Glacier National Park:
Bighorn Sheep and Canada Lynx Habitat

Analysis of Vulnerability to Climate Change and Identification of Priority Conservation Areas

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Executive Summary

Map 1. Glacier National Park, Montana

Glacier National Park (GNP) is situated in the northeast corner of Montana and encompasses over 400,000 hectares of diverse landscapes. The Rocky Mountains run through the heart of the park and anchor alpine glaciers and persistent snow fields before transitioning to coniferous and deciduous forests, grasslands, and riparian areas at lower elevations. The variety of ecosystems within the park provide critical habitat for numerous wildlife species. National Park Service (NPS) biologists and wildlife managers are particularly interested in learning more about bighorn sheep and Canada lynx populations and the areas they inhabit.

Species of Concern

Two species in particular, bighorn sheep and Canada lynx, occupy high-elevation areas within the Rocky Mountains which are especially threatened by habitat loss due to climate change. Compounding factors include respiratory disease threatening bighorn sheep populations and a reduction in overall size of boreal forest ecosystems, decreasing length of winters, and reduction in snowfall and persistent snow cover leading to lynx habitat degradation (NPS, 2021). NPS managers are studying the ecosystems preferentially inhabited by these species to better understand how to conserve and protect critical habitats to protect the future of both species within the park. Detailed analysis of bighorn and lynx habitat areas will contribute to knowledge about both species and inform future conservation and management decisions.

Methodology

Geospatial professionals, park managers, and wildlife biologists have previously collaborated to create habitat suitability models for bighorn sheep and Canada lynx. These models have identified highly suitable habitat areas for both species within the park. Detailed exploration of the relationships between variables like elevation, slope, and vegetation cover will lead to better understanding of ecological and geographical traits associated with high-suitability habitat. Information gained through analysis of these factors is used to create a combined habitat suitability model which identifies areas suitable for both bighorn and lynx habitat that should be incorporated into conservation and management plans.

Introduction

Source Data and Habitat Models

The bighorn sheep habitat model is an original work created by this author using data downloaded from the NPS Data Store[1]. All source data were converted to raster format using 100m cell size and projected to NAD 1983 UTM Zone 12N. Raster layers representing habitat criteria were derived from source data. Layers representing each criterion (slope, vegetation cover type, soil type, and distance from roads and trails) were combined to produce the final habitat model which ranked areas for habitat suitability on a scale from 1 (lowest) to 10 (highest). This raster was then reclassified to a scale of 1 (lowest) to 4 (highest) for analyses described in this report.

The Canada lynx habitat model was created by NPS staff using vegetation data from 2007 (Menicke, 2008). The model is based on lynx preference for coniferous vegetation types and elevations higher than 4000 feet. It also incorporates burn data from 1999-2007 to remove areas with moderate or severe burn intensity with the assumption that burned areas do not provide sufficient cover to support lynx populations.

Software and Tools Used

All analyses for this report were executed using ArcGIS Pro 2.8.2. The bulk of the report consists of statistical analyses of relationships between various ecological or geographical zones (elevation, slope, vegetation classifications). All analyses utilized raster data with a cell size of 100x100 meters (one hectare). These analyses relied on tools available within ArcGIS Pro's Spatial Analyst extension, which provides a multitude of tools that can be used for analysis and modeling of both raster (cell-based) and vector (feature) data. This report utilized two zonal tools: "Zonal Statistics as Table" and "Tabulate Area."[2]

The Zonal Statistics as Table tool calculates one or multiple statistics and creates a tabular output. The input layer defines the zones or classes of interest, and the value raster contains the values for which statistics will be calculated within each zone identified in the input layer. For example, to summarize elevation statistics within bighorn sheep habitat suitability zones, the layer identifying bighorn suitability classes will be the input raster and the layer with information about elevation values (in this case, the Digital Elevation Model or DEM) will be the value raster.

The Tabulate Area tool functions similarly to the Zonal Statistics as Table tool but is more appropriate to used when working with two layer which both have defined zones or classes. In the previous example explaining use of Zonal Statistics by Table tool, the value raster (DEM) contains continuous values representing elevation across the landscape. There are no distinct zones or classifications, in contrast to the input raster, which contains four habitat suitability zones. Parts of this report required analyses of two raster layers which both have defined zones or classes – for example, comparison of vegetation classification types within bighorn habitat suitability zones. Tabulate Area can be used in this situation to calculate a cross-tabulated area between the two datasets which can reveal relationships between the two layers.

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[1] See Appendix A for source data provenance and details.

[2] See Appendix B for more information about Zonal Tools in ArcGIS Pro.

Map 2. Combined Habitat Suitability Model

Combined Bighorn Sheep and Canada Lynx Habitat Suitability Model

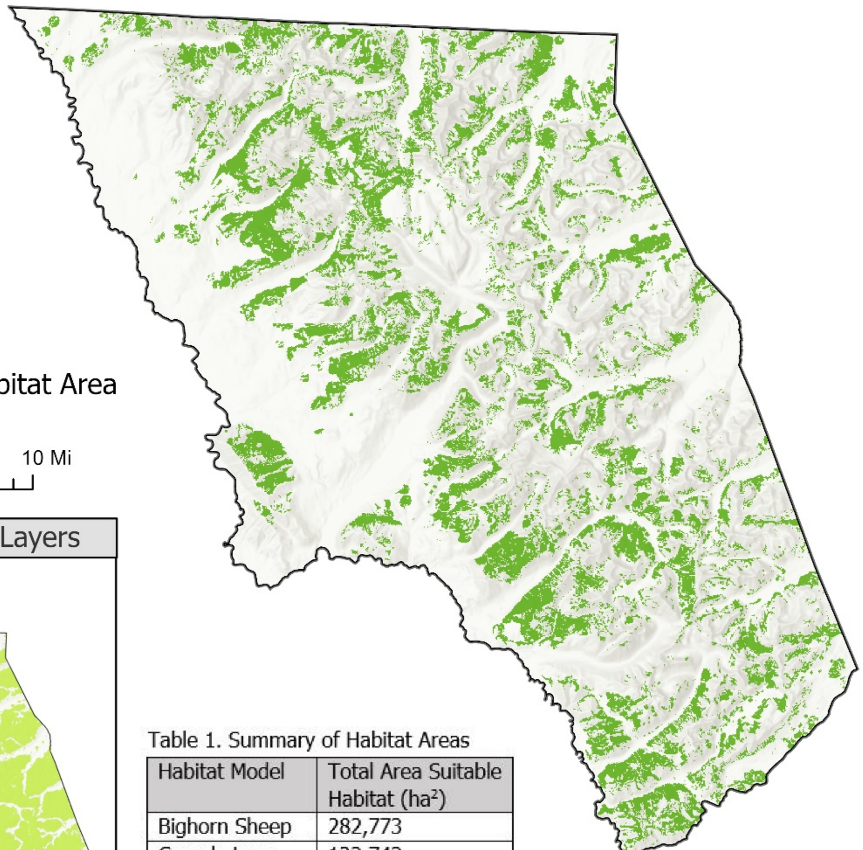
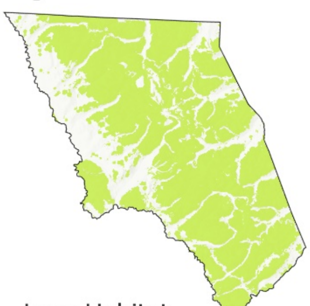


Figure 1. Habitat Layers

Bighorn Habitat



Lynx Habitat

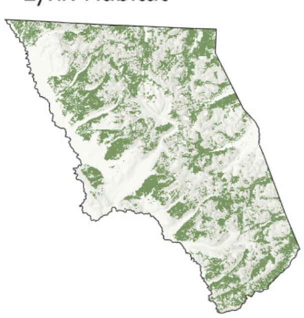


Table 1. Summary of Habitat Areas

Habitat Model	Total Area Suitable Habitat (ha^2)
Bighorn Sheep	282,773
Canada Lynx	122,743
Combined	80,406

Fig. 1 illustrates the input raster layers representing suitable habitat for bighorn sheep and Canada lynx. The two layers were combined using map algebra (times function) to create a final model identifying areas of suitable habitat that can support both species.

There are approximately 80,000 hectares of habitat which can support both species. This model is intended to identify general habitat areas which should be further characterized and is not designed for site-specific decisions.

Map created by Mary Straka December 2021. Data sources: ESRI, NPS. Datum and projection: NAD 1983 UTM Zone 12N.
Disclaimer: This map was created for University of Colorado Denver and shall not be used by NPS for management purposes.

1. Bighorn Sheep

1.1 Background

Glacier National Park is home to one of only two large native bighorn sheep populations in Montana. (GNPC, 2021). The GNP population is made up of multiple smaller, loosely connected herds. Currently, the patterns of movement within and between herds is poorly understood. GNP researchers and managers have requested detailed analysis of sheep habitat to learn more about characteristics of preferred habitat and gain insight into migration patterns. Better understanding of the habitat factors preferred by bighorn sheep will allow identification of areas where sheep are more or less likely to travel across the park. This information is critical when studying the spread of respiratory disease among populations and planning management strategies to reduce the spread and impact of disease to maintain healthy, viable sheep populations.

Bighorn sheep (*Ovis canadensis*) inhabit remote mountain and desert regions ranging from the Northern Rocky Mountains of Canada south through Baja California. Habitat includes areas of sparse or low vegetation like alpine meadows, woodlands, shrub, and dry pinyon-juniper plant communities (GNPC, 2021). The most critical habitat requirement is the presence of rock outcrops, steep slopes, cliffs, and canyons. These open and semi-open areas are known as escape terrain and are essential for predator evasion. Bighorn sheep also require areas far from human disturbance like development or roads, although some populations within GNP have become relatively comfortable navigating roads while traveling through the park.

1.2 Bighorn Habitat Suitability Model

Table 1 summarizes the criteria used to create a habitat suitability model for Bighorn sheep and the source data types from which criteria were derived. The model was created using ArcGIS Pro to process vector and raster data layers representing various habitat criteria. All layers were then converted to raster format and assigned values indicating areas which are suitable or unsuitable. Finally, overlay of all criteria layers produced the final suitability model which ranks each location in the park as very low, low, medium, or high suitability depending on the number of criteria satisfied (very low = 1, high = 4).[3]

Table 1. Bighorn Sheep Habitat Suitability Model Criteria

Habitat Criterion	Specifications
Open or Semi-open Vegetation	Land cover type: rock, bare soil, open, or semi-open vegetation
Escape Terrain	Slope: 27-85 degrees
Distance from Human Disturbance	Distance from roads: 300 meters Distance from hiking trails: 200 meters

[3] See Map 2, "Bighorn Sheep Habitat Suitability Model," p. 20.

1.3 Habitat Suitability Ranking and Elevation

The goal of this analysis is comparison of elevation values within each habitat suitability class to evaluate how important elevation values are in determining bighorn habitat suitability. The tool "Zonal Statistics as Table" was used to summarize statistics of elevation values within each habitat suitability class.

Table 2. Summary of Elevation Values within Habitat Suitability Classes

	Elevation Values (m)				
Suitability Ranking	Minimum	Maximum	Range	Mean	Median
Very Low	948	2,141	1,193	1,276	1,222
Low	947	2,449	1,502	1,419	1.367
Medium	949	3,050	2,101	2,101	1,716
High	970	3,185	2,215	2,215	2,080

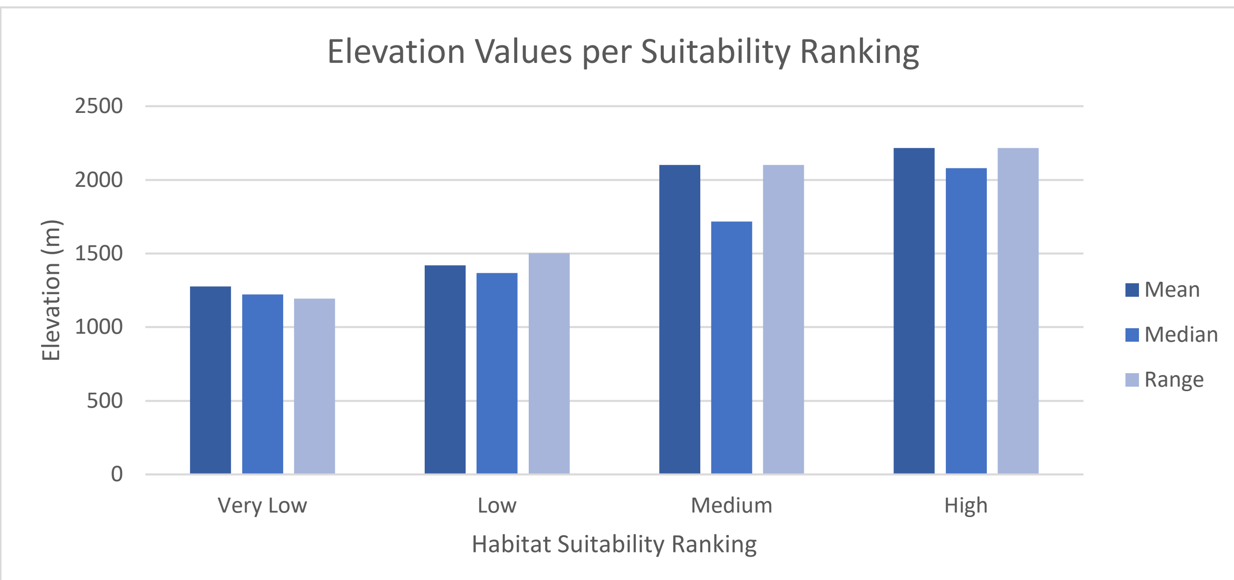


Figure 1. Elevation Values per Bighorn Habitat Suitability Ranking

Examination of relationships between habitat suitability classes and elevation values reveals a positive correlation between elevation and habitat suitability. Both mean and median elevation values for each suitability class increase as habitat suitability ranking increases. This trend indicates that habitat areas ranked as medium and high suitability are located at higher elevations than areas classified as low or very low suitability. Additionally, areas ranked as medium or high suitability have a greater range in elevation values than areas of low or very low suitability. This can be attributed to the importance of escape terrain in Bighorn Sheep habitat. A large range between minimum and maximum elevation values indicates greater variation of elevation throughout a landscape, which coincides with the occurrence of escape terrain, where the slope is steep and thus elevation values change relatively quickly. Areas classified as low or very low suitability have a much smaller range in elevation values, reflecting a landscape which is more uniform in elevation and lacks features required by bighorn sheep like steep cliffs and sheer rock faces. The correlation between elevation values and habitat suitability ranking indicates that elevation is an important factor to be considered when predicting locations and movements of bighorn populations through the park.

1.4 Habitat Suitability Ranking and Slope

The goal of this analysis is examination of how slope values (measured as percentage) vary within each habitat suitability class to better understand importance of slope in bighorn habitat. The tool "Zonal Statistics as Table" was used to summarize statistics of slope values within each habitat suitability class.

Table 3. Summary of Slope Values within Habitat Suitability Classes

	Slope Values (degrees)				
Suitability Ranking	Minimum	Maximum	Range	Mean	Median
Very Low	0	36.3	36.3	5.5	4.2
Low	0	76.1	76.1	9.7	8.5
Medium	0	82.7	82.7	21.2	20.1
High	0	87.2	87.2	37.2	35.8

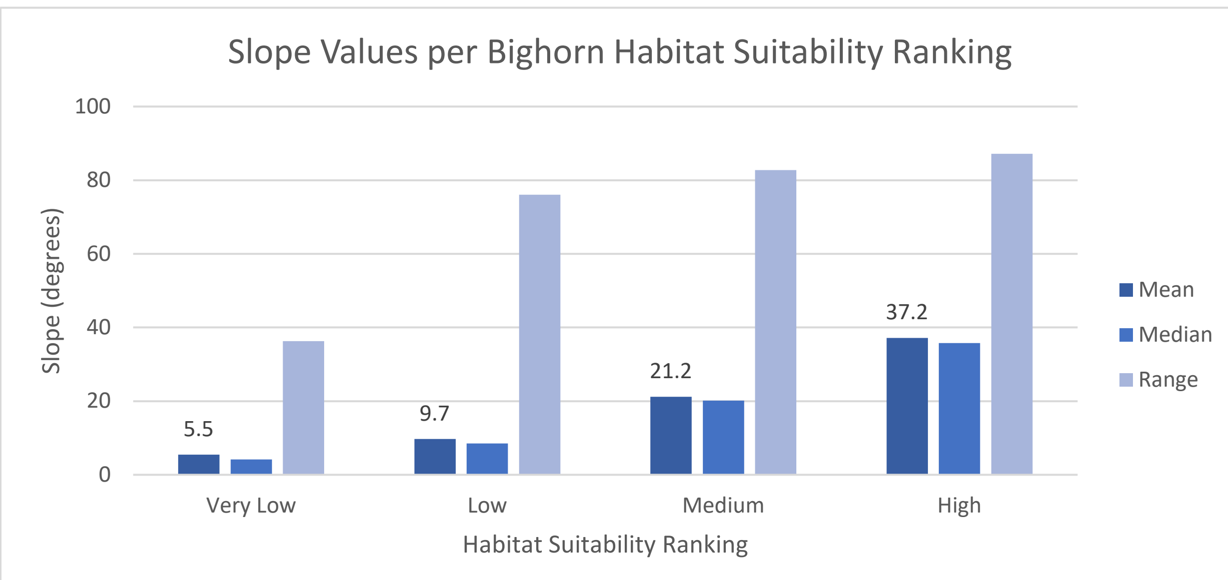


Figure 2. Slope Values per Bighorn Habitat Suitability Ranking

When evaluating the relationship between slope values and habitat suitability, again a positive correlation is found: the mean slope value increases as habitat suitability increases. Areas ranked as medium suitability have a mean slope value of 21 degrees while high suitability areas have a mean slope of 37 degrees. The inclusion of a desired range of slope values in the suitability model (slopes between 27 – 85 degrees) is reflected in these results, where a mean slope value within the desired range (37 degrees) is only found within highly suitable areas. Areas classified as medium suitability have a mean slope value of 21 degrees which is slightly below the desired range, but close enough that the class will also contain areas with slopes in the desired range (greater than 27 degrees). Similarly, median slope values within each suitability class reflect the same positive correlation. Area ranked as high or medium suitability have higher median slope values (20 and 35 degrees) while areas of very low and low suitability have very low median slope values (5 and 9 degrees).

Additional insight is gained from comparing variance of slope values from the mean across suitability classes. Slope values in higher suitability classes have a greater variance from the mean (measured by standard deviation). Greater variance of slope values in high suitability areas is related to escape terrain criteria used in the suitability model. Bighorn sheep prefer areas with steep slopes like rock outcrops, mountainsides, and cliffs. In these types of habitats there can be large changes in slope and elevation across the landscape, which results in the greater variance in slope values within higher suitability areas. Conversely, landscapes that are relatively flat and lacking terrain required by sheep like rock outcrops and cliffs are characterized by low slope values and low variance of slope values since the land is more uniform in elevation, resulting in lower habitat suitability ranking.

1.5 Vegetation Classification and Elevation

This analysis compares elevation values associated with various plant communities. Results can be combined with knowledge about the relationship between elevation and habitat suitability ranking to better understand which vegetation types are found in suitable bighorn habitat. The tool "Tabulate Area" was used to summarize statistics about elevation values found within various vegetation classes.

Table 4.Summary of Elevation Values within Vegetation Classification Zones

	Elevation Values (m)				
Vegetation Type	Minimum	Maximum	Range	Mean	Median
Forest and Woodland	948	2,622	1,674	1,600	1,578
Shrubland and Grassland	948	2,780	1,832	1,651	1,664
Polar and High Montane	1,024	2,880	1,856	2,124	2,140
Non-vegetated Land	947	3,088	2,141	1,682	1,500
Nonvascular and Sparse Vascular	1,011	3,183	3,183	2,312	2,331
Semi-Desert Scrub and Grassland	1,089	1,205	1,205	1,120	1,103

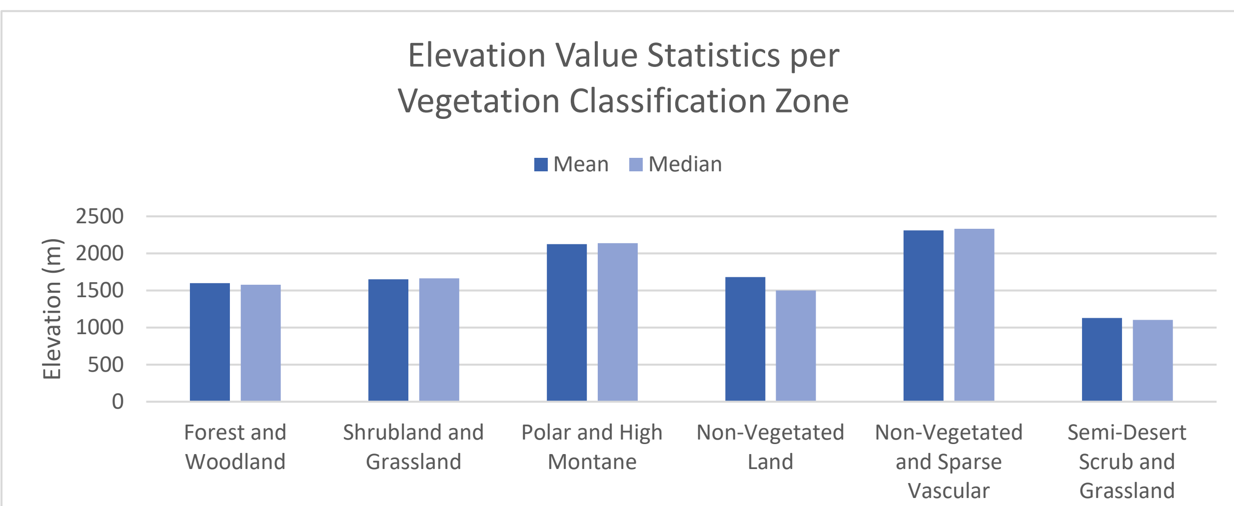


Figure 3. Elevation Values per Vegetation Classification Zone

Table 4 and Fig. 3 illustrate the relationship between elevation and vegetation classification. Comparison of mean elevation values shows that different plant communities inhabit different elevation zones. High elevation areas are commonly inhabited by nonvascular/sparse vascular and polar/high montane vegetation types (mean elevation values 2,312 and 2,124 meters, respectively). Based on the positive correlation found between elevation values and habitat suitability ranking (see Section 1.4) it can be concluded that plant communities found at high elevations will most likely be present in high suitability habitat areas. However, this does not mean that plant communities characterized by lower mean elevations are not found in suitable habitat areas. It is necessary to consider the geographic distribution of plant communities within the park which may affect mean values. Non-vegetated land, for example, has a lower mean elevation value of 1,682 meters. Perfunctory analysis may conclude that this lower mean elevation value indicates these plant communities are not associated with suitable habitat areas. But careful analysis considers that non-vegetated land includes escape terrain favored by bighorn sheep (non-vegetated rocky outcrops and cliffs) as well as other non-vegetated areas like paved or dirt roads. Most roads in the park are found at lower elevations, which explains why the mean elevation value for non-vegetated lands is skewed towards lower values. This theory is confirmed by the maximum elevation values for non-vegetated land, which is 3,088 meters. This elevation value is comparable to the maximum elevation values found in nonvascular and sparse vascular and polar/high montane plant communities (3,183 and 2,880 meters, respectively). Therefore, while results clearly indicate that non-vascular/sparse vascular and polar/high montane plant communities are found at high elevations and thus will also likely be found in high suitability areas, these results cannot be used to definitively exclude other plant communities from high suitability habitat areas.

1.6 Vegetation Classification and Slope

Results of this analysis can be combined with knowledge about the relationship between slope and habitat suitability ranking to understand the types of vegetation that are most likely to be present in high suitability habitat areas. The tool "Tabulate Area" was used to summarize statistics about slope values found within various vegetation classification zones.

Table 5. Summary of Slope Values within Vegetation Classification Zones

	Slope Values (degrees)				
Vegetation Type	Minimum	Maximum	Range	Mean	Median
Forest and Woodland	0	82.9	82.9	19.5	16.9
Shrubland and Grassland	0	82.1	82.1	20.5	20.0
Polar and High Montane	0	85.3	85.3	34.6	34.2
Non-vegetated Land	0	78.4	78.4	11.9	0
Nonvascular and Sparse Vascular	0	86.3	86.3	38.7	37.7
Semi-Desert Scrub and Grassland	0	3.2	3.2	0.6	0

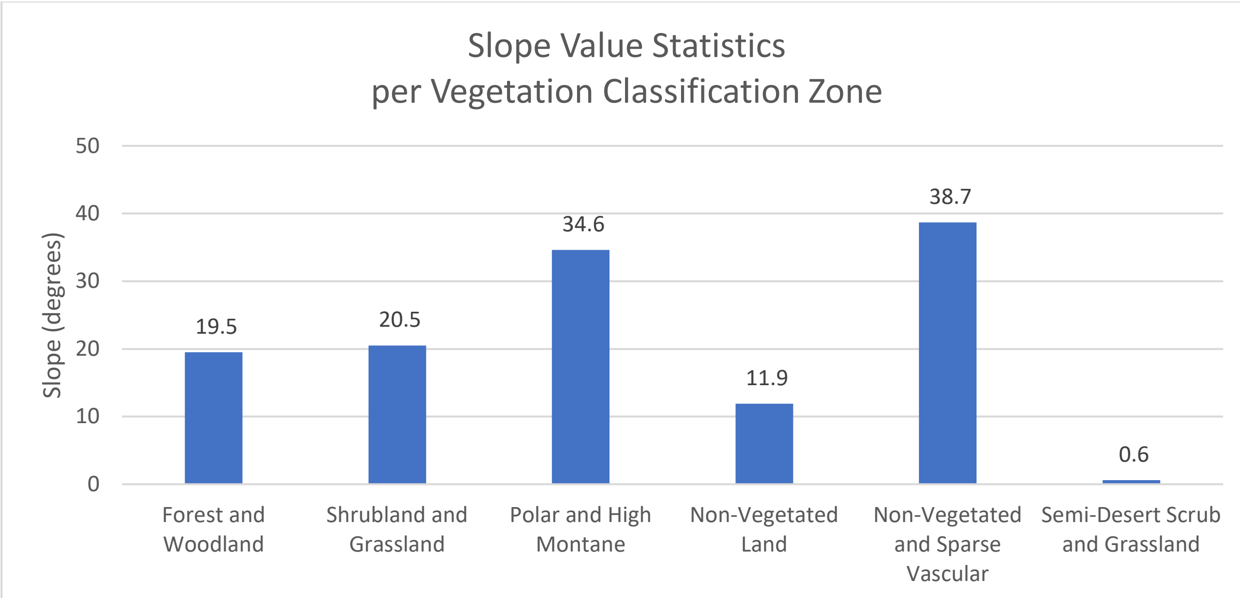


Figure 4. Slope Values per Vegetation Classification Zone

Table 5 and Fig. 4 illustrate the relationship between slope and vegetation type. Like results seen when comparing elevation values across vegetation types, the same vegetation types found at the highest average elevation (nonvascular/sparse vascular and polar/high montane) are also characterized by the highest mean slope values (34.6 and 38.7 degrees, respectively). As discussed previously (see Section 1.4) the positive correlation between slope values and habitat suitability ranking can be applied here to conclude that vegetation types found in areas with high slope values will also likely be present in high-ranked habitat suitability areas. The same caveat discussed previously regarding average values skewed low for non-vegetated land due to the presence of roads also applies; therefore, non-vegetated land should not be assumed to be absent from high suitability habitat areas based solely on average slope values.

1.7 Vegetation Classification and Habitat Suitability Ranking

Comparison of habitat suitability rankings found across different vegetation classification zones will supplement results from prior analyses comparing elevation and slope values across different vegetation classification zones. The tool "Tabulate Area" was used to summarize statistics about habitat suitability rankings across different vegetation classification zones.

Table 6. Percentage of Vegetation Type per Habitat Suitability Zone

	Habitat Suitability Ranking			
Vegetation Type	Very Low	Low	Medium	High
Forest and Woodland	75%	82%	72%	45%
Shrubland and Grassland	11%	10%	12%	10%
Polar and High Montane	0.1%	2%	9%	23%
Non-Vegetated Land	14%	7%	3%	5%
Nonvascular and Sparse Vegetation	< 0.1%	0.2%	4%	18%
Semi-Desert Scrub and Grassland	0.2%	< 0.1%	< 0.1%	< 0.1%

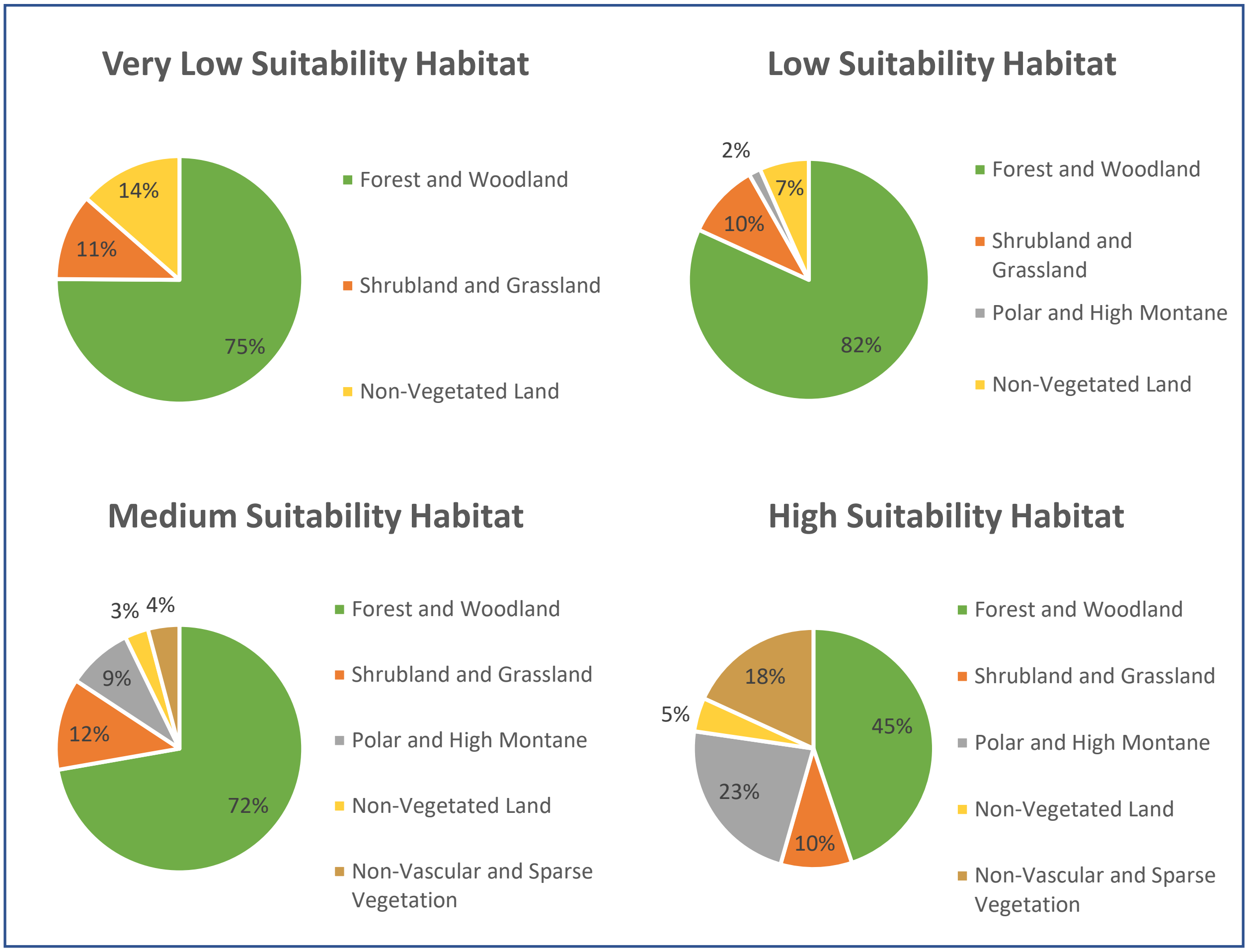


Figure 5. Proportion of Vegetation Type per Bighorn Habitat Suitability Ranking

Table 6 and Fig. 5 show the distribution of vegetation cover types as a percentage of total area within each habitat suitability zone. Forest/woodland is seen as the majority vegetation type within each suitability ranking zone, most likely because this is the majority vegetation type by area found within the park. Notably, the percentage of forest/woodland within high suitability habitat is lower (45%) than in areas ranked as medium, low, or very low suitability (72%, 82%, and 75%, respectively). Another distinction of high suitability areas is an increased proportion of polar/high montane and nonvascular/sparse vascular vegetation types (23% and 18%). Both of these vegetation types account for less than 10% of total vegetation by area within all lower suitability areas. These results support conclusions drawn from prior analyses which concluded that polar/high montane and nonvascular/sparse vascular vegetation is most likely associated with higher suitability habitat areas.

2. Canada Lynx

2.1 Background

The Canada Lynx (Lynx canadensis) is a mid-size carnivore which inhabits boreal spruce-fir forests across most of North America. The lynx is a habitat and prey specialist which requires dense boreal and subalpine forests with long winters, persistent deep powdery snow, and abundant snowshoe hare populations (US Fish & Wildlife Service, 2017). Morphological adaptations like large paws and long legs give lynx a competitive advantage in deep snow which allows them to occupy habitats that are seasonally unavailable to other terrestrial predators.

Lynx populations are found in six distinct geographic areas within the continental US, including North-central Washington, Greater Yellowstone Area, Northwestern Montana/Northeastern Idaho, Western Colorado, Northeastern Minnesota, and Northern Maine. (USFWS, 2017). Due to their highly specialized habitat and prey requirements, the biggest threat to lynx populations is habitat loss and fragmentation. In the northern US, boreal forests become naturally patchy as they transition to temperate forest types. Continued climatic warming is expected to cause a shift northward and reduction in total area of boreal forest habitat which will result in smaller, more fragmented and isolated patches of suitable lynx habitat. Other threats include climate-driven increases in intensity and frequency of wildfires which will further reduce suitable habitat area.

2.2 Lynx Habitat Suitability Model

Much of the Northwest Montana/Northeast Idaho lynx population occupies habitat within Glacier National Park. Researchers and NPS staff have created a suitability model to identify areas within the park that are high-quality lynx habitat to be prioritized for conservation and management programs.[4] The suitability model incorporated data about vegetation type and areas impacted by wildfires (Table 7). Areas classified as non-coniferous vegetation and/or with moderate or high burn severity were excluded since wildfire-impacted areas do not provide sufficient vegetation cover required to support lynx populations.

Table 7. Canada Lynx Habitat Suitability Model Criteria

Habitat Criterion	Specifications
Boreal Forest	Vegetation types: Engelmann Spruce-Wet Shrub Forest, Engelmann Spruce Forest, Lodgepole Pine Forest, Lodgepole Pine Wet Forest, Subalpine Fir-Engelmann Spruce Forest, Subalpine Fir-Engelmann Spruce Woodland, Subalpine Larch Woodland, Western Larch Forest
Low Wildfire Impact	Burn intensity: low or unburned

2.3 Habitat Suitability Ranking and Elevation

This analysis compares slope values found in areas classified as suitable or unsuitable lynx habitat. The tool "Zonal Statistics as Table" was used to summarize statistics for elevation values within each habitat suitability class.

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[4] See Map 3, "Canada Lynx Habitat Suitability Model," p. 21.

Table 8. Summary of Elevation Values within Habitat Classes

	Elevation Values (m)				
Habitat Type	Minimum	Maximum	Range	Mean	Median
Unsuitable Habitat	949	2,489	1,540	1,363	1,276
Suitable Habitat	1,208	2,613	1,405	1,678	1,663

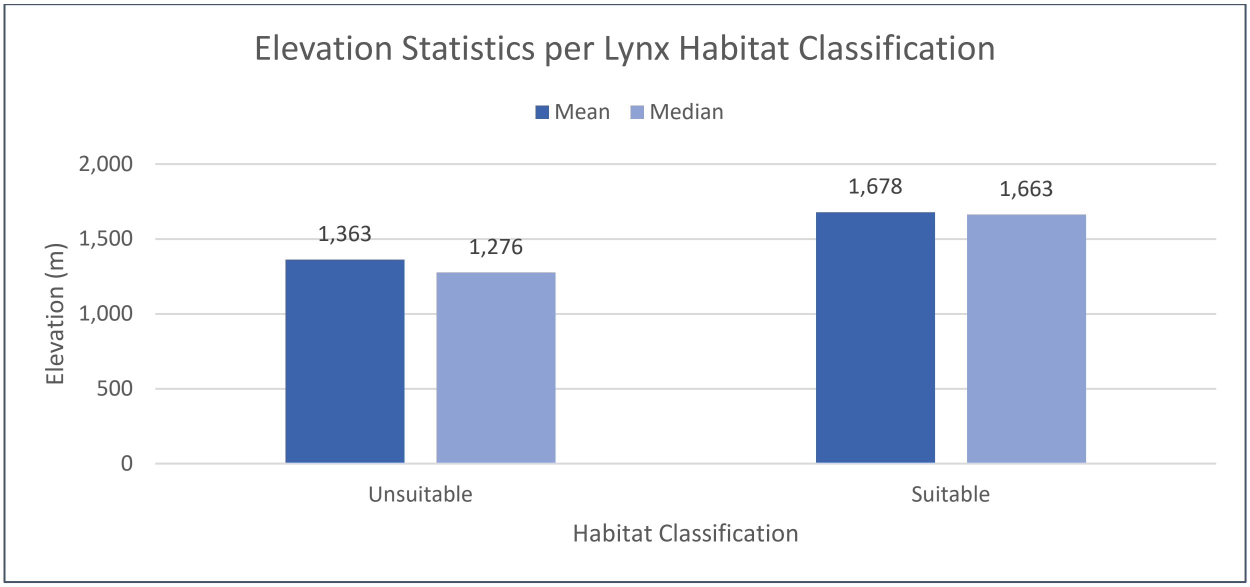


Figure 6. Elevation Statistics per Lynx Habitat Suitability Classification

Results shown in Table 8 and Fig. 6 indicate a positive correlation between lynx habitat ranking and elevation. Areas classified as suitable lynx habitat have higher minimum, maximum, mean, and median elevation values than unsuitable habitat areas. These results are consistent with inputs to the lynx habitat suitability model which included coniferous forest and woodland vegetation types. Additionally, higher elevation areas are more likely to have permanent or persistent snow cover required by lynx than lower elevation areas.

2.4 Habitat Suitability Ranking and Slope

This analysis compares slope values found in suitable lynx habitat areas with slope in unsuitable areas. The tool “Zonal Statistics as Table” was used to summarize statistics of slope values within each suitability class.

Table 9. Summary of Slope Values within Habitat Classes

	Slope Values (degrees)					
Habitat Type	Minimum	Maximum	Range	Mean	Median	Standard Deviation
Unsuitable Habitat	0	69.2	69.2	12.1	9.5	9.9
Suitable Habitat	0	81.8	81.8	19.3	16.9	12.5

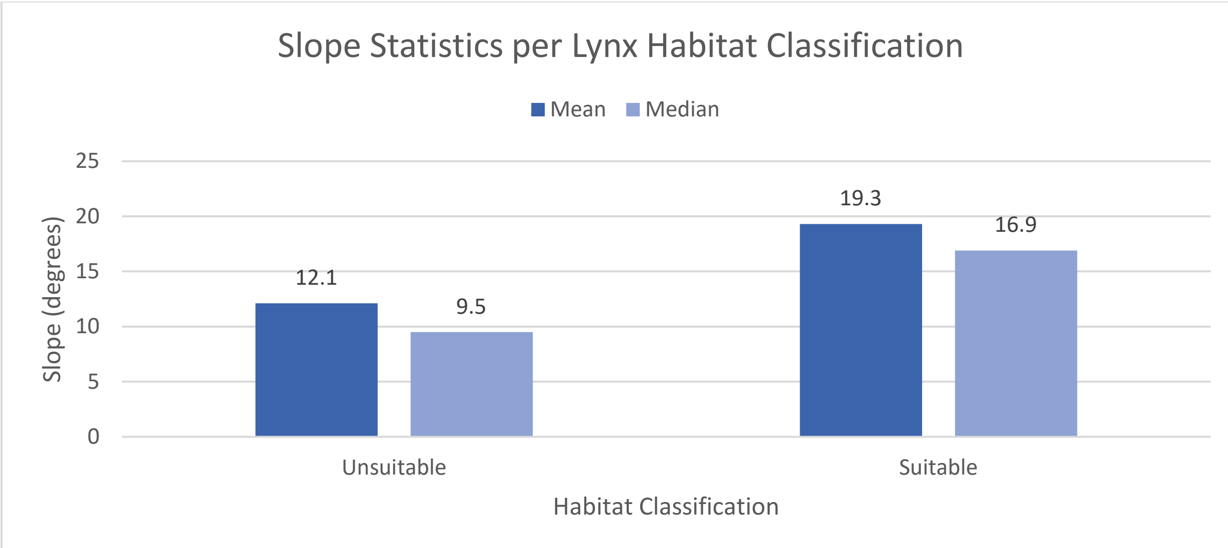


Figure 7. Slope Statistics per Lynx Habitat Suitability Classification

Statistics of slope values show minor variation in slope between suitable versus unsuitable lynx habitat areas. Unsuitable areas have slightly lower mean and median slope values (12.1 and 9.5 degrees) than suitable habitat areas (19.3 and 16.9 degrees). Compared to elevation value statistics, slope values do not appear to play a large role in determining lynx habitat suitability.

2.5 Habitat Suitability Ranking and Vegetation Classification

Comparison of vegetation types present in suitable versus unsuitable lynx habitat areas is expected to show a dominance of forest and woodland vegetation in suitable habitat areas. The tool "Tabulate Area" was used to summarize statistics about habitat suitability ranking across different vegetation classification zones.

Table 10. Summary of Vegetation Types within Habitat Suitability Ranking

	Total Area (ha^2)		**Percentage of Total Area**	
Vegetation Type	Unsuitable Habitat	Suitable Habitat	Unsuitable Habitat	Suitable Habitat
Forest and Woodland	54,047	110,154	95%	90%
Shrubland and Grassland	1,959	6,857	3%	6%
Polar and High Montane	302	3,927	1%	3%
Non-Vegetated Land	288	844	< 1%	< 1%
Nonvascular and Sparse Vegetation	78	896	< 0.1%	< 1%
Semi-Desert Scrub and Grassland	8	0.2	< 0.1%	< 1%

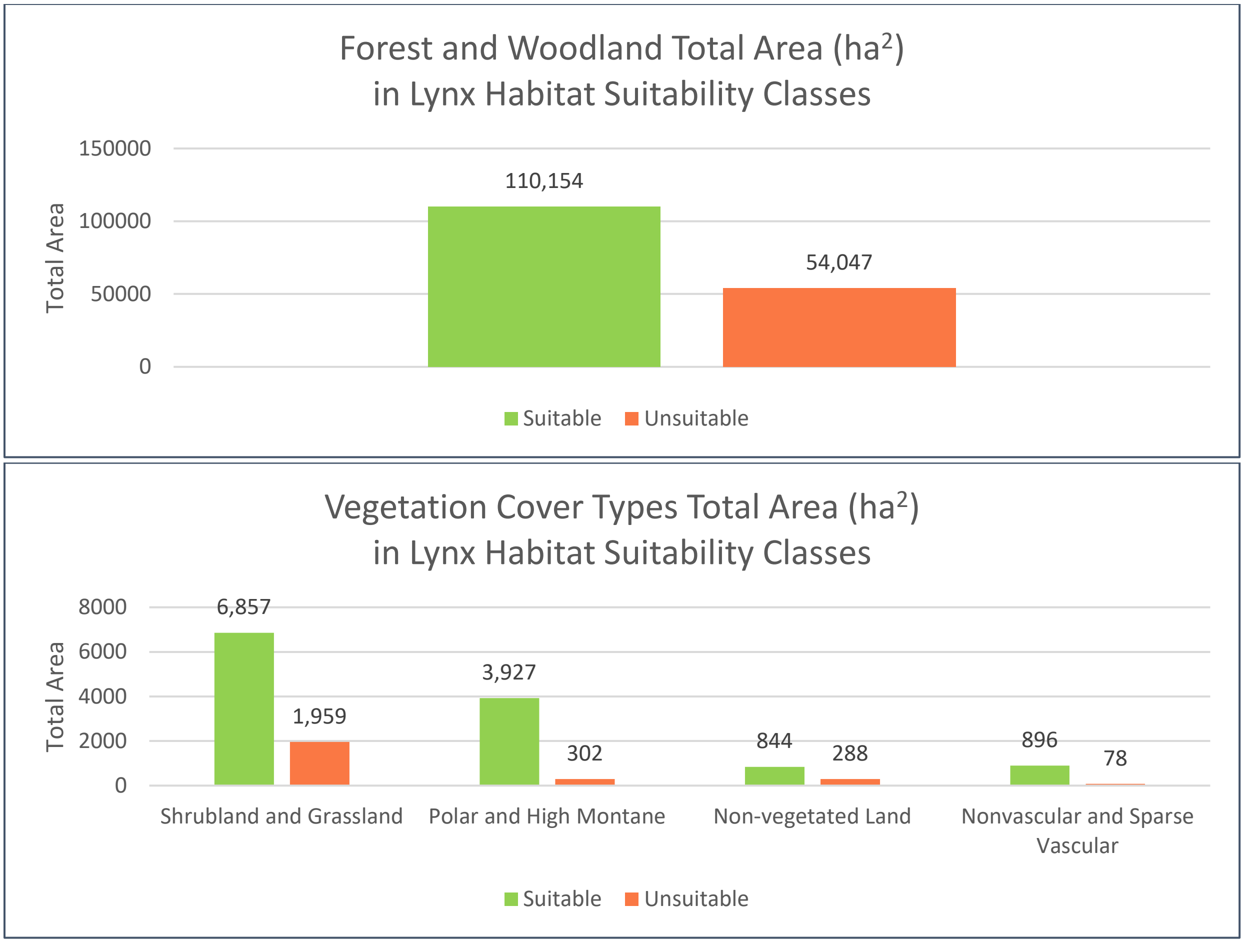


Figure 8. Vegetation Type by Area within Lynx Habitat Suitability Classification

Table 10 and Fig. 8 confirm expected results with forest and woodland seen to be the dominant vegetation type within suitable lynx habitat areas. An increase in presence of shrubland/grassland and polar/high montane vegetation types is seen in suitable lynx habitat areas as compared to unsuitable areas. Surprisingly, an increase in non-vegetated land and nonvascular/sparse vascular vegetation was also seen in suitable habitat areas. While this initially seems contrary to lynx habitat requirements (boreal forest with coniferous vegetation cover) it can be explained when considering the way these vegetation types vary with increasing elevation. At lower elevations, non-vegetated land and nonvascular/sparse vascular are most likely to be bare rock or soil, but at higher elevations, these areas are most likely covered with persistent or permanent snow and therefore can support lynx populations while the same vegetation type at lower elevations cannot.

3. Combined Habitat Suitability Model

3.1 Methodology

Existing habitat suitability models for bighorn sheep and Canada lynx were in two different formats. The bighorn sheep model was a scaled suitability model which ranked habitat on a scale of 1 to 4 depending on the number of criteria met by each location. The Canada lynx model was a simple suitability model which assigned each location a value of 1 if all criteria were met (suitable habitat) or 0 if any or all criteria were not met (unsuitable habitat). To combine both models, it was necessary first to convert the bighorn sheep model to a binary 0-1 scale to match the lynx model. To do this, habitat areas ranked as very low (1) or low (2) suitability were reclassified both to a value of 0 (unsuitable habitat). Habitat areas ranked as medium (3) or high (4) suitability were reclassified both to a value of 1 (suitable habitat). Once common suitability values were assigned across both models, map algebra tools were used to multiply the two models together on a cell-by-cell basis.[5] Input cells in both rasters have only two possible values (1 for suitability habitat, 0 for unsuitable habitat). Multiplication then results in only two possible outcome values (0 or 1). For each cell, if the value in either suitability model is 0, the output will be 0 (unsuitable). If both cells have a value of 1 in each model, the output will be 1 (suitable habitat). The overall result is a simple suitability model which identifies areas suitable for both bighorn sheep and Canada lynx with a value of 1. All other areas which are suitable for only one species or are unsuitable for both species will have a value of 0.[6]

3.2 Summary of Results

Tables 11 and 12 and Fig. 9 summarize statistics of elevation, slope, and vegetation classification types found in suitable versus unsuitable areas of the combined bighorn sheep and Canada lynx suitability model.

Table 11. Summary of Elevation and Slope Values in within Habitat Suitability Zones

	Unsuitable Habitat			**Suitable Habitat**		
	Minimum	Maximum	Mean	Minimum	Maximum	Mean
Elevation (m)	948	2,493	1,433	1,196	2,623	1,754
Slope (degrees)	0	69.3	11.4	0	81.6	23.8

Table 12. Percentage by Area of Vegetation Type within Habitat Suitability Zones

	Vegetation Percentage by Area	
Vegetation Type	Unsuitable Habitat	Suitable Habitat
Forest and Woodland	56%	29%
Shrubland and Grassland	43%	35%
Polar and High Montane	< 1%	27%
Non-vegetated Land	< 1%	3%
Nonvascular and Sparse Vascular	< 1%	6%
Semi-Desert Scrub and Grassland	< 1%	< 1%

[5] See Appendix A for more information about raster multiplication.

[6] See Map 4, "Combined Bighorn Sheep and Canada Lynx Habitat Suitability Model," p. 22.

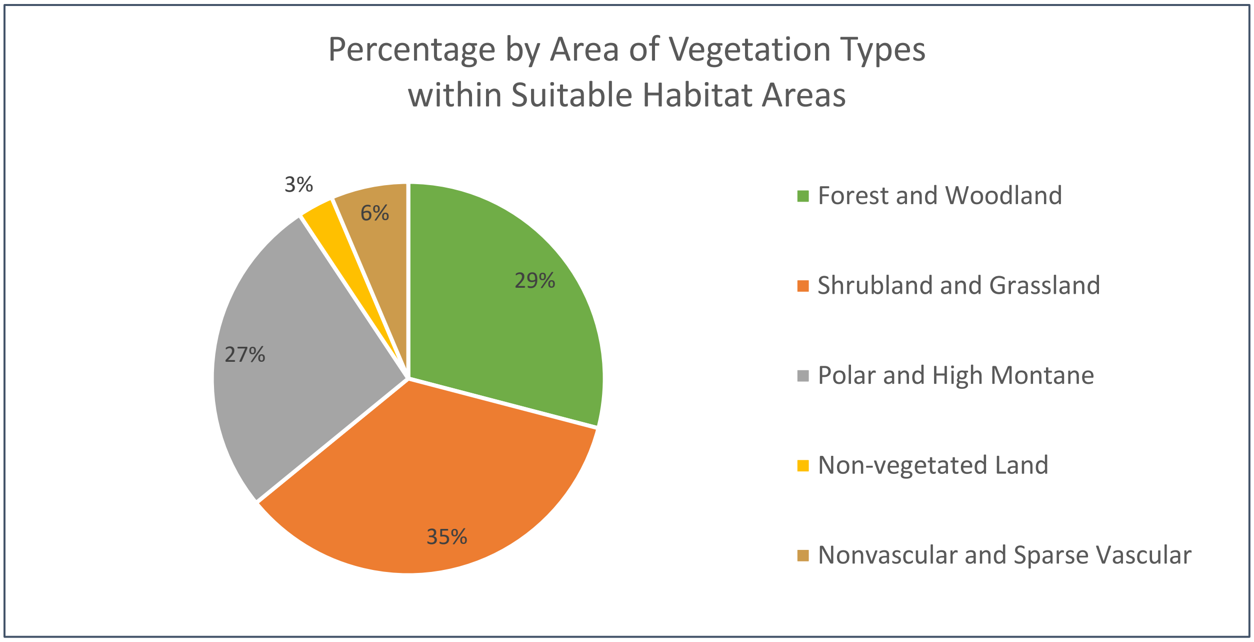


Figure 9. Percentage by Area of Vegetation Types within Suitable Habitat Areas

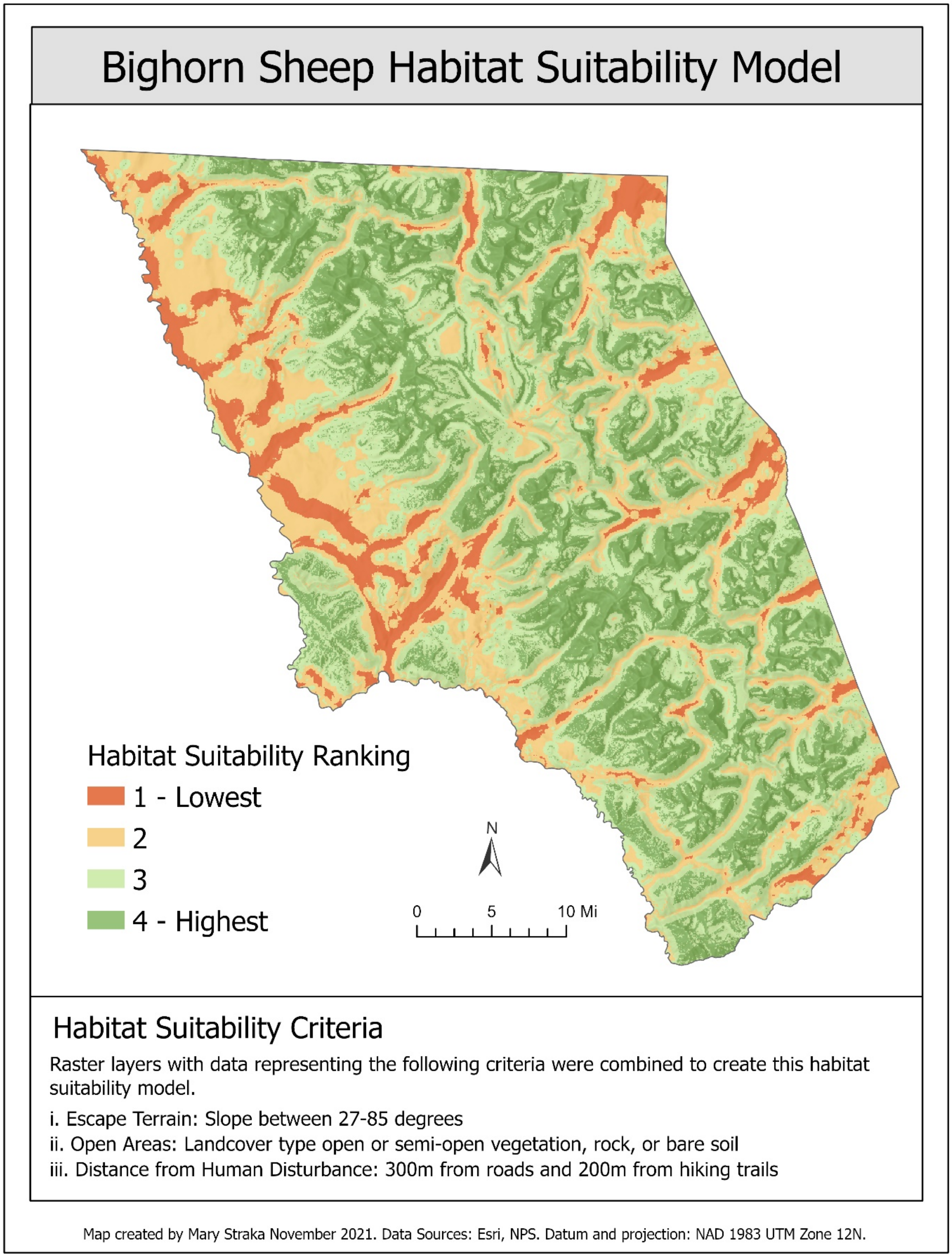
3.3 Discussion

Statistics about elevation values, slope values, and vegetation types present within suitable areas in the combined bighorn sheep and Canada lynx habitat model are consistent with relationships between these variables seen in analyses throughout this report. There is a positive correlation between habitat suitability ranking and both elevation and slope values where higher-ranked habitat areas have higher average elevation and slope values. Additionally, the same vegetation types are seen to be present in high suitability habitat areas in the combined suitability model. Where the bighorn model featured a higher proportion of polar/high montane, non-vegetated land, and nonvascular/sparse vascular vegetation (due to their requirement of escape terrain) and the Canada lynx model featured a higher proportion of forest/woodland and shrubland/grassland vegetation (due to their requirements for boreal forest and dense vegetation), the combined model balances both species' preferences, resulting in a relatively even proportion of forest/woodland, shrubland/grassland, and polar/high montane areas (29%, 35%, and 27%, respectively). These results provide valuable insight as they indicate areas of priority for both species: high elevation areas featuring forest/woodland, shrubland/grassland, and polar/high montane vegetation types.

Conclusion

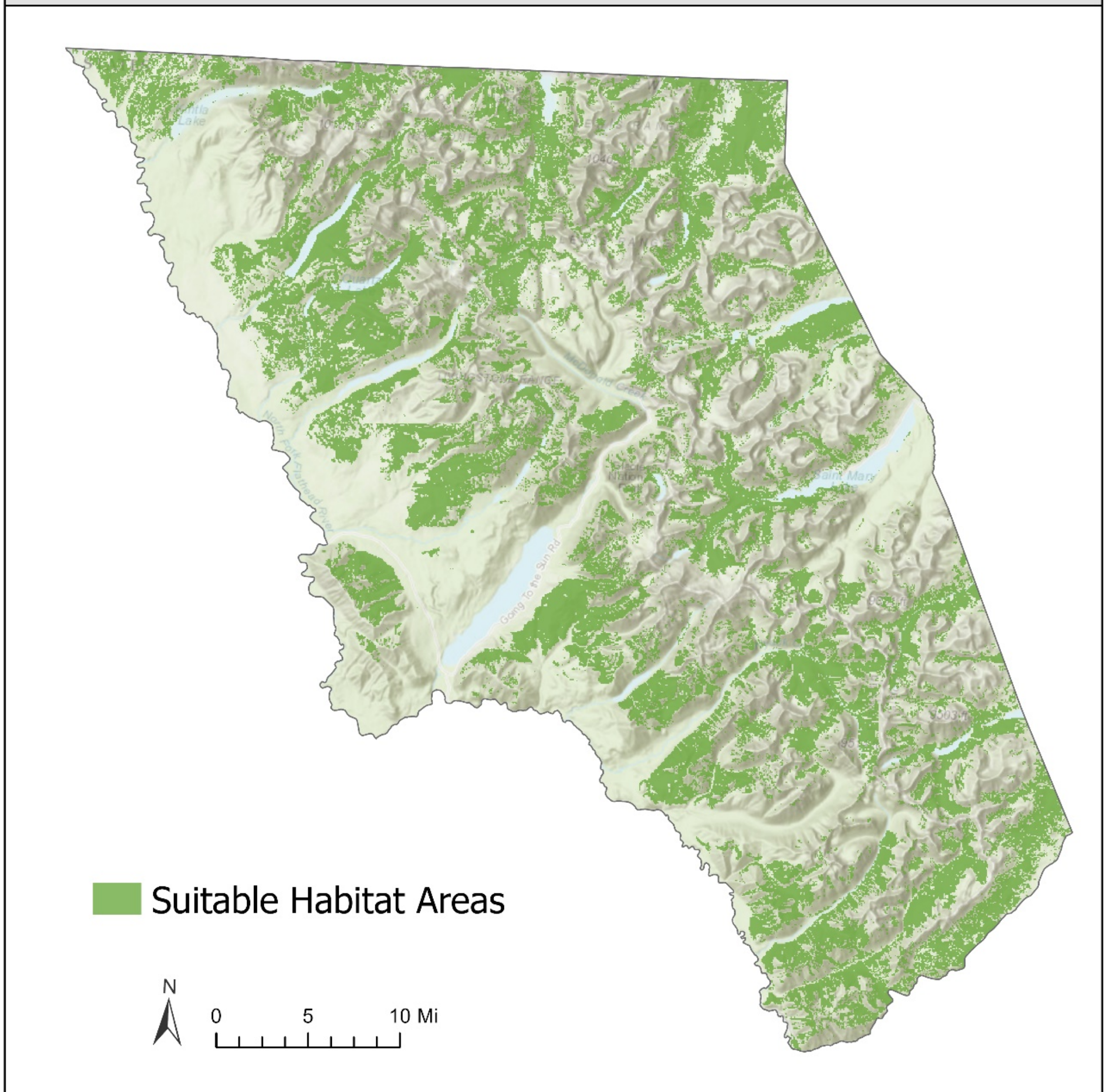
Map 4 (p. 22) illustrates areas within the park that are suitable habitat for both bighorn sheep and Canada lynx. The purpose of this model is to identify areas to focus management, monitoring, and conservation efforts. Ecological and geographical features and relationships within these areas should be further characterized to supplement current knowledge. Future analyses should identify specific habitat patches and movement corridors between patches. Continued analysis and monitoring is necessary to develop effective conservation and management programs to protect the future of bighorn sheep and Canada lynx populations within Glacier National Park and in the greater Montana/Idaho/Canada region.

Map 3. Bighorn Sheep Habitat Suitability Model



Map 4. Canada Lynx Habitat Suitability Model

Canada Lynx Habitat Suitability Model



Habitat Suitability Criteria

Lynx habitat suitability model created by NPS biologists using criteria specified below.

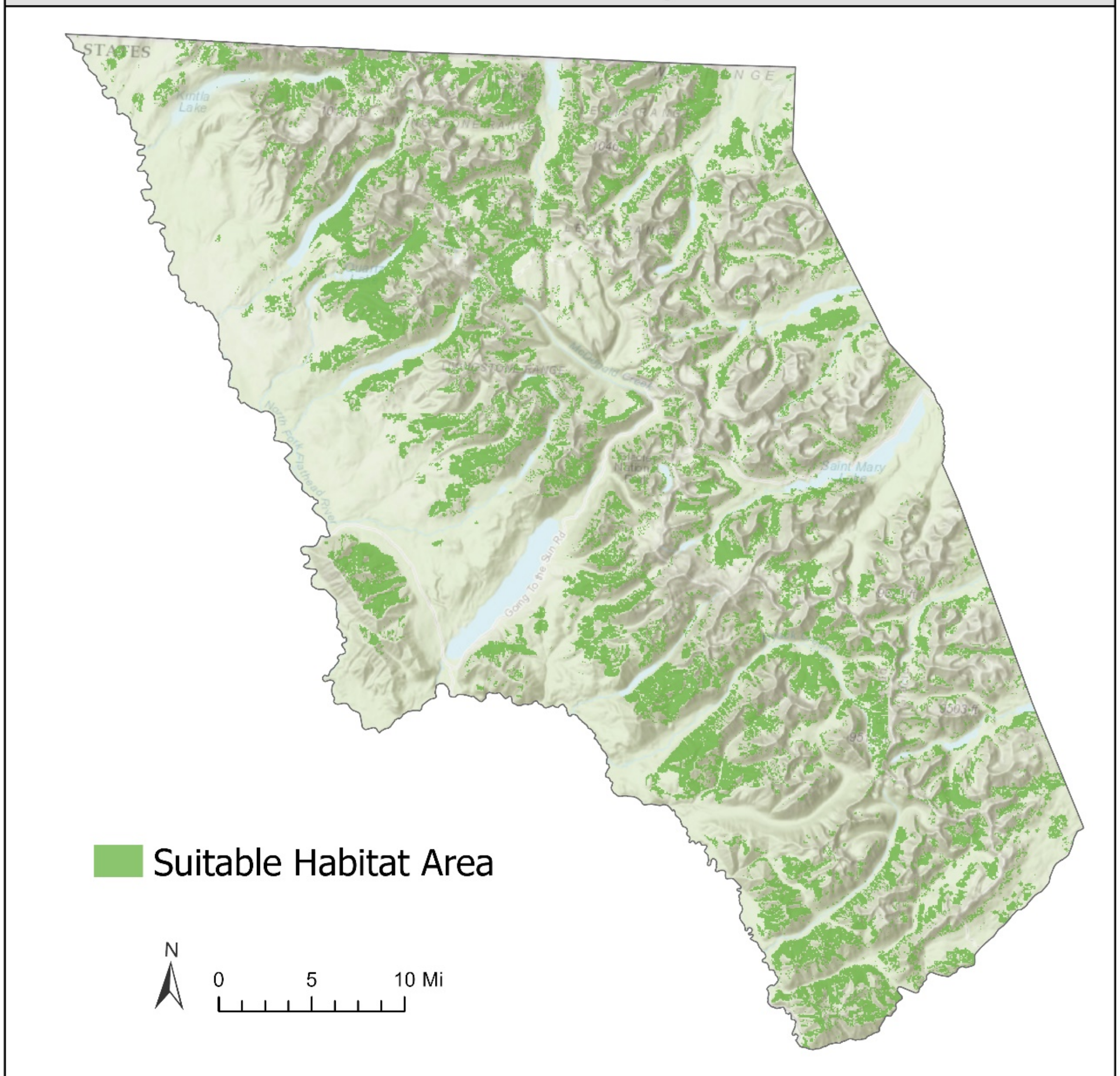
Vegetation: Coniferous forest
Elevation: Greater than 4000 feet
Wildfire Burn Severity: None or Low

Habitat Model: Menicke, R. (2008). "Lynx Habitat Model for Glacier National Park." National Park Service, October 2008.

Cartography by Mary Straka November 2021. Data Sources: Esri, NPS. Datum and projection: NAD 1983 UTM Zone 12N.

Map 5. Combined Bighorn Sheep and Canada Lynx Habitat Suitability Model

Combined Bighorn Sheep and Canada Lynx Habitat Suitability Model



Combination of bighorn sheep and Canada lynx habitat models illustrates areas suitable for both species. Identification of critical habitat areas is required so these locations can be effectively targeted by National Park Service staff and managers for management efforts. Maintenance of viable bighorn sheep and lynx populations will require ongoing monitoring and conservation efforts.

Map created by Mary Straka November 2021. Data sources: ESRI, NPS. Datum and projection: NAD 1983 UTM Zone 12N.

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Appendix A. Source Data Provenance

1. Bighorn Sheep Habitat Model Source Data

File Name	Source	Original Projection	Scale/Resolution	Accuracy/Error
Boundary2003.shp	NPS	NAD 1983 UTM 12N	1:24,000	12m horizontal error
Roads_public.shp	NPS	NAD 1983 UTM 12N	1:24,000	1-8m horizontal error
Trails_public.shp	NPS	NAD 1983 UTM 12N	1:24,000	15-20m horizontal error
Glac_lakes.e00	NPS	NAD 1927 UTM 12N	1:24,000	12m horizontal error
Glac_streams.e00	NPS	NAD 1927 UTM 12N	1:24,000	12m horizontal error
Glacveg.shp	NPS	NAD 1983 UTM 12N	1:24,000	80% accuracy
Glac_soils.shp	NPS	NAD 1983 UTM 12N	1:24,000	Accurate from 1:20,000-1:31,000
Glac_10mDEM.zip	NPS	NAD 1983 UTM 12N	10m	10m horizontal error

2. Lynx Habitat Model Source Data
Habitat Model Citation: Menicke, R. (2008). Lynx Habitat Model for Glacier National Park. Glacier National Park, Montana. (Link: https://irma.nps.gov/DataStore/Reference/Profile/2181440)

From NPS:

Abstract: Lynx habitat within Glacier National Park, Montana. GIS modeling derived the intersection of vegetation types preferred by Lynx and elevations above 4000-feet to define lynx habitat areas. Vegetation map classes selected by GNP Wildlife Biologist Steve Gniadek for habitat construction are include: Engelmann Spruce-Wet Shrub Forest Engelmann Spruce Forest Lodgepole Pine Forest Lodgepole Pine Wet Forest Lodgepole Pine Woodland Subalpine Fir-Engelmann Spruce Forest Subalpine Fir-Engelmann Spruce Woodland Subalpine Larch Woodland Western Larch Forest. Data source: Glacier NP Vegetation Map (USGS 2007).

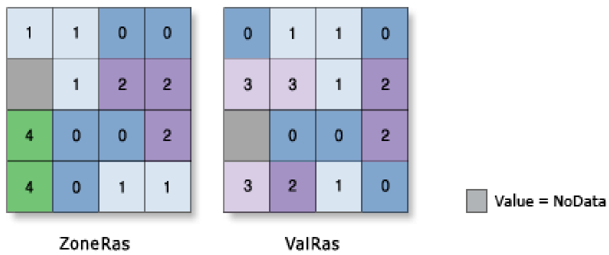
Supplemental Information: Vegetation classes were selected from the Park vegetation map (USGS 2007), which is based on August 1999 aerial photography. Burn severity grid files were used to identify changes to vegetation structure and composition in fire-affected areas (moderate to high severity and high severity). Burn data from 1999 - 2007 were used to “erase” habitat areas included in the vegetation map classes selected, with the assumption that these areas no longer provide forested cover.

Attribute Definition: VALUE field; 1 = lynx habitat; 0 = not lynx habitat (burned sinced 1999 or below 4000 feet or not confier veg type)

Use Constraints: Information is a general rendition of lynx habitat based on 1999 Vegetation mapping that was updated to reflect (i.e. remove) burn areas through 2007. These data provide a conceptual model of lynx habitat and should not be used for site-specific decisions.

Appendix B. ArcGIS Pro Spatial Analyst Tools

1. Zonal Statistics As Table Illustration



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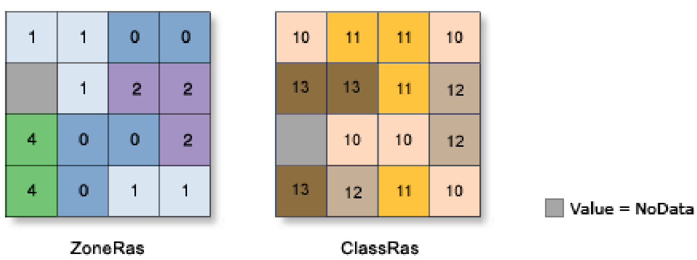
Rowid	VALUE	COUNT	AREA	MIN	MAX	MEAN
1	0	5	5	0	2	0.6
2	1	5	5	0	3	1
3	2	3	3	1	2	1.667
4	4	1	1	3	3	3

2. Tabulate Area Illustration



Tabarea1.dbf

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VALUE	VALUE_10	VALUE_11	VALUE_12	VALUE_13
0	3	1	1	0
1	2	2	0	1
2	0	1	2	0
4	0	0	0	1

3. Raster Multiplication Illustration