

Areas of high habitat use from 1999-2010 for radio-collared Canada lynx reintroduced to Colorado

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Introduction

The purpose of this report is to describe an analysis of current habitat use for the 218 Canada lynx that were reintroduced to Colorado from 1999 to 2006. The primary dataset used here is location data from collared individuals, and collected by the Colorado Division of Wildlife from 1999 until present. Data from individual animals were combined together to form a “population-level” estimate of habitat use by weighting locations based on the number of months data were collected for an individual. Basic descriptive and summary statistics such as a cumulative distribution function provide relative proportion of use in a given class of habitat. Note that this study was not intended to examine individual home range size, territoriality, or movement relative to land use and/or transportation corridors, nor is it intended to predict potential or future habitat use.

Methods

Preparation of location dataset

I received two datasets on lynx locations from CDOW (Tanya Shenk and Jake Ivan, *personal communication*) dated November 9, 2010. The VHF dataset was collected by locating individual lynx via telemetry during fixed-wing airplane flights. Most of the locations were south of I-70, as monitoring was focused on observing animals in the core release area, roughly defined as the high elevation areas in southwestern Colorado bounded by Taylor Mesa on the west, Gunnison basin on the north, Poncha Pass on the east, and New Mexico border on the south. Aerial locations were obtained outside of the core area on an opportunistic basis, typically only 1 location per 3 months. The entire VHF dataset had 11,356 observations for 257 individuals (103 females, 117 males) collected from 2/4/1999 to 6/22/2010.

The Argos data were collected from lynx that were outfitted with dual VHF/Argos satellite collars, beginning in April 2000. These collars were designed to provide locations

once per week. The Argos dataset had 33,778 observations for 196 individuals (97 females, 88 males), collected from 3/1/2000 to 8/11/2010.

Based on a number of discussions with lynx biologists and statisticians¹, we filtered the datasets in the following ways:

- a. Remove the first 6 months of locations after release for each individual to reduce likely bias of “just released” movements. This resulted in 35,276 locations dating from 9/13/1999 to 8/11/2010, representing 198 individuals (152 with >30 locations).
- b. Remove Argos locations with high spatial uncertainty (Table 1; Location Class 1, 0, A, B, Z) and retain the rest (Location Class 3 and 2). This resulted in 15,545 locations representing 197 individuals (129 with >30 locations).
- c. Remove locations that represent multiple fixes in a day, retaining the most precise location estimate (VHF, Argos 3, Argos 2). This resulted in 13,803 locations representing 197 individuals (118 with >30 locations).
- d. Remove records for individuals with less than 30 locations, resulting in 12,796 locations from 118 individuals

Thus, the final dataset used in the analysis included 12,796 observations for 118 individuals (Figures 1 & 2; number of individuals: f=64, m=54; total months of data: f=2679, m=1784). Note that I did not conduct an analysis that separates summer from winter use, or males from females. Figure 3 shows the distribution of lynx locations by year.

Table 1. Spatial uncertainty of the location data. * indicates data types used in the analysis.

Location source/class	Description	Radius (m) encompassing 68% of error distribution	Radius (m) encompassing 95% of error distribution
*VHF	Data collected by telemetry	200	400
*Argos 3	<250 m	250	500
*Argos 2	250-500 m	375	750
Argos 1	1500 m	1500	3000
Argos 0	N/A	Not used	
Argos A, B, Z	N/A	Not used	

¹ With Tanya Shenk (NPS) and Jake Ivan, Paul Lukacs, and Mindy Rice (CDOW)

Figure 1. The number of observations and months for 118 individual lynx used in the analysis of habitat use.

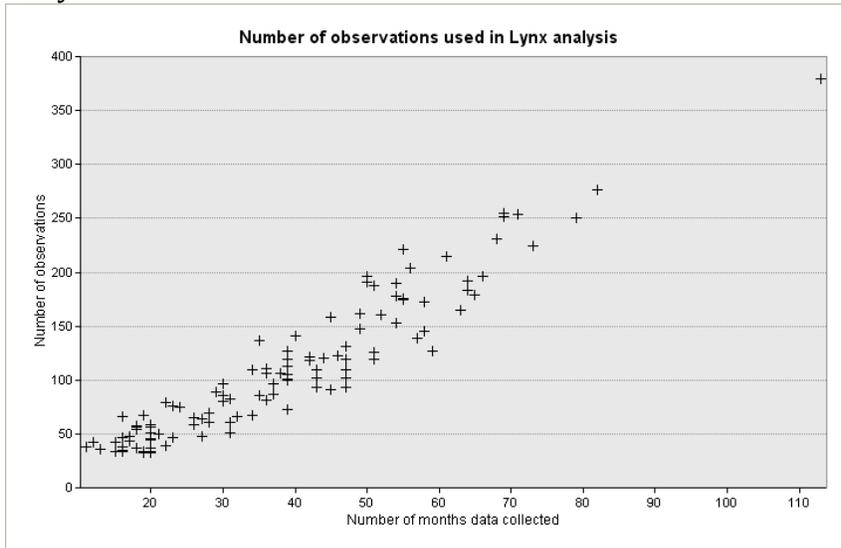


Figure 2. The distribution of 118 individual lynx used in the analysis of habitat use. Different colors denote different individuals.

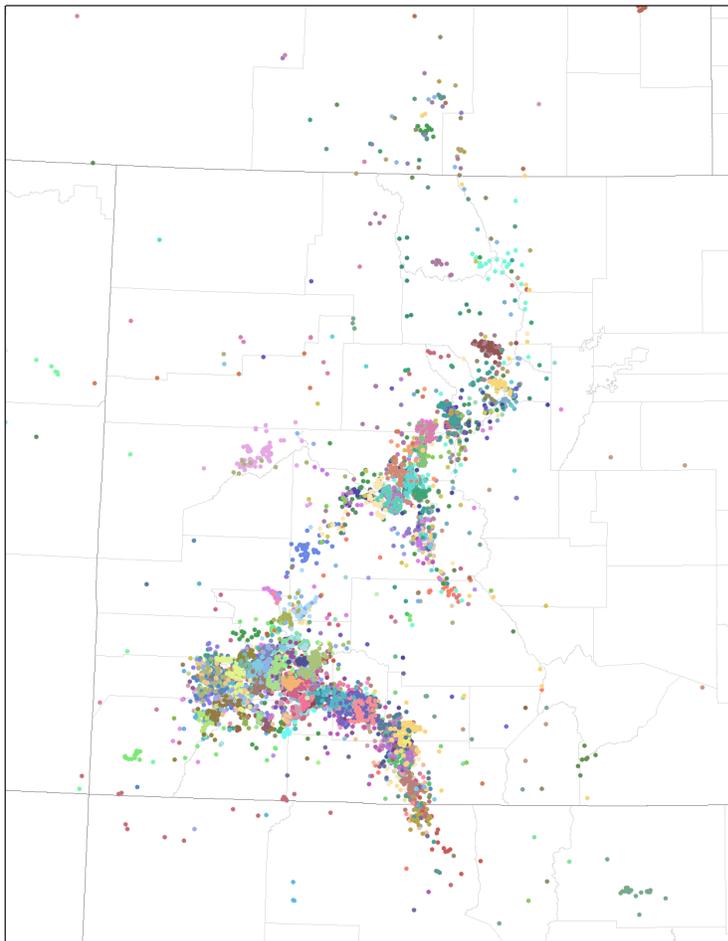
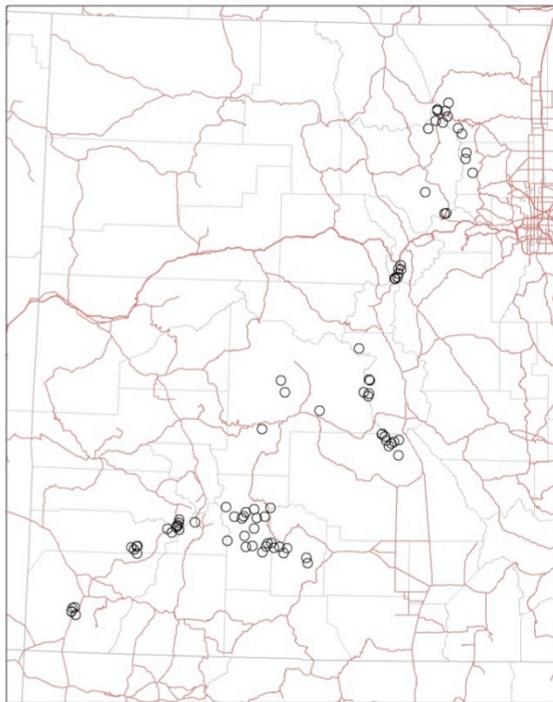
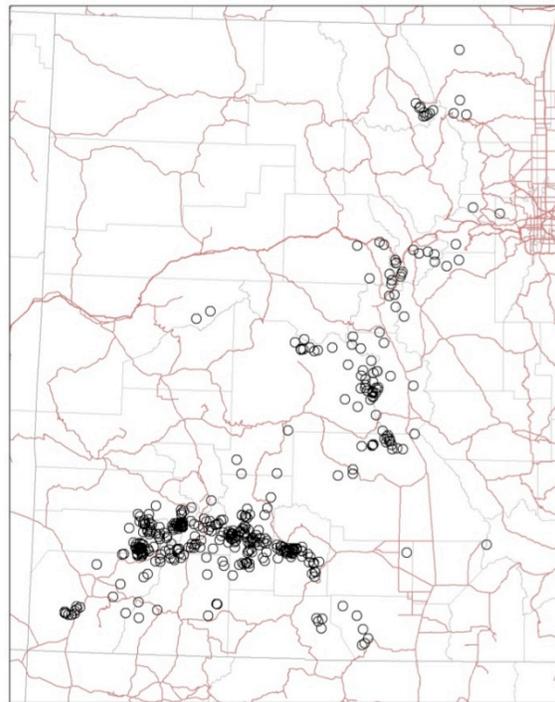


Figure 3. The distribution of lynx locations used in this analysis, displayed by year from 1999 to 2010.



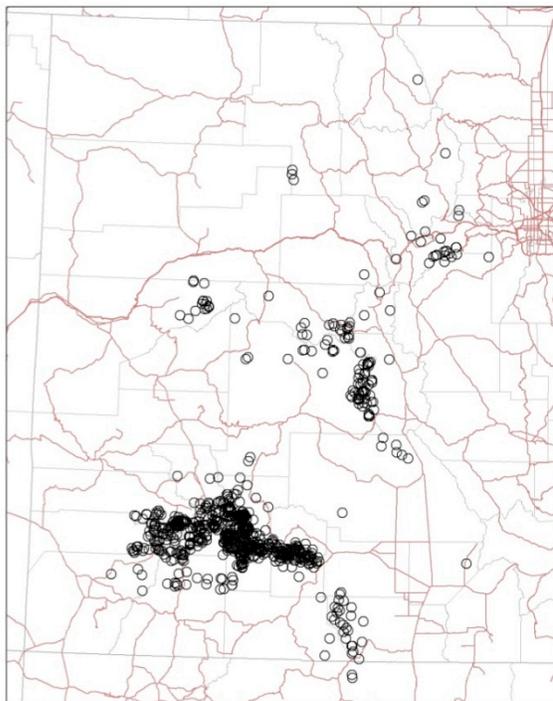
Lynx locations 1999

Map created by D. Theobald, Colorado State University, 20110221. Location data from Colorado Division of Wildlife, representing an analysis of habitat use based on the locations of 118 individuals over 1999 to 2010.



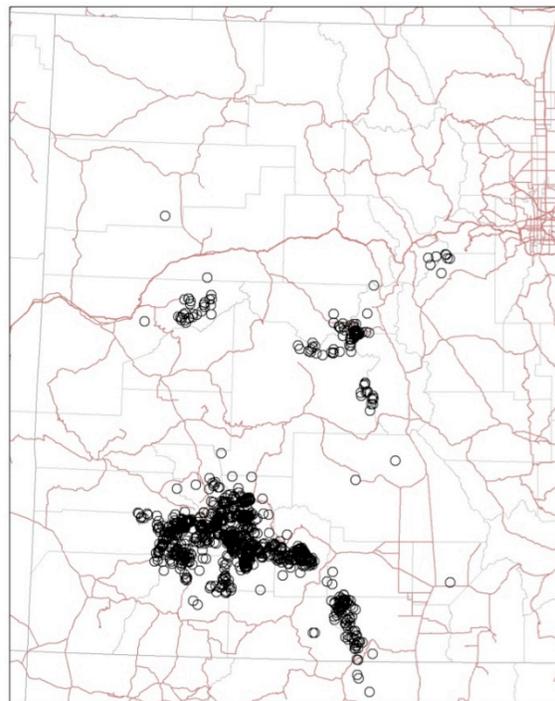
Lynx locations 2000

Map created by D. Theobald, Colorado State University, 20110221. Location data from Colorado Division of Wildlife, representing an analysis of habitat use based on the locations of 118 individuals over 1999 to 2010.



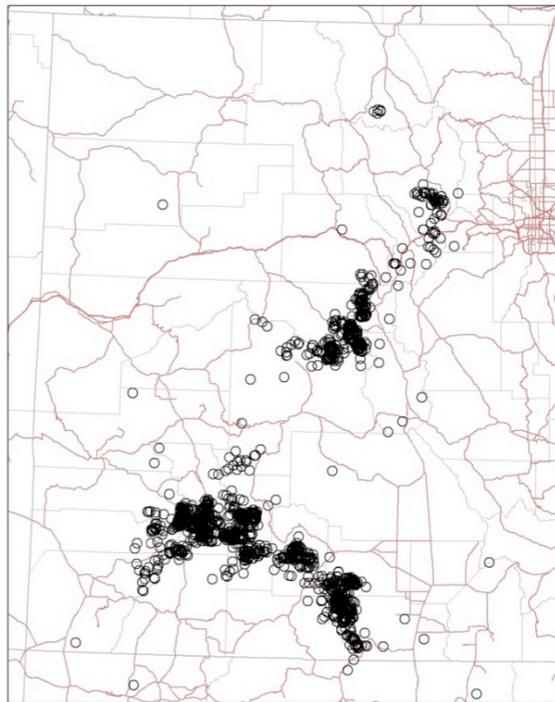
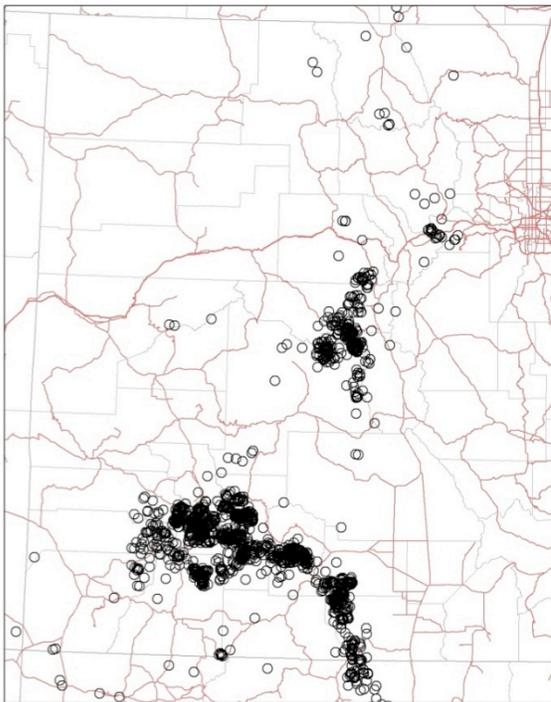
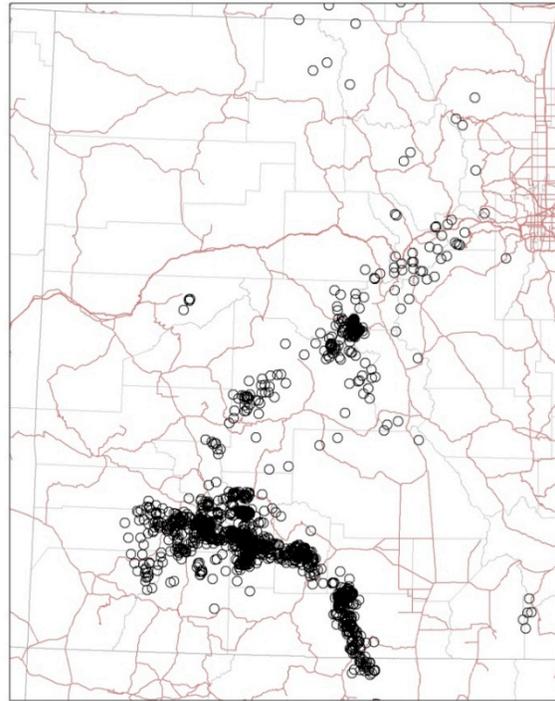
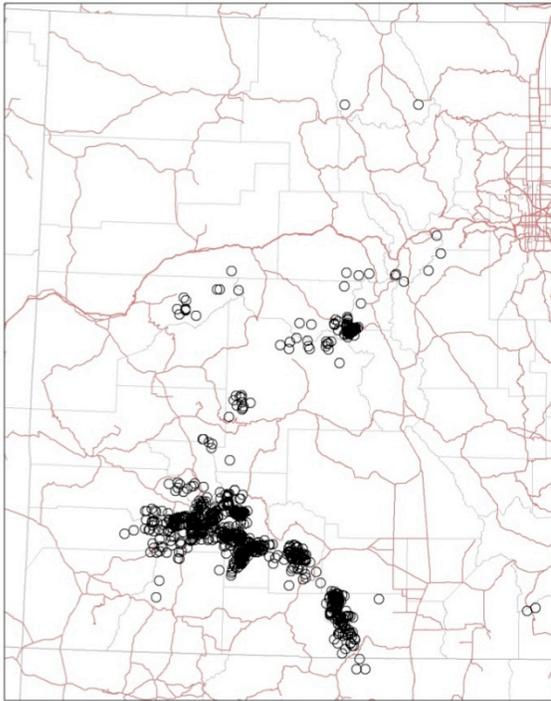
Lynx locations 2001

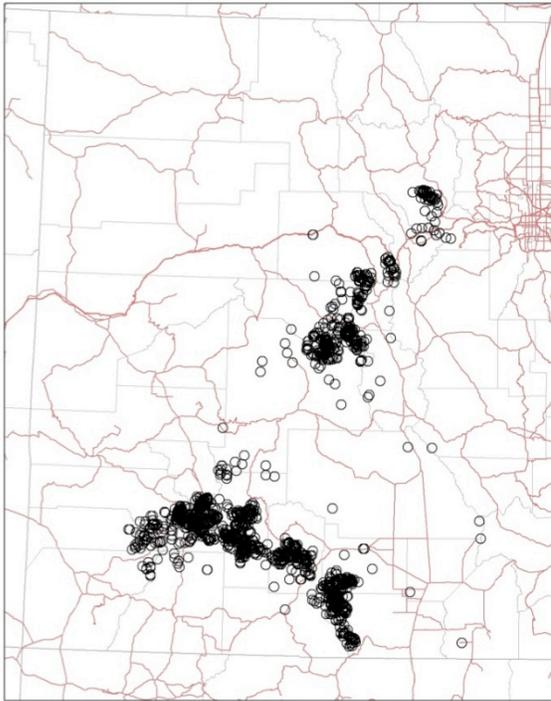
Map created by D. Theobald, Colorado State University, 20110221. Location data from Colorado Division of Wildlife, representing an analysis of habitat use based on the locations of 118 individuals over 1999 to 2010.



Lynx locations 2002

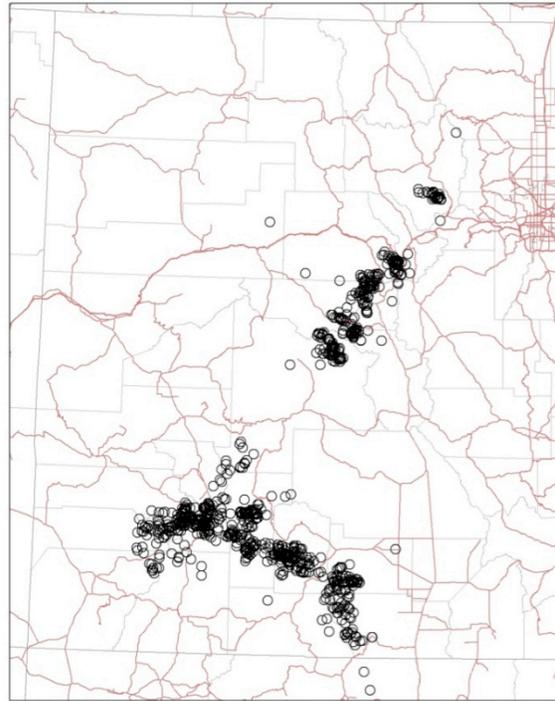
Map created by D. Theobald, Colorado State University, 20110221. Location data from Colorado Division of Wildlife, representing an analysis of habitat use based on the locations of 118 individuals over 1999 to 2010.





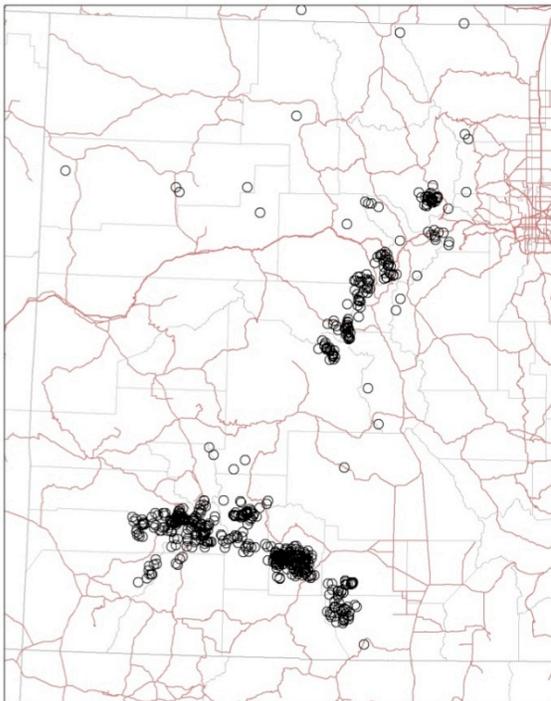
Lynx locations 2007

Map created by D. Theobald, Colorado State University, 20110321. Location data from Colorado Division of Wildlife, representing an analysis of habitat use based on the locations of 118 individuals over 1999 to 2010.



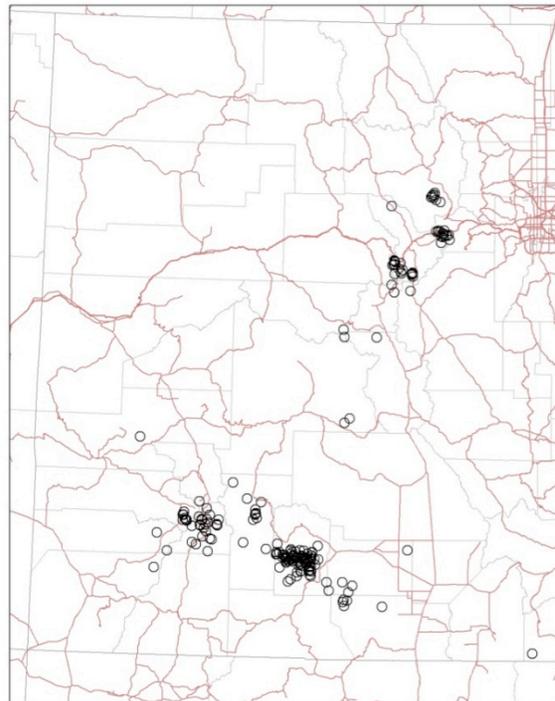
Lynx locations 2008

Map created by D. Theobald, Colorado State University, 20110321. Location data from Colorado Division of Wildlife, representing an analysis of habitat use based on the locations of 118 individuals over 1999 to 2010.



Lynx locations 2009

Map created by D. Theobald, Colorado State University, 20110321. Location data from Colorado Division of Wildlife, representing an analysis of habitat use based on the locations of 118 individuals over 1999 to 2010.



Lynx locations 2010

Map created by D. Theobald, Colorado State University, 20110321. Location data from Colorado Division of Wildlife, representing an analysis of habitat use based on the locations of 118 individuals over 1999 to 2010.

Generate utilization distributions

I followed the general approach of Millspaugh et al. (2006) to prepare the utilization distribution surface and explanatory variables.

First, I estimated the utilization distribution (UD) for each individual animal using a home range estimator called local convex hulls (LoCoH; Getz and Wilmers 2004). We selected this approach because it is non-parametric, produces a UD, and identifies abrupt “edges” in the spatial distribution that can occur because of edges in landscape features (e.g., topographic constraints) or territoriality among individuals. Generally, LoCoH extends the concept of convex hulls to delineate space use, but rather than encompassing all points at once (e.g., minimum convex polygon), it works on a sub-set of points to identify local convex hulls. That is, a small or “local” convex hull is identified around point i , which contains a set of k nearest neighbors. The local hulls are then sorted by area, smallest to largest, and the UD value (or isopleths) are determined by the proportion of points found in each local hull.

Specifically, we used the adaptive version called a -LoCoH because it is most insensitive to sub-optimal value parameterization (Getz et al. 2007). a -LoCoH identifies a variable number of k nearest neighbors such that it uses all points within a variable circle around a root point so that the sum of distance between the points and the root point does not exceed a user-defined threshold value, a . This method adjusts the radius so that smaller convex hulls arise in high use areas and provide more clearly defined isopleths in regions with higher density of location data. Getz et al. (2007) recommended setting a to the maximum distance between location points (with a minimum of $k=3$), when no other a priori information is available. I used the average of the width and height of the maximum enclosing convex hull because habitat use often occurred in disjunct clusters. To remove artifacts in the LoCoH output that can be introduced by spurious location values, I removed the 100% isopleth (leaving all isopleths $\leq 90\%$). Each UD was normalized so that the area under the UD summed to 1.0.

Second, to combine the UD for the 118 individuals into a general, population-level estimate of habitat use, I computed the number of months of location data for each individual. This provided a weight such that individuals who had a relatively short duration of locations would have minor influence, while an individual with a long duration (many months) of location data available would have more influence on the population-level UD surface. The weights ranged from 11 to 113, with a mean of 37.82 (SD=18.49). For each cell within an individual, normalized UD values were multiplied by the appropriate weight and the result was summed at each raster cell across all individuals.² Thus, if one cell or general area is used intensely by only one individual, it will be high intensity use. Conversely, if numerous individuals have used a location, each at a lower intensity, it too, will have a high UD.

Third, I smoothed the UD values from a resolution of 90 m to a more biologically-based resolution that was equal to the area of the smallest observed “high use” UD observed across all individuals – 225.0 ha. I aggregated the 90 m cells to a cell size of 1440 m (~207 ha).³ This provides 11,934 cells (at 1,440 m) in the population-level UD (pUD).

² Multiplied by 100,000,000 and divided by total to get integer grid, from 1-1701.

³ Aggregated based on the smallest high-quality habitat from 90 to 1440 m using MEAN, not a moving window average.

Generate habitat variables

Based on previous work with CDOW lynx biologists that identified likely important explanatory variables for habitat use, I developed a set of landscape-level datasets based on regionally-available datasets (Table 2). These data included compositional measures of the proportion of various vegetation types computed from LANDFIRE existing vegetation type classes (30 m), topographic variables calculated from the USGS National Elevation Dataset (30 m), and distance variables computed from Colorado Department of Transportation highways data. In addition, I examined the relationship of habitat use to individual tree species to discern what specific forested vegetations types were used more (or less) by lynx.

Table 2. Description of the landscape-level variables used to examine habitat use of lynx.

Type	Variable	Description
Composition	BHD	Census block housing density (SERGoM v1.1, units * 1000 per ha). Data source from Theobald (2005), Bierwagen et al. (2010)
	RDENS	Road density (km/km ²)
Proportion	Lf1	Water (Lakes, reservoirs, large rivers)
	LF2	Rock, snow, ice
	LF3	Urban/built-up
	LF4	Agriculture (cropland, pasture)
	LF5	Forest (upper montane) – Spruce-fir, subalpine, lodgepole, mixed aspen-conifer, Douglas fir
	LF6	Forest (lower montane) – ponderosa pine, pinyon-juniper
	LF7	Shrublands
	LF8	Grasslands – includes sub-alpine meadows and alpine tundra
	LF9	Shrub (steppe)
	LF10	Riparian & wetlands
Topographic	DEM	Elevation (meters)
	SLOPE	Slope – average slope in degrees (computed from 30 m)
	TWIP	Topographic wetness index plus solar insolation
Distance	D4P5HA	Forest (mesic) patches at least 50 ha
	D4r2k	Highways with AADT <2k
	D4R2_5K	Highways with 2k<=AADT<5k
	D4R5_10K	Highways with 5k<=AADT<10k
	DR410K	Highways with AADT>10k
	D4RDS	All non-highway roads

Results

Following convention, I defined lynx habitat as areas within the 90% isopleth. Over 3.5 million acres in Colorado and New Mexico were found to be currently within lynx habitat. Figure 4 shows the distribution of the population-level utilization distribution surface, while Figure 5 shows the number of individuals that were found in each of the UD polygons and Figure 6 depicts a cumulative distribution function of the UD values. Table 3 provides a summary of the landscape variables for lynx habitat.

The average elevation for lynx habitat was 3,285 m (10,780 ft), with the majority (68% or + and - 1 SD) of habitat located between 3,027 and 3,543 m (9,900-11,620 ft). The average slope for lynx habitat was 18.9 (with the majority between 12.8 and 25.1 degrees). The average topographic wetness index value (TWI+) was 3.38, ranging from 2.64 to 4.12 (low values indicate high soil moisture near the foot of slopes on north aspects while high values indicate low soil moisture indicative of ridge tops and south-facing aspects).

Housing density in lynx habitat was low, with a mean value of 0.011 units per ha (~1 unit per 80 ha); the majority of habitat was below 0.102 units per ha (~1 unit per 10 ha). Road density in lynx habitat was also low, with a mean value of 0.51 km/km², and the majority of habitat below 1.22 km/km².

The average proportion of forest (upper montane) in lynx habitat was 0.65, with the majority occurring in areas with at least 20% forested (upper montane) cover. Habitat use was also associated with distance from large patches (>50 ha) of forest (upper montane) cover, with the majority of habitat within 3.35 km, and the average at 0.36 km. The average proportion of grasslands was 0.16. There was little association of lynx habitat use areas with other land cover types.

Lynx habitat use areas occurred away from highways with high traffic (AADT >10k), averaging at least 43 km, with majority at least 27 km away. This declined to between 25.9 and 16.0 km average distance for other highway types, with the majority of habitat being at least 5.2 km from the nearest highway. Table 4 provides a summary of the most common land cover types (from LANDFIRE) found to occur in lynx habitat use areas. Appendix 4 provides scatterplots for species specific forested vegetation types. Subalpine/spruce-fir forest dominates the UD polygons area with 43.3%. Other upper montane and tundra cover types are identified, combining to over 86%. Because of the grain of the vegetation data (aggregated to 2.25 km²), cover types such as barren/rock and tundra cover likely include small stands of forest and riparian cover.

Table 3. Summary of landscape variables for the lynx habitat use areas. Units are in proportion (0.0 → 1.0) if not otherwise denoted. Also see Appendix 1 for cumulative distributions of these variables and Appendix 2 for distribution maps of each variable.

Type	Variable	Min	-1 SD	Mean	+1 SD	Max
Composition	Housing density (units per ha)	0	N/A	0.011	0.102	10.531
	Road density (km/km ²)	0	N/A	0.513	1.22	12.7
Proportion (0→1)	Water (Lakes, reservoirs, large rivers)	0	N/A	0.005	0.03	0.9
	Rock, snow, ice	0	N/A	0.063	0.16	0.9
	Urban/built-up	0	N/A	0.002	0.01	0.7
	Agriculture (cropland, pasture)	0	N/A	0.003	0.04	0.95
	Forest (upper montane)	0	0.4201	0.653	0.89	0.99
	Forest (lower montane)	0	N/A	0.009	0.06	1
	Shrublands	0	N/A	0.008	0.06	0.95
	Grasslands	0	N/A	0.163	0.36	1
	Shrub (steppe)	0	N/A	0.061	0.14	0.94
	Riparian & wetlands	0	N/A	0.031	0.06	0.56
	Topographic	Elevation (meters)	1399	3027	3285	3543
Slope (degrees)		0.1	12.8	18.9	25.1	37.6
Topographic wetness index plus		1.40	2.64	3.38	4.12	15.20
Distance (km)	Highways with AADT ≥10k	0.20	27.86	43.88	59.91	77.00
	Highways with 5k≤AADT<10k	0.20	14.59	25.96	37.32	51.80
	Highways with 2k≤AADT<5k	0.20	6.15	16.05	25.95	39.90
	Highways with AADT <2k	0.20	5.22	14.35	23.48	40.70
	All non-highway roads	0.03	N/A	1.88	4.26	35.00
	Forest (upper montane) patches ≥50 ha	0.00	N/A	0.36	3.35	27.10

Figure 4. The population-level utilization distribution for 118 lynx in the analysis dataset, shown with major highways and county boundaries for reference. Low-intensity use is shown in yellow, moderate in orange, high in blue.

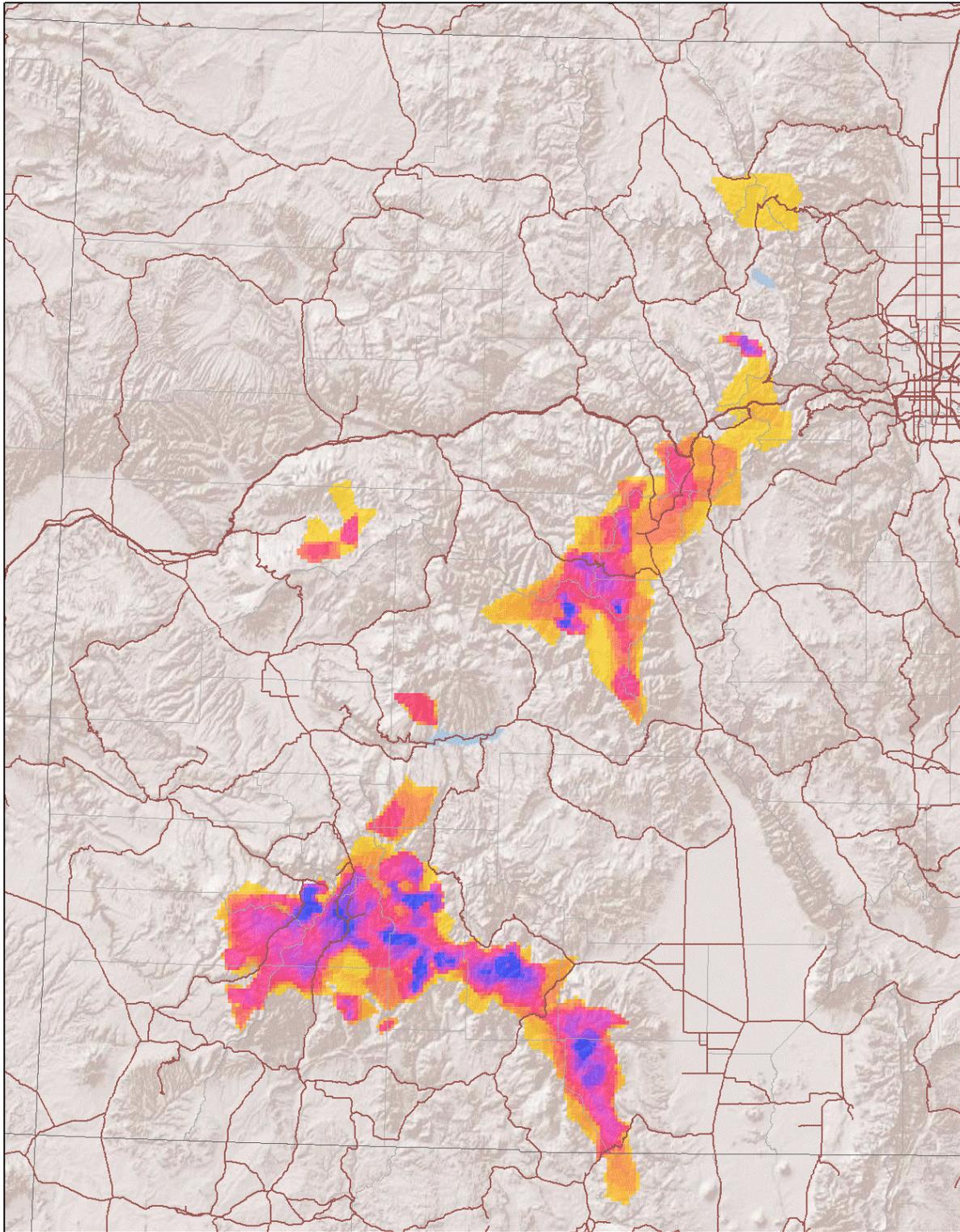
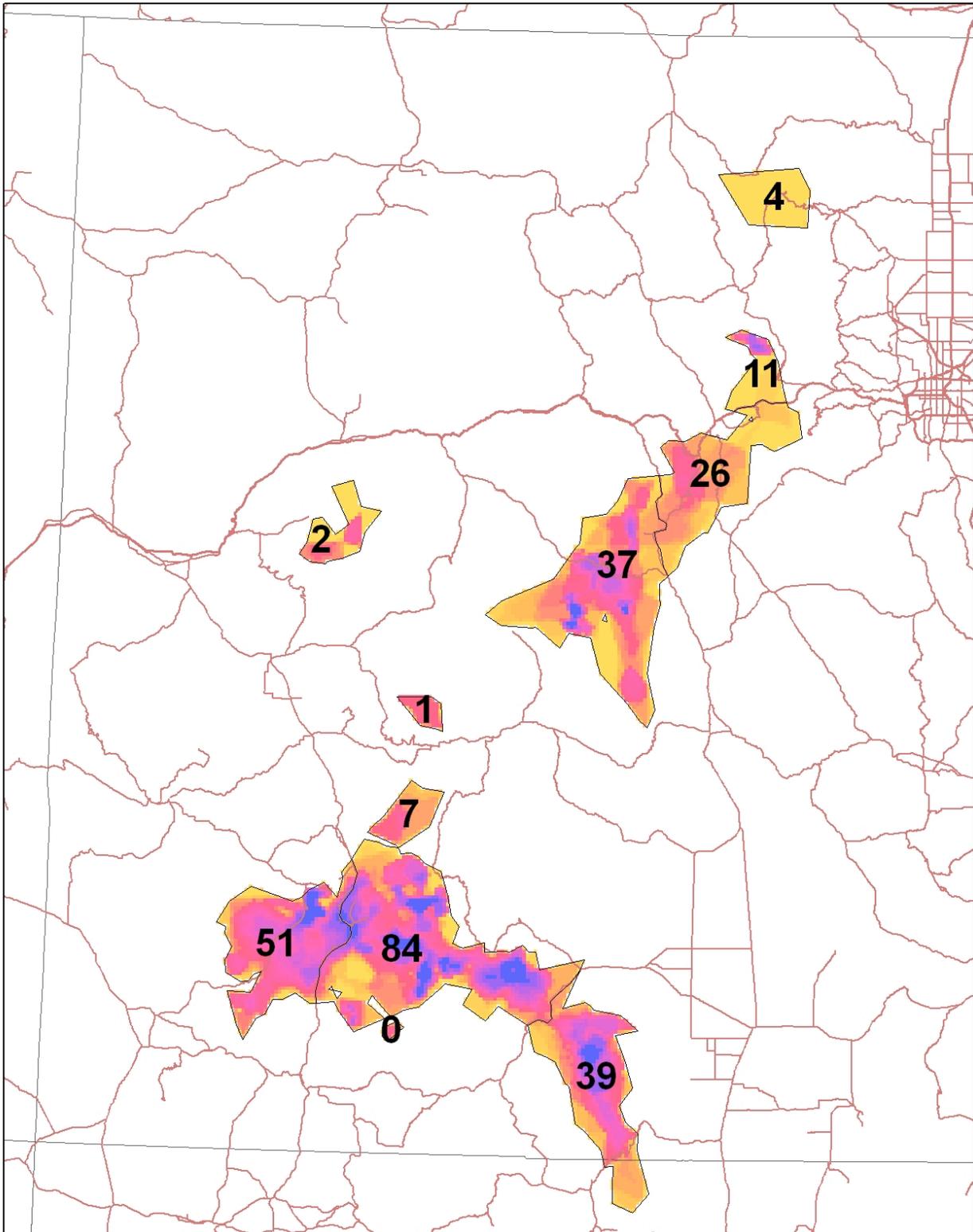


Figure 5. The number of individual lynx that were found in polygons of the population-level utilization distribution, shown with major highways for reference.



Lynx individuals in UD

Map created by D. Theobald, Colorado State University, 20110321. Location data from Colorado Division of Wildlife, representing an analysis of habitat use based on the locations of 118 individuals over 1999 to 2010.

Figure 6. The cumulative distribution function for the population-level utilization distribution. Roughly 50% of the UD has values less than 12, about 25% between 12 and 30, and the top 25% between 31 and 950.

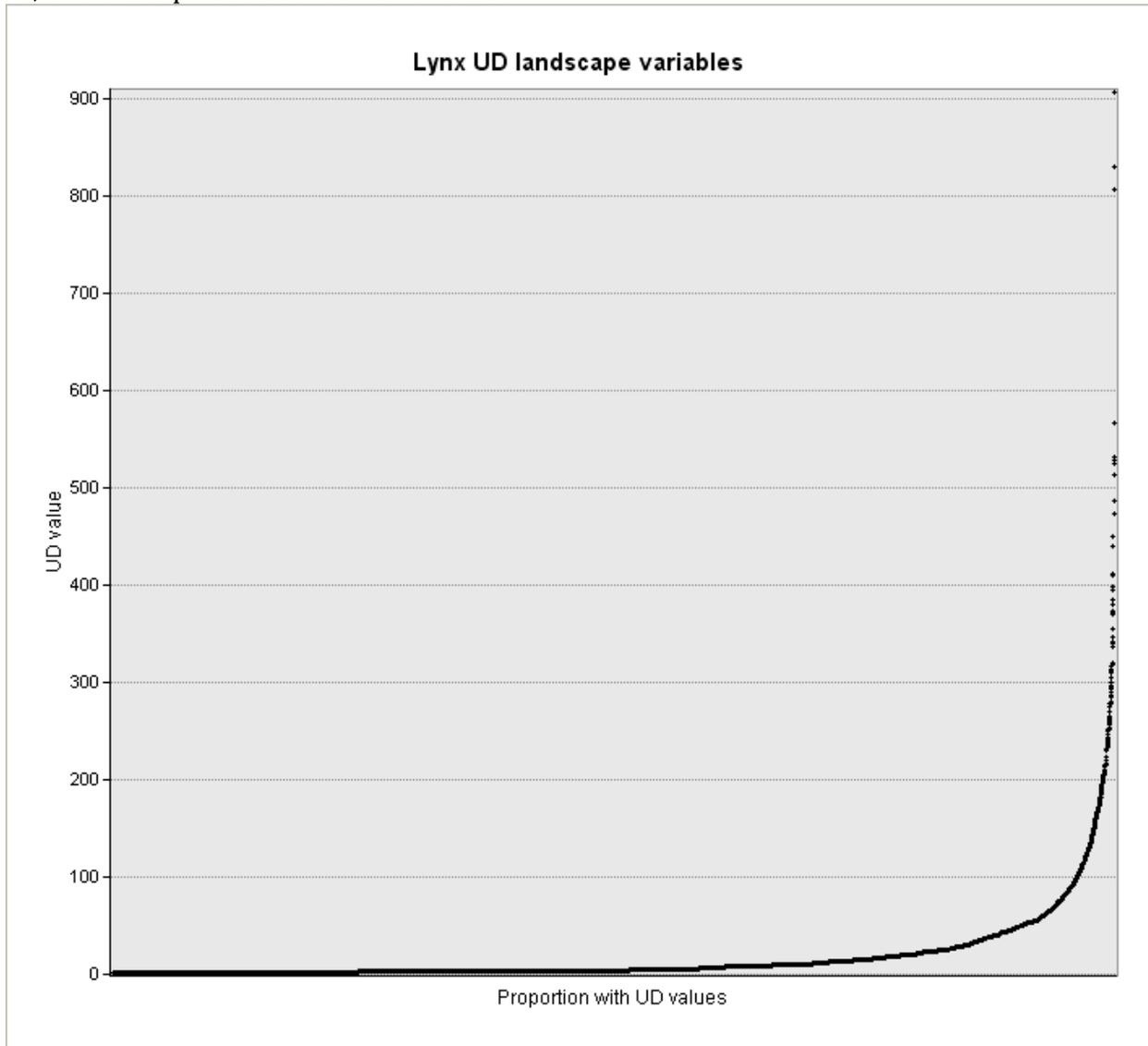


Table 4. The proportion of dominant land cover types (from LANDFIRE) occurring in lynx habitat use areas. (All remaining cover types are less than 1%).

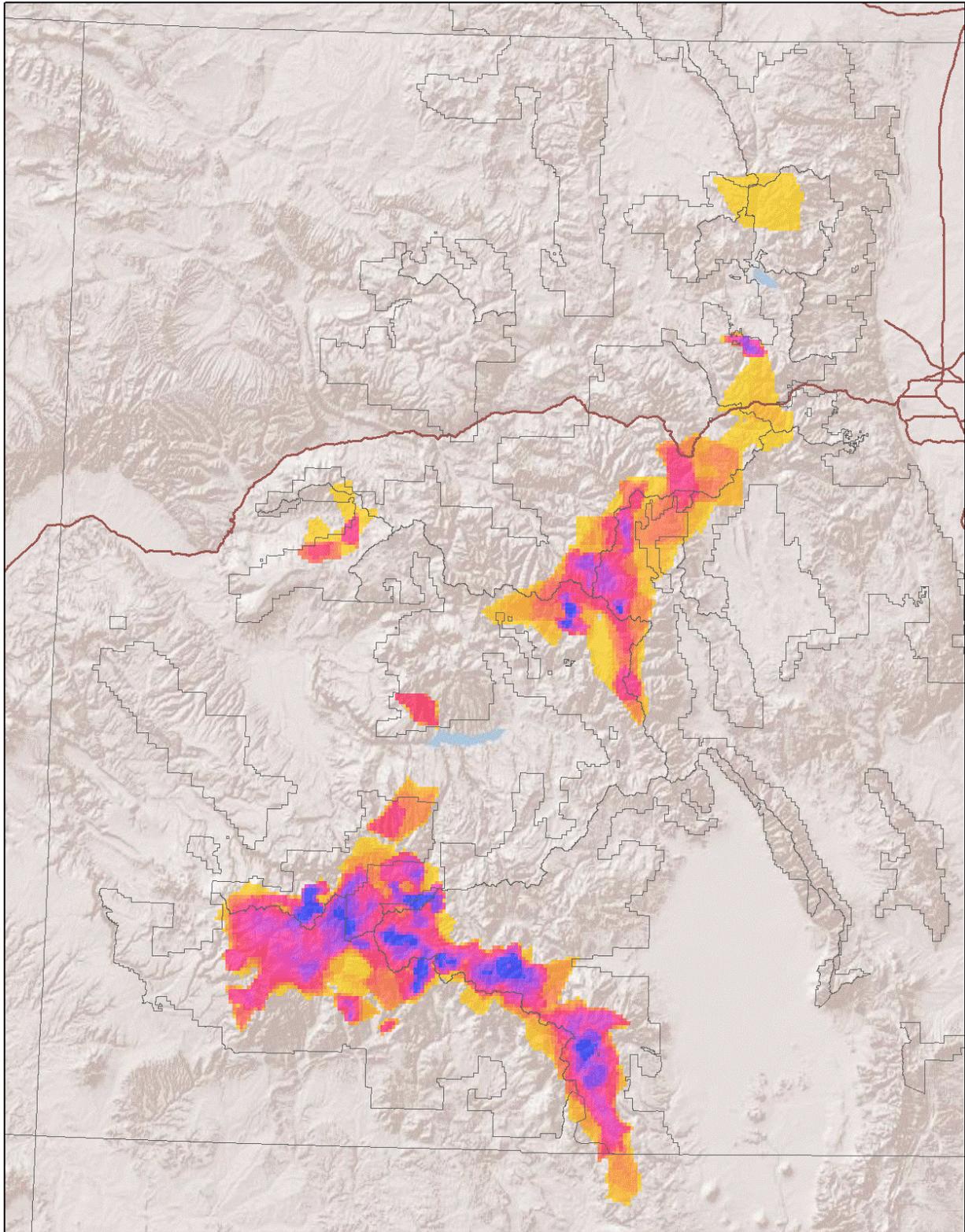
Existing vegetation type	Percentage
Subalpine/Spruce-fir forest	43.3
Barren/rock/tundra	13.3
Alpine tundra (“turf”)	7.8
Aspen forest	7.1
Aspen-mixed conifer forest	6.8
Subalpine/upper montane riparian	6.3
Snow-ice	2.1
Subalpine/spruce-fir (mesic)	1.7
Subalpine montane meadow	1.5

Discussion/conclusion

This report provides the first estimate of the overall, population-level habitat currently used by lynx in Colorado, with over 3.5 million acres. The majority of the current lynx use areas are located on US Forest Service lands (Figure 7). Two large contiguous areas of habitat use are found in the San Juan mountain range and the Collegiate Peaks ranging north of Monarch Pass to Vail Pass and spanning I-70 near Loveland Pass to the Frasier Experimental Forest. Three other smaller areas were identified, on the Grand Mesa, in the West Elks just north of Black Canyon of the Gunnison, and an area centered around Rocky Mountain National Park. Eleven of 25 downhill ski areas in Colorado are located in lynx habitat.

The central findings of this analysis are consistent with previous reports that the Canada lynx reintroduced to Colorado have primarily used high elevation spruce-fir and aspen vegetation types as habitat. These reports are based on vegetation data collected during aerial surveys as well as “on the ground” snow-track surveys (CDOW 2009; Shenk 2009).

Figure 7. – The utilization distribution for current lynx habitat in Colorado, with forest service administrative boundaries.



High use areas (those with larger UD values) are characterized by a high percentage of upper montane forest, high elevations, and high moisture positions (i.e. low TWI+ values; Figure 8 and Appendix 4). Within forest vegetation types, the strongest relationship to UD were sub-alpine/Spruce-fir, and aspen and aspen/mixed conifer vegetation types (Figure 9).

Figure 8. Comparison of UD for current lynx habitat versus upper montane forest (upper left), Topographic wetness index plus (upper right), and elevation (lower left).

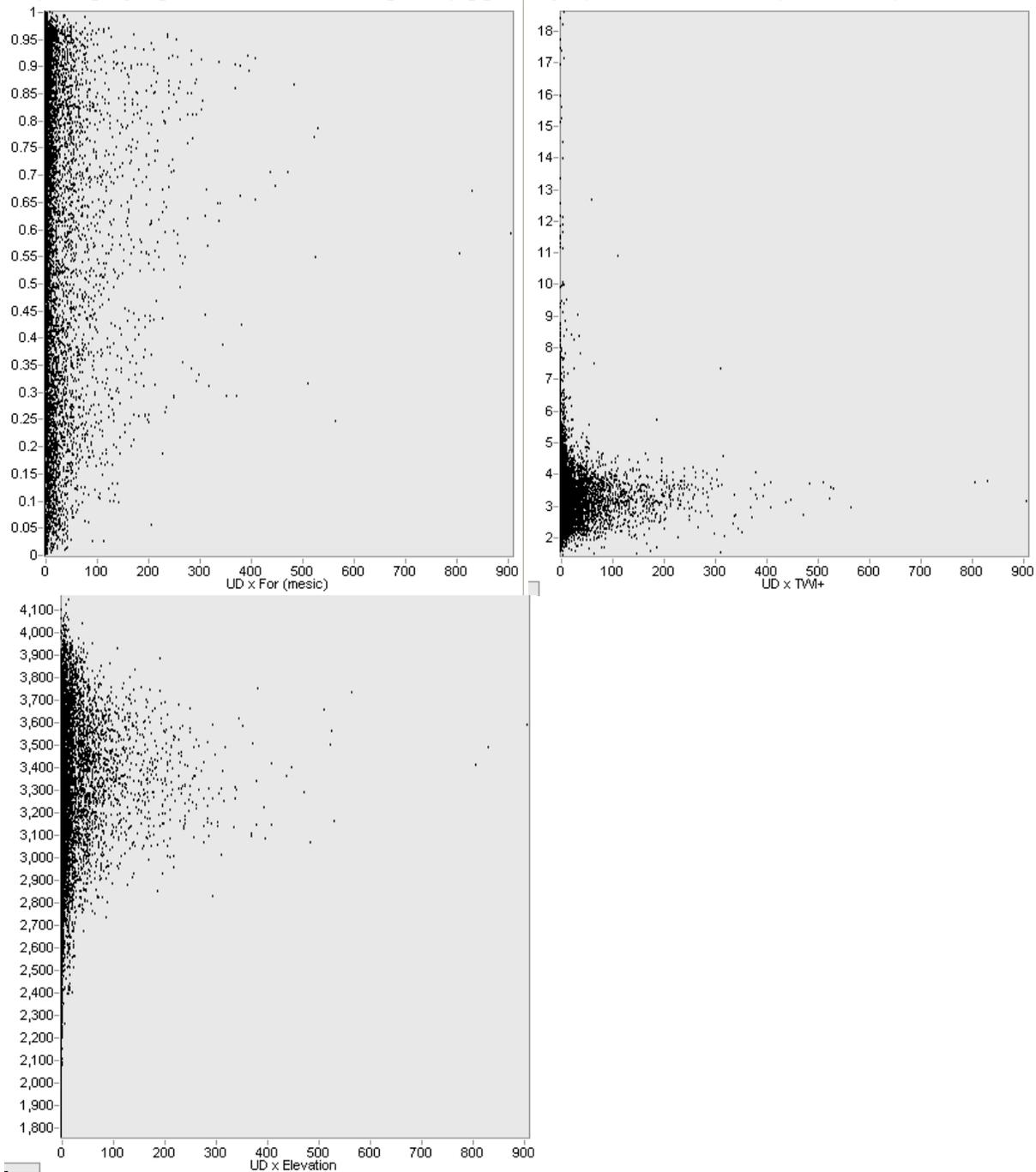
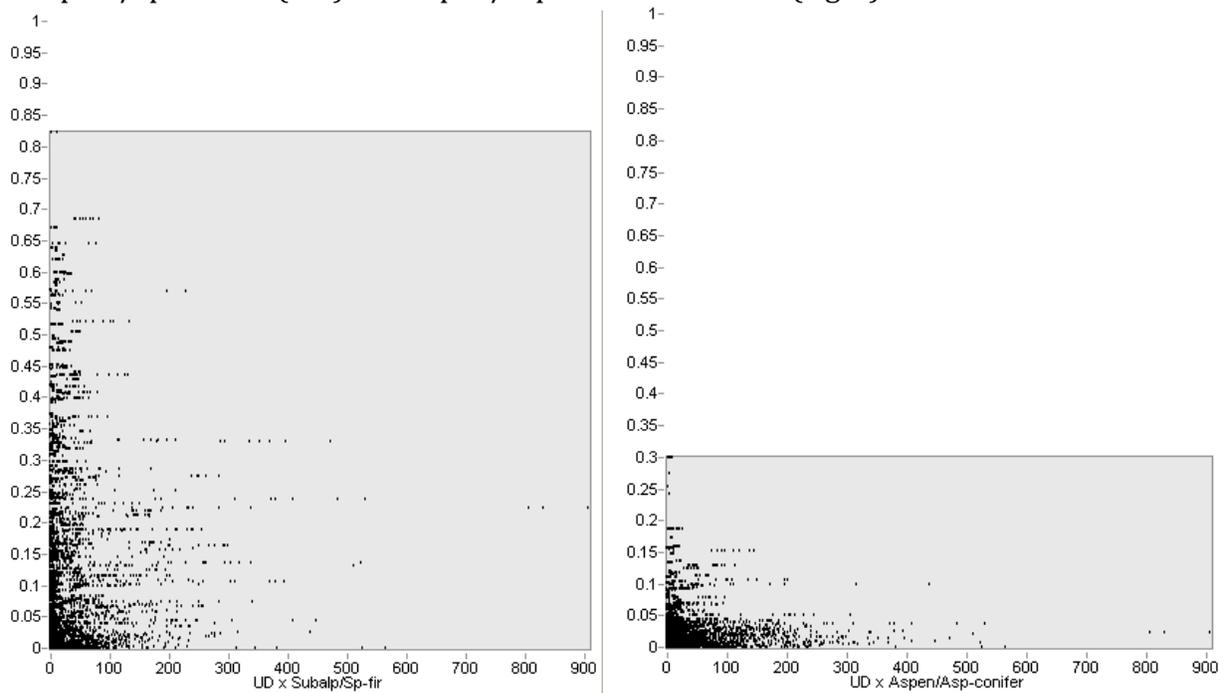


Figure 9. Forest vegetation types with strong positive association with current lynx habitat: subalpine/spruce-fir (left) and aspen/aspen-mixed conifer (right).



Limitations of analysis

A key limitation to the findings here is that the data represent only a sample of lynx in the state. Initially, 100% of the individual lynx were collared, but the percent of lynx in the state that were tracked diminished over time. For example, the number of lynx sampled in 2010 represents about $\frac{1}{4}$ of the number sampled during 2005 (Table 5).

Table 5. Annual summary of number of individuals and locations.

Year	# individuals	# locations
1999	9	78
2000	40	443
2001	38	798
2002	35	1099
2003	51	1011
2004	70	1811
2005	95	2082
2006	85	1891
2007	73	1546
2008	57	936
2009	43	786
2010	27	315

When interpreting the results, it is important to recall that the analysis is restricted to areas with lynx habitat use. That is, even “low” use areas provide important habitat, it is just relatively lower compared to high use areas. Also, remember that when thinking about the relationship between use and the various landscape variables, the various cover types are restricted to the habitat use areas, not the full extent of cover types within a broader

area (e.g., core release site, southern rockies ecoregion, etc.). Areas that are outside of the UD polygons identified in this analysis may still be used, and the UD polygons of habitat use might change with future distributions of lynx.

Be careful to interpret the landscape variables that are estimated originally at 30 m resolution (from LANDFIRE) because many fine-grain variables, such as narrow riparian areas are not recorded in these data. Also, these data do not capture variation in understory vegetation, rather the satellite imagery predominately captures over-story conditions.

Recommendations for further analysis

There are three logical next steps for the analysis of lynx distributions in Colorado: (a) comparison of these results to field-collected vegetation data on understory and topographic characteristics; (b) prediction of suitable lynx habitat beyond the core reintroduction area; and (c) examination of movement including highway crossing locations.

- a. A first step is to compare the findings of this report based on lynx locations and landscape-level variables against the site-scale habitat data collected by CDOW during snow-tracking of lynx (for winter seasons for all years). At each site, data were recorded on the lynx tracked, slope, aspect, forest structure class (grass/forb, shrub/seedling, sapling/pole, mature, and old growth), location, and elevation (Shenk 2006). These data have been compiled into a database and summarized in reports (e.g., Shenk 2009). Currently, CDOW are conducting a quality control process to enable more detailed, spatially-explicit comparison of the site-level habitat variables against landscape-level variables (Jake Ivan, *personal communication*).
- b. A second step is to develop a spatially-explicit model that predicts habitat use within the state of Colorado, based on the relationships between lynx locations and landscape variables such as those described in this report. Generally, the type of model that is appropriate depends on the specific management question being asked, as well as the nature and quality of the data being used. In particular, understanding whether the location data are best considered presence-absence data or presence-only. "... if presence-absence survey data are available, we believe it is generally advisable to use a presence-absence modelling method, since in that case the models are less susceptible to problems of sample selection bias, the survey method will often be known and can be used to appropriately define the response variable for modelling, and we take advantage of all information in the data (Elith et al. 2011; pgs 45-46). The lynx dataset used in this report and that would be available for a spatial predictive model have some sampling bias issues, but should not be considered "presence-only" data – because of the systematic collection of locations via VHF/aerial methods and the complementary data from ARGOS. Certainly there are some issues with the location data – such as a focus on data collected south of I-70 and likely missing ARGOS locations in high topographic relief/dense vegetation – but compared with most other wildlife studies of habitat use the database is robust given the large number of individuals and duration of the study. The CDOW has held preliminary discussions in December/January 2011 about possible modeling approaches and candidate variables. A particular challenge is to understand the

potential habitat use of lodgepole pine – since it is so prevalent in forests north of I-70, yet much of the existing (1999-2010) locations are dominated by locations near the San Juan core area that has very little lodgepole pine. Data on forest stand age/structure are a potential surrogate for understory vegetation types that are thought to be important for high-quality habitat (for snowshoe hares).

- c. A third step is to examine lynx movement in relation to transportation and other potential conflicting land uses. Given the spatial and temporal resolution of the lynx locations, it is reasonable to examine the dataset for some broad, landscape-level quantification of highway crossings. But, the data are not suited to conduct analyses to identify specific locations (<~10 km) where lynx may be crossing highways and to examine how other land uses might be influencing habitat quality.

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