

**Identifying low-return areas for caribou habitat protection under future  
climates in Alberta, Canada.**

by

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## Abstract

Lichen availability is a key determinant of winter habitat suitability for woodland caribou. Because lichens are sensitive to climate, ongoing and future climatic change may constrain where lichen-rich forests can persist, regardless of conservation or restoration effort. This thesis models lichen habitat under historical and projected climates and uses those projections to assess the long-term viability of caribou winter forage habitat. The aim is to identify where habitat protection and restoration are most likely to remain effective, and where restrictions on forestry and other development may deliver limited long-term conservation gains.

Percent lichen cover from 1,532 Alberta Biodiversity Monitoring Institute sites with 277,264 survey plots was modeled using the RandomForest ensemble classifier and projected across five 30-year climate periods. These include two historical climate normals (1971–2000 and 1991–2020), representing baseline and already observed climate change; a present-day period based on ensemble projections for 2011–2030 under SSP2–4.5; and projected mid-century (2041–2070) and late-century (2071–2100) climates under the same scenario. The most influential predictors of lichen abundance were May–September precipitation, precipitation as snow, mean annual temperature, and climatic moisture deficit, indicating that lichen habitat potential is governed by moisture balance interacting with warming, rather than temperature alone.

Projected suitability maps show a directional declines in high-value lichen habitat both for historically observed and projected climate change. From the baseline period 1971–2000 to a recent climate normal average 1991–2020, habitat suitability declined by 9%. By 2011–2030 (the best current climate representation) the decline was 23%, and by mid and late century the decline was predicted to be 34 and 40% respectively, across Alberta’s eleven caribou ranges. Although all ranges decline, Bistcho Lake, Upper Smoky, and Caribou Mountains retain relatively higher suitability by late century compared with other regions. In contrast, Cold Lake, Wandering River, and Slave Lake exhibit the lowest projected suitability under future climate conditions.

Summaries by active Forest Management Areas (FMAs) indicate an even more pronounced downward trend, with average suitability declining by up to 60% from historical to late-century periods. No FMA retains high suitability under projected climates. Millar Western Forest Products, Vanderwell Contractors, and Weyerhaeuser Edson fall among the lowest late-century values and exhibit substantial proportional declines. These patterns indicate a broad contraction of climatic capacity to support lichen habitat across managed forest tenures.

These results identify climatically constrained landscapes where lichen habitat is unlikely to be sustained or recovered over the long term. In such low-return areas, strict forestry constraints intended to protect caribou forage are less likely to deliver durable ecological gains. The findings support a climate-informed prioritization approach that concentrates conservation and restoration efforts in areas that retain comparatively higher late-century suitability, while allowing greater management flexibility in persistently low-suitability landscapes. Such an approach recognizes that climatic limits reduce the potential for full recovery in some regions and may help reduce conflict between caribou conservation objectives and forest management under continued climate change.

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## 1. Introduction

Woodland caribou (*Rangifer tarandus caribou*) are the subject of some of Alberta's most intensive conservation planning, but most herds continue to decline (Government of Alberta, 2017; Wilson, 2024). Under Canada's *Species at Risk Act* (SARA), boreal caribou ranges are meant to retain at least 65 percent undisturbed habitat to sustain self-reproducing populations (Environment and Climate Change Canada [ECCC], 2018). Alberta reaffirmed this standard in the *2020 Canada–Alberta Section 11 Agreement*, which calls for sub-regional range planning, habitat restoration, and regular progress reporting (Government of Alberta, 2020). In practice, however, many herds inhabit landscapes where disturbance approach 80 percent, largely due to forestry and energy development. Much of this activity occurs within Forest Management Areas (FMAs), which define the spatial extent of commercial forestry operations across Alberta (Alberta Environment and Parks, 2022b). The pace of new industrial activity continues to surpass restoration, revealing a widening gap between policy ambition and ecological outcomes (Environment Canada, 2012; Yemshanov et al., 2025).

To reverse these trends, three main policy options have been proposed. The first is large-scale habitat protection, involving moratoria on new industrial development to preserve intact forest blocks. The second is strict enforcement of disturbance thresholds, which would limit new access for resource extraction until ranges meet or maintain the 65 percent target. A third approach emphasizes habitat restoration, including recovery of legacy industrial footprints and forest structure. While each approach is grounded in ecological science, they can produce significant social and economic tension. Protecting large intact forests would yield the strongest ecological benefits but restrict access to timber and energy resources, raising concerns among industry and northern municipalities. Enforcing strict disturbance limits could accelerate recovery but also slow industrial output and reduce revenues. Restoration focused approaches are often viewed as more socially acceptable, but their effectiveness depends on long recovery timeframes and favourable environmental conditions.

The debate over caribou recovery also reflects social and political divisions. Indigenous governments, whose communities rely on caribou for food, ceremony, and cultural identity, view strong habitat protection as essential to their treaty rights. Conservation organizations share this

position, warning that delays will make recovery unlikely. Forestry and energy sectors emphasize employment and regional economic stability, advocating more flexible approaches. Provincial planners often seek compromise through incremental restoration and adaptive management, but these measures have not produced measurable improvements in herd outcomes (ECCC, 2024; David Suzuki Foundation et al., 2025). As a result, conflicts between ecological goals and economic dependence remain unresolved.

Climate change further complicates these efforts. Alberta has warmed by approximately 0.27 °C per decade since 1950, with winter temperatures rising by more than 4 °C and wildfire frequency and size increasing markedly (Alberta Environment and Protected Areas, 2025; Palm et al., 2022). These changes threaten the forest conditions that support terrestrial lichens, the caribou's primary winter forage. Increased drought and more frequent wildfires shorten the disturbance intervals needed for lichen regrowth (Coxson & Marsh, 2001; Joly et al., 2003; Morneau & Payette, 1989; Palm et al., 2022), reducing undisturbed habitat and suitable forage. Under continued warming, some landscapes may no longer support the climatic conditions required for sustained lichen recovery, even where conservation and restoration efforts are applied.

Continued conservation and recovery investments in these areas will likely have limited ecological benefits. Treating all habitat as equally recoverable risks directing resources toward locations unlikely to support long-term persistence. A more targeted strategy is therefore required. This research proposes a spatially differentiated conservation approach that prioritizes protection and restoration in regions projected to retain lichen habitat across historical and future climate periods, where management is most likely to yield durable ecological benefits. Areas projected to lose suitability through the 2050s and 2080s could instead accommodate a greater share of forestry and energy activity at lower ecological cost, reducing conflict between conservation and development. By identifying where habitat stability is most likely, this study supports land-use planning that aligns ecological effectiveness with practical economic realities in a warming boreal landscape.

## 1.1. Research objectives

This study aims to identify regions likely to lose long-term lichen suitability, and those expected to remain resilient. My goal is to help direct resources effectively for long-term conservation of caribou habitat, while also recommending where industrial activity should be allowed because long-term maintenance of lichen habitat, or recovery of lichen habitat is improbable due to climate change. To address this challenge, this thesis uses ecological inventory and climate datasets to identify the environmental factors that shape lichen abundance, project habitat suitability under mid-century climate change scenarios, and evaluate their implications for caribou range planning. Specifically, the objectives are to:

1. Model current and future lichen habitat distribution across Alberta using ecological and climate data for five 30-year climate periods. These include two historical climate normals (1971–2000 and 1991–2020), representing baseline and already observed climate change; a present-day period based on ensemble projections for 2011–2030 under SSP2–4.5; and projected mid-century (2041–2070) and late-century (2071–2100) climates under the same scenario. These periods are also referred to as the 1980s, 2000s, 2020s, 2050s, and 2080s, respectively.
2. Determine the key climatic predictors that control lichen abundance using RandomForest modeling, a machine-learning approach that builds an ensemble of decision trees to capture nonlinear relationships and interactions among predictors while providing robust measures of variable importance.
3. Assess differences in projected lichen habitat suitability among caribou sub-regional boundaries and FMAs to locate areas that maintain suitable climatic conditions for lichen under climate change, where conservation or restoration efforts are most likely to be effective.

By providing this spatially explicit guidance, I aim to help balance conservation priorities with economic activity in a way that minimizes conflict and supports the long-term ecological integrity of caribou habitat in Alberta.

## **2. Literature review**

### **2. 1. Threats to woodland caribou**

Woodland caribou (*Rangifer tarandus* ssp. *caribou*) are impacted by industrial development that has transformed large areas of Alberta's boreal forest into fragmented landscapes that have changed food availability and predator-prey dynamics. Seismic exploration has created more than 300,000 km of linear clearings that modify local microclimates and facilitate predator movement, to the detriment of caribou populations (Viliani et al., 2024). The linear features act as efficient travel corridors for wolves, enabling deeper incursions into caribou habitat and increasing encounter rates with herds (DeMars & Boutin, 2018). Clearcuts and access roads also stimulate early successional growth of shrubs and graminoids, attracting moose and deer, which in turn draw their predators into formerly secure caribou ranges (DeMars et al., 2023).

Woodland caribou primarily consume graminoids and other vascular plants over the course of the growing season (Webber et al., 2022), but they rely on ground and arboreal lichens as their principal winter food source. These lichens, especially the ground lichen *Cladonia* spp., provide carbohydrates that sustain caribou in winter (Andreyev, 1977; Silva et al., 2019; Svihus & Holand, 2000). Lichen availability is therefore a primary ecological constraint on caribou survival and distribution. Disturbances such as logging and resource infrastructure development alter canopy cover, soil structure, and litter accumulation in boreal forests, leading to lower ground lichen abundance (Esseen et al., 2022). The cumulative impacts of increased predator access and reduction of forage have been identified as the primary causes of caribou population declines (Environment Canada, 2012).

### **2. 2. Ground and arboreal lichens as food source for caribou**

Woodland caribou rely on both ground and arboreal lichens as their winter food resource (Webber et al., 2022). In winter, areas with shallow snowpacks that caribou can crater through, ground lichens form the bulk of the diet. When snow becomes deep, dense, or wind-packed, caribou turn to arboreal lichens that hang above the snow surface and remain accessible throughout winter. In British Columbia, shallow-snow caribou that feed mainly on ground

lichens are classified as the northern ecotype, whereas populations in deep-snow regions feed primarily on arboreal lichens and are referred to as the mountain ecotype (ECCC, 2014; Heard & Vagt, 1998; Stevenson & Hatler, 1985). Habitat selection in these systems is scale-dependent, governed by snow conditions, forage accessibility, and landscape structure (Apps et al., 2001). In Alberta, caribou that feed primarily on ground lichens, but spend part of their annual cycle in the mountains, where they show forage patterns like British Columbia's northern ecotype but are classified as mountain caribou (Alberta Sustainable Resource Development & Alberta Conservation Association, 2010; ECCC, 2014).

Ground lichen availability is shaped by forest structure, disturbance history, and site conditions. Lichen biomass is highest in mature conifer stands with sparse canopy cover and remains low under dense cover (Silva et al., 2019). Ground lichens grow very slowly, typically only 4 to 5 mm per year (McMullin & Rapai, 2020). Field and remote sensing studies show that ground lichens such as *Cladonia* spp. are most abundant on well drained soils and in stands that have not burned for extended periods (Hillman & Nielsen, 2020; Silva et al., 2019). A model selection from Ontario also shows these patterns, identifying ecosite, time since fire, and canopy closure as the strongest predictors of ground lichen presence and biomass. Sparse conifer ecosites consistently support higher abundance, while dense conifer ecosites are negatively associated with lichen occurrence (Silva et al., 2019).

Arboreal lichens such as *Alectoria* spp. and *Bryoria* spp. grow on tree branches within mature conifer canopies, where shaded and humid conditions support their persistence, and this reliance on stable canopy microclimates makes them vulnerable to harvesting and fragmentation that reduce moisture and increase exposure (Esseen et al., 2022). Lichens in general are highly sensitive to changes in ambient moisture because they do not regulate evapotranspiration like vascular plants. Instead, they are resilient to dehydration. However, their metabolic activity declines when humidity decreases, and thalli lose water (Johansson, 2008). Hydration therefore controls lichen activity, and warming increases vapor-pressure deficit, shortening hydration periods and reducing photosynthetic performance (Stanton et al., 2023).

### **2. 3. Disturbance threats to ground and arboreal lichens**

At the landscape scale, wildfires, seismic lines, and forest harvesting activities create a mosaic of suitable and unsuitable lichen habitats. These disturbances reset forest succession, replacing mature conifer stands with early successional vegetation dominated by mosses and shrubs, with little habitat suitability for ground and arboreal lichens (Skatter et al., 2014; Whitman et al., 2019), so that an abundance of early successional stands limit forage availability for caribou in winter (Dabros et al., 2021; Esseene et al., 2022).

Because lichens grow only a few millimetres per year, recovery after disturbance is exceptionally slow. Research has shown that ground lichen communities can take several decades, typically 30 to 70 years, to regain substantial biomass, and in some sites recovery may extend beyond a century (Greuel et al., 2021). This biological constraint makes restoration efforts difficult and requires long-term, landscape level forestry planning and growth modeling. Such models can incorporate lichen recovery into long-term forest management planning (Miina et al. 2020), although opportunities for empirical validation of such models are limited, and may become increasingly unreliable under continued climate warming that significantly alter lichen habitat over the time frame of many decades.

Interactions between climate change and wildfire frequency makes long-term recovery projections and habitat planning even more complex. When fire intervals shorten, succession can restart before lichens have re-established, effectively removing forage from portions of the landscape entirely (Greuel et al., 2021). This feedback, in which reburning can erase restoration progress, poses a major challenge as warming and drying trends increase ignition risk. Effective planning for caribou habitat resilience therefore depends on integrating restoration design with climate change and fire-risk modeling, recognizing that functional lichen recovery unfolds over many decades or even centuries.

### **2. 4. Climate change threats to ground and arboreal lichens**

Climate change is also a direct threat to lichen habitat, as lichens are sensitive to warming and moisture stress. Because they respond rapidly to changes in moisture, temperature and light exposure, lichens are widely used as indicators of environmental conditions and climatic change

(Esseen et al., 2022). Alberta has warmed by about 0.27 °C per decade since 1950, with especially strong winter increases (Alberta Environment and Protected Areas, 2025). Across western Canada, wildfire frequency, severity, and area burned have risen sharply, shortening the recovery intervals required for lichen regrowth and mature forest reestablishment (Skatter et al., 2014).

Warming and drying directly affect lichen physiology by reducing hydration cycles, shortening photosynthetic periods, and increasing heat stress. Experimental and field measurements from sixty-nine plots monitored over ten years documented measurable lichen biomass declines under moderate warming in northwestern Canada (Errington et al., 2022). Satellite analyses indicate that lichen cover has declined across about 60 percent of boreal landscapes since the 1980s, with regional patterns shaped by a combination of climate warming, vegetation shifts, and disturbance history (He et al., 2024). The climatic and disturbance trends interact to reduce the late-successional habitat that support ground and arboreal lichens, as well as reducing the period where lichens have sufficient moisture and suitable microclimates to grow and persist.

Climate change-driven vegetation shifts further reinforce these effects. Expanding deciduous and mixedwood species alter canopy composition, light penetration, and litter dynamics, creating microclimates less suitable for lichen persistence. Regional modeling shows that warming may cause a contraction of conifer-dominated forest zones and an expansion of temperate deciduous assemblages (Hamann & Wang, 2006). As nonvascular, slow-growing organisms dependent on stable moisture and shade, lichens are poorly equipped to adapt to these transitions. Together, these patterns indicate increasing vulnerability of caribou forage and accelerating fragmentation and reduction of viable caribou winter habitat.

## **2. 5. Research contribution**

The literature review has shown that lichen availability is shaped by climate, disturbance history, and long-term forest structure, and that these factors influence the winter forage base required by woodland caribou. Disturbance slows lichen recovery for decades, and frequent fire, harvesting or industrial activity can repeatedly reset succession, making some areas unlikely to regain functional lichen cover under future conditions. These circumstances highlight the importance of

identifying locations where environmental conditions can support sustained lichen regrowth as the climate warms.

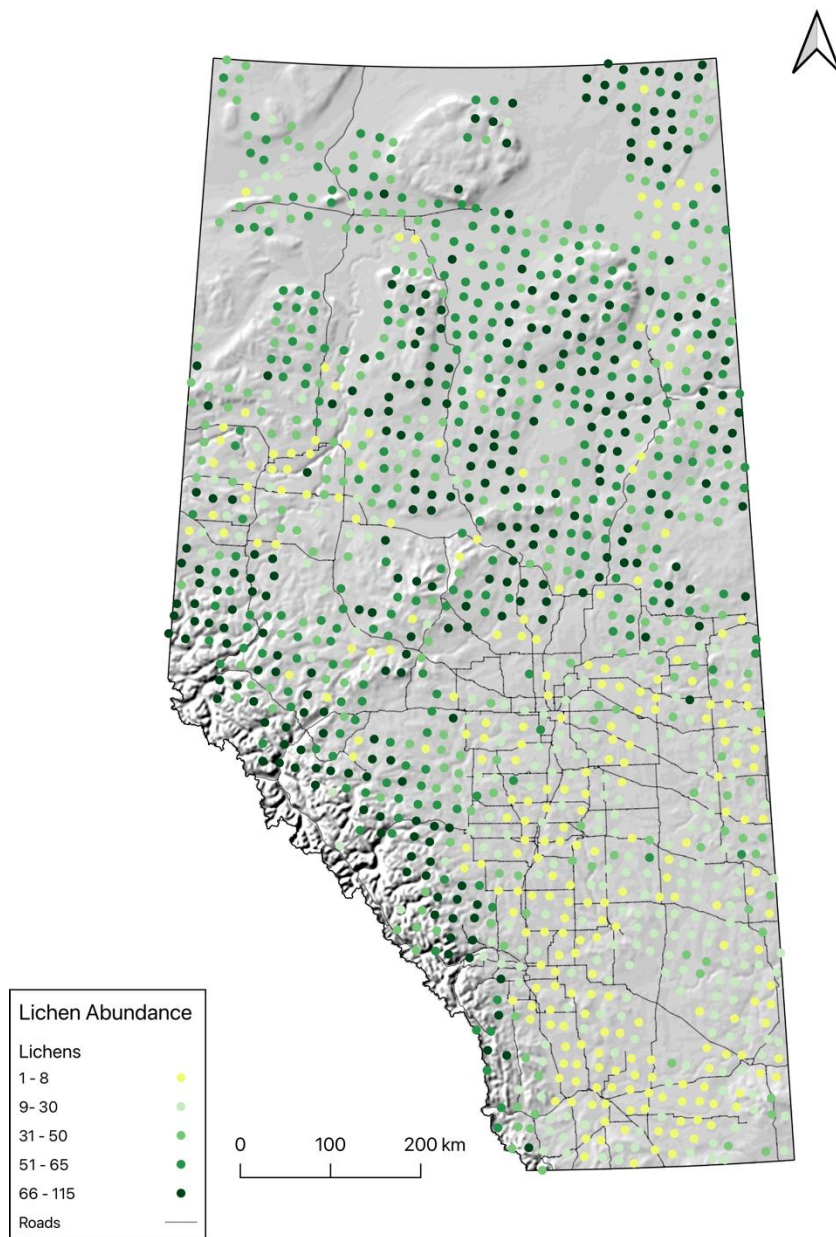
This thesis aims to contribute to answering this question by integrating ecological field observations, environmental predictors, and mid-century climate projections to estimate where lichen habitat is likely to remain suitable across historical and future climate periods. The analysis distinguishes areas with long-term potential for sustaining lichen forage from regions where climatic conditions and disturbance regimes are likely to limit recovery. By comparing projected lichen suitability across caribou sub-regional boundaries and Forest Management Areas, this study provides a spatial basis for identifying where conservation and restoration efforts are most likely to be effective under future climate conditions.

This distinction supports more strategic conservation planning by directing restoration and protection efforts toward landscapes with the highest likelihood of retaining lichen habitat.

### **3. Methods**

#### **3. 1. Lichen data**

In order to project how suitable lichen climate habitat may shift in response to climate change across Alberta, this study used lichen plot records from the Alberta Biodiversity Monitoring Institute (ABMI) (Alberta Biodiversity Monitoring Institute [ABMI], 2024). ABMI sites are systematically and randomly selected using a 20 km by 20 km grid applied across the entire province, resulting in 1,532 unique sampling sites within the present dataset. This dataset contains 277,264 plots contained lichen species (Figure 1).



**Figure 1.** Lichen frequencies in plot data from ABMI dataset.

Field measurements were primarily carried out between 2001 and 2022. Lichen-rich plots occur mainly in western Alberta near the Rocky Mountain and foothill regions, including areas adjacent to Banff and Jasper National Parks, and in parts of the northern boreal forest. Central and southern Alberta contain fewer lichen occurrences and low lichen percentages.

### **3. 2. Climate analysis**

Climate data for this study were obtained from ClimateNA. ABMI field measurements were collected after 2000. The 1980s climate normals (1971–2000) therefore represent pre-sampling baseline climatic conditions. In contrast, the 2000s climate normals (1991–2020) temporally overlap with the period of field data collection and most closely reflect the climatic conditions under which the observed lichen data were recorded; this period was used to represent contemporary climate. Climate variables were then extracted for three additional periods to assess projected change: the 2020s (2011–2030, SSP2–4.5), the 2050s (2041–2070, SSP2–4.5), and the 2080s (2071–2100, SSP2–4.5).

For each period, ClimateNA provided eight temperature and moisture variables for all plot locations: Mean Annual Temperature (MAT), Mean Warmest Month Temperature (MWMT), Mean Coldest Month Temperature (MCMT), Temperature Difference (TD), Mean Annual Precipitation (MAP), May–September Precipitation (MSP), Precipitation as Snow (PAS), and Climatic Moisture Deficit (CMD). Among these predictors, MAT and MSP were selected because they showed strong predictive influence on lichen abundance during preliminary model assessment (Wang et al., 2016).

### **3. 3. Caribou sub-regional boundaries and FMAs**

Caribou Sub-Regional Boundaries were added in QGIS to show the current distribution of Alberta’s eleven caribou management areas and to provide spatial context for the projected lichen maps (Alberta Environment and Parks, 2022a). The boundaries were overlaid on the predicted lichen surfaces for all climate periods to evaluate where projected lichen conditions overlap with areas occupied by caribou.

FMA boundaries were also added in QGIS after lichen suitability was projected under the four future climate periods (Alberta Environment and Parks, 2022b). Viewing the predicted lichen maps with these boundaries allowed assessment of lichen suitability within Alberta’s forest

tenure areas across the climate periods and identified where projected conditions may reduce lichen presence within operational areas.

These boundary layers provided the spatial framework for interpreting the projected lichen maps and for assessing implications for caribou habitat and forest management. A summary table was produced that scored each FMA across the five climate periods, where green indicates high projected lichen suitability and red indicates low suitability. FMAs with repeated low scores represent areas where lichen habitat is unlikely to remain viable under future climates, and where conservation or restoration investment may yield limited ecological return. These areas may be more suitable for industrial activity under a managed structure. FMAs with consistently high scores identify regions where conservation actions are more likely to sustain caribou forage under future conditions.

### **3. 4. Random forest modeling and spatial analysis**

A Random Forest model was used to identify climate variables that influence lichen abundance and to project lichen suitability under future climate conditions. Random Forest is a machine-learning method that constructs many decision trees and aggregates their predictions to improve accuracy and reduce overfitting (Breiman, 2001). Random Forest is used in ecological modeling because it quantifies the influence of each predictor, models nonlinear responses, and captures interactions among climate variables (Cutler et al., 2007; Mi et al., 2017).

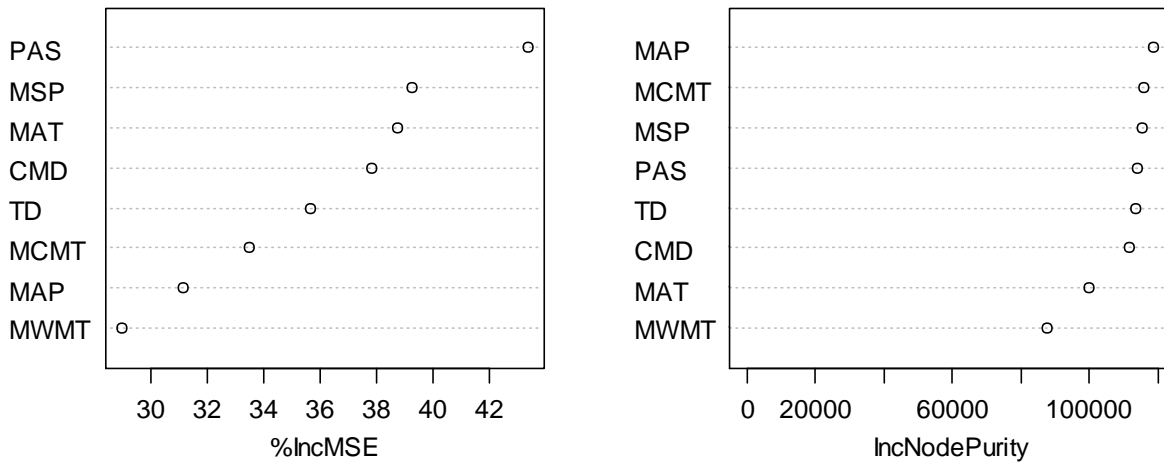
Percent lichen cover from the ABMI plots served as the response variable, and climate variables from the 1980s were used as predictors when training the model. These climate values correspond to the period when most ABMI field measurements were collected. After the model was trained, the projected climate grids for the 2020s, 2050s, and 2080s were supplied to the model to generate lichen suitability for every 1-km grid cell across Alberta. ABMI plots were not projected; their role was limited to model training.

This modeling and spatial analysis provided the basis for comparing lichen patterns across time and for assessing how projected climate change may affect caribou forage and land-use planning.

## **4. Results**

#### 4. 1. Predictor variable importance

The model evaluated eight temperature and moisture variables from ClimateNA, and their relative importance is shown in Figure 2. %IncMSE measures how much prediction error increases on average when a variable is removed based on many permutations. Higher values mean the model depends strongly on that variable. IncNodePurity measures how much a variable reduces variance across all splits in the trees, and higher values indicate stronger structural influence on the model.



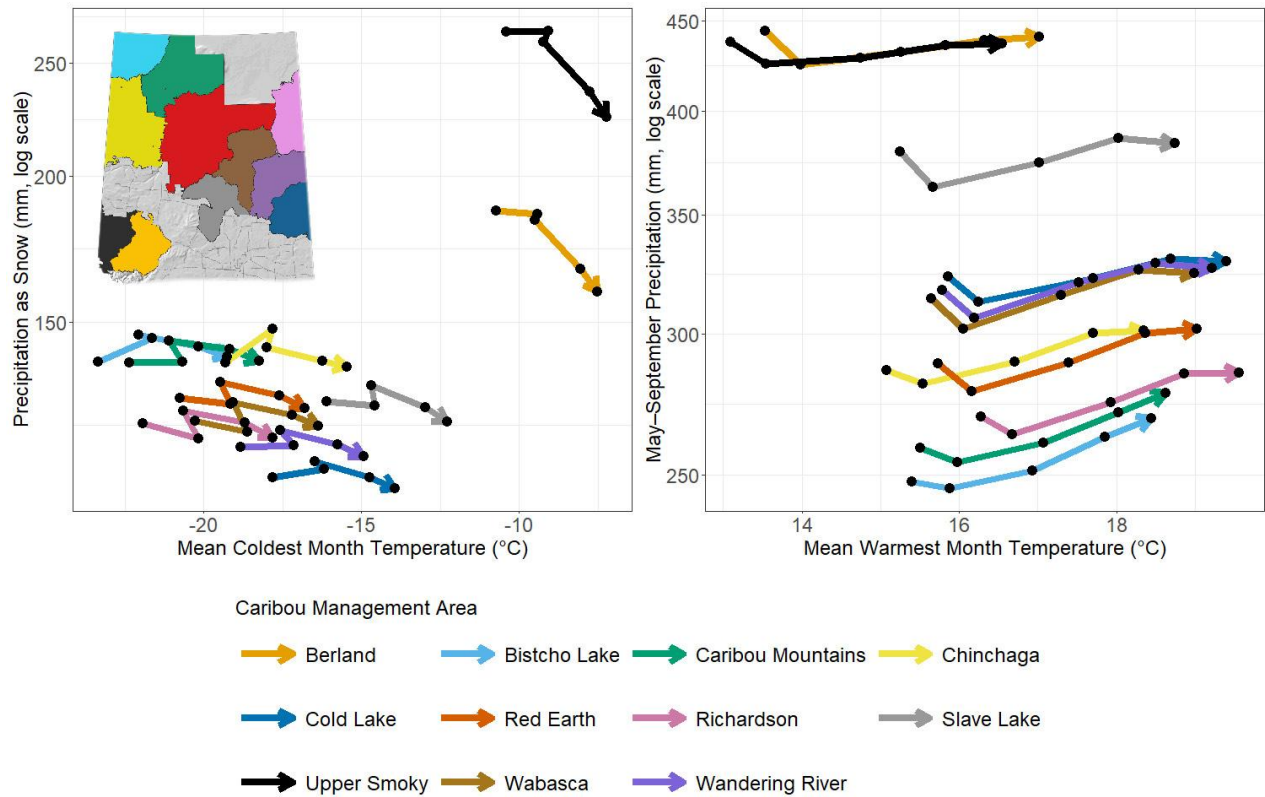
**Figure 2.** Relative importance of the eight ClimateNA predictor variables in the Random Forest model.

MSP and PAS rank highest for both metrics, indicating that growing season moisture and winter snowfall have the strongest influence on lichen abundance. MAT, CMD, TD, MCMT, MAP, and MWMT show lower but measurable importance and contribute through temperature contrast and moisture balance effects.

For subsequent analyses, PAS and MCMT were selected to represent winter climate conditions, as PAS showed high model importance and MCMT captures winter temperature variation. Similarly, MSP was paired with MWMT to represent summer climate conditions, given their strong and complementary influence on lichen abundance. This variable selection enables direct comparison of winter and summer climate space and facilitates evaluation of how seasonal climate conditions shift over time in relation to lichen habitat suitability.

#### 4. 2. Predicted and observed climate change

Figure 3 presents winter and summer climate trajectories for Alberta’s eleven caribou ranges from the 1980s to the 2080s. Winter conditions (left) are represented by precipitation as snow (PAS) plotted against mean coldest month temperature (MCMT), while summer conditions (right) are represented by May–September precipitation (MSP) plotted against mean warmest month temperature (MWMT). Together, the two panels illustrate shifts in winter and summer climate conditions across the five climate periods and differences in these trajectories among caribou ranges.



**Figure 3.** Climate trajectories for eleven Alberta caribou ranges from the 1980s to the 2080s. The left panel shows PAS versus MCMT (winter condition), and the right panel shows MSP versus MWMT (summer condition). Each line represents one caribou range, with points marking the 1980s, 2000s, 2020s, 2050s, and 2080s.

In the left panel, before the 2020s, PAS varies among caribou ranges, whereas after the 2020s all ranges converge toward a consistent decline in snowfall. Upper Smoky and Berland exhibit distinct winter climate trajectories, characterized by higher PAS and warmer winter temperatures relative to other ranges. Upper Smoky has the highest PAS and shows a 13% reduction from the 1980s to the 2080s, accompanied by an increase in MCMT of roughly 3.5 °C. Berland follows a

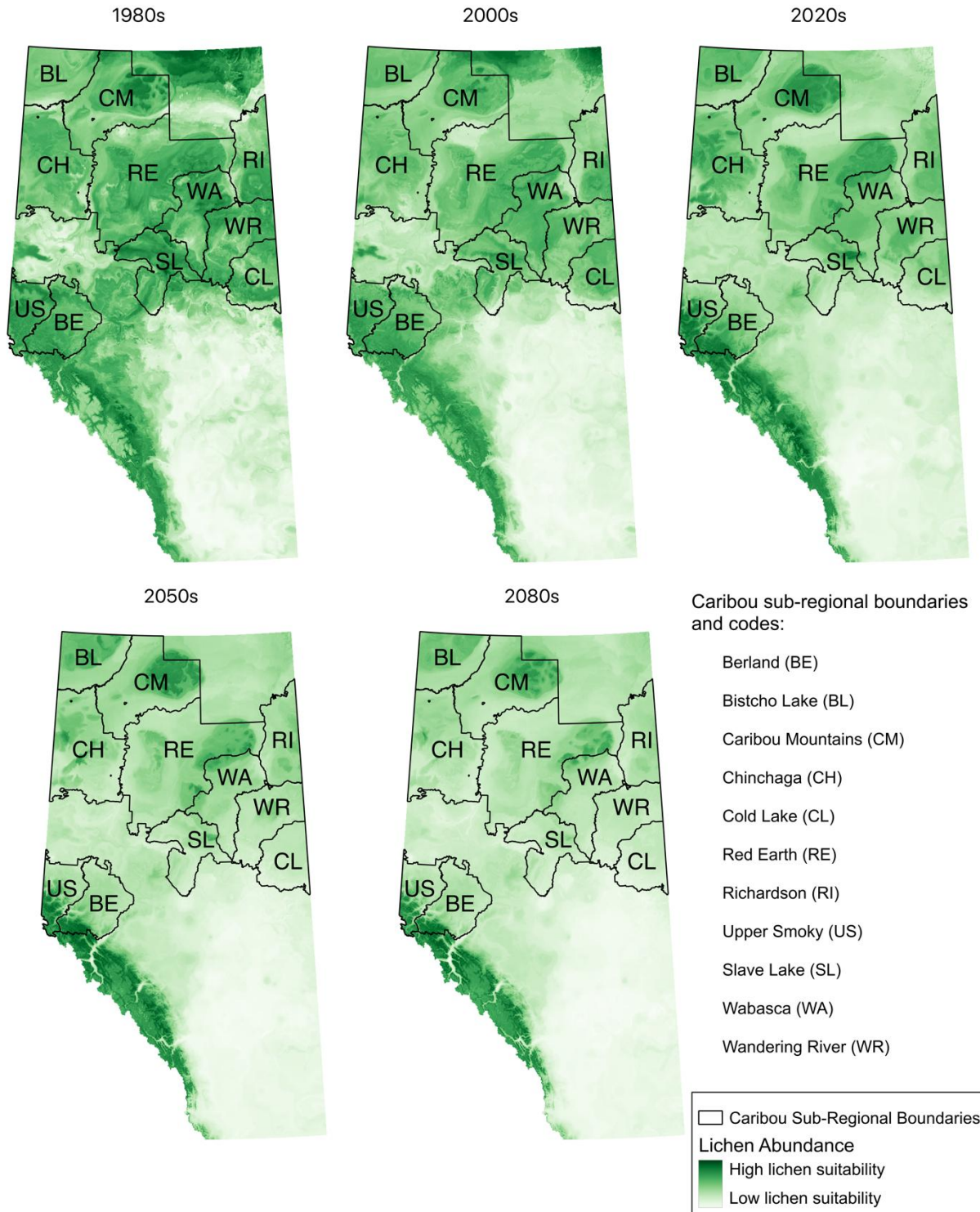
similar pattern, with precipitation as snow also declining by around 13% and MCMT increasing by about 3.5 °C over the same period. These two ranges experience the largest relative reductions in snowfall and the strongest winter warming among all caribou ranges.

All other ranges cluster closely in both variables, showing smaller proportional declines in PAS and relatively similar coldest month temperatures through time. Cold season temperatures generally span a narrow range of approximately 3.5–5 °C, corresponding to a confined PAS range of roughly 110–150 mm. Within this cluster, Slave Lake and Cold Lake exhibit slightly higher MCMT than the other grouped ranges, although they remain below Upper Smoky and Berland. Bistcho Lake occupies the coldest portion of the climate space and experience smaller relative reductions in snowfall. Reduced PAS shortens snow cover duration and lowers winter moisture inputs.

In the right panel, MSP shows a non-linear pattern across most caribou ranges, with higher values in the 1980s, a decline in the 2000s, and increases under future climate projections. At the same time, all ranges exhibit consistent summer warming across the five climate periods, with MWMT increasing by approximately 3.5 °C from the 1980s to the 2080s. Most ranges occupy a summer temperature range of 15–20 °C, whereas Upper Smoky and Berland remain cooler, between 13 and 17 °C. Upper Smoky and Berland combine the coolest summer temperatures with the highest MSP, consistently exceeding 420 mm. Slave Lake shows MWMT comparable to other clustered ranges but maintains higher MSP, generally between 360 and 385 mm, with limited temporal change. The remaining ranges form a tight central group, with MSP constrained to 245–330 mm. Most ranges show similar MSP in the 1980s and 2080s, whereas Bistcho Lake and Caribou Mountains exhibit the largest proportional increases, approximately 10% over time.

#### **4. 3. Lichen climate habitat projections**

Figure 4 shows the predicted lichen suitability for the 1980s, 2000s, 2020s, 2050s, and 2080s across the 11 caribou sub-regional boundaries. Dark green indicates higher predicted lichen values, and white indicates low or no lichen. The maps show a consistent shift in lichen habitat distribution across climate periods, reflecting the combined effects of warming and changes in moisture availability.



**Figure 4.** The predicted lichen suitability for the 1980s, 2000s, 2020s, 2050s, and 2080s, where dark green indicates higher predicted lichen values and white indicates low or no lichen. Caribou sub-regional boundaries are labeled using the following short codes: Berland (BE), Bistcho Lake

(BL), Caribou Mountains (CM), Chinchaga (CH), Cold Lake (CL), Red Earth (RE), Richardson (RI), Upper Smoky (US), Slave Lake (SL), Wabasca (WA), and Wandering River (WR).

Table 1 summarizes average lichen suitability values for each caribou range across all climate periods, where darker green indicates higher suitability and red indicates lower suitability. Across all caribou ranges, average lichen suitability declines by 39.6% from the 1980s to the 2080s. Although many ranges exhibit high suitability in the 1980s, far fewer retain high values by the 2080s, indicating a broad reduction in high-quality lichen habitat over time.

**Table 1.** Average predicted lichen suitability in units of percent cover within each caribou sub-regional boundary for the historic (1971–2000, 1991–2020) and projected climate periods (2020s, 2050s, 2080s).

Caribou Sub- Regional Boundary	Historic		Projected		
	1971-2000	1991-2020	2020s	2050s	2080s
Bistcho Lake	45.0	46.1	43.0	41.6	39.6
Upper Smoky	60.9	56.0	47.7	41.0	38.1
Caribou Mountains	52.0	47.4	43.8	40.6	38.0
Berland	56.3	53.8	43.9	37.3	35.0
Red Earth	53.8	46.4	41.4	35.6	32.5
Richardson	48.5	44.0	40.2	35.0	31.8
Wabasca	56.0	52.5	43.6	35.4	31.5
Chinchaga	49.0	44.2	43.0	34.3	31.1
Slave Lake	60.7	48.8	36.8	29.7	27.6
Wandering River	56.1	46.8	39.6	29.7	27.4
Cold Lake	51.0	45.2	33.6	25.4	24.0
Average	53.6	48.3	41.5	35.1	32.4

Under the 1980s historical baseline, lichen suitability is relatively high across all sub-regions, with no extremely low values observed. The highest average suitability occurs in western and foothill ranges, particularly Upper Smoky and Slave Lake, followed closely by Berland and Wandering River. These regions correspond to extensive areas of high suitability shown in Figure 4 and elevated values in Table 1. In contrast, Bistcho Lake and Richardson exhibit comparatively lower average suitability, although values remain moderate overall. Northern foothill ranges generally display intermediate to high conditions.

By the 2000s, average lichen suitability declines across most caribou sub-regional boundaries, representing an approximate 10% decline relative to the 1980s baseline. Although Upper Smoky,

Wabasca, and Berland retain comparatively higher suitability than other regions, all ranges experience reductions relative to historical conditions. Slave Lake shows a decline of approximately 20%, and Wandering River decreases by about 17%, indicating an early contraction of high-suitability habitat.

By the 2020s, lichen suitability continues to decline across the province, with the overall average decreasing by approximately 23% relative to the 1980s baseline and by 14% relative to the 2000s period. Reductions are spatially widespread, affecting both northern and western foothill ranges.

Further decreases occur in the 2050s and 2080s. Relative to the 2020s, average suitability declines by approximately 15% by the 2050s and by a further 8% by the 2080s. Overall, comparison of the 1980s and 2080s indicates a total decline of approximately 40% in average lichen suitability across caribou ranges.

By the 2080s, none of the caribou sub-regional boundaries remain within the high (green) lichen suitability class. Bistcho Lake, although not the highest under the historical baseline, maintains the highest projected suitability by the end of the century. Upper Smoky and Caribou Mountains follow, retaining comparatively higher values than other ranges. In contrast, Cold Lake, Wandering River, and Slave Lake exhibit the lowest projected suitability. These results indicate that all boundaries shift to moderate or low suitability levels by the 2080s.

#### **4. 4. Lichen conditions within FMAs**

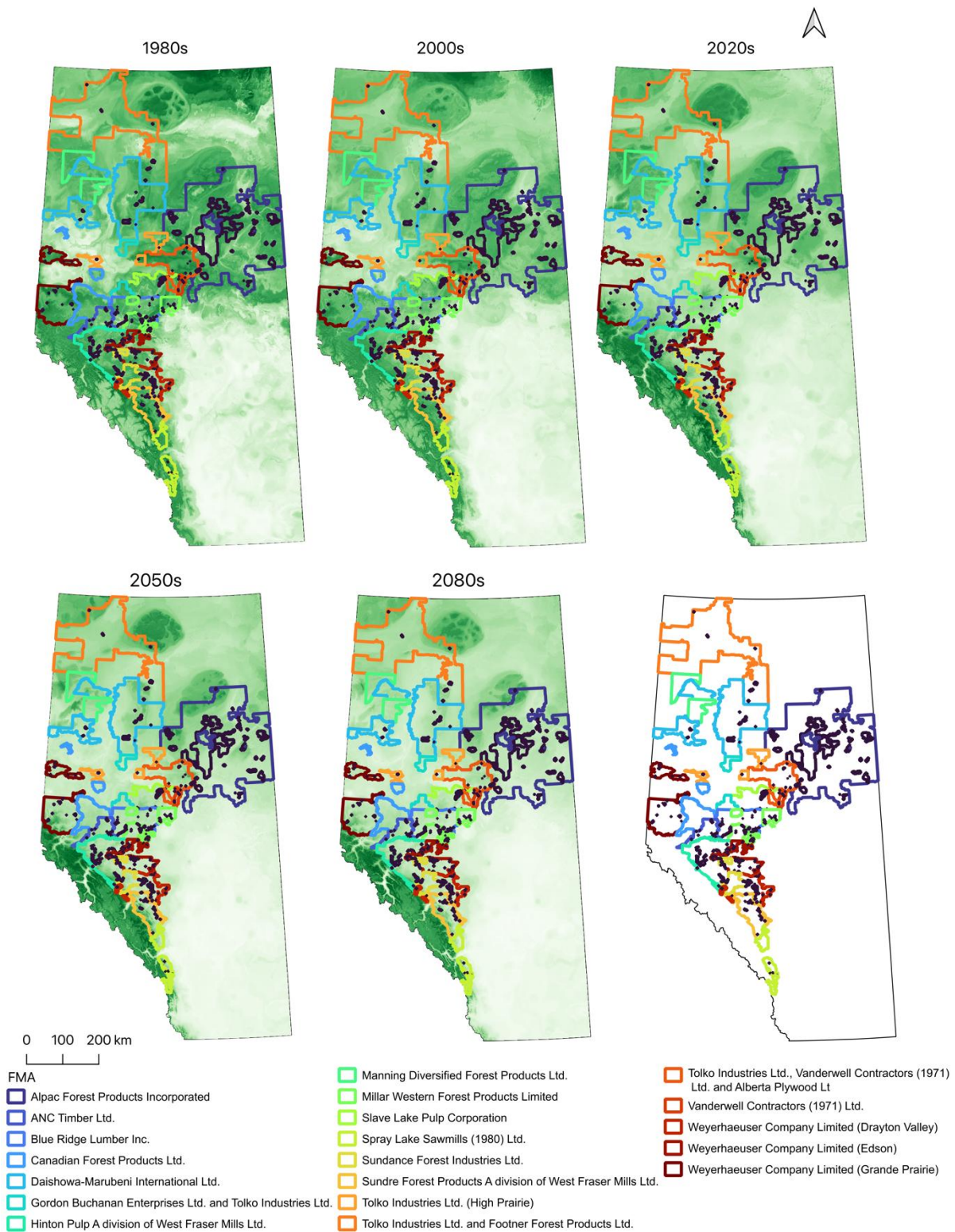
Predicted values for each period were exported as rasters using the *terra* package in R and aligned with the 1-km ClimateNA grid (Mahony et al., 2022; Wang et al., 2016). The rasters were imported into QGIS and overlaid with the Caribou Sub-Regional Boundaries and FMA boundaries, allowing direct assessment of lichen suitability within each tenure area across the 1980s, 2000s, 2020s, 2050s, and 2080s.

The FMA summaries in Table 2 and Figure 5 indicate a consistent decline in average lichen suitability from the historical baseline to the late-century period, decreasing by approximately 47% between the 1980s and the 2080s. This downward trend is observed across nearly all Forest Management Areas. FMAs with high historical suitability, including Sundre Forest Products,

Spray Lake Sawmills, and Vanderwell Contractors, exhibit substantial reductions over time. Areas with comparatively lower historical suitability also decline rather than increase, resulting in a uniform downward shift in suitability values. By the 2080s, no FMA retains high suitability, and most fall within moderate to low classes, indicating a broad contraction of high-quality lichen habitat across managed forest landscapes.

**Table 2.** Predicted lichen suitability in units of percent cover within FMAs for historic (1971–2000, 1991–2020) and projected climate periods (2020s, 2050s, 2080s).

FMA	Historic		Projected		
	1971-2000	1991-2020	2020s	2050s	2080s
Tolko Industries Ltd. and Footner Forest Products Ltd.	49.1	43.5	40.4	36.8	34.9
Manning Diversified Forest Products Ltd.	54.9	49.1	47.9	36.6	33.1
Sundre Forest Products A division of West Fraser Mills Ltd.	63.3	58.4	45.5	36.3	32.6
Weyerhaeuser Company Limited (Grande Prairie)	59.8	53.9	40.2	33.9	31.5
ANC Timber Ltd.	51.7	51.2	39.9	33.1	31.5
Hinton Pulp A division of West Fraser Mills Ltd.	56.7	54.9	44.3	35.1	31.5
Spray Lake Sawmills (1980) Ltd.	66.6	64.6	50.4	37.4	31.3
Alpac Forest Products Incorporated	56.3	48.9	41.7	33.2	30.2
Canadian Forest Products Ltd.	54.3	47.8	33.9	31.1	30.1
Daishowa-Marubeni International Ltd.	52.1	45.1	40.4	32.8	29.9
Tolko Industries Ltd., Vanderwell Contractors (1971) Ltd. and Alberta Plywood Lt	65.7	54.7	41.1	31.9	29.4
Sundance Forest Industries Ltd.	54.9	49.5	38.7	31.5	29.4
Weyerhaeuser Company Limited (Drayton Valley)	47.7	38.3	32.5	29	29.2
Slave Lake Pulp Corporation	55.3	50.7	33.8	30	28.6
Gordon Buchanan Enterprises Ltd. and Tolko Industries Ltd.	54.1	42.8	33	29.3	28.5
Blue Ridge Lumber Inc.	53.5	44.6	33	29.5	28.1
Tolko Industries Ltd. (High Prairie)	50.9	42.7	36.2	28.9	27
Weyerhaeuser Company Limited (Edson)	49.2	36.6	29.8	26.1	26.7
Millar Western Forest Products Limited	54.6	38.7	29.7	27.2	26.2
Vanderwell Contractors (1971) Ltd.	62.3	41.8	27.7	24.7	23.4
<b>Average</b>	<b>55.7</b>	<b>47.9</b>	<b>38</b>	<b>31.7</b>	<b>29.7</b>



**Figure 5.** Predicted lichen suitability with FMA boundaries for the 1980s, 2000s, 2020s, 2050s, and 2080s, where dark green indicates higher predicted lichen values and white indicates low or no lichen.

A first group of FMAs maintains the highest relative lichen suitability by the 2080s, despite substantial declines over time. Tolko Industries Ltd. and Footner Forest Products Ltd., Manning Diversified Forest Products Ltd., and Sundre Forest Products remain among the highest late-century values, although each declines by approximately 37–49% relative to the historical baseline. These FMAs begin with comparatively high historic suitability and retain a relative advantage over other tenure areas, even as absolute values decrease across successive climate periods.

A second group, including ANC Timber Ltd., Hinton Pulp, and Weyerhaeuser Grande Prairie, exhibits moderate historical suitability followed by steady declines through the 2020s, 2050s, and 2080s. Reductions in this group generally range from approximately 39–45% relative to the 1980s baseline. While these FMAs do not experience the largest proportional losses, they transition from moderate to lower suitability classes by late century.

A third group, such as Slave Lake Pulp Corporation, Sundance Forest Industries, Blue Ridge Lumber, and Canadian Forest Products, begins with moderate historic values but declines to clearly lower suitability levels by the 2080s. These FMAs show reductions of approximately 45–50%, reflecting a sustained downward trajectory without evidence of stabilization or recovery.

A final group exhibits the strongest proportional declines and lowest late-century suitability. Spray Lake Sawmills and Vanderwell Contractors fall within this category. Spray Lake Sawmills declines by approximately 53% from the historical baseline to the 2080s, while Vanderwell Contractors shows a reduction of more than 60%, the largest decline among all FMAs. By the 2080s, these tenure areas occupy the lowest suitability class, indicating limited projected climatic capacity to sustain high-quality lichen habitat.

## **5. Discussion**

### **5. 1. Moisture availability controls lichen habitat across Alberta**

The Random Forest analysis shows that May to September precipitation and snowfall are the strongest predictors of lichen abundance (Figure 2). These variables shape both summer hydration and winter moisture inputs, which determine the periods when lichens can photosynthesize and maintain metabolic activity. The climate trajectories in Figure 3 further indicate that some ranges, including Upper Smoky and Berland, experience pronounced reductions in snowfall along with rapid winter warming. These conditions shorten moisture retention and increase exposure to drying stress.

This evidence demonstrates that the distribution of lichen habitat depends primarily on regional water balance rather than temperature alone. Restoration actions that focus on disturbance reduction will not be sufficient in locations where future moisture availability shifts outside the range that supports lichen growth. Management plans therefore need to recognize that the climatic controls on lichen activity set a fundamental limit on habitat potential for caribou forage.

An important implication of this result is that climatic constraints act independently of restoration timelines. Even where disturbance is reduced or seismic lines are successfully restored, lichen growth remains limited by physiological thresholds that management cannot overcome.

### **5. 2. Climate change reduces lichen habitat suitability across the province**

Maps of predicted lichen suitability show a progressive reduction in high-suitability habitat from the 1980s through the 2080s (Figure 4). The darkest green areas present under historical conditions contract over time, and by the 2080s no caribou sub-regional boundary remains within the high-suitability class. Table 1 confirms this pattern, with average suitability declining by approximately 40% between the 1980s and the 2080s.

Unlike earlier interpretations suggesting spatial compensation, the updated results indicate a broadly consistent downward trend across the province. Although some ranges retain

comparatively higher suitability by late century, all experience substantial proportional declines. Bistcho Lake maintains the highest relative suitability in the 2080s despite not having the highest historical baseline, while Upper Smoky and Caribou Mountains follow. In contrast, Cold Lake, Wandering River, Slave Lake, and Chinchaga exhibit the lowest late-century values. These patterns reflect differences in magnitude rather than direction of change; no region shows sustained improvement under projected climate conditions.

Taking Chinchaga as an example of a consistently low-suitability region, Government of Alberta (2017) reports that 97% of the range is disturbed by natural and anthropogenic footprint, and the area contains extensive oil and gas activity, including more than 62,000 km of legacy seismic lines. This level of disturbance reduces habitat integrity and aligns with the projected decline in future lichen suitability.

However, the updated results indicate that climate change produces a largely consistent decline in lichen habitat suitability across Alberta rather than a spatial redistribution toward new areas of moderate suitability. Although the magnitude of decline varies among caribou sub-regional boundaries, all ranges exhibit reductions from the 1980s to the 2080s. High-suitability areas contract progressively through time, and no boundary retains values within the highest suitability class by late century.

Rather than reflecting a transition toward a broader distribution of moderate habitat, the projections indicate a downward shift across suitability classes. Regions that maintain comparatively higher values by the 2080s do so relative to other ranges, not because suitability improves or stabilizes. Differences among ranges represent variation in the rate of decline rather than divergent climatic trajectories.

In contrast, persistently low-suitability regions identify landscapes where climate constrains lichen recovery. In these areas, restoration is unlikely to re-establish high lichen abundance because moisture and winter conditions remain limiting. Recognizing these limits supports climate-informed planning by directing conservation to high-return areas and reducing constraints where ecological gains are unlikely.

### **5. 3. Climate change reduces lichen suitability across most FMA**

Table 2 shows that Forest Management Areas exhibit a consistent decline in lichen habitat suitability from the 1980s to the 2080s. On average, suitability across FMAs decreases by approximately 47% over this period. This pattern mirrors the downward trend observed within caribou sub-regional boundaries and indicates a broad reduction in climatic capacity to support lichen across managed forest landscapes.

Although all FMAs decline, the magnitude of reduction varies. FMAs with high historical suitability, including Spray Lake Sawmills, Sundre Forest Products, and Vanderwell Contractors, experience some of the largest proportional decreases, ranging from approximately 49% to more than 60% by the 2080s. These areas retain relatively higher values compared with other tenure areas in early periods but lose a substantial share of their climatic suitability through time.

Other FMAs begin with moderate historical values and decline steadily across successive climate periods without evidence of stabilization or recovery. By the 2080s, no FMA remains within the highest suitability class, and most transition into moderate or low categories. Differences among tenure areas therefore reflect variation in the rate of decline rather than contrasting improvement trajectories.

These results indicate that projected climate change reduces lichen habitat potential across the majority of managed forest tenures. While management actions may influence disturbance patterns, the climatic envelope supporting high lichen abundance contracts progressively across all FMAs. Climate-informed planning should therefore account for declining baseline suitability and prioritize areas that retain comparatively higher late-century potential, while recognizing that absolute habitat quality is projected to decrease province-wide.

## 6. Conclusion

A central finding of this study is that climate change drives a consistent decline in lichen habitat suitability across Alberta. Average suitability decreases substantially from the 1980s to the 2080s, and no caribou sub-regional boundary retains high-suitability conditions by late century. The Random Forest analysis demonstrates that lichen abundance is governed primarily by moisture balance, particularly summer precipitation and snowfall. Projected reductions in snowfall and altered seasonal moisture regimes reduce the climatic capacity to sustain high lichen abundance across the province.

Although the magnitude of decline varies among regions, all caribou sub-regional boundaries exhibit downward trajectories. Bistcho Lake retains the highest relative suitability by the 2080s, followed by Upper Smoky and Caribou Mountains, but these areas still experience substantial proportional losses relative to historical baselines. In contrast, Cold Lake, Wandering River, and Slave Lake exhibit the lowest projected suitability values. Differences among ranges therefore reflect variation in the rate of decline rather than contrasting improvement or stabilization.

Forest Management Areas follow a similar pattern. Average suitability across FMAs declines markedly between the 1980s and the 2080s, and no tenure area retains high suitability under late-century conditions. While some FMAs maintain comparatively higher relative rankings, all experience substantial reductions in climatic capacity to support lichen.

At the same time, the results identify a set of climatically constrained regions where lichen habitat is unlikely to recover meaningfully under projected future conditions. Within Forest Management Areas, Millar Western Forest Products, Vanderwell Contractors, and Weyerhaeuser Edson fall among the lowest projected suitability values by the 2080s and exhibit substantial proportional declines relative to historical baselines. Similarly, caribou sub-regional boundaries including Cold Lake, Wandering River, and Slave Lake remain at the lower end of projected habitat potential. In these landscapes, reductions in snowfall and altered seasonal moisture balance constrain the climatic envelope supporting lichen persistence.

These climatically limited landscapes represent lower-return areas for lichen-focused habitat investment under continued climate change. While broader biodiversity, regulatory, and socio-economic considerations remain relevant, projected climatic conditions indicate limited potential to restore lichen habitat to historical levels in these regions. Climate-informed planning should therefore prioritize areas that retain comparatively higher late-century suitability, while recognizing that absolute habitat quality is projected to decline province-wide under ongoing warming.

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