{125} + Roughness_{2500} + TPI_{500}$	16	52,484.34	47.23	0	−26226.2
$Highway_{2500} + Elevation_{125} + Elevation^2_{125} + ForestEdge_{500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + North_{2500} + Precip + Precip^2 + RdDensity_{125} + Slope_{125} + Roughness_{2500} + TPI_{500}$	17	52,530.61	93.49	0	−26248.3
$Highway_{2500} + Elevation_{125} + Elevation^2_{125} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + North_{2500} + Precip + Precip^2 + RdDensity_{2500} + Slope_{125} + Roughness_{2500} + TPI_{500}$	17	52,581.75	144.64	0	−26273.9
$Highway_{2500} + Elevation_{125} + ForestEdge_{500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + North_{2500} + Precip + Precip^2 + RdDensity_{125} + Slope_{125} + Roughness_{2500} + TPI_{500}$	16	52,615.75	178.64	0	−26291.9
$Highway_{2500} + Elevation_{125} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + North_{2500} + Precip + Precip^2 + RdDensity_{2500} + Slope_{125} + Roughness_{2500} + TPI_{500}$	16	52,619.33	182.22	0	−26293.7
$Highway_{2500} + Elevation_{125} + Elevation^2_{125} + ForestEdge_{500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + Precip + Precip^2 + RdDensity_{125} + Slope_{125} + Roughness_{2500} + TPI_{500}$	16	52,681.12	244	0	−26324.6
$Highway_{2500} + Elevation_{125} + Elevation^2_{125} + ForestEdge_{500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + North_{500} + Precip + Precip^2 + RdDensity_{125} + Slope_{125} + Roughness_{2500} + TPI_{500}$	17	52,681.75	244.63	0	−26323.9
$Highway_{2500} + Elevation_{125} + Elevation^2_{125} + ForestEdge_{500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + North_{2500} + Precip + Precip^2 + RdDensity_{2500} + Slope_{125} + Roughness_{2500} + TPI_{500}$	17	52,685.36	248.25	0	−26325.7
$Highway_{2500} + Elevation_{125} + ForestEdge_{500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{125} + Evergreen^2_{125} + North_{2500} + Precip + Precip^2 + RdDensity_{2500} + Slope_{125} + Roughness_{2500} + TPI_{500}$	16	52,758.39	321.28	0	−26363.2

Table B.3

Model selection table for hybrid snowmobile RSF models showing habitat selection of winter recreationists driving snowmobiles while engaging in hybrid-assisted skiing. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript '2'. Further information on environmental covariates is given in Table 1 of the manuscript.

Model Covariates	K	AIC	Δ AIC	AIC Wt	LL
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{125}$ + Canopy$_{2500}$ + Canopy$^2_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{2500}$	16	95,901.39	0	1	−47934.7
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Canopy$_{2500}$ + Canopy$^2_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{2500}$	16	96,122.37	220.98	0	−48045.2
Highway$_{1250}$ + Highway$^2_{1250}$ + Canopy$_{2500}$ + Canopy$^2_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{2500}$	15	96,129.87	228.48	0	−48049.9
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{125}$ + Canopy$_{2500}$ + Canopy$^2_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{500}$	16	96,376.94	475.55	0	−48172.5
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Canopy$_{2500}$ + Canopy$^2_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{500}$	16	96,519.77	618.38	0	−48243.9
Highway$_{1250}$ + Highway$^2_{1250}$ + Canopy$_{2500}$ + Canopy$^2_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{500}$	15	96,534.58	633.19	0	−48252.3
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{125}$ + Canopy$_{2500}$ + Canopy$^2_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2	15	96,558.35	656.96	0	−48264.2
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Canopy$_{2500}$ + Canopy$^2_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2	15	96,645.06	743.67	0	−48307.5
Highway$_{1250}$ + Highway$^2_{1250}$ + Canopy$_{2500}$ + Canopy$^2_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2	14	96,656.74	755.35	0	−48314.4
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Canopy$_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{125}$ + Slope$_{1250}$ + Roughness$_{2500}$ + Temp + Temp^2	14	98,926.79	3025.4	0	−49449.4

Table B.4

Model selection table for hybrid ski RSF models showing habitat selection of winter recreationists skiing downhill while engaging in hybrid-assisted skiing. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript '2'. Further information on environmental covariates is given in Table 1 of the manuscript.

Model Covariates	K	AIC	Δ AIC	AIC Wt	LL
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Canopy$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{2500}$	15	10,971.81	0.00	0.96	−5470.90
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Canopy$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2	14	10,978.98	7.18	0.03	−5475.49
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Canopy$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{500}$	15	10,980.81	9.00	0.01	−5475.40
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{500}$	15	11,015.75	43.94	0.00	−5492.88
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{500}$ + Canopy$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{500}$	15	11,035.22	63.41	0.00	−5502.61
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2	14	11,037.28	65.47	0.00	−5504.64
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Evergreen$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{2500}$	15	11,037.46	65.65	0.00	−5503.73
Highway$_{125}$ + Highway$^2_{125}$ + Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{2500}$ + Canopy$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{2500}$	15	11,045.83	74.02	0.00	−5507.92
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{500}$ + Canopy$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2	14	11,049.88	78.07	0.00	−5510.94
Highway$_{1250}$ + Highway$^2_{1250}$ + ForestEdge$_{500}$ + Canopy$_{125}$ + North$_{2500}$ + Precip + RdDensity$_{1250}$ + Slope$_{125}$ + Slope$^2_{125}$ + Roughness$_{2500}$ + Temp + Temp^2 + TPI$_{2500}$	15	11,050.23	78.42	0.00	−5510.12

Table B.5

Model selection table for backcountry ski RSF models showing habitat selection of winter recreationists engaged in backcountry skiing or snowboarding. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript ‘2’. Further information on environmental covariates is given in Table 1 of the manuscript.

Model Covariates	K	AIC	Δ AIC	AIC Wt	LL
$Highway_{2500} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{500} + Evergreen^2_{500} + North_{500} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2 + TPI_{125}$	15	90,376.84	0	1	−45173.4
$Highway_{2500} + ForestEdge_{2500} + Evergreen_{500} + Evergreen^2_{500} + North_{500} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2 + TPI_{125}$	13	90,522.59	145.75	0	−45248.3
$Highway_{2500} + ForestEdge_{2500} + Canopy_{2500} + Evergreen_{500} + Evergreen^2_{500} + North_{500} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2 + TPI_{125}$	14	90,523.19	146.35	0	−45247.6
$Highway_{2500} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{500} + Evergreen^2_{500} + North_{1250} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2 + TPI_{125}$	15	90,525.74	148.9	0	−45247.9
$Highway_{2500} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{500} + Evergreen^2_{500} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2 + TPI_{125}$	14	90,573.21	196.37	0	−45272.6
$Highway_{2500} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{500} + Evergreen^2_{500} + North_{500} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2 + TPI_{2500}$	15	90,626.04	249.2	0	−45298
$Highway_{2500} + ForestEdge_{2500} + Evergreen_{1250} + Evergreen^2_{1250} + North_{500} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2 + TPI_{125}$	13	90,640.83	263.98	0	−45307.4
$Highway_{2500} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{500} + Evergreen^2_{500} + North_{500} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2$	14	90,651.89	275.05	0	−45312
$Highway_{2500} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{500} + Evergreen^2_{500} + North_{1250} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2 + TPI_{2500}$	15	90,764.08	387.24	0	−45367
$Highway_{2500} + ForestEdge_{2500} + Canopy_{2500} + Canopy^2_{2500} + Evergreen_{500} + Evergreen^2_{500} + North_{1250} + Precip + RdDensity_{125} + Roughness_{125} + Temp + Temp^2$	14	90,784.79	407.95	0	−45378.4

Appendix C. Mapped spatial predictions of selection for each type of winter recreation modeled with resource selection functions within the elevation range of winter recreation (2300 m–4250 m) in western Colorado, 2010–2013.

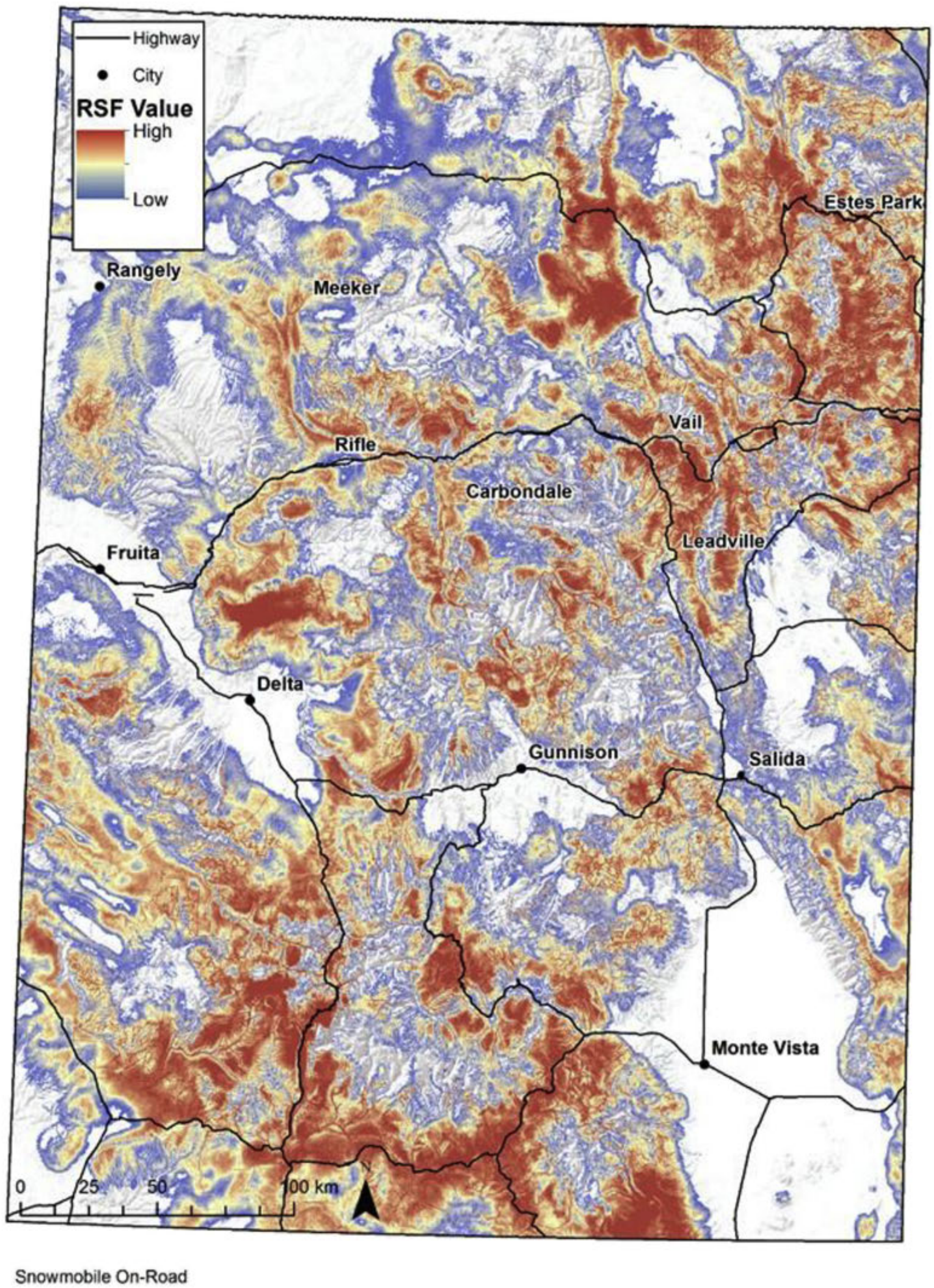

Figure C.1. Predicted probabilities of selection from the resource selection function model for on-trail snowmobile recreation across western Colorado. Warm colors indicate higher probability of selection, cool colors indicate an area is less likely to be selected.

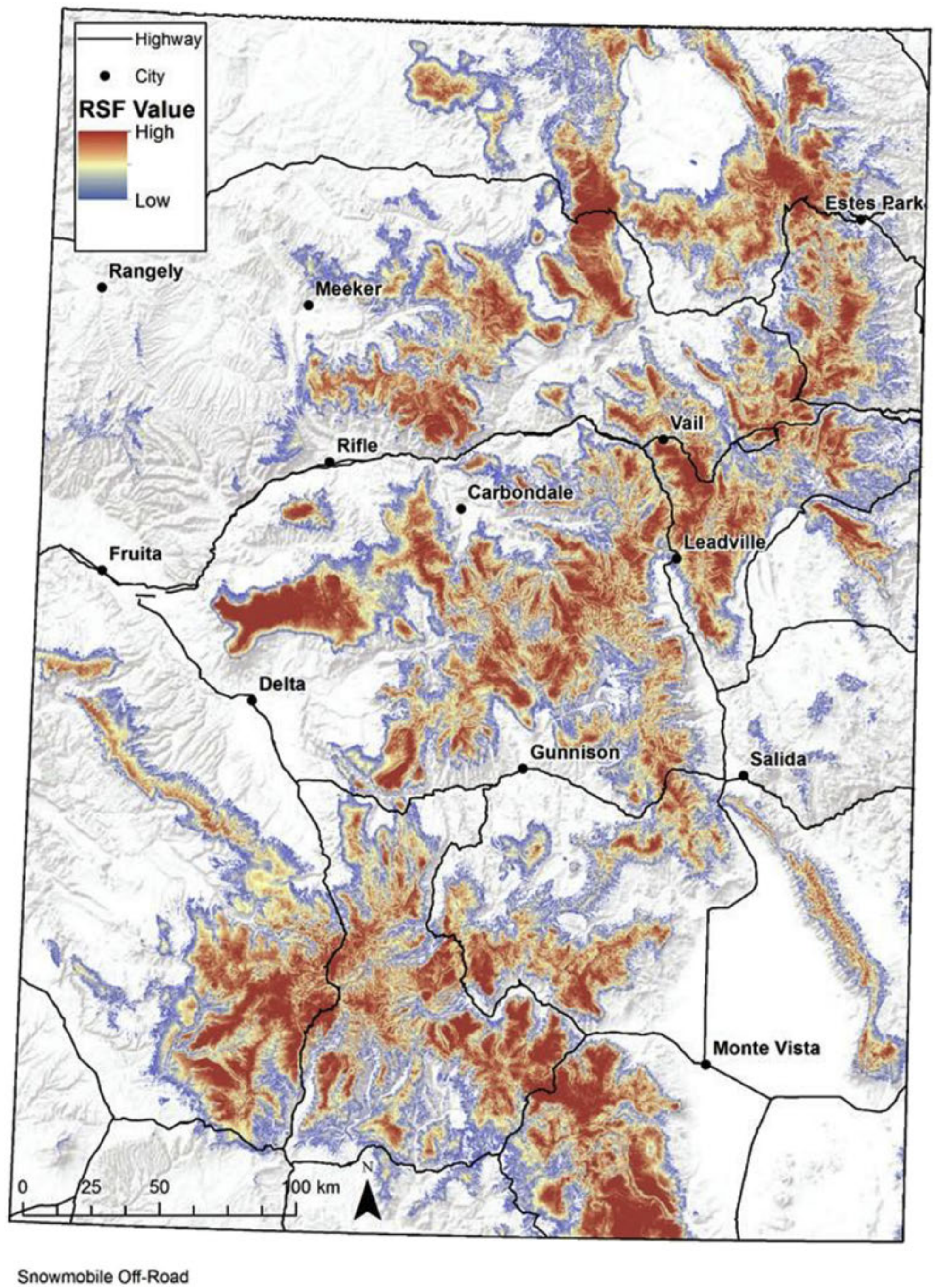

Figure C.2. Predicted probabilities of selection from the resource selection function model for off-trail snowmobile recreation across western Colorado. Warm colors indicate higher probability of selection, cool colors indicate an area is less likely to be selected.

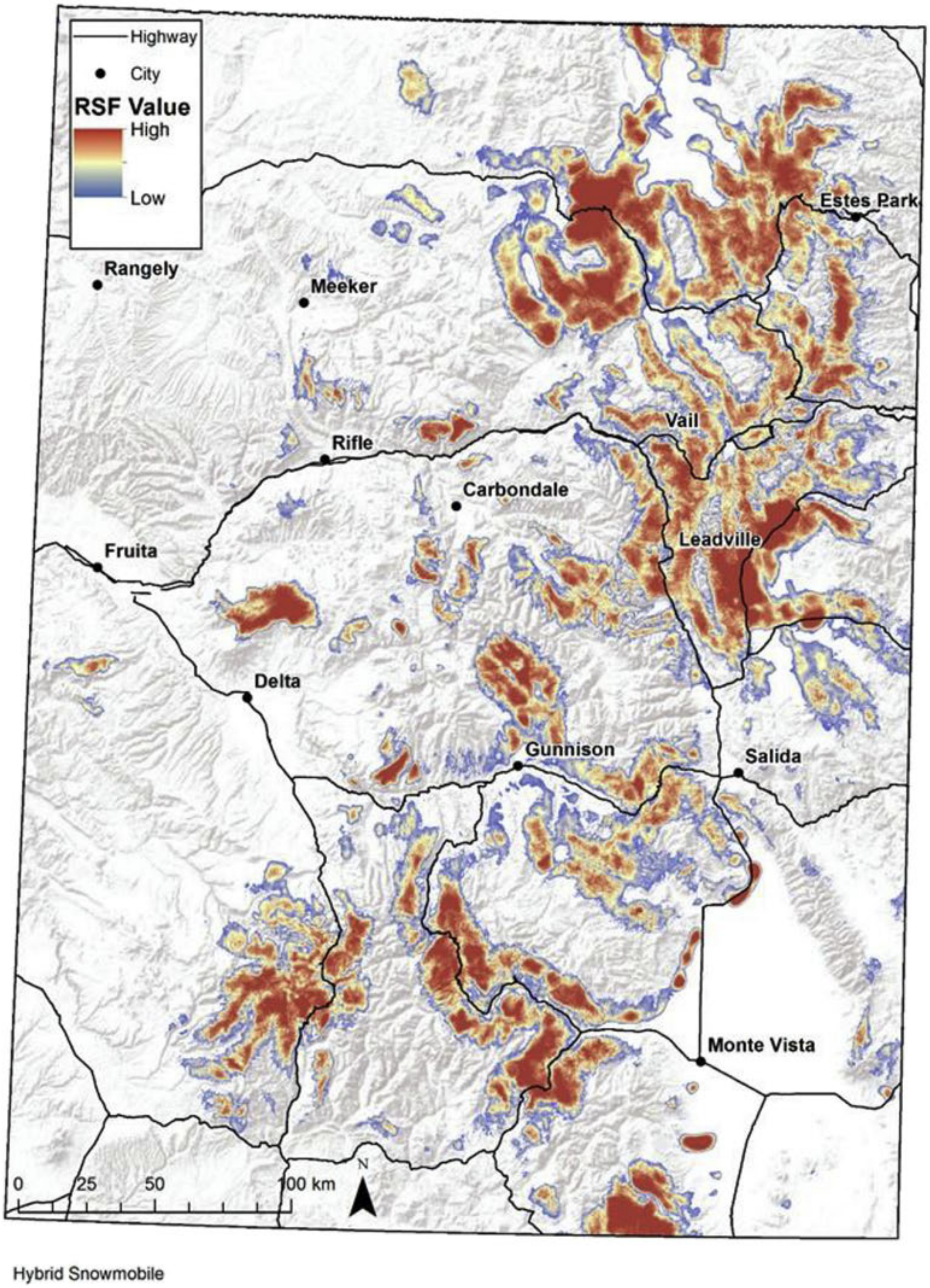

Figure C.3. Predicted probabilities of selection from the resource selection function model for hybrid snowmobile recreation across western Colorado. Warm colors indicate higher probability of selection, cool colors indicate an area is less likely to be selected.

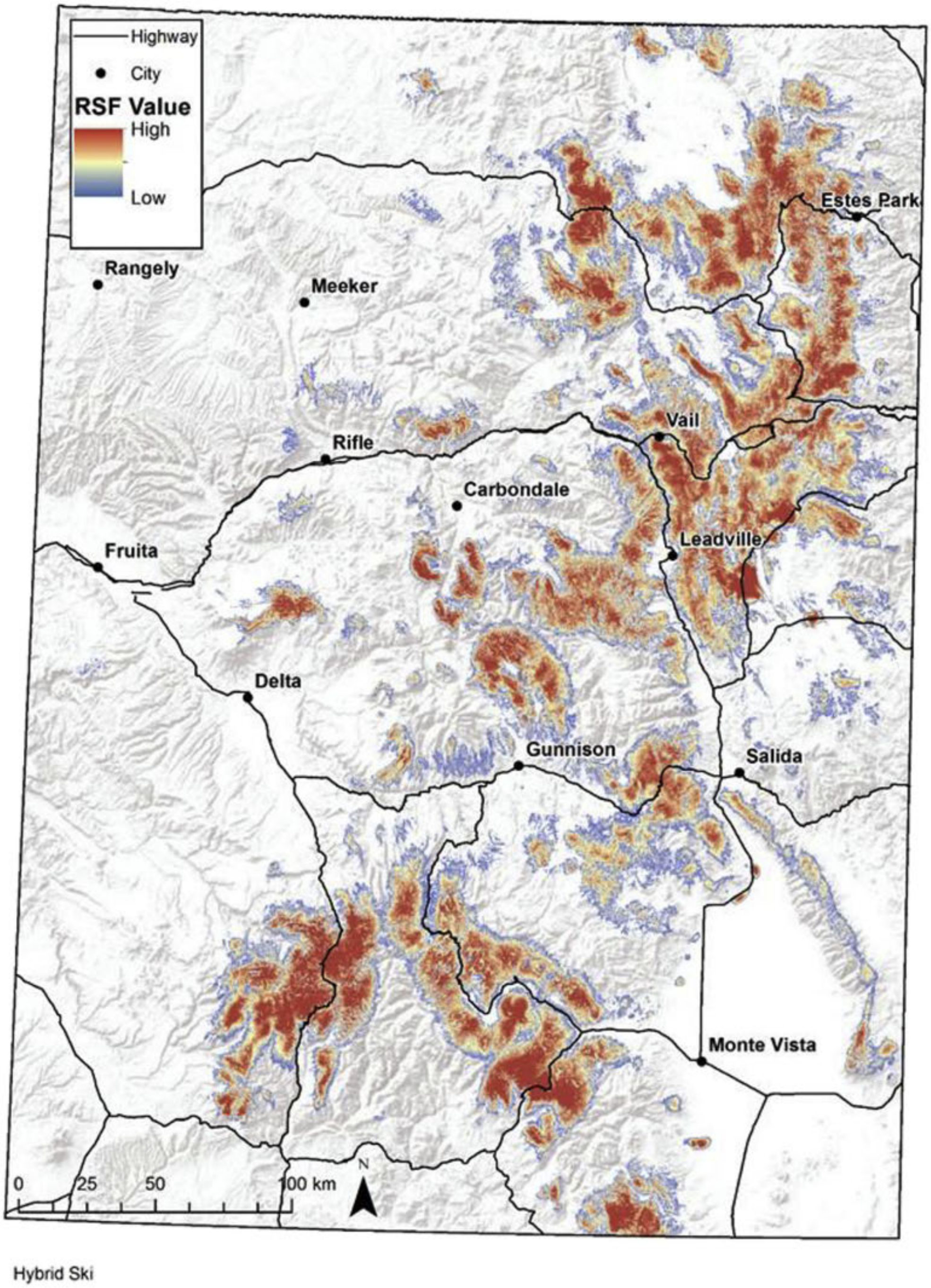

Figure C.4. Predicted probabilities of selection from the resource selection function model for hybrid ski recreation across western Colorado. Warm colors indicate higher probability of selection, cool colors indicate an area is less likely to be selected.

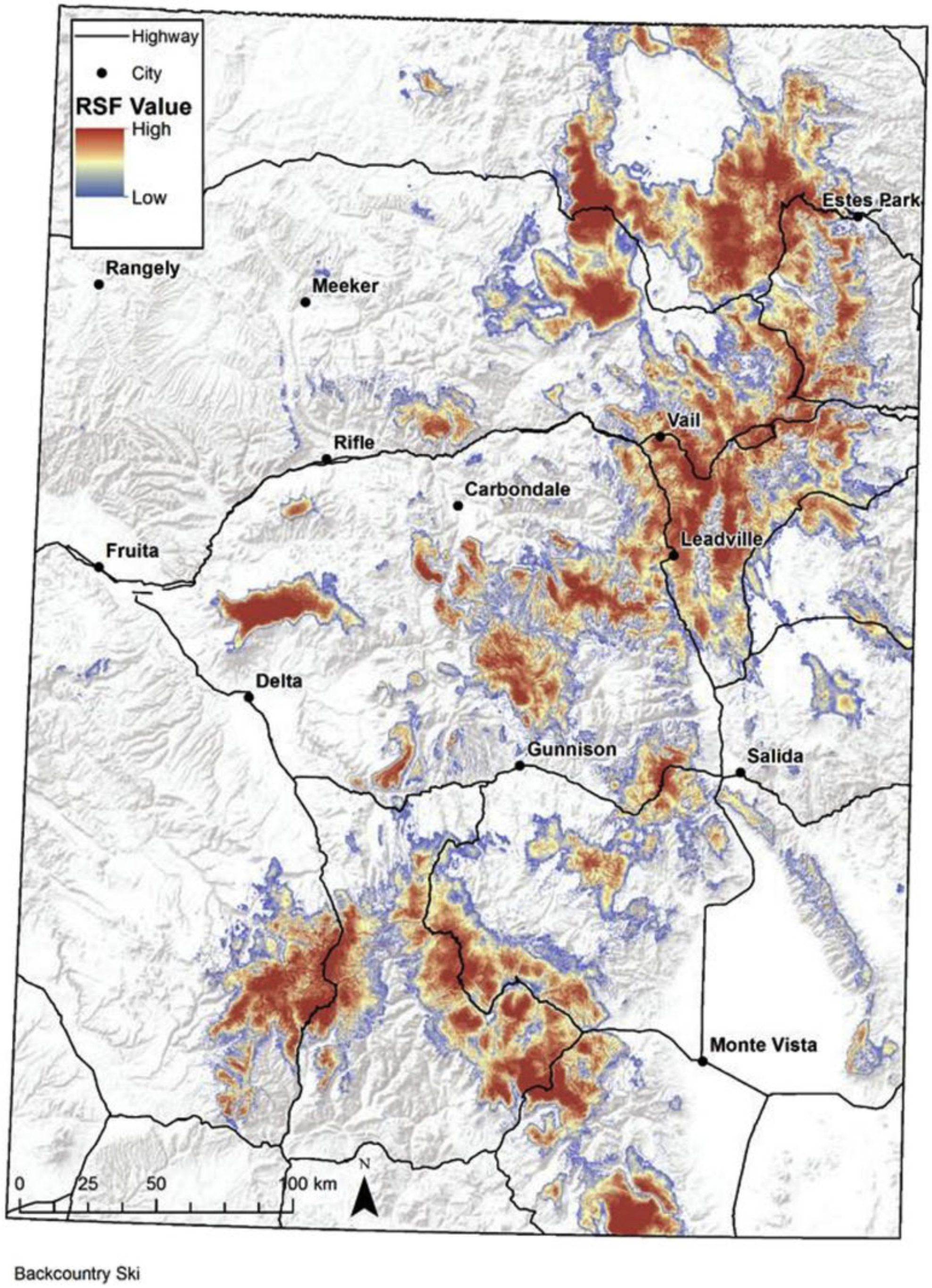

Figure C.5. Predicted probabilities of selection from the resource selection function model for backcountry ski recreation across western Colorado. Warm colors indicate higher probability of selection, cool colors indicate an area is less likely to be selected.

Appendix D. Model selection results showing the top 10 models from step selection functions (SSF) for each recreation type studied in western Colorado, USA from 2010 to 2013.

Table D.1
Model selection table for on-trail snowmobile SSF models showing selection of movement paths by winter recreationists driving snowmobiles on trails. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript ‘2’. Further information on environmental covariates is given in Table 1 of the manuscript.

Model Covariates	K	AIC	Δ AIC	AIC Wt	LL
$Elevation_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI_{125}	10	340,845.00	0.00	0.59	−170,412.50
$Elevation_{125}$ + $Elevation^2_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI_{125}	11	340,847.00	1.99	0.22	−170,412.50
$Elevation_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI_{125}	9	340,849.20	4.17	0.07	−170,415.60
$Elevation_{125}$ + $ForestEdge_{500}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI_{125}	10	340,849.90	4.80	0.05	−170,414.90
$Elevation_{125}$ + $Elevation^2_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI_{125}	10	340,851.20	6.17	0.03	−170,415.60
$Elevation_{125}$ + $Elevation^2_{125}$ + $ForestEdge_{500}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Slope_{500}$ + $0Roughness_{125}$ + TPI_{125}	11	340,851.80	6.80	0.02	−170,414.90
$Elevation_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Roughness_{125}$ + TPI_{125}	9	340,853.80	8.78	0.01	−170,417.90
$Elevation_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI_{125}	9	340,853.90	8.88	0.01	−170,418.00
$Elevation_{125}$ + $Elevation^2_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Roughness_{125}$ + TPI_{125}	10	340,855.60	10.60	0.00	−170,417.80
$Elevation_{125}$ + $Elevation^2_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $RdDensity_{125}$ + $RdDensity^2_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI_{125}	10	340,855.90	10.90	0.00	−170,418.00

Table D.2
Model selection table for off-trail snowmobile SSF models showing selection of movement paths by winter recreationists driving snowmobiles on off-trail play areas. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript ‘2’. Further information on environmental covariates is given in Table 1 of the manuscript.

Model Covariates	K	AIC	Δ AIC	AIC Wt	LL
$Highway_{500}$ + $Elevation_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI_{125}	10	102,826.30	0.00	0.42	−51403.15
$Highway_{125}$ + $Elevation_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI_{125}	10	102,826.90	0.64	0.31	−51403.46
$Highway_{500}$ + $Elevation_{500}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI +	10	102,828.50	2.24	0.14	−51404.26
$Highway_{125}$ + $Elevation_{500}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI +	10	102,829.10	2.86	0.10	−51404.57
$Highway_{500}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI +	9	102,834.00	7.70	0.01	−51408.00
$Highway_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI +	9	102,834.40	8.15	0.01	−51408.22
$Elevation_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI +	9	102,834.50	8.25	0.01	−51408.27
$Highway_{500}$ + $Elevation_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI	9	102,836.20	9.94	0.00	−51409.12
$Elevation_{500}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $North_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI +	9	102,836.30	9.98	0.00	−51409.14
$Highway_{125}$ + $Elevation_{125}$ + $ForestEdge_{125}$ + $Canopy_{125}$ + $Canopy^2_{125}$ + $RdDensity_{125}$ + $Slope_{500}$ + $Roughness_{125}$ + TPI +	9	102,836.90	10.60	0.00	−51409.43

Table D.3
Model selection table for hybrid snowmobile SSF models showing selection of movement paths by winter recreationists driving snowmobiles while engaging in hybrid-assisted skiing. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript '2'. Further information on environmental covariates is given in Table 1 of the manuscript.

Model Covariates	K	AIC	Δ AIC	AIC Wt	LL
$Highway_{125} + ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	14	333,152.20	0.00	1.00	−166,562.10
$Highway_{500} + ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	14	333,169.40	17.18	0.00	−166,570.70
$Highway_{125} + ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	13	333,204.50	52.22	0.00	−166,589.20
$Highway_{125} + Elevation_{500} + ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + TPI_{500} + TPI^2_{500}$	14	333,214.40	62.15	0.00	−166,593.20
$Highway_{125} + Elevation_{500} + Elevation^2_{500} + ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + TPI_{500} + TPI^2_{500}$	15	333,216.00	63.76	0.00	−166,593.00
$Highway_{125} + ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + TPI_{500} + TPI^2_{500}$	13	333,216.20	63.94	0.00	−166,595.10
$ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	13	333,216.30	64.05	0.00	−166,595.10
$Highway_{500} + ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	13	333,223.30	71.03	0.00	−166,598.60
$Highway_{500} + Elevation_{500} + ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + TPI_{500} + TPI^2_{500}$	14	333,228.40	76.13	0.00	−166,600.20
$Highway_{500} + ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + RdDensity^2_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + TPI_{500} + TPI^2_{500}$	13	333,230.00	77.74	0.00	−166,602.00

Table D.4
Model selection table for hybrid ski SSF models showing selection of movement paths by winter recreationists skiing downhill while engaging in hybrid-assisted skiing. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript '2'. Further information on environmental covariates is given in Table 1 of the manuscript.

Model Covariates	K	AIC	Δ AIC	AIC Wt	LL
$ForestEdge_{125} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{500} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	12	37,666.77	0.00	0.67	−18821.38
$ForestEdge_{125} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	11	37,669.51	2.73	0.17	−18823.75
$ForestEdge_{125} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	12	37,670.83	4.06	0.09	−18823.41
$ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{500} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	12	37,673.18	6.41	0.03	−18824.59
$ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	11	37,673.20	6.43	0.03	−18825.60
$ForestEdge_{500} + Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	12	37,674.45	7.68	0.01	−18825.22
$Canopy_{125} + Canopy^2_{120} + North_{500} + Precip + RdDensity_{500} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	11	37,684.50	17.72	0.00	−18831.25
$ForestEdge_{125} + Canopy_{125} + Canopy^2_{125} + Precip + RdDensity_{500} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	11	37,685.77	18.99	0.00	−18831.88
$Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	10	37,686.15	19.38	0.00	−18833.07
$Canopy_{125} + Canopy^2_{125} + North_{500} + Precip + RdDensity_{125} + Slope_{500} + Roughness_{125} + Roughness^2_{125} + Temp + TPI_{500} + TPI^2_{500}$	11	37,687.52	20.75	0.00	−18832.76

Table D.5
Model selection table for backcountry ski SSF models showing selection of movement paths by winter recreationists engaged in backcountry skiing. Only the top 10 models are shown. K is the number of model parameters, LL is model log likelihood. The scale at which the covariate was measured (in meters) is given in subscript numbers; covariates included as quadratics are indicated with a superscript '2'. Further information on environmental covariates is given in Table 1 of the manuscript.

Model Covariates	K	AIC	Δ AIC	AIC Wt	LL
Highway$_{500}$ + Highway$^2_{500}$ + Elevation$_{500}$ + Elevation$^2_{500}$ + ForestEdge$_{500}$ + Canopy$_{500}$ + Canopy$^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + Precip + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	14	195,195.80	0.00	0.55	−97583.89
Highway$_{500}$ + Highway$^2_{500}$ + Elevation$_{500}$ + Elevation$^2_{500}$ + ForestEdge$_{500}$ + Canopy$_{500}$ + Canopy$^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	13	195,196.80	1.00	0.33	−97585.39
Highway$_{500}$ + Highway$^2_{500}$ + Elevation$_{500}$ + Elevation$^2_{500}$ + Canopy$_{500}$ + Canopy$^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + Precip + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	13	195,200.30	4.54	0.06	−97587.16
Highway$_{500}$ + Highway$^2_{500}$2 + Elevation$_{500}$ + Elevation$^2_{500}$ + Canopy$_{500}$ + Canopy$^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	12	195,201.70	5.96	0.03	−97588.87
Highway$_{500}$ + Highway$^2_{500}$ + Elevation$_{500}$ + Elevation$^2_{500}$ + ForestEdge$_{125}$ + Canopy$_{500}$ + Canopy$^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + Precip + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	14	195,202.30	6.50	0.02	−97587.14
Highway$_{500}$ + Highway$^2_{500}$ + Elevation$_{500}$ + Elevation$^2_{500}$ + ForestEdge$_{125}$ + Canopy$_{500}$ + Canopy$^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	13	195,203.70	7.91	0.01	−97588.85
Highway$_{500}$ + Elevation$_{500}$ + Elevation$^2_{500}$ + ForestEdge$_{500}$ + Canopy $_{500}$ + Canopy $^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + Precip + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	13	195,207.50	11.67	0.00	−97590.73
Highway$_{500}$ + Elevation$_{500}$ + Elevation$^2_{500}$ + ForestEdge$_{500}$ + Canopy$_{500}$ + Canopy$^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	12	195,210.80	15.00	0.00	−97593.40
Highway$_{500}$ + Elevation$_{00}$ + Elevation$^2_{500}$ + Canopy$_{500}$ + Canopy$^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + Precip + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	12	195,212.50	16.75	0.00	−97594.27
Highway$_{500}$ + Elevation$_{500}$ + Elevation$^2_{500}$ + ForestEdge$_{125}$ + Canopy$_{500}$ + Canopy$^2_{500}$ + Evergreen$_{125}$ + Evergreen$^2_{125}$ + Precip + RdDensity$_{125}$ + Roughness$_{125}$ + TPI$_{500}$ + TPI$^2_{500}$	13	195,214.50	18.69	0.00	−97594.24

Appendix E. Pairwise similarities between the continuous predicted maps generated by the top-performing resource selection function models for each recreation type studied in western Colorado, USA 2010–2013, as measured by Pearson correlation. Pairs of recreation types with higher Pearson correlations are predicted to have greater similarity of terrain selection, and thus potentially greater interpersonal conflict.

Table 6
Pearson correlations between predicted surfaces for each of the recreation activities. Recreation activities shown are on-trail snowmobiles (Snmb on-tr), off-trail snowmobiles (Snmb off-tr), snowmobile segments of hybrid-assisted skiing (Hybrid snmb), ski segments of hybrid-assisted skiing (Hybrid ski), and back-country ski or snowboard (BC Ski).

	Snmb on-tr	Snmb off-tr	Hybrid snmb	Hybrid ski	BC Ski
Snmb on-rd	1.00	0.07	0.04	0.07	0.14
Snmb off-rd		1.00	0.03	0.05	0.12
Hybrid snmb			1.00	0.18	0.20
Hybrid ski				1.00	0.25
Ski/board					1.00

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