Using Multi Criteria Evaluation and Machine Learning to Model Seasonal Ranges of the Bathurst Caribou Herd

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Abstract

The Bathurst caribou herd is a population of keystone barren-ground caribou (*Rangifer tarandus*) whose range extends throughout the Northwest Territories and into Nunavut. For the past few decades, this herd has experienced a drastic population decline as a result of heightened stress from environmental and anthropogenic alterations within their range. Identifying regions of prime habitat of the Bathurst herd provides important insight for generating management and protective approaches in government and conservation authority decision-making. To determine suitable habitat for Bathurst caribou we investigated the seasonal factors that influence herd distributions in the summer and winter seasons and developed a Habitat Suitability Index (HSI) using a Multi-Criterion Evaluation (MCE). An MCE was developed from the suitability scores of data layers containing criteria and constraints described in literature. Each criterion within the MCE was ranked as most suitable to least suitable for Bathurst caribou presence. The weights and respective importance of each criterion were determined using a machine learning model, validated against in-situ caribou collar data using overall accuracy assessments. This model randomized the weights of each seasonal factor over 1000 iterations, saving the weight values that resulted in the highest overall accuracy within an iteration. The model determined that wind, temperature, NDVI and elevation had the greatest influence on range in the summer, and temperature, biome class and snow depth had the largest influence on range in the winter. These values are supported by overall accuracies of 84.18% and 81.97% respectively. The decline of keystone barren-ground caribou herds, such as the Bathurst herd, has already altered ecosystems and the lives of those who rely on them as a primary food source. Understanding their specific habitat preferences through an MCE model can guide government and conservation authorities in their decision-making to better preserve the herd and predict future migration paths in the face of increasing environmental and anthropogenic stressors.

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1. Introduction

Barren-ground caribou (*Rangifer tarandus*) populations across Canada have been steadily declining for the past several decades, from approximately two million nationwide to only 800,000 in 2015 (EC, 2022). This subspecies of the reindeer can be found throughout Nunavut and the Northwest territories (NWT) and are further divided into specific herds. The Bathurst caribou herd, whose range extends from Southern and central NWT to Bathurst Inlet of Nunavut, has experienced one of the most dramatic population declines in the country. The herd has dropped from approximately 470,000 individuals to about 6,400, a loss of 98% between 1986 and 2021, as a result of environmental and anthropogenic stresses (GNWT ENR, 2021). Surrounding caribou herds have also experienced population decline, however, to lesser extents than the Bathurst herd. Bathurst and surrounding barren-ground caribou herds are of extreme importance to the indigenous way of life in Canada's North. The decline of the Bathurst herd has already altered the lives of those who rely on them as a primary food source, and due to their diminishing populations, hunting caribou from this herd is currently prohibited (GNWT ENR, 2021). Barren-ground caribou are also considered a keystone species, such that without them and their effects on the surrounding environment, entire ecosystems would biotically and abiotically change in response (EC, 2022). Therefore, the overall protection and conservation of this herd, and those surrounding it, is of ever-growing importance.

Barren-ground caribou are one of the most well studied species in Canada, and papers addressing human and environmental factors which influence their migration have been published extensively. However, there are no definitive ways of predicting the exact movements of caribou, and the overall ranges which they occupy each season varies annually (Nicholson et al., 2013). The numerous factors which influence the movement of barren-ground caribou are well understood in literature. Human disturbances (Boulanger et al., 2021), population (Joly et al., 2021), temperature (Witter et al., 2012), seasonality (Virgil et al., 2017), food availability (Gurarie et al., 2019), biome class (Gurarie et al., 2019), and snow/ice cover and precipitation (Cameron et al., 2021) are some of the known factors that affect a caribou herd's seasonal habitat, and migration routes. Many of the human-induced influences to caribou movements in Canada's north are due to resource extraction practices, stemming from the expansion of human features, such as rare Earth mines, population centres, road networks, and pipelines. Current migration research involves the use of data from radio collaring individual caribou, a cost-effective method for remotely tracking the movement of a species within its environment. Land use maps are developed from individual herd collar data which allow for consistent tracking of current and historic herd locations (Wilson et al., 2016). This data is also currently being used to create a mobile conservation zone around the herd (BCAC, 2021). However, the extent to which each of the aforementioned factors influence land use and migration of caribou is widely unknown, especially in relation to one another.

Due to barren-ground caribou having one of the longest migrations of land animals in the world (Wilson et al., 2015), it is important to know and predict where these animals can be found; both GIS and remote sensing are already important tools used in the conservation of caribou herds. Radio collar data has been available for the Bathurst Caribou herd for years, and comprehensive maps of their seasonal ranges have been created from the telemetry data that dates back as far as 1996 (BCAC, 2020). Based on this data, it is evident that the habitat occupied by the Bathurst herd varies from season-to-season. This variability in land occupancy suggests that Bathurst caribou have particular seasonal habitat preferences that, when understood, can be useful for predicting regions of critical habitat.

As mentioned, predicting barren-ground caribou movements is currently a challenge which requires knowledge of their specific habitat preferences, which is an issue that this study attempts to address. A Multi-Criteria Evaluation (MCE) model can be used to determine prime caribou habitat based on seasonal factors, and can help guide government and conservation authorities in their decision making to better preserve the herd. Additionally, an MCE can be used to model the most suitable areas for the herd on a seasonal basis, and the use of openly available in-situ telemetry data from the herd can be used to determine the relative importance of the many factors affecting their migration and habitat use. Knowing the degree of influence, or weights, these factors have on caribou land use is also important as this knowledge can be used to inform policy and the management strategies which would benefit the herd the most. Furthermore, future effects, such as climate change, can be modelled if long-term datasets are chosen (e.g., lichen coverage and temperature). This would allow for the monitoring, and potential forecasting of where caribou are expected to be found over time, which GPS collars are not able to accomplish. The main purpose of this project is to develop a GIS model to determine the relative importance of each factor affecting the Bathurst caribou herd, which can then be tasked with creating predictive models of seasonal land use.

2. Research Objectives

1. Compiling relevant data pertaining to variables associated with migration, habitat, and behaviour of caribou.
2. Generating a habitat suitability index (HSI) using a multi-criteria evaluation (MCE) which employs all established variables in the decision-making process, for both the summer and winter seasons.
3. Determining variable weights which result in the closest representation of in-situ data as possible, utilizing a machine learning model paired with in-situ telemetry data for validation of optimal weights.

3. Study Area

The Bathurst Caribou Herd is made up of migratory tundra caribou, which can be found throughout the North Slave Region of the Northwest Territories and extending North into the Kitikmeot region of Nunavut. With a cumulative annual range of over 350 000 km^2, this herd of barren-ground caribou falls on the traditional land of the Dene, Tłı̨chǫ, and Inuit People (Boulanger et al., 2011, Dearborn & Danby 2022). The native people of these regions have relied on this herd as a vital food source for decades (Dokis-Jansan et al*.,* 2021), and caribou play integral roles as a keystone species within their range. A land use plan known as the *Bathurst Caribou Range Plan* (BCRP) has been created through the collaboration between 21 different groups, governments, and organizations (Table 1) within the NWT and Nunavut (BRCP, 2019). This plan comprises an area within the traditional range of the Bathurst herd according to indigenous traditional knowledge and is to be managed with the herd's protection in mind. For the purposes of this study, it was decided to use the official area of management related to the Bathurst herd as the central area of study (Figure 1).

Table 1*: List of governments, organizations and groups involved in the creation of the Bathurst Caribou Range Plan and determining the official area of management applicable to the herd.*

Type	Name
Public Governments and Government Agencies	Government of Nunavut - Environment GNWT[1] - Department of Environment and Natural Resources GNWT - Department of Industry, Tourism and Investment GNWT - Department of Lands Indigenous and Northern Affairs Canada - Nunavut NWT and Nunavut Chamber of Mines - Exploration NWT and Nunavut Chamber of Mines - industry
Indigenous Governments and Organizations	Athabasca Denesų̂łiné Néné Land Corporation Łutsël K'é Dene First Nation Northwest Territories Métis Nation North Slave Métis Alliance Nunavut Tunngavik Incorporated Tłı̨chǫ Government Yellowknives Dene First Nation
Other Management Authorities	Barren-ground Caribou Outfitters Association Canadian Parks and Wilderness Society Kitikmeot Inuit Association Kitikmeot Regional Wildlife Board Kugluktuk Angoniatit Association (Hunters' & Trappers' Organization) NWT Wildlife Federation Wek'èezhìı Renewable Resources Board

[1] Government of Northwest Territories (GNWT)

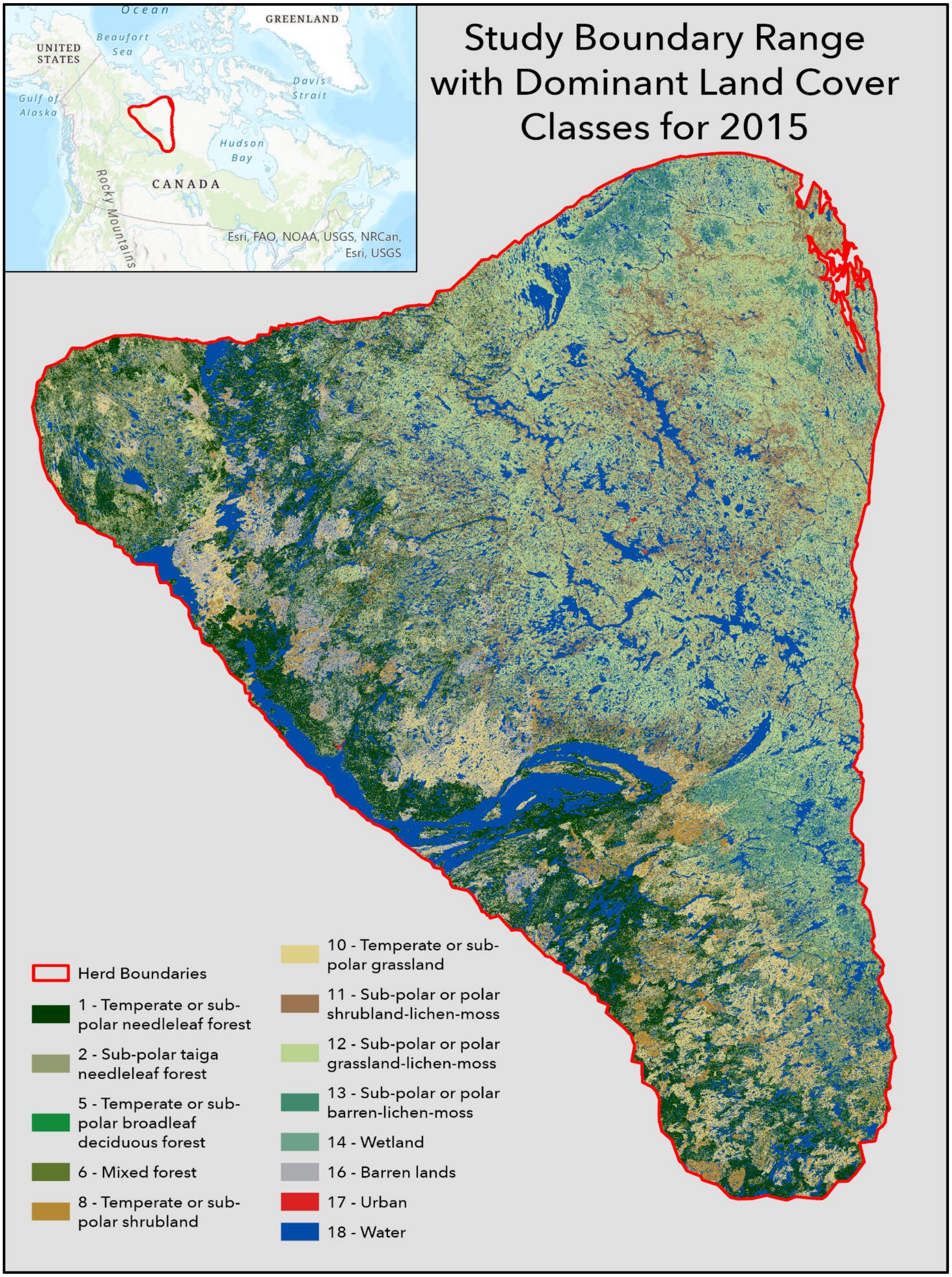

***Figure 1**: Project Boundary and biome classification for MCE Analysis of Bathurst Caribou, as established by the Bathurst Caribou Range Plan (BCRP).*

4. Research Methods

4.1 Compiling Variables Associated with the Migration, Habitat, and Behaviour of Caribou

There are several anthropogenic factors that influence the processes and seasonal movements of the Bathurst caribou herd and many of these variables stem from human-induced land-use practices and anthropogenic activities (Table 2). Additionally, there are numerous environmental factors which influence caribou migration and habitat use. The most important criteria according to literature that were considered in this study are displayed in Figure 2, with additional information on each variable found in Appendix A.

Table 2: *Description of Environmental and Anthropogenic variables considered in this study.*

Variable	Description*	Data Source/Info
Industrial Features	Mining operations throughout the study range have direct and indirect impacts on caribou health and migratory patterns (e.g., dust, noise; Chen et al., 2017). A buffer was created based on the research by Boulanger et al., (2017), where a 38 km zone of influence (ZOI) was established around these features.	Geofabrik, 2018a Geofabrik, 2018b
Urban Features	Urban areas (i.e., settlements, towns, agriculture, airports, roads etc.,), similar to industrial areas, tend to be avoided by Bathurst caribou as permitted by their expansive range (Allen et al., 2019). The same ZOI as *Industrial Features* (38 km) was used as a buffer for this variable due to the dataset used combining urban features with industrial features. The ZOI for roads was determined to be 6 km, which is an average based on the ZOIs of the various road types described by Boulanger et al., (2017; Figure 2).	Geofabrik, 2018a Geofabrik, 2018b
Temperature (*°C*)	Temperature has a large impact on the amount of insect harassment caribou endure during the summer, and directly influences habitat use year-round (Toupin et al., 1996; Witter et al., 2012). Temperature data was collected from a total of 17 weather stations. 16 of these were used to determine summer temperatures, and 14 were used to interpolate winter temperatures (Figure 2).	EC, 2020
Wildfires	Wildfires are capable of reducing food availability and increasing the risk for predation by removing vegetation cover, and depending on the time of the wildfire, the suitability of burned areas for caribou changes (BCAC, 2021). For this reason, recent wildfires were assigned lower suitability scores than older ones.	NRC, 2021

Table 2: *Continued*

Variable	Description*	Data Source/Info
Elevation ***(m)***	Areas of higher elevations are critical for caribou relief from insect harassment due to greater wind speeds (Witter et al., 2012). Elevation data was incorporated in the MCE in a way that makes upland areas most suitable during the summer.	NRC, 2015
Seasonality	Many environmental variables, such as caribou food availability, temperature, and weather, are influenced by seasonal variability within the Bathurst herds range (Joly et al., 2021). Dates for each season according to Virgil et al., (2017) were accounted for when deriving criterion datasets and in the creation of HSI's.	**Summer:** 15 Jun - 31 Aug **Winter:** 1 Nov - 30 Apr
Biome & NDVI	High quality forage (e.g., mosses and lichen) is influential for migration and habitat preferences of caribou (Joly et al., 2021, Webber et al., 2022). The availability of this forage to the Bathurst herd is dependent on both its overall density and the type of biome it can be found in.	NRC, 2019
Water Bodies	Since caribou habitat is not directly located in water or directly on ice, these areas were considered a constraint in this study.	NRC, 2019
Snow Depth ***(cm)***	The depth of snow has direct impacts on the ability of caribou to forage and navigate (Tyler, 2010). Daily values corresponding to the winter season were used to derive a single mean value for the entire season. Regions with deeper snow were assigned lower suitability scores during the winter season.	Brown & Brasnett, 2010
Wind Speed (*km/h*)	Insect harassment on caribou populations is dependent on summer wind speeds, with speeds over 20 km/h showing a reduction in harassment (Joly et al., 2021, Toupin et al., 1996). Wind speed data was derived from the same weather stations as used for temperature and a gradient map was created that shows higher suitability for greater wind speed (i.e., >20 km).	EC, 2020
In-Situ Data	In-situ collar data from the herd is needed to compare the estimated range to the actual range of the herd. Interpolated collar data was most easily obtainable from the Government of the Northwest Territories in 2015-2016, which is why this year was chosen.	GNWT ENR, 2016

*Detailed descriptions of each variable can be found in Appendix A.

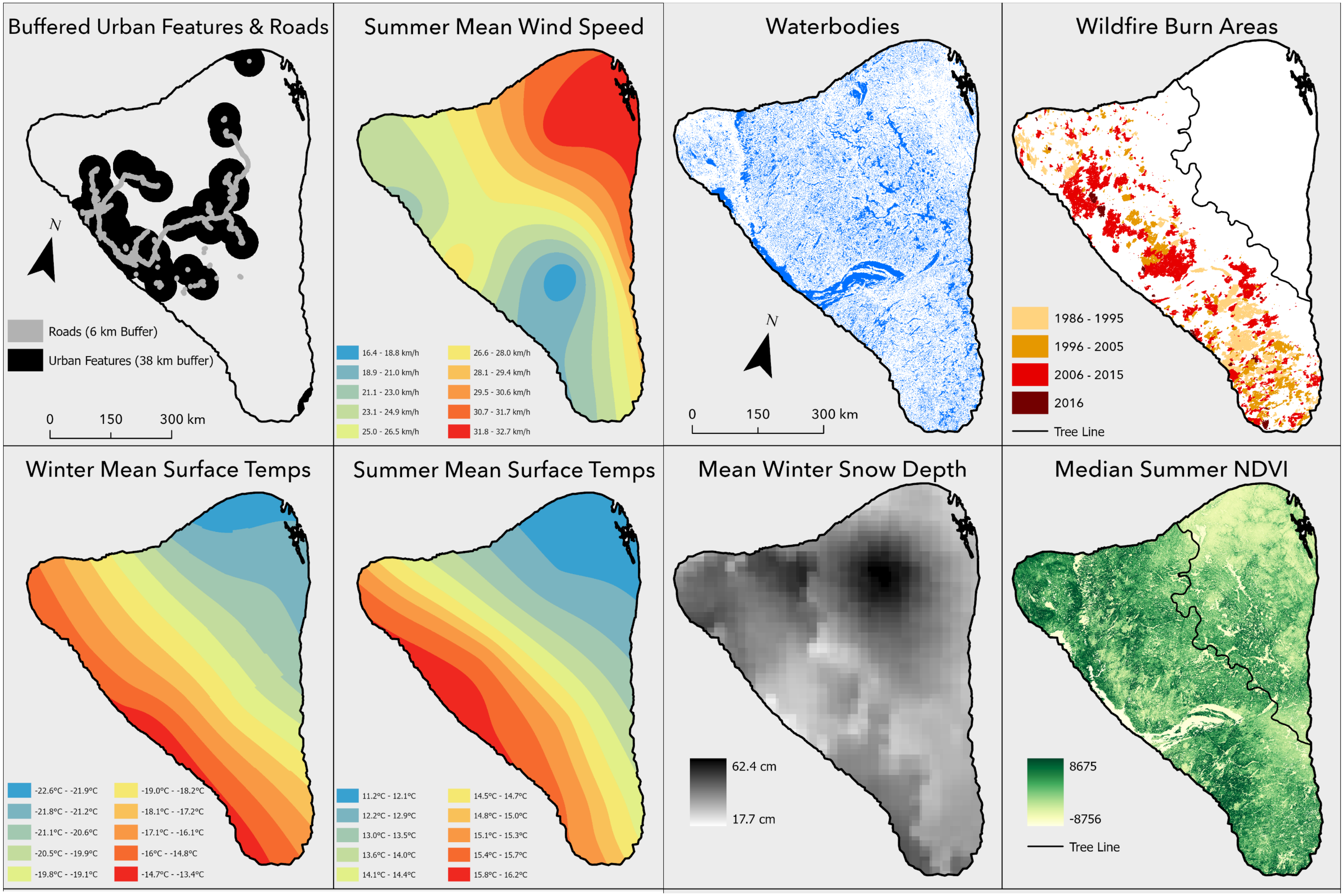

***Figure 2**: Base dataset visualizations for key variables before standardization and rasterization.*

4.2 Raster Standardization

The criteria used within the MCE model were reclassified into standardized cost rasters on a scale from 1 - 5 (Figure 3), with greater values being indicative of higher suitability for the herd (Table 3). The method used for creating the cost rasters varied depending on the dataset. Wind speed and summer/winter temperature cost rasters were created by editing the original data into 5 classes in the symbology tool in ArcGIS and using a geometric interval, which was the method used in the source data. Biomes were standardized with the reclassify tool in relation to Webber et al., (2022) to define the most and least suitable habitat based on their caribou diet study of 30 papers on. Wildfires were reclassified based on the number of years since the last recorded forest fire. NDVI, DEM and snowpack were standardized by classifying the raster to 5 classes using Jenks natural breaks. Human features were classified using a Euclidean distance of 6 km for roads and 38 km for other human features. These were then classified into four groups using equal intervals; the most suitable area for both factors was given to the rest of the raster. The sole constraint utilized in this study is associated with the presence of water bodies. This constraint was only considered in the summer with values of 1 representative of areas with water (unsuitable) and 0 representing areas without water (suitable).

***Table 3**: A summary of the parameter classification scheme incorporated in the MCE model.*

Criteria/Constraint	Classification	Ranking	Abbreviation	Label
Biomes	High forage quality is better	1 - 5	Biome	W_B
NDVI	Denser is better	1 - 5	NDVI	W_N
Mean Snowpack Depth	Less is better (winter)	1 - 5	Snow	W_{SP}
Mean Seasonal Temperature	Lower is better (summer) Higher is better (winter)	1 - 5	Temp	W_T
Mean Wind Speed	Higher is better (summer)	1 - 5	Wind	W_W
Elevation	Higher is better	1 - 5	Elevation	W_E
Distance from Urban & Industrial Features	Further is better	1 - 5	UrbanDist	W_{DU}
Distance from Roads	Further is better	1 - 5	RoadDist	W_{DR}
Areas burnt by Wildfires	Older is better	1 - 5 (5 = unaffected)	Fire	W_F
Constraint: Water	Cannot be water	Water = 1 Non-Water = 0	Water	

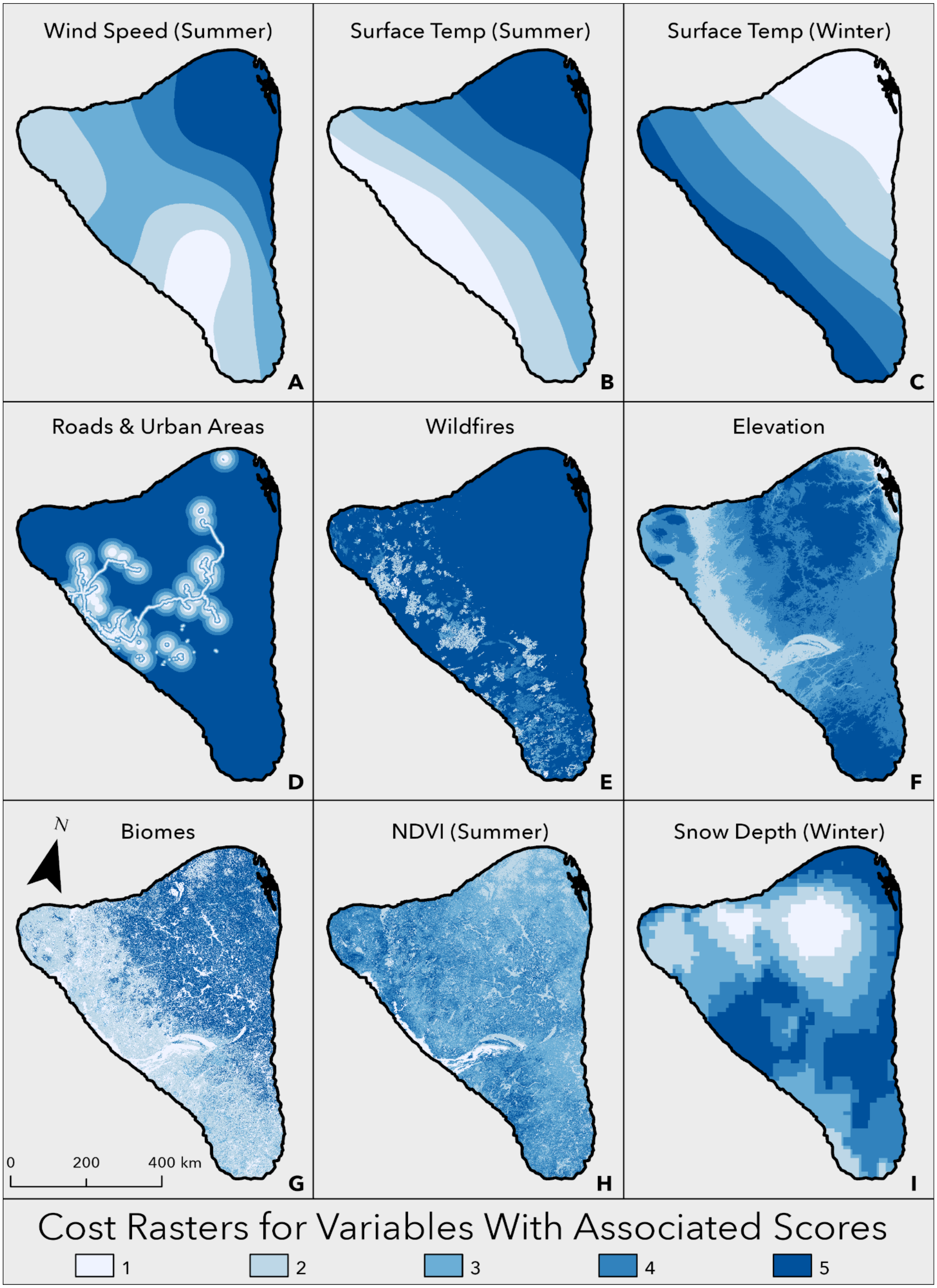

***Figure 3**: MCE cost rasters of the chosen primary factors (water bodies constraint not shown), derived from base datasets.*

4.3 Developing a GIS Model that can be Applied for Summer and Winter Seasons

For the purpose of this project, an MCE model was chosen over other models for several reasons. MCE models can effectively and easily incorporate multiple criteria, such as land cover, topography, climate, and other environmental variables, into the analysis, which allows for a more comprehensive evaluation of habitat suitability and can help to identify areas that are most suitable for Bathurst caribou. Furthermore, it allows for the relative importance of each variable to be determined in relation to each other in a spatial context. Our MCE model is flexible and does not require assumptions about variable weights, as they are determined using a machine learning script rather than being arbitrarily chosen. However, there are assumptions which were made when choosing the classifications of input datasets as seen in table 3. The goal of using machine learning and MCE together is to minimize assumptions about the significance of the criteria used, which is important as the relationships between habitat suitability and the numerous environmental, climatic, and anthropogenic factors are complex. This complexity ultimately adds to the difficulty of modeling using traditional statistical approaches such as linear regression, especially in a spatial context.

Equation 1*: Derived Habitat Suitability MCE Equation for Summer*

$$\textbf{Habitat Suitability Index} = [(\text{Constraint}_{Water}) * (W_B * \text{Criteria}_{Biome}) + (W_N * \text{Criteria}_{NDVI}) + (W_T * \text{Criteria}_{Temp}) + (W_w * \text{Criteria}_{Wind}) + (W_E * \text{Criteria}_{Elevation}) + (W_{DU} * \text{Criteria}_{UrbanDist}) + (W_{DR} * \text{Criteria}_{RoadDist}) + (W_F * \text{Criteria}_{Fire})]$$

Equation 2*: Derived Habitat Suitability MCE Equation for Winter*

$$\textbf{Habitat Suitability Index} = [(\text{Constraint}_{Water}) *(W_B * \text{Criteria}_{Biome}) + (W_{SP} * \text{Criteria}_{Snow}) + (W_T * \text{Criteria}_{Temp}) + (W_E * \text{Criteria}_{Elevation}) + (W_{DU} * \text{Criteria}_{UrbanDist}) + (W_{DR} * \text{Criteria}_{RoadDist}) + (W_F * \text{Criteria}_{Fire})]$$

4.3 Modifying Model Parameters to Best Align with In-Situ Data

As mentioned earlier, most MCEs rely on weights that are subjectively chosen based on generalized input from literature and expert opinions. This is less than ideal because in the event that weights are assigned improperly, the resulting analyses may be biased or misleading. Choosing optimal weights for a study of this size and scope can be quite difficult, given the massive extent of our study area and the significant influence of seasonality on caribou movement. This issue was resolved by incorporating a simple machine learning script to generate optimal variable weights within the MCE for the summer and winter seasons.

As a result of efforts made by conservation groups and government institutions through the BCAC, we had the added benefit of having access to historic seasonal herd location data, which provides a generalized representation of herd range based on the radio-collaring of select individuals within the herd (Figure 4). In herd species, such as barren-ground caribou, only a small proportion of individuals need to be collared to represent the entirety of the herd, as they tend to remain in large groups. The government of the Northwest Territories has therefore created estimated maximum seasonal range maps of the Bathurst herd based on the GPS collar data for years. The summer core and late summer ranges were combined to make the overall summer habitat use raster.

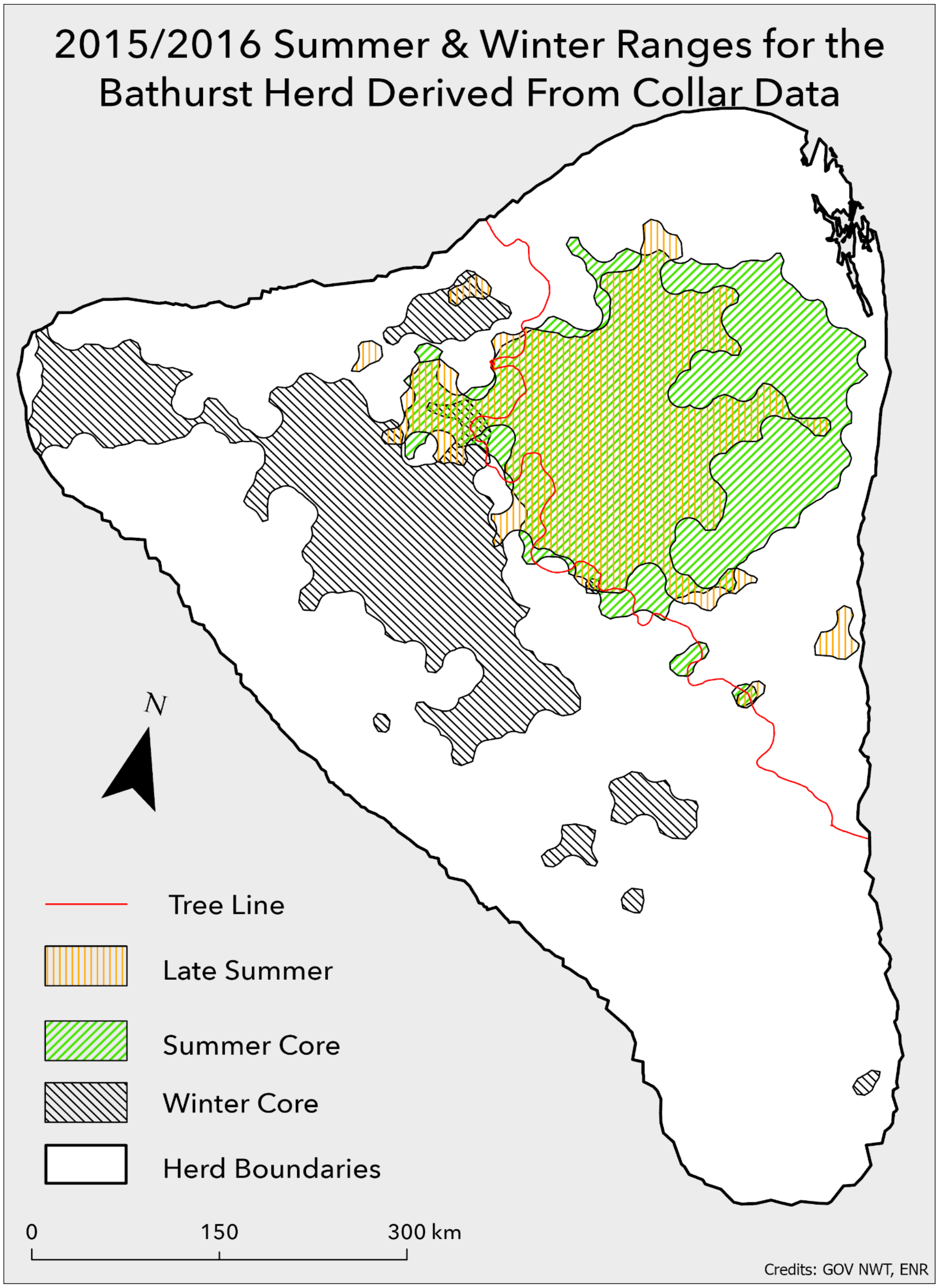

Figure 4*: Collar data for Bathurst Caribou within the study area for summer/winter seasons.*

These range maps have enabled validation of our MCE and have permitted us to computationally generate the best possible criteria weights through an iterative "machine learning" script. This script assigns random variable weights for each criterion and generates an MCE using these weights multiplied by the factors outlined in Figure 3. Following this, it validates the results using a binary suitability threshold of the MCE by overlaying it with rasterized radio-collar data for the summer and winter seasons, respectively, to produce a measurement of overall-accuracy for the generated weights. The script would then save the values for the criteria weights and overall-accuracy, only if the resulting overall-accuracy was higher than the overall-accuracy for previous iterations.

In total, two looping scripts were created: one for the summer season and one for the winter season. The only difference between the two being the inclusion or exclusion of season-specific criteria discussed earlier (shown in Table 3). The scripts were written using Python 3.10, as well as the ArcPy and NumPy packages. For each iteration, individual parameter weights were generated using the random() module present in the NumPy library. Randomly generated weights for the criteria were normalized and corrected in order to cumulatively sum to 1. Next, a study range wide MCE was produced using the generated weights and the previously created MCE input factors. The resultant MCE map denoting suitability was converted into a binary map to directly compare and validate the resulting weights and suitability with the in-situ data (Figure 4). As such, a suitability threshold of 80% of the maximum possible suitability was established, and deemed most appropriate since our initial cost rasters were ranked on a scale of 5. This meant that an overall suitability of 4/5 or greater would be considered suitable caribou habitat. This 80% suitability threshold was used to generate a binary thresholded suitability raster from the MCE. The resultant binary suitability raster was finally directly compared against the respective binary summer or winter in-situ data raster, on a cell-by-cell basis to derive a measure of overall accuracy based on where the binary rasters did or did not overlap. Overall accuracy was calculated by dividing the number of raster cells in agreement within each iteration by the total number of cells within the study area. If the overall accuracy produced was higher than the variable storing the previous highest overall accuracy, then all of the criteria weights would be saved to their own individual variables and the overall accuracy variable would then be overwritten with the new highest overall accuracy therefore only saving the single best one.

The scripts were initially run for 100 iterations for testing, then again for 1000 iterations to ultimately produce a final output of the optimal model weights and the best overall accuracy. In addition, each time a new best overall suitability was found, new maps for overall suitability, threshold and agreement were also generated. The GIFs shown in Appendix B provide a visualization of the improvement in overall accuracy (agreement) with each newly generated set of most optimal weights over 1000 iterations.

5. Results

It was determined that based on the season, weights differed quite extensively. During the summer, the best overall accuracy after 1000 iterations was 84.18% (Table 4). This was primarily associated with mean wind speed (22.96%), NDVI (22.58%), mean summer temperature (22.13%), and elevation (21.83%; Table 4). Three of these four factors; average wind speed, average temperature and elevation are associated with helping caribou avoid insect harassment to the best of their abilities (Witter et al., 2012). NDVI also accounts for a considerable amount of the predicted suitable area, which is evidence that both a higher density and quality of forage are very important to the range of the herd as well. The biome class (7.00%) had an intermediate influence in the model, this could potentially be due to caribou being generalists and not relying on any one specific tundra biome class for food (Webber et al., 2021).

For the winter outputs, an overall accuracy of 81.97% was determined with biome class (37.64%), mean winter temperature (33.26%) and snowpack depth (15.36%) accounting for 85% of the model weight (Table 4). Caribou tend to spend their winters below the treeline due to the benefits provided by additional warmth and shelter (Dokis-Jansen et al., 2021). This suggests that caribou favor forested areas more than others during the cold months, which may explain the contrasting weight of the biome class factor for the winter season. Additionally, the treeline is also associated with higher temperatures, which corresponds with the higher weight for temperature. Snowpack depth is also an important factor, with lower levels of snow making it easier for caribou to forage for food and traverse the landscape. These results showcase not only the importance of variables on a seasonal basis, but also that there are different variables which need to be considered in different contexts depending on the season for the conservation of the herd. Figures 5 and 6 provide a visualization of these results with the MCE displayed in the left panel, binary threshold (80%) suitability raster in the middle panel, and overall-accuracy in the right panel.

Climate and environmental variables tended to be well represented by the model in reference to literature, with temperature, wind speed, snow depth, NDVI, Elevation and Biome class all being supported when it comes to the importance of these factors on caribou habitat use and migration. However, anthropogenic factors and wildfires were not well represented by the model, each with values less than 3% when literature supports them having a very large effect on habitat use (Table 4).

***Table 4**: Criteria considered in the MCE models and their best weights after 1000 iterations.*

Criteria	**Weight Summer (%)**	**Weight Winter (%)**
Biomes	6.99	37.64
NDVI	22.58	
Snowpack Depth		15.36
Mean Seasonal Temperature	22.13	33.23
Mean Wind Speed	22.96	
Elevation	21.83	9.63
Distance from Urban & Industrial Features	1.86	0.23
Distance From Roads	0.19	2.80
Areas Burnt from Wildfires	1.46	1.11
Overall Accuracy	**84.18%**	**81.97%**

6. Discussion

The importance of weights found within this study can aid in conservation efforts due to the relative significance of each variable compared to one another. The most important climate and environment factors for the summer were determined to be: 1) Wind speed 2) NDVI 3) Temperature and 4) Elevation. This has implications for conservation, as it offers potential grounds for the NWT government and Bathurst Caribou Advisory committee to enact supplementary measures in protecting highlands that the herd routinely uses during the summer. It additionally provides further insights for climate related initiatives across the country, due to the importance of these variables for both the summer and winter seasons.

We found the winter season had the following primary variables: 1) Biome class 2) Temperature and 3) Snowpack. Biome class, being the most important when it comes to winter range, can be attributed to the significance of forests for shelter from snow and wind (EC, 2017). Temperature is an interesting variable within winter for several reasons. Warming temperatures both reduce the southern range of Bathurst caribou in the summer, while expanding habitat in the winter. This can have varying effects on caribou herds across the

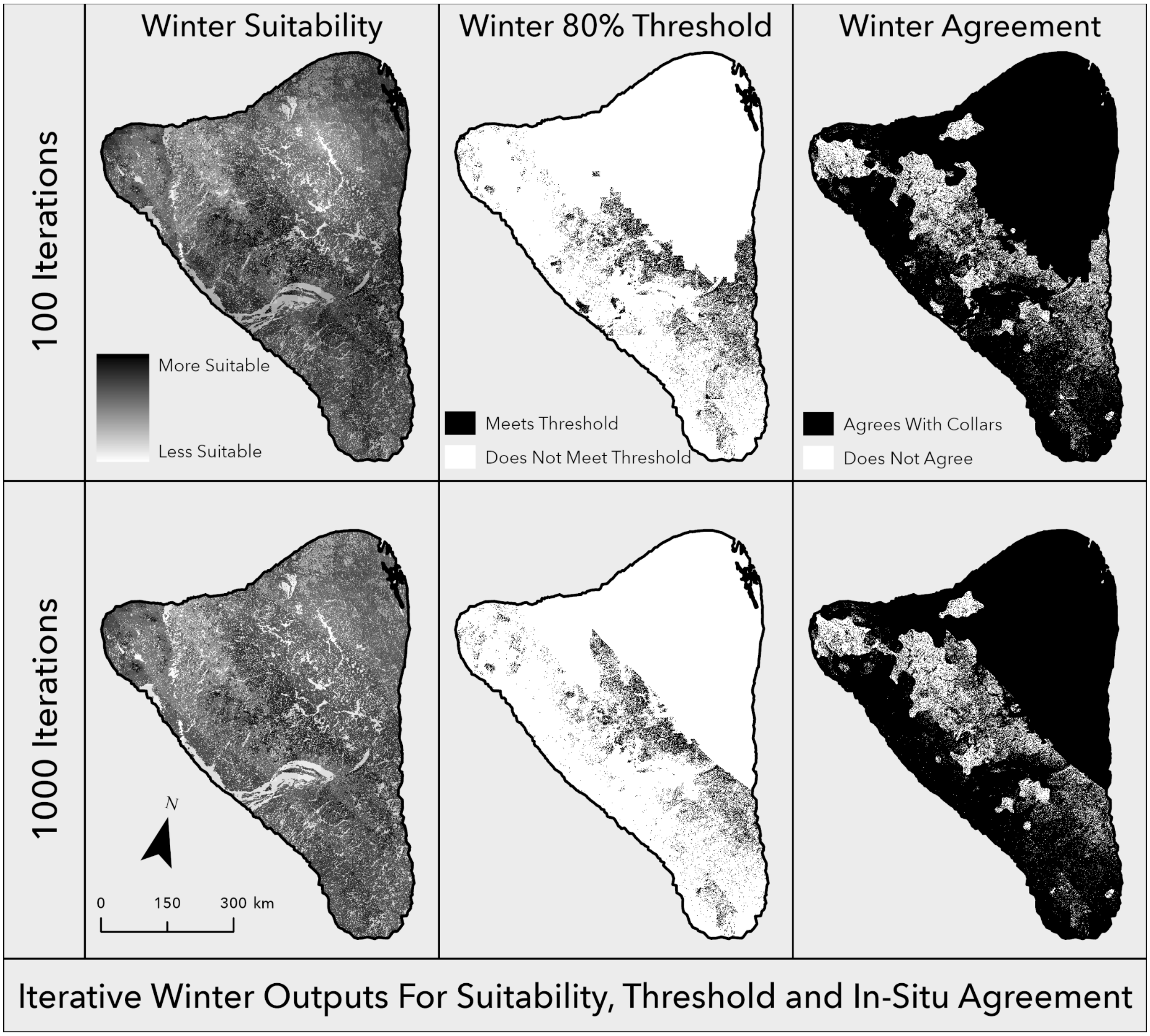

***Figure 5**: Comparison of iterative outputs for overall suitability, threshold and overlap with in-situ collar data for the winter season after 100 and 1000 iterations.*

country based on their proximity to the treeline, as well as how close the treeline is to the Northernmost point of their range. Finally, snowpack was determined to be the third most important factor in winter. Due to the added difficulty of traversal, as well as the increased prevalence of freeze-thaw cycles, layers of ice buildup on snow making it difficult for caribou to forage during the beginning and end of the winter season (Joly et al., 2021). Therefore, based on our model, caribou prefer habitat with an overall lower snowpack depth which can increase ability to forage during the winter months.

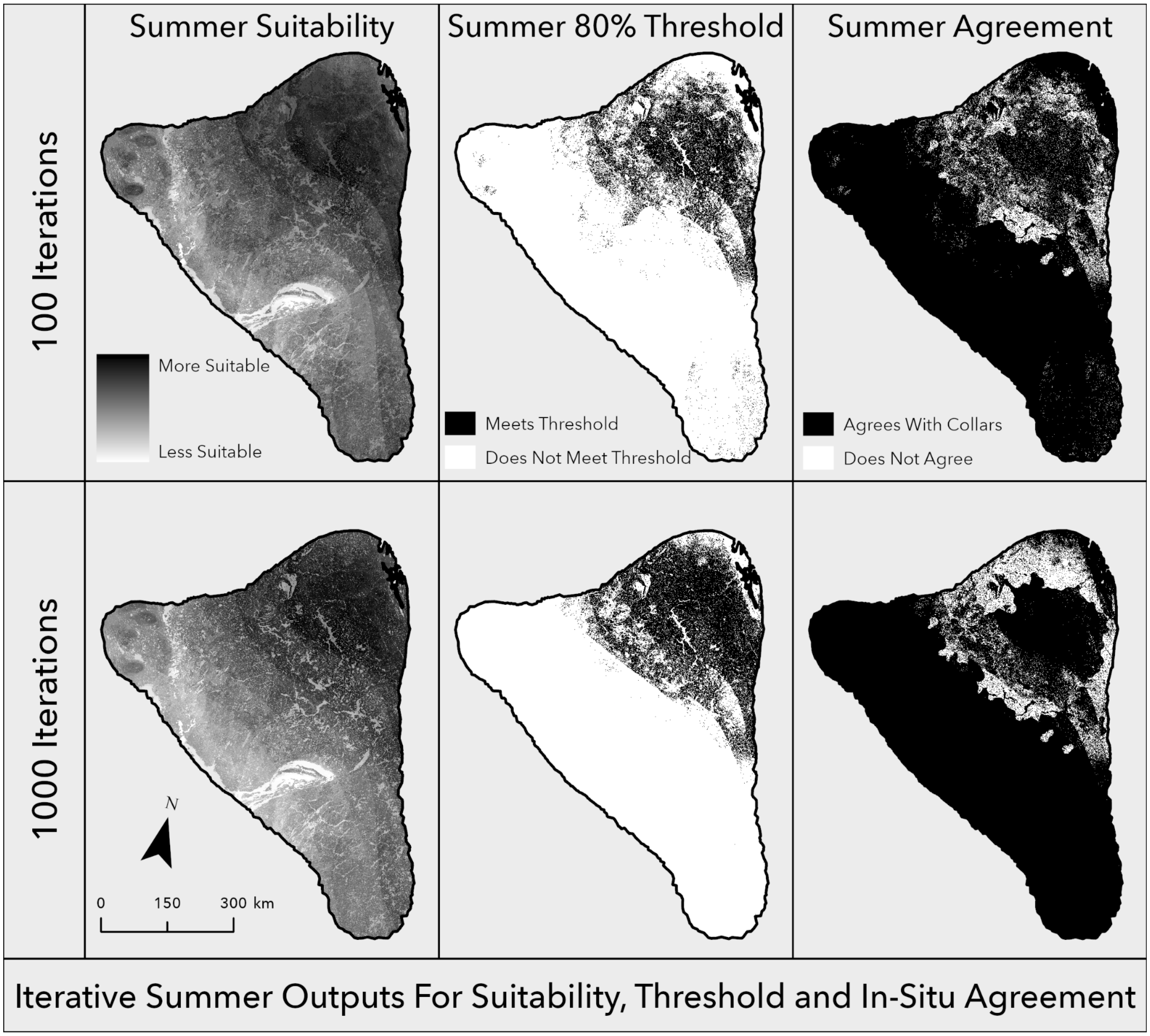

Figure 6*: Comparison of iterative outputs for overall suitability, threshold and overlap with in-situ collar data for the winter season after 100 and 1000 iterations.*

7. Limitations and Flaws

The model utilized in this study, however, contains some limitations. Only 1000 iterations were run for each season due to computational restrictions. This resulted in the summer model, which was run 100 times to test it, having a higher overall accuracy (85.00%) than the 1000 iteration model (84.18%) (Figure 6). Due to the random nature of the model, the chances of getting the most suitable values for each variable within the same model are extremely low, and therefore running more iterations would result in higher chances of getting accurate values. This was however limited by computing power, and 1000 was therefore chosen due to time constraints (i.e., 1000 iterations took about 10 hours to run). With unlimited time and computing power, a much greater number of iterations (e.g., 10,000) would be preferable for each season.

Furthermore, the model is entirely dataset dependent, and depending on the methods used to reclassify data for each season, there may be issues stemming from improperly weighted data. This is most likely true for the example seen in winter, which had very little overlap with the herd area (Figure 5). The areas which were represented as suitable within this model were not cohesive, and these areas were instead primarily peppered throughout the range rather than a unit, as seen in the summer model. The one variable for winter which remained the same as those in summer was the DEM. This was due to a lack of literature surrounding elevation and its effect on the herd in the winter, and finding data which supports the reclassification of this dataset would be needed before altering it. Rather than making any assumptions about this variable, it was left the same. This error was a result of prioritizing the quality of the summer dataset over that of winter, and without supporting evidence, this variable most likely should have been removed from the winter model.

Due to the methods that are used by the NWT government to interpolate the caribou collar data, there is also potential for error. The method they use depicts the range of the herd, by filling in the area within the maximum range recorded by collared individuals. Open pit mines and other areas caribou would need to avoid, such as urban settlements, are located within the area filled in as part of the range. Therefore, any avoidance by caribou within the area is not considered within the dataset. This would immediately nullify the influences of both roads (0.19% summer, 2.80% winter), and urban development (1.86% summer, 0.23% winter) within the model as exhibited by the very low weights (Table 3). If this model were to be utilized again, raw GPS data from caribou would be preferred over the interpolated range maps.

8. Conclusion

With the stress of environmental and anthropogenic factors deteriorating populations of the Bathurst caribou herd, the need for determining prime seasonal habitat for these caribou is of ever-growing concern. Through the use of an MCE and a machine learning script to determine criterion weights, it was found that wind speed, vegetation density (NDVI), temperature, and elevation (summer) were the most influential determining variables for Bathurst caribou in the summer. Similarly, the most influential variables during the winter were discovered to be biome type, temperature, and snow depth. Understanding the significance of these variables on keystone barren-ground caribou provides important insight for conservation agencies and government wildlife legislation to ensure the preservation of not only the Bathurst herd, but neighboring herds as well. It should be noted that findings from this study are based on data available for the summer and winter seasons, respectively, and further analysis should be done to account for the fall and spring seasons to assist in annual conservation and management strategies.

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Appendix A

Detailed Description of variables considered in the MCE

Industrial and Urban Areas/Features

The mining of precious metals (e.g diamonds) within the range of the Bathurst Caribou herd of Northwest Territories has been an ongoing industry since the 1980s (Chen et al., 2017). Inuit traditional knowledge (IEK; Thorpe, 2002) and other traditional knowledge has suggested that although the herd tends to avoid mining operations, they have both direct and indirect impacts on caribou health and migratory patterns (Chen et al., 2017). Chen et al., (2017) discovered that dust from diamond mines and adjacent transport roads accumulates on vegetation (e.g., lichen) up to 1 km away. Furthermore, the urban features that can be found in the Bathurst herd's range vary from areas with human presence, to features that have been created by humans. These include reservoirs, settlements, towns, built-up areas, well sites, agriculture, oil and gas facilities, dams, and unknown features. Additionally, linear features include cutblocks, roads, railways, powerlines, seismic exploration lines, and pipelines. It is outlined in a study by Allen et al., (2014) that red deer, like the barren-ground caribou, avoid human infrastructure in their movements due to their expansive range. By having this large range, these caribou tend to avoid urban areas, as they are considered threatening (Allen et al., 2014). A buffer zone of approximately 38 km was applied (Figure 2) around all industrial and urban features, as this corresponds to the zone of influence (ZOI) footprint established to be significant by existing studies (Boulanger et al., 2017). From this, a cost raster with progressively increasing suitability scores up to the threshold was incorporated into the MCE (Figure 3D). The effect of roads (both permanent and seasonal) as well as known hunting & snowmobile trails were included in the model as well, with a 6 km ZOI applied as an average of the values provided for the effects of various road types described by Boulanger et al., (Figure 2). Industrial sites, urban features, and road datasets were all obtained through OpenStreetmap using the Geofabrik website for a batch download of all features within the NWT and Nunavut.

Temperature (°C)

Temperature has a large impact on the amount of insect harassment caribou endure, and directly influences habitat use (Toupin et al., 1996; Witter et al., 2012). During the summer months, insects such as mosquitos, deer flies and black flies are abundant. In response, caribou have shown a preference for cooler, higher elevation upland areas with higher overall wind speeds where insects are often found to be more tolerable (Toupin et al., 1996; Witter et al., 2012). Preferred habitat also varied during insect harassment with a preference to utilizing snow patches (Toupin et al., 1996), and upland areas (Witter et al., 2012) over other biome classes. Values below 10℃ will be the most suitable, and values above 13℃ the least (Toupin et al., 1996). Temperature data was collected from a total of seventeen weather stations. Sixteen of these were used to determine summer temperatures, and 14 were used to interpolate winter temperatures. This was done due to data limitations in the recording of temperatures as specific weather stations on a seasonal basis. These weather stations were originally selected to be within 100km of the study area, however supplementary stations were selected to interpolate the area in its entirety once limitations of stations became apparent. Interpolation of this data was done using Empirical Bayesian Kriging within the geostatistics tool with edge smoothing values of 0.2, This allowed for temperature gradient maps to be created for both summer and winter (Figure 3C).

Elevation (m)

As mentioned in the Witter et al., paper, upland areas are important for caribou relief from insect harassment due to higher wind speeds. Elevation data was derived from the Canadian Digital Elevation Model (CDEM) and incorporated in a way that makes upland areas most suitable during warm summers (Figure 3F).

Wind Speed (km/h)

Studies have shown that wind speed is directly correlated with insect harassment (Joly et al., 2021, Toupin et al., 1996). Wind speeds above 20 km/h have been found to reduce insect harassment (Joly et al., 2021, Toupin et al., 1996). Areas with higher average wind speeds (>=20 km/h) were considered more suitable than places with lower (Figure 3A). This only applies for the summer season. Wind speed data was also recorded at the same weather stations used for temperature; 15 stations had wind speed data for the date range necessary for the study. A gradient map was also created through interpolating these values using Empirical Bayesian Kriging within the geostatistics wizard of ArcGIS (Figure 2).

Seasonality

Seasonality in Canada's North is extremely variable, with temperature, food availability and precipitation being some of the environmental variables affected (Joly et al., 2021). Seasonality was directly accounted for in this project through the creation of separate MCE's for the summer and winter seasons, respectively. Dates of seasons, as outlined in literature (Virgil et al., 2017):

Spring: 1 May - 14 June

Summer/Post Calving: 15 June - 31 August

Autumn: 1 September - 31 October

Winter: 1 November - 30 April

Water bodies

Frozen water bodies in winter can act as efficient migration routes (Leblond *et al,* 2016), with an increase as much as 28% distance traveled per day. Caribou however, cannot live in water or on ice for long periods of time and it is therefore considered a constraint (Figure 2).

Snowpack depth (m)

Extremely deep snow can impede foraging ability for caribou in winter (Tyler, 2010), therefore higher average values of snow depth were less suitable than lower values. Snowpack data was obtained from the Canadian Meteorological Centre (CMC) Daily Snow Depth Analysis dataset at a resolution of 24 km. Daily values corresponding to the winter season from November 1, 2015 - April 30, 2016 were used to derive a single mean value for the entire season. Daily values were downscaled to 150m resolution using Nearest Neighbour (NN) interpolation. Deeper snow was considered to be an obstacle to navigation for caribou, and prescribed lower suitability scores. Areas with shallower snow were thus considered more suitable (Figure 3I).

Biome and NDVI

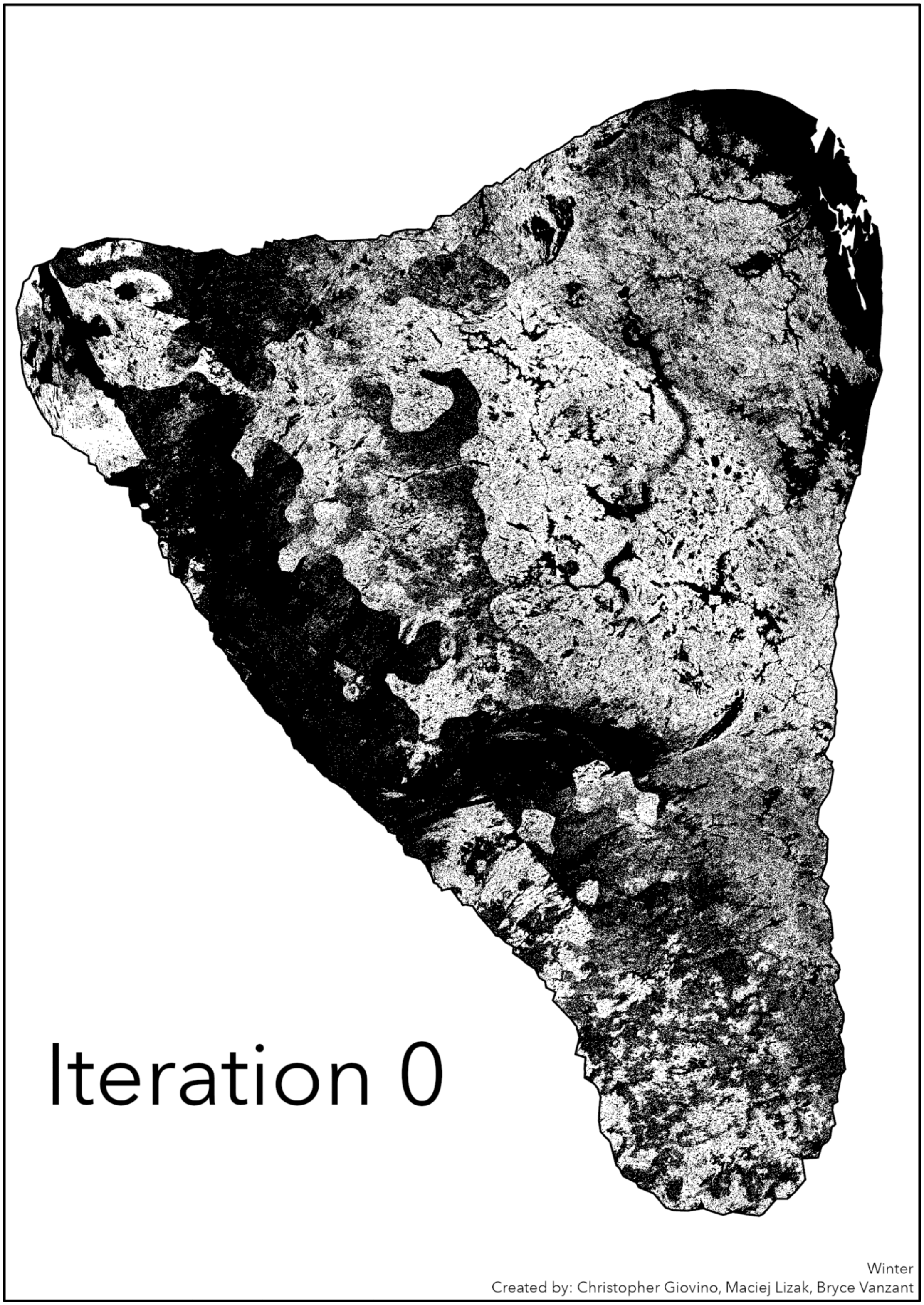
The pursuit of high quality forage influences caribou migration immensely (Joly et al., 2021, Webber et al., 2022), and the proportion of nine plant groups within the caribou diet varies according to season (Webber et al., 2022). Additionally, the availability of forage for Bathurst caribou is both biome- and density-dependent. Using this dietary data, the most suitable habitat for caribou will be areas made from both biome location (Figure 1) and a Normalized Difference Vegetation Index (NDVI) (Figure 2). Biome data was derived from the official NRC Land Cover of Canada Dataset at a scale of 30m. Class data was upscaled to the study resolution of 150m utilizing NN resampling. The NDVI dataset was obtained from the Google Earth Engine, with code provided to us by DeVries, Mardian, and Wang. It is a dataset of the mean NDVI across the study range over the summer months.

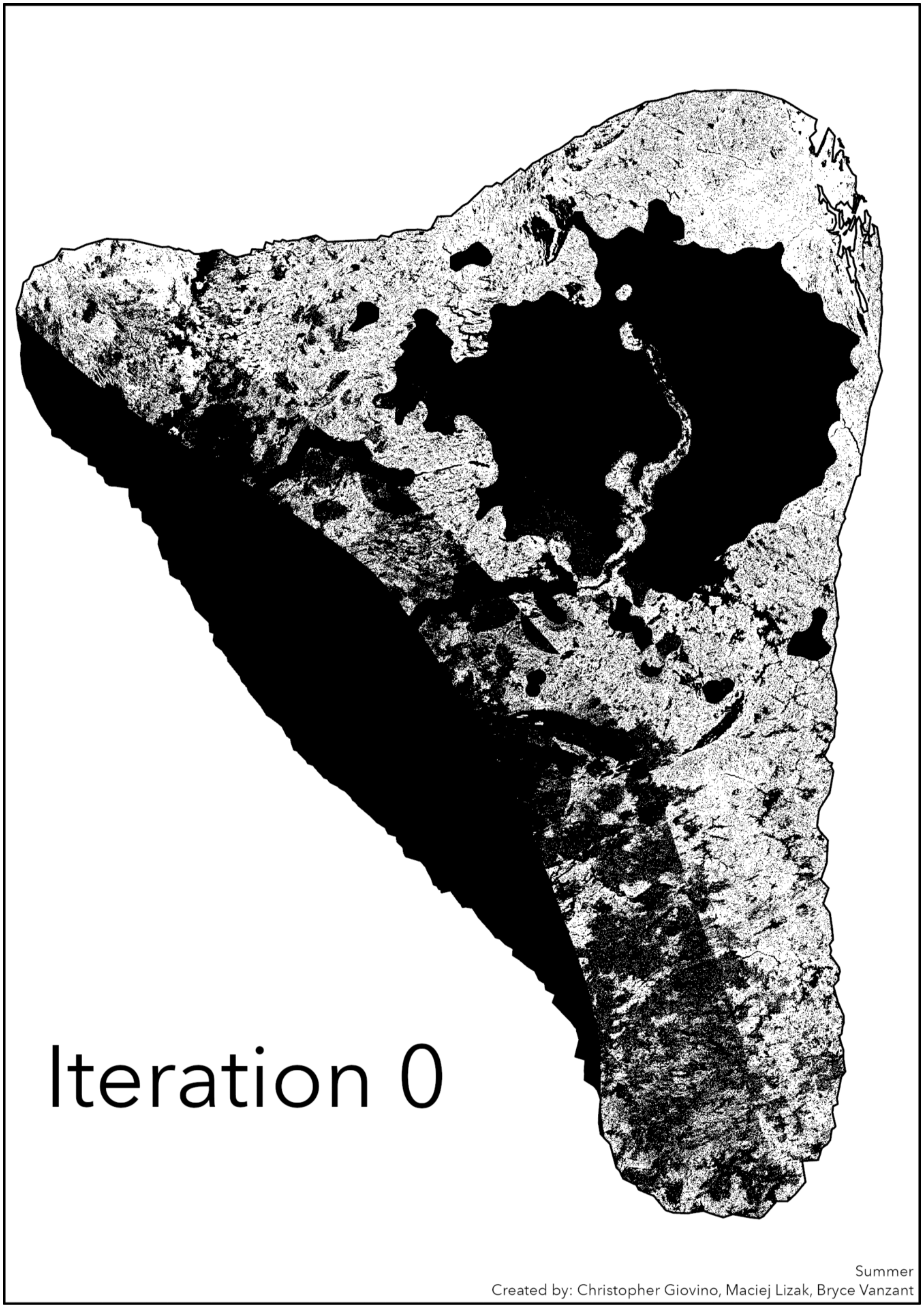
Wildfires

Wildfires can have a significant impact on the habitat ranges of seasonal caribou. They can destroy or alter the vegetation composition and structure, reducing food availability, and increasing predation risks (BCAC, 2021). Given that mosses and lichen are the main sources of food for Bathurst Caribou, and that lichen coverage takes about 40-50 years to recover post-fire, areas burned more recently are considered less suitable for caribou than historic burns (BCAC, 2021). Yearly wildfire data was obtained from the Canadian Wildland Fire Information System for all years from 1986-2016 (Figure 2). Data was incorporated into the cost raster by assigning the lowest suitability scores to more recent wildfires, with suitability values increasing with the age of the burn (Figure 2). Unburned lands were assigned the maximum score of 5.

Appendix B

Time lapse of best consecutive iterative agreement outputs (out of 1000) for the winter and summer seasons (see attached files)




Iteration 0
Summer
Created by: Christopher Giovino, Maciej Lizak, Bryce Vanzant