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 habitat suitability for woodland caribou as winter forage. Because lichens are sensitive to climate, ongoing and future climatic change may constrain where lichen-rich forests can persist, regardless of conservation management or restoration efforts. 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 be effective, and where restrictions on forestry and other development to conserve caribou habitat may not meet long-term conservation objectives.

Percent lichen cover from 6,134 Ecological Site Information System plots was modeled using the RandomForest ensemble classifier and projected across five 30-year climate periods. These include two historical climate normals (1961–1990 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 decline in high-value lichen habitat, with an average 28% reduction in lichen suitability from 1971–2000 to 2071–2100 across Alberta's eleven caribou ranges. Several northern ranges (Bistcho Lake, Richardson, Wabasca, and Caribou Mountains) retain relatively higher suitability in future projections, whereas others (Chinchaga, Slave Lake, and Cold Lake) remain consistently low. Summaries by active Forest Management Areas (FMAs) show a modest average increase in suitability (about 17%), with many tenure areas stable or improving through time. A smaller subset of FMAs, including Spray Lake Sawmills and Vanderwell Contractors, remain low or decline under future climate conditions.

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 benefits. The study proposes that climate-informed prioritization that concentrates conservation and restoration in climatically stable or improving areas, while allowing greater flexibility in persistently low-suitability landscapes, can reduce conflict between caribou conservation 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 (1961–1990 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. Lierature 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 predictors 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; Esseen 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 Ecological Site Information System (ESIS), now known as Ecological Information System (ECOSYS) (Government of Alberta, 2016). ESIS contains over 17,000 plots, of which 6,134 plots contained lichen species (Figure 1). Across these plots, 54 lichen species were recorded, falling into four major types: reindeer lichens (*Cladonia* spp.), shrub or fruticose lichens (e.g., *Bryoria*, *Usnea*, *Evernia*), foliose lichens (e.g., *Cetraria*, *Hypogymnia*, *Peltigera*), and a small number of crustose lichens (e.g., *Bacidia*, *Xanthoria*). Each species has a code matched to the *PSP Manuals – Master Appendices* for identification (Government of Alberta, 2005).

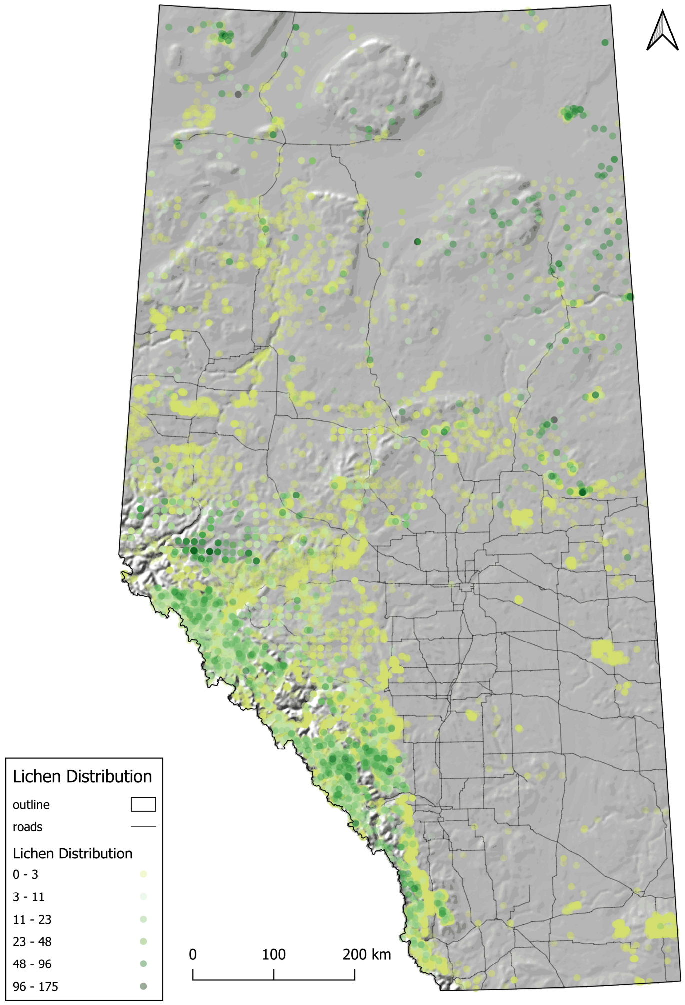

Figure 1. Lichen frequencies in plot data from the ESIS dataset.

Field measurements were primarily carried out between 1975 and 2006. 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. ESIS field measurements were collected between 1965 and 2005, so the 1980s climate normals (1971–2000) represent the conditions under which the observed lichen data were recorded. This period served as the baseline for evaluating climate effects on lichen. Climate variables were then extracted for four additional periods to assess projected change: the 2000s (1991–2020 normals), 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 16,454 ESIS 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 from 1 to 10 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 ESIS 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 ESIS field measurements were collected. After the model was trained, the projected climate grids for the 2000s, 2020s, 2050s, and 2080s were supplied to the model to generate lichen suitability for every 1-km grid cell across Alberta. ESIS 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.

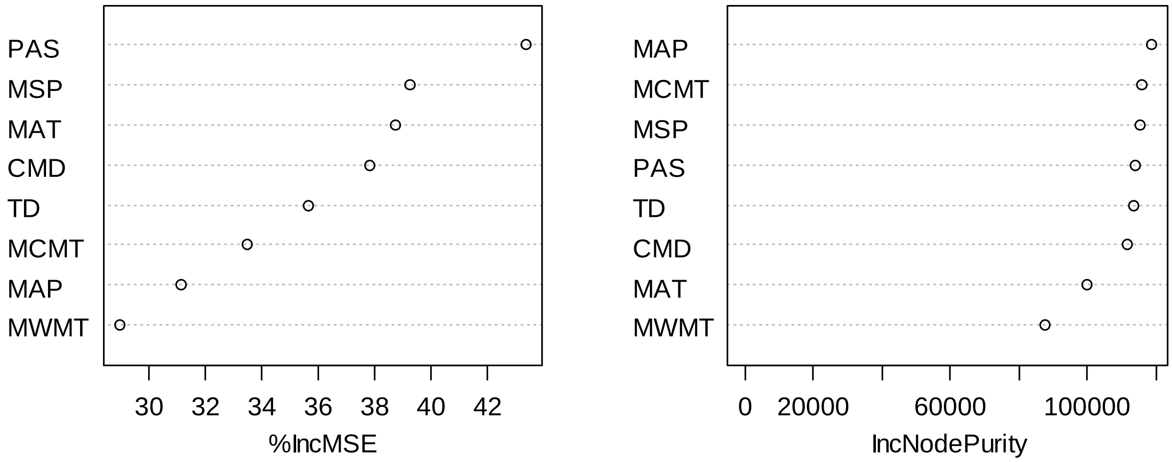

Figure 2. Relative importance of the eight ClimateNA predictor variables in the Random Forest model.

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.

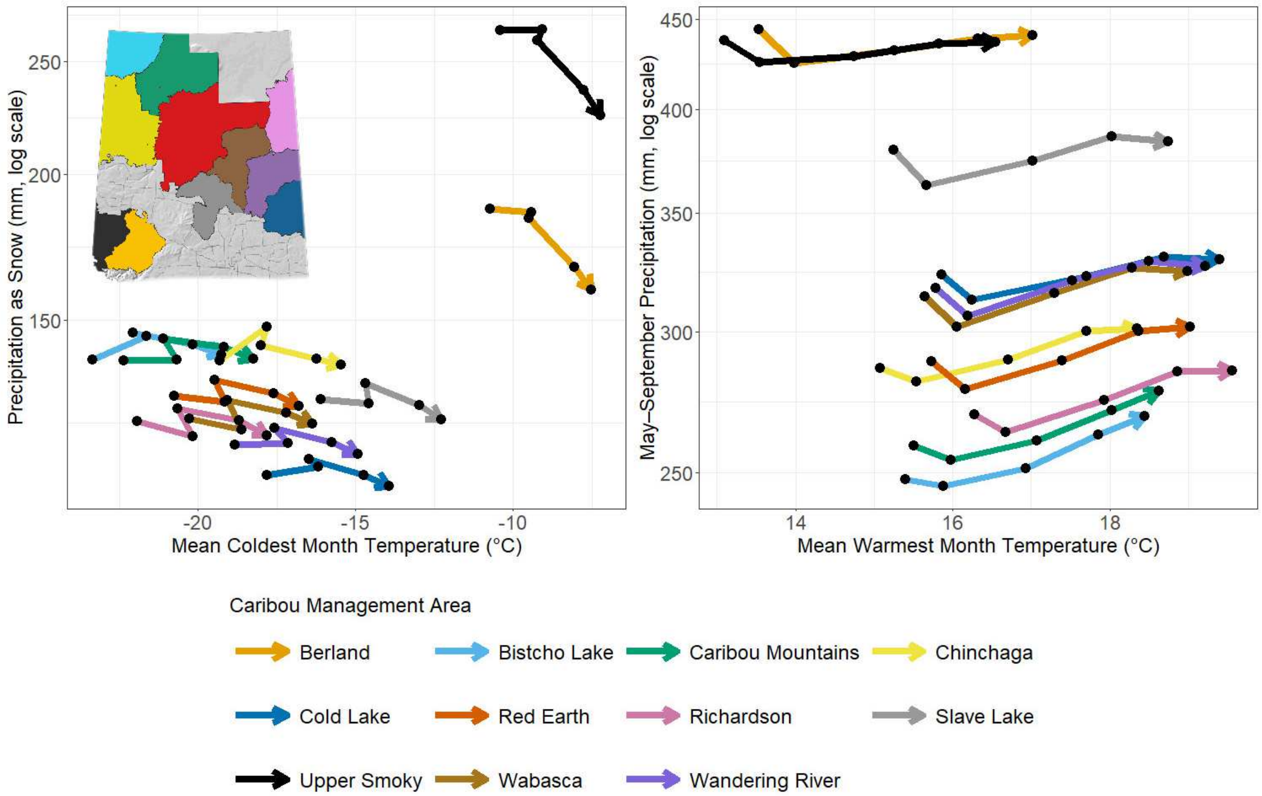

Figure 3. Climate trajectories for eleven Alberta caribou ranges from the 1980s to the 2080s. The left panel shows PAS versus MCMT (winter condition), and the right panel shows MSP versus MWMT (summer condition). Each line represents one caribou range, with points marking the 1980s, 2000s, 2020s, 2050s,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

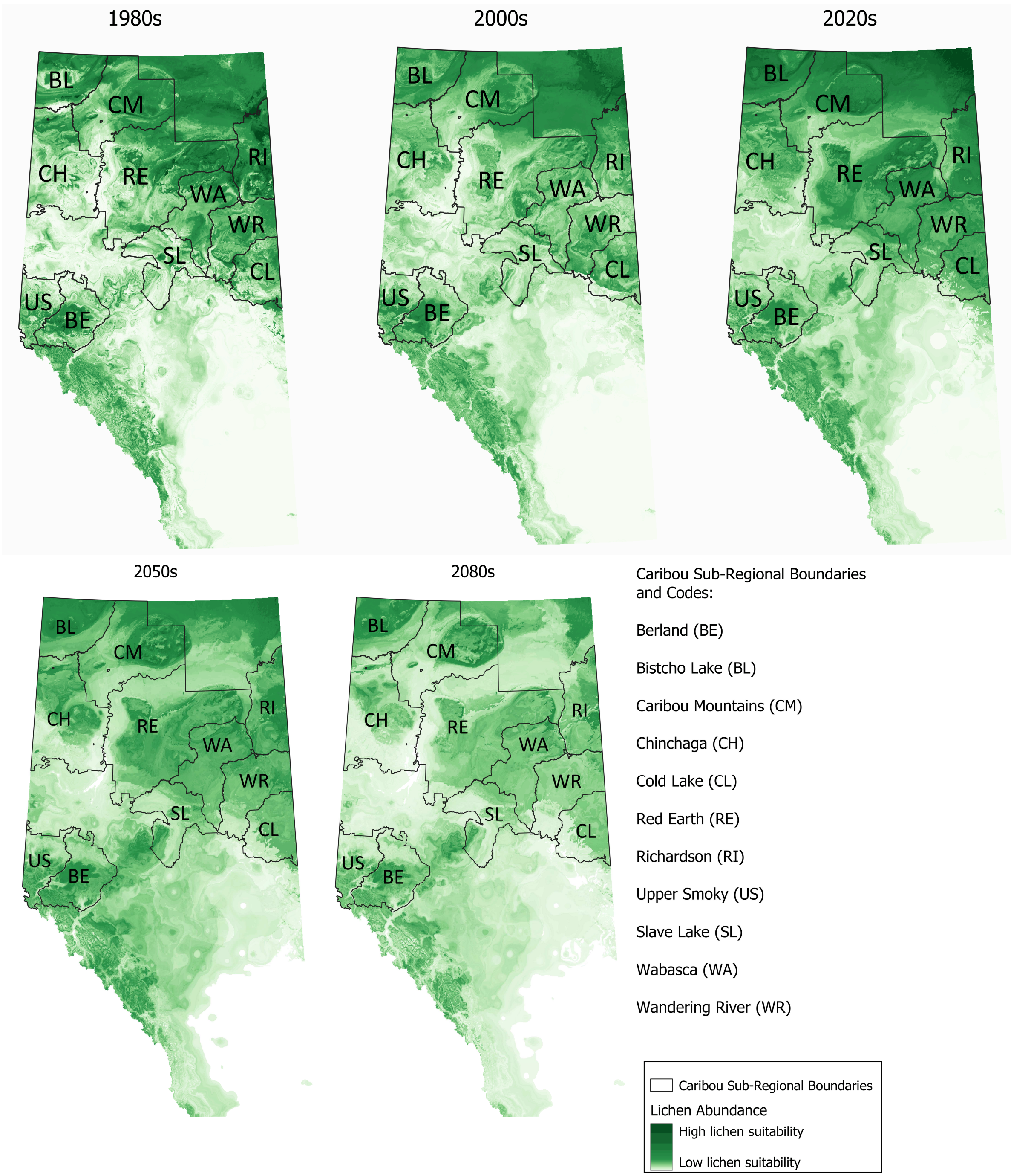

Figure 4. The predicted lichen suitability for the 1980s, 2000s, 2020s, 2050s, and 2080s, where dark green indicates higher predicted lichen values and white indicates low or no lichen. Caribou sub-regional boundaries are labeled using the following short codes: Berland (BE), Bistcho Lake (BL), Caribou 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 28% 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).

	Historic		Projected		
Caribou Sub-Regional Boundary	1971-2000	1991-2020	2020s	2050s	2080s
Bistcho Lake	10.8	8.7	16.6	10	9.2
Richardson	18.3	8.1	11.7	7.9	6.7
Wabasca	8.6	5.1	9.2	6.7	6.5
Caribou Mountains	8.9	7.4	11.9	7.7	6.2
Berland	6.2	6.3	5.7	6.3	6.2
Red Earth	8.4	4.9	8.3	5.7	5.2
Wandering River	7.5	5.2	7.5	5.6	4.8
Upper Smoky	4.4	5.2	4.4	4.9	4.8
Cold Lake	6	5.4	6.9	4.6	4.5
Slave Lake	3.1	3.3	4.6	4.1	4.1
Chinchaga	3.8	3.6	5.4	4.5	3.8
Average	7.8	5.7	8.4	6.2	5.6

Under the 1980s historical baseline, average lichen suitability is highest in northern and foothill ranges, particularly Richardson, Bistcho Lake, Caribou Mountains, and Wabasca. These ranges correspond to extensive areas of high suitability in Figure 4 and elevated average values in Table 1. In contrast, Slave Lake and Chinchaga exhibit the lowest average suitability, consistent with larger areas of low or no lichen shown on the maps. Western foothill ranges show intermediate conditions, with Berland exhibiting moderate suitability and Upper Smoky slightly lower values relative to the northern ranges.

By the 2000s, average lichen suitability declines across most caribou ranges. Although Richardson, Bistcho Lake, and Caribou Mountains retain the highest values, suitability is lower than under the 1980s baseline. Wabasca and Red Earth, which are spatially adjacent, exhibit some of the strongest early declines, with average suitability decreasing by 41% and 42%, representing a loss of nearly half of high-value lichen habitat despite continued spatial extent.

By the 2020s, average lichen suitability increases across most caribou ranges, rising by 47% relative to the 2000s. This level exceeds the average suitability observed under the 1980s baseline. Changes in lichen suitability are concentrated in northern ranges, while western foothill ranges remain relatively stable. Wabasca provides a clear example of this recovery, where average suitability increases by 133% from the 2000s to the 2020s.

By the 2050s and 2080s, lichen suitability declines in successive periods. Relative to the 2020s, average suitability decreases by 26% by the 2050s and by a further 10% by the 2080s. Comparison of the 1980s and 2080s reveals a clear spatial shift. In the 1980s, high-suitability areas are widespread across much of Alberta. By the 2080s, these high-value patches contract substantially, and the landscape is dominated by moderate suitability values, indicating a loss of concentrated high-lichen habitat.

By the 2080s, Bistcho Lake remains the only range with consistently high lichen suitability. Richardson, Wabasca, Caribou Mountains, and Berland exhibit intermediate suitability, whereas Red Earth, Wandering River, Upper Smoky, and Cold Lake fall into lower suitability classes. Slave Lake and Chinchaga remain persistently low.

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 show a net increase in average lichen suitability from the historic baseline to the late-century period, rising by 17%. This pattern reflects contrasting trajectories among Forest Management Areas. Several FMAs with low historic suitability increase to moderate values under future climate conditions, while FMAs with higher historic suitability decline through time. These opposing trends offset one another, producing a modest increase in the overall mean.

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 1971-2000	Historic 1991-2020	Projected 2020s	Projected 2050s	Projected 2080s
ANC Timber Ltd.	7.6	6.7	6.4	7.2	7.0
Hinton Pulp A division of West Fraser Mills Ltd.	4.7	5.3	4.8	6.1	5.9
Tolko Industries Ltd. and Footner Forest Products Ltd.	9.5	6.9	10.8	6.7	5.9
Manning Diversified Forest Products Ltd.	4.6	5.3	6.9	6.8	5.8
Blue Ridge Lumber Inc.	2.9	3.6	4.0	5.8	5.7
Sundance Forest Industries Ltd.	3.2	4.1	5.0	5.9	5.7
Slave Lake Pulp Corporation	2.8	3.0	4.3	5.3	5.7
Alpac Forest Products Incorporated	8.6	5.4	8.3	6.2	5.6
Millar Western Forest Products Limited	2.0	2.8	3.1	4.7	4.7
Sundre Forest Products A division of West Fraser Mills Ltd.	3.6	4.1	4.3	4.8	4.6
Canadian Forest Products Ltd.	4.1	3.9	4.8	4.7	4.6
Weyerhaeuser Company Limited (Drayton Valley)	2.1	2.8	4.3	4.2	4.3
Weyerhaeuser Company Limited (Edson)	1.9	2.3	3.8	4.2	4.3
Weyerhaeuser Company Limited (Grande Prairie)	3.6	4.5	3.9	4.2	4.1
Daishowa-Marubeni International Ltd.	3.1	2.9	6.1	4.8	4.1
Gordon Buchanan Enterprises Ltd. and Tolko Industries Ltd.	2.8	2.2	3.2	3.4	4.0
Tolko Industries Ltd., Vanderwell Contractors (1971) Ltd. and Alberta Plywood Lt	3.9	3.4	4.9	4.1	3.9
Tolko Industries Ltd. (High Prairie)	4.1	2.6	4.3	3.6	3.7
Vanderwell Contractors (1971) Ltd.	1.9	2.4	3.7	3.2	3.1
Spray Lake Sawmills (1980) Ltd.	5.3	3.6	2.6	2.4	2.7
Average	4.1	3.9	5.0	4.9	4.8

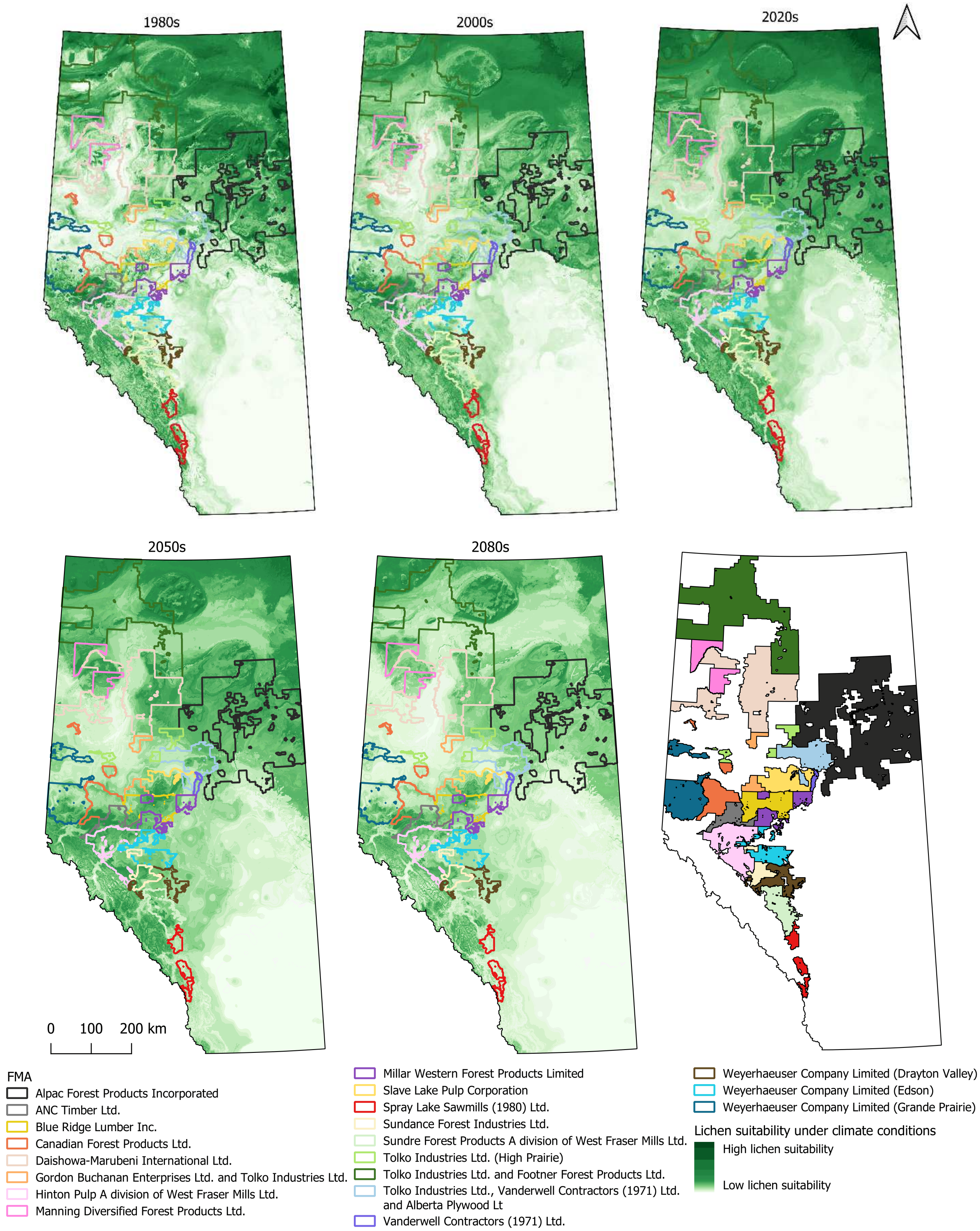

Figure 5. Predicted lichen suitability with FMA boundaries for the 1980s, 2000s, 2020s, 2050s, and 2080s, where dark green indicates higher predicted lichen values and white indicates low or no lichen.

A group of FMAs maintains the highest lichen suitability by the 2080s, despite differing trajectories over time. ANC Timber, Hinton Pulp, Tolko Industries and Footner Forest Products, and Manning Diversified Forest Products. exhibit higher suitability in the 2020s than during at least one historical baseline period, followed by modest declines by the 2080s. Although suitability does not increase monotonically across all periods, these FMAs retain the highest late-century values relative to other tenure areas.

A second group, including Slave Lake, Sundance, and Blue Ridge, shows gradual improvement from historic lows to mid-range values in the future periods. This moderate upward trend suggests that these FMAs remain viable for lichen-sensitive management, even though they do not reach the suitability levels of northern or foothill FMAs. To highlight this increase, Figure 6 presents the change in lichen suitability for the Slave Lake FMA as an example, showing a continued upward trend across all climate periods.

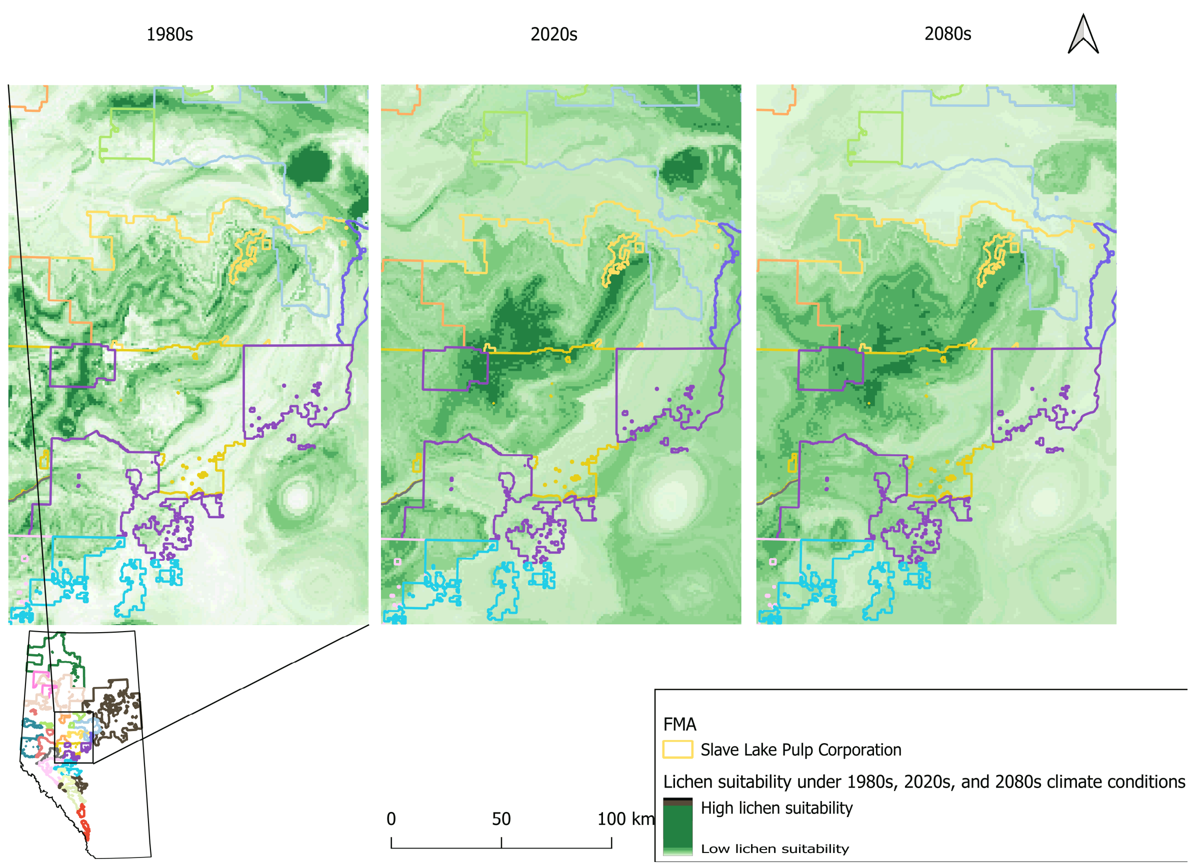

Figure 6. Lichen suitability for the Slave Lake FMA under 1980s, 2020s, and 2080s climate conditions, illustrating a continued increase in suitability across all periods.

A third group, Weyerhaeuser Edson and Weyerhaeuser Drayton Valley begin with low historic values but improve to moderately low levels by the 2020s–2080s. Their shift from red to orange shading reflects a relative increase in climate suitability. These FMAs retain more management value than persistently low areas and may justify continued habitat-focused actions.

A final group of FMAs exhibits persistently low lichen suitability across all periods. Spray Lake Sawmills and Vanderwell Contractors fall into this category, with low historic values that remain low or decline further under future climate conditions. Spray Lake Sawmills shows a pronounced reduction in average lichen suitability, declining by 49% from the historic period to the 2080s, while Vanderwell Contractors maintains consistently low values across all periods. These patterns indicate limited climatic capacity to sustain or recover lichen habitat. As a result, continued investment in lichen focused management within these FMAs is unlikely to deliver substantial ecological returns compared with areas showing greater climatic resilience. Figure 7 illustrates this downward trajectory for the Spray Lake FMA, where areas of higher lichen suitability contract over time and regions of low or no suitability expand.

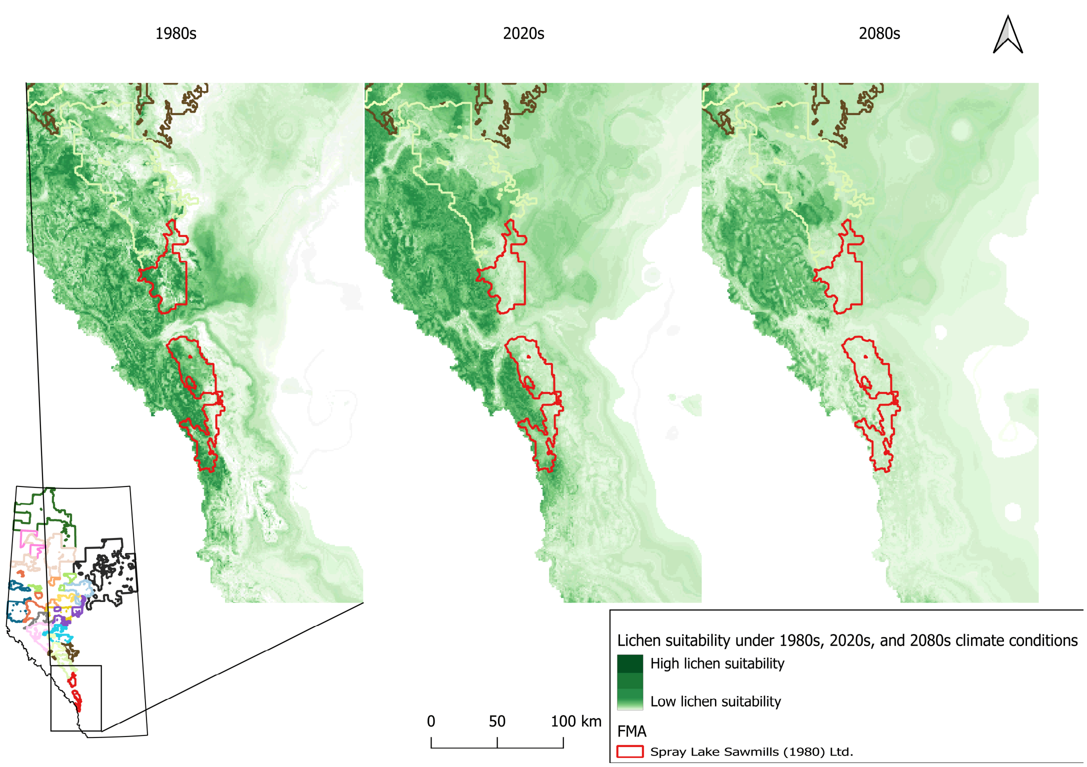

Figure 7. Change in lichen suitability for the Spray Lake FMA under 1980s, 2020s, and 2080s climate conditions, illustrating a continued decline over time.

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 somewhat reduces lichen habitat suitability across the province

Maps of predicted lichen suitability show a steady decline in high-value habitat from the 1980s to the 2080s (Figure 4). Areas with the darkest green values in the 1980s become progressively lighter, indicating a reduction in sites capable of supporting high lichen abundance. Table 1 supports this pattern, with most caribou ranges exhibiting lower average suitability under future conditions compared with historical periods.

The results also show that the northern part of the province does not respond uniformly. Bistcho Lake, Richardson, Wabasca, and Caribou Mountains retain relatively strong suitability, while

Chinchaga and Slave Lake remain low through all periods. The western foothill ranges, Upper Smoky and Berland, change little across time, suggesting that their climatic setting provides some stability.

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, although some areas lose lichen over time, the overall results show that climate change does not cause a uniform decline in lichen habitat across Alberta. Although areas of high suitability decrease from the 1980s to the 2080s, the extent of low to moderate suitability expands in several northern and higher-elevation regions. Increased summer precipitation in these areas partially offsets warming-driven increases in evapotranspiration, allowing lichen habitat to persist even as peak suitability declines.

This pattern reflects a shift from concentrated high-quality habitat toward a broader distribution of moderate suitability. Climate change therefore produces a more differentiated landscape rather than a simple loss of lichen. Areas that maintain stable or improving suitability function as refugia for caribou forage and represent locations where conservation and restoration are most likely to yield long-term benefits.

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. Most FMAs show stable or improving lichen habitat with some exceptions

Table 2 shows that Forest Management Areas exhibit a different response to climate change than caribou sub-regional boundaries. On average, lichen suitability across FMAs increases by 17% from the 1980s to the 2080s, whereas average suitability within caribou ranges declines over the same period. This contrast indicates that many FMAs retain or gain climatic capacity to support lichen, even as high-suitability habitat becomes less extensive across the broader landscape.

Most FMAs follow stable or improving trajectories through time. Several tenure areas with low historic suitability increase to moderate levels under future climate conditions. Other FMAs begin with relatively high suitability and decline modestly over time but remain among the highest values province-wide by the 2080s. These offsetting trends contribute to the net increase in average suitability across FMAs while reducing the spread between high and low values.

A smaller group of FMAs remains persistently constrained. Spray Lake Sawmills shows a pronounced decline in average lichen suitability of around 49% from the 1980s to the 2080s, indicating a substantial reduction in climatic support for lichen. Vanderwell Contractors (High Prairie) remains consistently low across all periods, despite a modest increase, reflecting limited climatic capacity for sustaining lichen habitat. In these areas, projected conditions remain well below those observed in most other FMAs.

Overall, the FMA results reveal divergent climate trajectories. Some tenure areas maintain moderate to high suitability under future climates, while others experience persistent or worsening constraints on lichen persistence. These patterns suggest that climate-informed planning should differentiate among FMAs, directing habitat-focused management toward areas with sustained climatic capacity for lichen and limiting investment in locations where long-term recovery is unlikely.

6. Conclusion

A central finding of this study is that climate change does not produce a uniform decline in lichen habitat suitability across Alberta. Instead, large portions of the province are projected to retain moderate climatic capacity for lichen persistence under future conditions. The Random Forest analysis demonstrates that lichen abundance is governed primarily by moisture balance, and ClimateNA projections indicate that increases in summer precipitation partially offset warming-driven moisture loss in many regions. As a result, several northern ranges and higher-elevation foothill landscapes maintain conditions capable of supporting lichen habitat through the 2050s and into the 2080s, even as peak suitability declines.

Forest Management Areas such as ANC Timber, Hinton Pulp, Tolko Industries and Footner Forest Products, and Manning Diversified Forest Products retain relatively higher lichen suitability by the late century compared with other tenures. Although suitability within these FMAs may fluctuate across periods, their projected values remain among the highest under future climates, indicating continued potential to support caribou forage. These landscapes therefore represent high-return conservation areas, where habitat protection or restoration is most likely to yield durable ecological benefits.

At the same time, the results identify a smaller but important set of climatically constrained regions where lichen habitat is unlikely to recover meaningfully. FMAs such as Spray Lake Sawmills and Vanderwell Contractors (High Prairie) show persistently low or declining suitability from the 1980s through the 2080s. Similarly, caribou ranges such as Chinchaga and Slave Lake remain at the lower end of habitat potential across all climate periods. In these locations, reduced snowfall, limited summer moisture, and warming trends combine to restrict lichen growth, regardless of restoration effort.

These climatically limited landscapes represent low-return areas for lichen-focused caribou habitat protection. Imposing strict forestry constraints in such locations is unlikely to generate substantial ecological gains and may unnecessarily intensify conflict with industry. Recognizing these limits supports a climate-informed planning approach that directs conservation investment toward areas with strong climatic capacity to sustain lichen, while allowing greater operational flexibility in regions where long-term habitat potential is constrained. Such an approach aligns ecological effectiveness with economic practicality and provides a clearer basis for reconciling caribou conservation and forest management under continued climate change.

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