Forecasting Alaskan Boreal Ecosystem Changes: A Landscape Analysis of Permafrost Thaw and Hydrological Trajectories Resulting from Climate-Driven Change in the Fire Regime and Conifer Decline

by

Gabriel A. Abreu-Vigil

A thesis accepted and approved in partial fulfillment of the

requirements for the degree of

Master of Science

in Geography

Thesis Committee:

Dr. Melissa Lucash, Chair

Dr. Daniel Gavin, Member

University of Oregon

Spring 2024

© 2024 Gabriel A. Abreu-Vigil

THESIS ABSTRACT

Gabriel A. Abreu-Vigil

Master of Science in Geography

Title: Forecasting Alaskan Boreal Ecosystem Changes: A Landscape Analysis of Permafrost Thaw and Hydrological Trajectories Resulting from Climate-Driven Change in the Fire Regime and Conifer Decline

Boreal forests, covering about 30 percent of Earth's forested area, are dominated by coniferous forests and deemed crucial reservoirs of permafrost and belowground carbon. Undergoing rapid ecological changes from a warming rate nearly three times the global average, questions remain about future interactions of increased wildfire, vegetation shifts, permafrost thaw, and soil moisture for tree growth. Utilizing the LANDIS-II landscape forest model, we simulated soil temperature and moisture, forest succession, and disturbance regimes over a century across 380,400 hectares in interior Alaska under historical and future RCP 8.5 climate scenarios. This integrated approach marks a significant advancement in simulating the dynamic and interconnected processes that define boreal forest resilience and response to climate change. [It would be good if there can be statements here about the predictive capacity of the model…calibration and validation studies, for example]. Under future climate change, permafrost at near-surface levels (3 m) is projected to disappear by mid-century with a thaw rate of 26 cm/year and 18 cm/year under extreme and moderate climate forcing respectively. Exacerbated by a changing fire regime and landscape-level shifts from insulative coniferous to less insulative hardwood coverage, these shifts are accompanied by increased soil temperatures

and decreased moisture levels. The complex interplay between these dynamics in the face of a changing climate has profound implications for boreal forests and the global system alike.

CURRICULUM VITAE

NAME OF AUTHOR: Gabriel A. Abreu-Vigil

GRADUATE AND UNDERGRADUATE SCHOOLS ATTENDED:

University of Oregon, Eugene

West Virginia University, Morgantown

DEGREES AWARDED:

Master of Science, Geography, 2024, University of Oregon

Bachelor of Arts, Geography, 2021, West Virginia University

Bachelor of Arts, Environmental Geoscience, 2021, West Virginia University

AREAS OF SPECIAL INTEREST:

Landscape Ecology

Geographic Information Science

Remote Sensing

PROFESSIONAL EXPERIENCE:

Graduate Teaching Assistant, Department of Geography, University of Oregon, Fall 2022 – Spring 2024

Graduate Research Assistant, Department of Geography, University of Oregon, Fall 2022 – Spring 2024

Graduate Research Assistant, National Aeronautics and Space Administration, Summer 2023

Teaching Assistant, North American Language and Culture Assistant Program, I.E.S. Mar Mediterraneo, Fall 2021 – Spring 2022

GIS Technician, Department of Geography and Geology, West Virginia University, Fall 2018 – Spring 2021

GRANTS, AWARDS, AND HONORS:

University of Oregon Rippey Research Grant, University of Oregon, 2023
Innovation Summit Travel Award, Environmental Data Science Innovation & Inclusion Lab, 2023
President's List, West Virginia University, 2017, 2018, 2019, 2020, 2021
Summa Cum Laude Graduate, West Virginia University, 2021
Student Scholarship, American Society for Photogrammetry and Remote Sensing, 2021
Geography Undergraduate Scholarship, West Virginia University, 2020

ACKNOWLEDGMENTS

This research would not have been possible without the guidance and support of many individuals and organizations. I wish to express my sincere appreciation to my advisor, Dr. Melissa Lucash, for her unwavering support, invaluable feedback, and the immense amount of time she invested in me and this project. Her dedication and passion for science inspire me every day. Dr. Shelby Weiss also played a crucial role in helping parameterize, calibrate, and run the model. Her assistance and willingness to answer my questions were instrumental throughout this process. I am also grateful to my committee member, Dr. Dan Gavin, for his insightful feedback and for teaching me much about fire ecology and landscape dynamics in Oregon and beyond.

A special thanks to the TEEL lab for their endless support and sense of community over the past two years and for helping create the best lab on campus (or in the world). Colin, James, Hana, and Wesley, I could not have asked for a cooler, smarter, and more fun lab. I wish you all the best and you always have a good friend here (wherever I go). Additionally, I am thankful for the camaraderie and support from Addy Pletcher, Alex Casey, and the rest of the Geograds, who have made graduate school less challenging and more enjoyable.

On a personal note, I want to thank my family—Hernan Abreu, Demica Vigil, and my sister Reyna Abreu-Vigil—for their support and encouragement throughout my graduate studies. Their love and belief in me have been a constant source of strength.

I also want to acknowledge my collaborators Adrienne Marshall, Kate Hayes, Brian Buma, and Dmitry Nicolsky, whose contributions were vital in getting this project off the ground. The Bonanza Creek LTER, especially the modeling team, provided invaluable support and a fantastic boreal forest research community in Alaska. Finally, this research was funded by the National

Science Foundation (NSF # DEB 2224776), and I am grateful for their financial support, which made this work possible.

Table of Contents

LIST OF FIGURES

Figure Page

LIST OF TABLES

Table Page

INTRODUCTION

Boreal forests under a changing climate

Boreal forests, also known as taiga, cover around 30% of the world's forested area and are renowned for their vast wilderness and significance as the largest soil reservoir of global terrestrial carbon, locked within 'permanently' frozen soil (Pan et al., 2013; Apps et al., 1993). This carbon has incredible potential to change the global system, with this pool containing roughly twice the carbon in the atmosphere (Baillargeon et al., 2022). Overlaying much of the world's permafrost zones, climatic and ecological changes in these northern landscapes are critically important for both the Arctic and global climate. High-latitude regions, particularly Alaska, have become focal points due to their heightened vulnerability to rapid climate changes, primarily through wildfire, permafrost thaw, and shifts in post-fire successional trajectories (Helbig et al., 2016; Johnstone et al., 2010; Wolken et al., 2011). Over the past six decades, Alaska has experienced a warming trend three times faster than the contiguous U.S., especially in winter, leading to unprecedented regional changes (Chapin et al., 2014; Taylor et al., 2013). Alongside temperature increases, precipitation in this region is projected to rise in all seasons, notably as rain (Douglas et al., 2020).

The uncertainties of these climatic shifts necessitate comprehensive ecological modeling to simulate the complex dynamics of these systems under various future climate scenarios. While the impact of these changing climate variables on the presence and thickness of permafrost is profound, other critical drivers of permafrost vulnerability include wildfires and alterations in overlying vegetative cover. These elements threaten the stability of permafrost and amplify the feedback loops, contributing to further climate change (Loranty et al., 2016). The losses of permafrost carbon are irreversible at centennial timescales, and there remains significant uncertainty regarding the timing and magnitude of emissions from permafrost (IPCC, 2023). Most climate models still do not include permafrost processes. However, the remaining carbon budgets featured in AR6 WG1 include emissions from permafrost for the first time, using a simplified estimate that assumes a linear relationship between warming and permafrost emissions. This estimate excludes critical thaw processes such as abrupt thaw and fire-permafrost interactions, potentially underestimating permafrost carbon emissions (IPCC, 2023). Understanding and mitigating these drivers is essential for preserving the integrity of boreal forests and their role in the global carbon cycle. Each assessment report highlights the increasing urgency to reduce carbon emissions to avoid the most catastrophic impacts of climate change, emphasizing the need to address the magnitude of permafrost carbon emissions and incorporate them into models (IPCC, 2023).

Wildfire

Wildfire research in North American boreal forests underscores the pivotal role of fires in shaping these ecosystems (Johnstone et al., 2010; Hollingsworth et al., 2013; Weiss et al., 2023). Fires are frequent and essential for maintaining the health of boreal forests, clearing away the organic layer, and stimulating the growth of fire-adapted, early seral species like black spruce and birch (Roland et al., 2019; Shabaga et al., 2022). This process releases stored nutrients, enriching the soil and supporting new vegetation growth (Sturm et al., 2005). This nutrient enrichment is a natural fertilizer, enhancing the ecosystem's regenerative capacity.

However, recent fire patterns indicate that rising temperatures and altered precipitation have increased the frequency and size of fires in the region (Kasischke et al., 2010; Hollingsworth et al., 2013). These intensified wildfires exacerbate permafrost thaw in near-surface (0-3 meters deep) by imputing heat into the soil and removing the insulating coniferous vegetation (Helbig et al., 2016). As fires become more frequent and intense, the processes that historically rejuvenated the ecosystem now pose significant challenges to its equilibrium. This shift highlights a critical juncture for the resilience and stability of boreal forests, with far-reaching implications for their future under changing climatic conditions.

Vegetation

Coniferous forests, dominated by black spruce in lowlands/northern aspects and white spruce in uplands, have been both keystone and legacy species in Alaska for millennia, shaping the ecosystem with their unique adaptations (Lynch et al., 2002; Higuera et al., 2009). These species are well adapted to fires, with features such as semi-serotinous cones and fast post-fire regeneration. However, the changing fire regime, exacerbated by climate change, increases their vulnerability due to uniform age structures, high flammability, and susceptibility to pests (Johnstone et al., 2020). In contrast, hardwood deciduous species like birch and aspen, with rapid growth, high seed dispersal rates, and higher moisture content, are often found in southern aspects and are less prone to fire. Increased temperatures and storm activity leading to higher fire occurrence can dry out and ignite coniferous forests before they reach sexual maturity, interrupting their historical cycle (Hoecker & Turner, 2022). This shift in fire frequency and intensity increasingly favors the spread of hardwood forests (Weiss et al., 2023).

The interplay between permafrost-driven conditions, water use, and fire adaptation shapes the intricate mosaic of the boreal landscape in interior Alaska. Producing and maintaining a thick insulating layer of organic material, coniferous forests are vital in maintaining permafrost and influencing hydrological dynamics (Zasada et al., 1992). This organic layer, more pronounced in coniferous forests due to slow decomposition rates, retains moisture and insulates the ground, impeding the establishment of hardwood species (Johnstone & Chapin, 2006; Greene et al., 2007). Hardwood trees, requiring better-drained soils and having smaller seeds, struggle to penetrate this deep, moist layer of decomposing material in mature, unburned stands (Sturm et al., 2005).

This natural barrier helps maintain higher soil moisture level conditions less conducive to hardwood growth. Conifer species, with efficient water-use strategies and needle leaves that reduce water loss, thrive in these water-limited conditions. In contrast, hardwoods with broader leaves face higher water loss through transpiration (Krause & Lemay, 2022). The distinct water-use strategies of conifers and hardwoods underscore the complexity of forest dynamics and their intricate relationship with the environment. A warming climate and variable precipitation threaten to unbalance this relationship, potentially disrupting legacy ecosystem functions and further driving permafrost thaw.

Permafrost

In interior boreal Alaska, permafrost is extensive yet discontinuous (Jorgenson et al., 2010; Fisher et al., 2016; Nicolsky et al., 2017). This perennially frozen rock, soil, and ice, modulated by temperature (<0°C for at least two consecutive years), is a critical foundational layer for the ecosystem. The ecological impacts of permafrost thaw are acute and dynamic, both responding to and influencing many processes. Recent observations indicate substantial and accelerated changes in permafrost due to warming temperatures and increased rainfall (Jorgenson et al., 2010; Douglas et al., 2020; Hansen et al., 2023). As permafrost thaws, carbon from organic matter is released into the atmosphere as carbon dioxide or methane following decomposition

(Schuur et al., 2018). Once considered a slow and gradual process, permafrost thaw is now rapidly advancing due to changing climatic conditions.

Much of the boreal vegetation has adapted to the presence of permafrost over time. As permafrost becomes unstable, vegetation dynamics are disrupted. Black spruce, covering approximately 40% of the landscape, particularly faces challenges as the ground beneath it shifts and becomes less supportive (Cleve & Viereck, 1983; Jafarov et al., 2013). The relationship between this species and near-surface permafrost is outlined in Fryer et al. (2014) and Osterkamp et al. (2000), which describes a spatial signature of the presence of black spruce aligning with that of permafrost, making them spatial proxies for each other. The interplay between permafrost thaw, driven by climate and landscape change, has far-reaching consequences on the boreal forest ecosystem and beyond.

Hydrology

A critical factor in boreal hydrology is the delicate balance between permafrost, water storage in the landscape, and its uptake by vegetation. Altered precipitation amounts and forms under future climate change will further influence boreal hydrological and biological cycles, extending to below-ground attributes (Jones et al., 2006). As permafrost thaws, it triggers several cascading effects, particularly in hydrology. The once-frozen ground, which acts as a natural barrier to water infiltration, weakens, allowing increased water infiltration (Ebel et al., 2019). These changes affect drainage patterns and the stability of the entire ecosystem, impacting both surface and subsurface flows. This shift in soil moisture influences tree growth, with more variable precipitation conditions impacting overall forest composition. Shallow-rooted trees face challenges in establishment and growth under these variable hydrological conditions. Moreover, periods of variable precipitation influence moisture conditions at the near surface and fire ignition and spread by drying vegetation and ground fuels (Beck et al., 2011). These fires, in turn, impact hydrology by altering streamflow patterns, increasing sediment transport, and potentially compromising water quality (Potter et al., 2020). This interlinked dynamic underscores the complexity of boreal forest ecosystems and the critical role of permafrost in maintaining their stability.

Interconnected dynamics and modeling

At the precipice of profound changes to Alaska's climate and ecology, modeling tools are essential for accurately representing and simulating these dynamics under various emissions pathways. Comprehensive and robust models are crucial for understanding how climate, vegetation, hydrology, permafrost, and wildfire interactions will evolve in response to ongoing and future climatic shifts. While models for permafrost exist, they often lack the integration of wildfire and vegetation influences within a spatially interactive framework. These integrative tools enable researchers to illuminate how climate change and landscape disturbances impact boreal ecosystems' resilience in Alaska.

Using the model LANDIS-II, Weiss et al. examined the influence of multiple fire events and changing climatic conditions on the boreal landscape. Their findings reveal that conifer-dominated forests risk significant declines, especially under scenarios characterized by frequent and severe fires combined with pronounced climate change. The study highlights substantial declines in conifer dominance when multiple fires coincide with extreme (hot and wet) climate change scenarios. These abrupt transitions indicate non-linear behavior and potential ecological tipping points (Scheffer et al., 2012). This aligns with ecological theory, emphasizing that positive feedback loops could lead to rapid shifts from conifer to hardwood dominance (Chapin et al., 2004; Kurkowski et al., 2008). Compounding with increased climate change, wildfire and vegetation drivers of permafrost thaw are crucial for understanding the future conditions of this boreal system.

The intricate relationship between fire, vegetation dynamics, and climate change underscores the delicate balance between natural processes and ongoing anthropogenically forced environmental changes. The evolving fire regime and its implications for ecosystem resilience highlight the pressing need for comprehensive research, management strategies, and policy considerations to ensure the sustainable coexistence of natural processes and human activities in this changing landscape.

Research question

How do climate change and wildfire modulate changes in permafrost thaw, soil temperature, and moisture in boreal Alaska?

Hypothesis

H1: Changes in the fire regime under future climate scenarios will significantly shift vegetation from conifer-dominated to hardwood-dominated forests, influencing near-surface soil temperature and site water balance dynamics.

H2: Under future climate change scenarios (NCAR and GFDL) (2000-2100), permafrost will thaw more rapidly than under historical conditions (years 1970-1999).

H3: Rising soil temperatures and altered precipitation under climate change will lead to decreased soil moisture, especially under conditions of enhanced permafrost thaw.

METHODS

Study area

The scope of this research focuses on a boreal landscape spanning 380,400 hectares in interior Alaska, divided into 4-hectare (0.2 km x 0.2 km resolution) grid cells (Figure 1). Interior boreal Alaska experiences a continental climate with cold winters with average January temperatures of -23.5°C and warm, dry summers with average July temperatures of 16.3°C. With a growing season lasting from May to September, the average annual precipitation in Fairbanks is 287 mm, with around 35% of it as snowfall. This landscape lies within Alaska's intermontane basin and plateau region, between the Alaska and Brooks Mountain ranges.

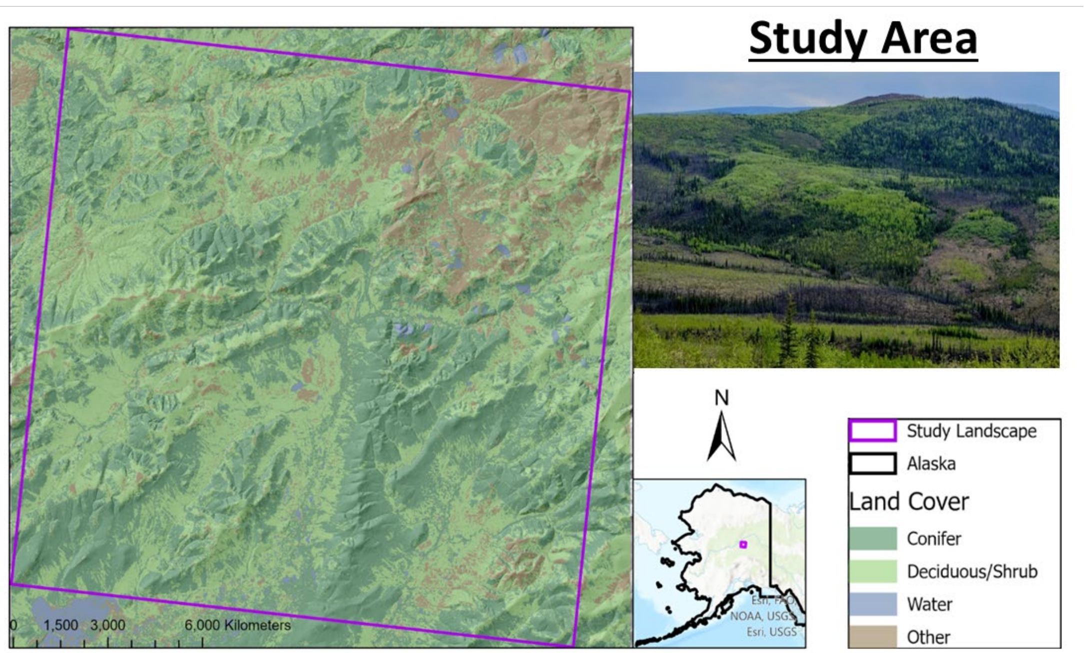


Figure 2: Map of the study area (purple) with forest functional types on the landscape classified from 2022 Landsat 8 image.

The study landscape falls within the extent of North America's boreal forests (Figure 2a), generally associated with the discontinuous permafrost zone where 50-90% of the land has near-surface permafrost (Figure 2b). In this permafrost extent, much of the 'permanently' frozen ground is found beneath coniferous land cover in cool, wet lowlands and at the base of north-facing slopes (Fryer et al., 2014; Stralberg et al., 2020). This area displays various surface hydrology features ranging from oligotrophic lakes and ponds to braided streams and rivers. In the past 40 years, the area in the study landscape has seen 13 fires (Figure 2c), and during the period from 1992 to 2015, the study area encountered an average of 1.05 wildfires annually. With the typical fire size being 3,795 hectares on average and a fire rotation of 119 years (Short, 2023), the forest on the landscape would historically burn once every century.

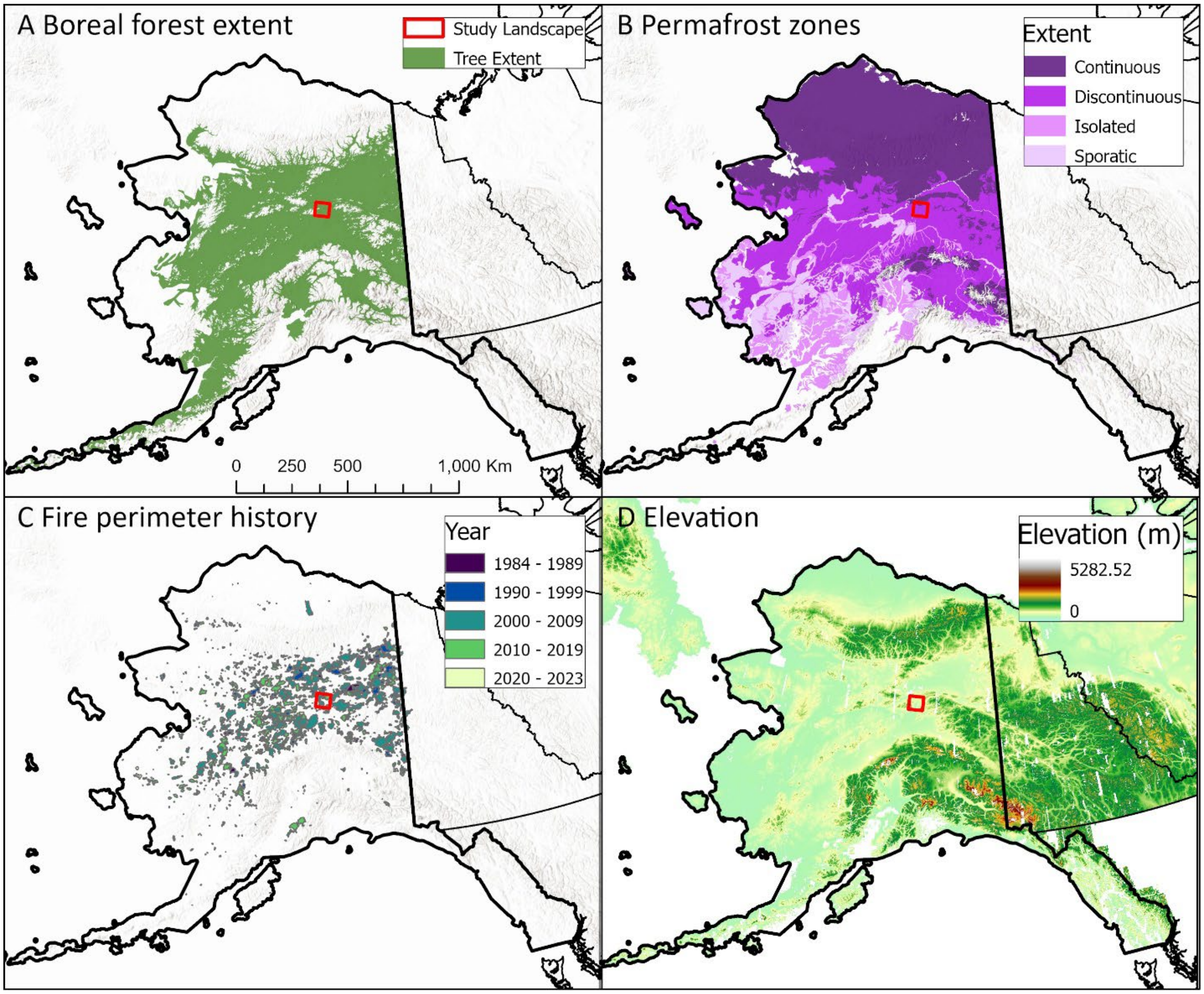


Figure 2: Alaskan reference maps of boreal forest extent (A), permafrost zones (B), fire history (C), and elevation (Brandt, 2009; Jorgenson et al. 2008; MTBS; Porter et al., 2023)

It showcases a variety of topographic complexity with undulating hills, river valleys, lake plains, and other post-glacial landscape features (Begét et al., 2006). This area's elevation (Figure 2d) ranges from 92 to 976 meters, with an average elevation of 331.4 meters. The study area is generally flat, with an average slope of 6.3 ° (standard deviation: 5.0 °), although the steepest slope measures 36.13 °.

LANDIS-II model

This study employed LANDIS-II (version 7.0), a modular, open-source forest landscape model that spatially simulates dynamic landscape ecological processes and interactions (Scheller et al., 2007). LANDIS-II operates on a grid-based system where each cell is populated with species-age cohorts, allowing for detailed representations of forest succession and the interactions of multiple ecological processes within and across these cells. The model's core strength lies in its flexibility to incorporate various extensions that simulate different ecosystem processes and disturbances (e.g., wildfire, succession, harvest). These account for the complexity of forest conditions, enhancing the model's applicability to diverse forest dynamics scenarios. Forests are modeled with species-aged cohorts that grow and compete over time, with cells possibly containing multiple cohorts of each species. Within LANDIS-II, specific ecological parameters are assigned to these various groups, including species longevity, reproductive maturity, shade tolerance, seeding distance, and post-disturbance regeneration strategies like serotiny or resprouting. These are crucial for modeling the succession and survival of cohorts within a cell and in interaction with neighboring cells. The model's extensions leverage various deterministic and stochastic processes, allowing for simulations that reflect both expected and random ecological outcomes. This dual approach captures the unpredictable nature of ecological responses to climatic and environmental changes. Spatial heterogeneity is represented through the concept of “ecoregions” on the modeled landscape, areas with homogeneous climate and site characteristics that influence the transmission of disturbances and the biological responses of the forested landscape. To address the impacts of climate change, LANDIS-II integrates climate scenarios via a Climate Library (Lucash & Scheller, 2021), which provides synchronized climate inputs across all modules, ensuring that the model reflects up-to-date and region-specific climate conditions. Through this sophisticated modeling approach, LANDIS-II provides a comprehensive framework for understanding and predicting the complex interactions and feedback mechanisms that drive forest landscape dynamics under varying environmental and climatic conditions.

DGS succession extension

The DGS (DAMM-McNiP GIPL SHAW) extension, integrated within the LANDIS-II model, simulates vegetation succession, hydrology, carbon and nitrogen dynamics, soil temperature, and soil moisture. we implemented this extension on our landscape to simulate boreal forest successional dynamics, improving on its succession extension predecessor (NECN), particularly in modeling belowground processes, which are crucial in high-latitude systems affected by permafrost and freeze/thaw dynamics (Lucash et al., 2023). A notable advancement is DGS's ability to model soil temperature and soil moisture at various user-defined soil depths. This extension incorporates two key models for below-ground processes: SHAW (Simultaneous Heat and Water) and GIPL (Geophysical Institute Permafrost Laboratory) 2.0 (Nicolsky et al., 2009). SHAW, a physically based model, simulates vertical heat, water, and solute transfer through the soil-vegetation-atmosphere continuum (Flerchinger, 2000). It simulates evapotranspiration, snow accumulation and melting, surface runoff, infiltration, and soil moisture. GIPL 2.0, on the other hand, solves a nonlinear heat equation with phase change and is specialized for simulating permafrost dynamics down to 75m (Marchenko et al., 2008; Nicolsky et al., 2017). It receives total water and ice content values from SHAW. It computes ground temperature profiles used to calculate the presence of permafrost, active layer (depth to permafrost) thickness, and talik (unfrozen layer within permafrost) thickness.

Within the DGS extension, cells are assigned to Temperature-Hydrology Units (THUs) based on climate zone, vegetation type, topography, and time since disturbance. Each THU has a specific set of input parameters for SHAW and GIPL, defining soil thermal and hydrological properties. GIPL computes soil temperature profiles, which informs the lower boundary condition for SHAW. SHAW then computes soil moisture, which is shared with vegetation succession within DGS. The DGS extension uses this information to assess water and temperature limitations for species cohort growth. Vegetation growth is simulated monthly in DGS based on species-specific life history attributes, temperature, age, competition, water and nitrogen availability, and disturbances. Additionally, the simulation of leaves, wood, fine roots, and coarse roots ensures the comprehensive modeling of vegetation attributes critical in the interaction with above- and below-ground interactions such as fire and water/nutrient uptake from soil. Regeneration is influenced by species attributes, light, and water availability and is also captured with the simulation of vegetation reproduction and subsequent seed production/dispersal. DGS models mortality as a result of senescence (the continual shedding of trees and branches), age (to capture the rise in mortality as a species nears its life expectancy), and disturbances (particularly fire in this study). Soil carbon and nitrogen (CN) dynamics in DGS rely on the DAMM-MCNiP model, which simulates seven soil pools that can be compared to in-situ observations. These soil pools are sensitive to soil moisture, temperature, oxygen concentration, substrate CN stoichiometry, and other factors (Lucash et al, 2023; Abramoff et al. 2017).

SCRPPLE fire extension

The SCRPPLE (Social-Climate Related Pyrogenic Processes and their Landscape Effects) extension, designed to simulate wildfire behavior and its effects on landscapes, was used to simulate the primary disturbance in this landscape (v. 3.2; R. Scheller et al., 2019). This extension uses a data-driven approach to parameterize fire behavior based on climatic variables and landscape characteristics. It allows for the simulation of fire regimes that respond dynamically to changes in climate, including temperature, precipitation, wind direction, and wind speed. The extension's core algorithms include ignition, fire spread, fire intensity, and fire mortality, and it can simulate three types of fires: lightning, human unintentional (accidental), and prescribed fire (RxFire).

The SCRPPLE extension models ignition using a "supply and allocation" approach in which maps of fire ignition probability are fed into the extension. These probabilities are calculated using the map of ignitions integrated with the Fire Weather Index (FWI). The spread of fire occurs from cell to cell, and the probability of spread is based on the FWI, effective wind speed, and fine fuels. Fire spread continues until it reaches a maximum daily spread area, which is determined by empirical relationships between daily fire spread areas, FWI, and Effective Wind Speed. The extension defines three classes of fire intensity: Low, Moderate, and High. These intensity levels correspond to flame lengths and are used to categorize fire behavior. Fire intensity influences mortality and is determined by various factors, including fine fuels, ladder fuels, and neighboring fire intensity. Fire mortality varies based on this intensity, as well as tree species, and tree age. Mortality tables are defined for each fire intensity class and tree species, specifying the probability of mortality for different age ranges for each species.

Parameterization and calibration

Vegetation inputs

To establish initial ecological and environmental conditions in our simulation landscape, we relied on a combination of data sources to parametrize various key components, including vegetation, biophysical, and climate inputs. U.S. Forest Service Forest Inventory and Analysis (FIA) data from the Tanana region surveys in interior Alaska (USDA-Forest Service, 2018) served as a foundational resource for the initial vegetation composition. Complementing this data, we incorporated information from the Alaska Center for Conservation Science Mosaic Landcover Map of Alaska (AKCCS, 2019) to establish initial spatial vegetation patterns. Six tree species, three shrub genera, and three moss functional types were modeled on our simulated landscape, as outlined in Appendix Table 1. Methodology from Lucash et al. (2019) and Weiss et al. (2023), where FIA plots were associated with specific land cover types, elevation data (USGS, 2020), and climate region mapping were used to establish initial conditions. Notably, tree ages within FIA plots were estimated using site index curves, while species-age cohort data from FIA plots were assigned to individual cells on the landscape. This was based on site characteristics such as elevation categories and hierarchical land cover type classifications. For shrub species, since the FIA database lacked biomass information, constructed estimates based on percent cover, height class, and associated stand ages were made (Weiss et al 2023). Specifically, linear models were developed to relate shrub biomasses at specific height classes to percent cover, leveraging data from Bonanza Creek Long-Term Ecological Research (LTER) datasets (Viereck et al., 2010) and allometric equations provided by Berner et al. (2015). The result was a comprehensive map detailing the age cohorts of tree species and shrub species, as well as select moss functional types, along with their relative biomasses, for each cell on the landscape. Details regarding the construction of this initial vegetation map can be found in Weiss et al. 2019 and the appendices of Lucash et al. (2023).

Biophysical and climate inputs

Biophysical inputs encompass critical factors such as soil texture, soil depth, soil drainage class, field capacity, wilting point, and organic matter, all of which are essential for modeling below-ground and vegetation and below-ground dynamics at the landscape scale. These inputs were derived from the State Soil Geographic data provided by USDA-NRCS, (National Cooperative Soil Survey). Inputs to the SHAW module of the DGS extension were sourced from a combination of literature values and GLUE analyses conducted by Marshall et al. (2021), while the GIPL soil temperature module inputs were obtained through the assimilation of temperature observations from various sites across interior Alaska (Lucash et al., 2023).

Daily weather inputs were pivotal in providing climatological information for the succession and fire extensions within the LANDIS-II framework. We utilized climate data from two General Circulation Models (GCMs) to establish historical (1970–1999, NCAR-CCSM4) and future (2000–2100, GFDL-CM3 and NCAR-CCSM4) climate streams. These data were obtained from the Scenarios in Arctic Planning Group (SNAP) and dynamically downscaled to a 20 km resolution using the Weather Research and Forecasting (WRF) model (Bieniek et al., 2016; Lader et al., 2017). Following the methodology of Lucash et al. (2019), k-means cluster analysis was employed to identify areas with similar climate patterns, utilizing average monthly precipitation and temperature data from 2000 to 2100. The optimal number of clusters was determined based on average silhouette values and the sum of squares errors, resulting in a five-cluster solution. By employing the climate regions of LANDIS-II to group areas with similar climates, a consistent climate stream to all cells within each region was achieved. A map of climate regions used in this study can be seen in Appendix Figure 2. A quantile mapping approach was adopted to ensure the consistency of climate outputs with historical observations, using the ERA-Interim reanalysis data to bias correct each variable for each climate region on the landscape.

Parameterization and calibration of DGS succession extension

Parameters for the GIPL module of DGS were derived from a combination of published literature values and field estimates in Interior Alaska. The latter of these are from ground temperature data from two Ameriflux sites representative of black spruce (Smith Lake 2) and paper birch dominance (UPA1). SHAW module parameters were initially set using literature estimates and field data, then optimized through a Generalized Likelihood Uncertainty Estimation analysis conducted by Marshall et al. (2021). SHAW provides water and ice content values to GIPL. In the DGS model, these modules are coupled to provide interdependent information. For instance, SHAW provides water and ice content values used by GIPL and GIPL soil temperature for SHAW, iteratively linking the dynamics of soil attributes. The performance of DGS was calibrated and tested using field data from three sites representing different vegetation and successional states: a burned site, a black spruce-dominated site, and a hardwood deciduous site. Single-cell simulations were used to represent each site. DGS's performance was compared to a similar LANDIS-II extension, NECN, which has a less complex representation of soil pools, fluxes, and dynamics related to soil moisture and ground temperature. DGS outperformed NECN in representing seasonal trends in soil moisture and temperature at sites in interior Alaska (Lucash et al., 2023).

Vegetation growth within the DGS extension is also simulated using inputs and calibration specific to various species' functional groups. Maximum relative gross primary productivity data across a range of soil water contents and soil temperature at 10cm depth from Ameriflux sites in interior Alaska (Kobayashi et al., n.d-a, 2019b; Ueyama et al., n.d.-a, 2018b, 2018a) were used to fit nonlinear temperature and soil moisture response functions for conifers, hardwoods, shrubs, and mosses. To calibrate individual species growth, single-cell simulations were run with single young cohorts (one year with 100 gm-2 biomass) for 200 years under historic climate forcing. Biomass trends from these simulations were compared with FIA tree biomass data plotted against stand age, serving as a reference growth trajectory. Simulations were iteratively adjusted using variables with high uncertainty (KLAI, MaxANPP, FCFRAC, MAXLAI, K) through a particle swarm optimization algorithm with the hydroPSO package in R (Zambrano-Bigiarini & Rojas, 2018) to match species single cohort trajectories with reference data. For validation, simulated biomass trajectories were compared with field data by populating a 20,000-ha test landscape with woody plant composition from plots measured at sites that had not experienced a fire for 12-15 years. Simulations of 200 years were run under historic climate forcing with wildfires, and trends in species biomass from cells with a fire history consistent with reference plots from an upland and lowland site were analyzed and compared.

Parameterization and calibration of SCRPPLE fire extension

Parameterization and calibration of the SCRPPLE model involved utilizing climatic variables and landscape-specific attributes to align simulations closely with observed fire behaviors and effects. Calibration was performed by comparing the modeled results, such as ignition rates and fire spread, against established databases like the GeoMac daily fire perimeters and the Alaska Large Fires Database. These comparisons, detailed in the supplemental graphs of Weiss 2023 dissertation, helped pinpoint discrepancies and adjust parameters like ignition probability and fire spread dynamics linked to fire weather indices and fuel biomass. Around

90% of fires in Alaska started from lightning ignition, which was the only fire source in our study. The zero-inflated Poisson model for fire ignition probability and the probabilistic model for fire spread was calibrated using historical ignition (Short, 2021) and perimeter data (GeoMAC, 2019; GeoMAC, 2020), alongside meteorological (Menne et al., 2012), topographical (USGS, 2020a), and fine fuels data (USGS, 2020b). This calibration ensures accurate simulation of wildfire dynamics on the virtual landscape, facilitating robust ecological analysis of future trajectories in boreal Alaska. Each fire's spread is limited by a maximum daily area, determined by historical fire area data and effective wind speed. Fire mortality is assessed on two levels: site-level and cohort-level. Site-level mortality is influenced by soil characteristics, the previous year's climate, and available fuels during the fire. Cohort-level mortality factors include fire severity at the site level, age of the vegetation cohort, and specific traits such as the bark thickness of the species involved. Accurately simulating wildfire on this virtual landscape, paired with the DGS extension for vegetation succession, facilitated robust landscape ecological analyses of boreal Alaskan future trajectories.

Simulations

A total of 30 simulations were conducted, with 10 of them serving as replicates for the 'historical' climate data stream using NCAR-CCSM4 historical data from SNAP, and 10 replicates for each of the RCP 8.5 scenarios using both NCAR-CCSM4 (NCAR) and GFDL-CM3 (GFDL). Each simulation spanned 100 years, during which the historic scenarios randomly selected one year of data from the 30 available years in the data stream annually. This random selection ensured that each historical replicate had a unique sequence of climate inputs for the 100 years. The GFDL scenario was considered the more extreme of the two future climate change, characterized by higher end-of-century temperature and precipitation values (Figure 3). While each replicate shared identical input parameters within its respective scenario, inherent stochastic processes such as wildfire and seed dispersal led to unique end-of-century outcomes across replicates. In subsequent analyses, averages and variability were computed across replicates to offer insights into the range of model outcomes resulting from these stochastic processes. Particularly, R (version 4.2.3) was used to process the SHAW and GIPL output to determine landscape attributes related to permafrost and its thaw from driving forces of vegetation change, climate, and related disturbance (R Core Team, 2021).

Analysis

We investigated transition states between conifer vegetation dominance and that of hardwood functional groups using the Output Reclass extension (Scheller & Mladenof, 2004). Annual maps of forest type were used to determine the prevailing vegetation type within each grid cell at yearly time intervals. Three primary vegetation categories were considered: conifer-dominant, hardwood dominant, and non-forest. Changes in these categories were also used in tandem to understand shifts in the permafrost extent, active layer depth, and hydrological aspects of the landscape.

The spatial correlation of raster output from DGS and Output Reclass was calculated using Pearson's correlation in R to validate the relationship between permafrost presence and the occurrence of conifer vegetation. This relationship, highlighted in Jafarov et al. (2013) investigates the association between these two variables. The binary data of these rasters (1 for conifer, permafrost; 0 for hardwood, no permafrost) were tested with a correlation coefficient to quantify the degree of spatial relationship between permafrost and conifer presence.

An effect size analysis was carried out to assess the influence of multiple environmental factors on soil temperature and moisture (volumetric water content, VWC) in this landscape. This statistical method was chosen to understand the main effects and interaction effects between four key independent variables: climate region, time since disturbance (greater or less than 10 years), vegetation type (conifer or hardwood), and climate scenario. These factors were hypothesized to influence changes in soil temperature and moisture, an essential indicator of ecological shifts due to climate change. This method allows for examining each factor independently (main effects) and the interaction between factors (interaction effects). This is crucial in ecological studies where the combined influence of multiple factors differs from the sum of their individual effects. The model was specified as follows:

$$ST\_mean \sim ClimateRegion \times TimeSinceDisturbance \times VegetationType \times ClimateScenario$$

and

$$VWC\_mean \sim ClimateRegion \times TimeSinceDisturbance \times VegetationType \times ClimateScenario$$

Each factor was treated as a fixed effect. The dependent variables, mean soil temperature (ST_mean) or mean VWC, were obtained from annual model output. Partial eta-squared values were calculated to quantify the magnitude of the effects observed in the factorial ANOVA. This measure of effect size indicates the proportion of total variation attributable to each factor and their interactions after accounting for the variation explained by other factors in the model. Effect sizes were calculated using the effectsize package in R, which provides a standardized measure of how much variance each predictor is responsible for in the response variable, independently of other predictors (Ben-Shachar et al., 2020). Partial eta squared values identify which factors most affect the dependent variables, thereby guiding further analysis and interpretation. This method was chosen over others, such as multifactorial ANOVA, since p-values are inappropriate for this type of data in modeling studies that can be replicated under different simulations to achieve optimal results. Effect sizes were particularly important in this study to distinguish between statistically significant results that may have limited ecological impact versus those that explain a substantial portion of the variance in soil temperature and moisture.

RESULTS

Climate, wildfire, and forest type

Under a historical climate, our baseline forcing shows stable trends in both precipitation and temperature throughout the simulation period with relatively low year-to-year natural variability (Figure 3). Under moderate climate change (NCAR), average precipitation increased by 33%, and temperature increased by 6.5 °C. Under the extreme future climate (GFDL) scenario, precipitation and temperature increased more rapidly by 77% and 10 °C, respectively. Year-to-year variation in both future climate change scenarios was higher than in historic climate forcing.

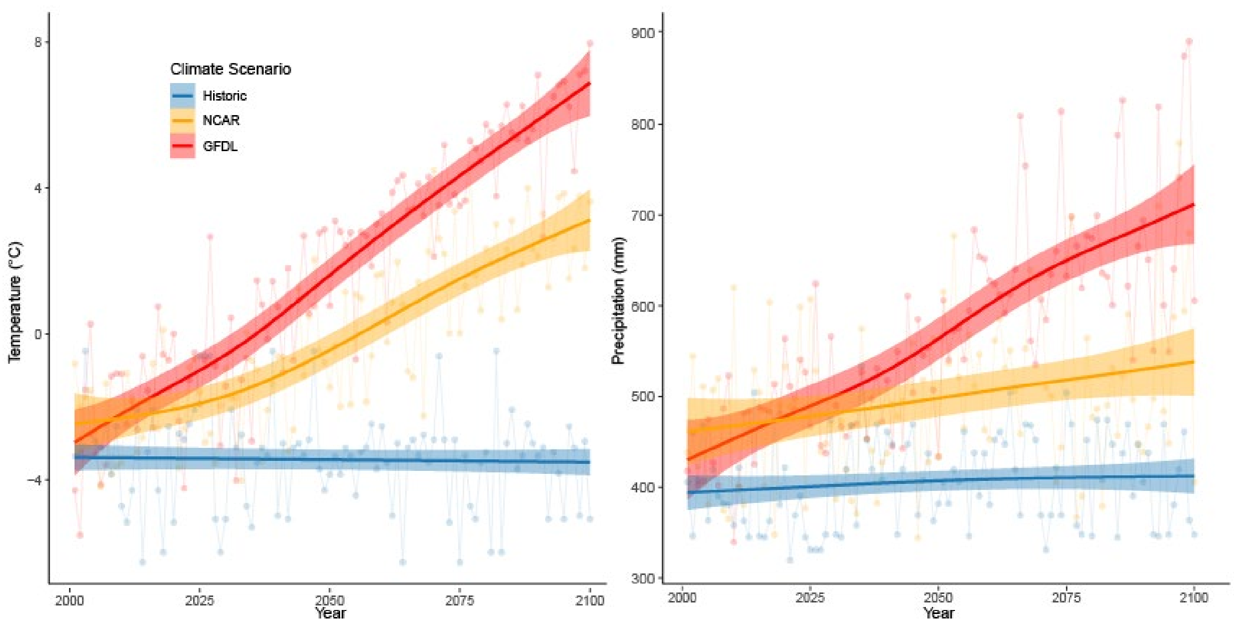


Figure 3: Climate forcing for century-long model simulation under three climate pathways: historic (baseline) and two future climate change scenarios (NCAR, moderate; GFDL, extreme). Yearly variations in precipitation and temperature are seen as transparent points and thin lines, and trends are seen in thick lines with standard error ribbons.

Aspects of an altered fire regime under future climate change are seen in relative changes in number of fires, fire size, area burned, and rotation period between scenarios. An annual number of wildfires was comparable across scenarios, but historic conditions predicted less variability in max fires per year and average mean fire per year (Figure 4a). Both mean and maximum fire sizes increased under future conditions. Max fire size with NCAR and GFDL was up to 7,000 and 18,000 ha (9 and 19%) larger than historic baselines (Figure 4b, Figure 4c). Throughout the century, the NCAR scenario saw a significant increase in cumulative hectares burned, with a 75,000 ha (9%) increase (Figure 4d) than historic. GFDL projected the steepest rise in area burned, exceeding historic conditions by approximately 125,000 ha (15% higher). Fire rotation periods dropped significantly in both future climate change scenarios, with a decline from 110 to approximately 85 years (p = 0.0039; Figure 4e).

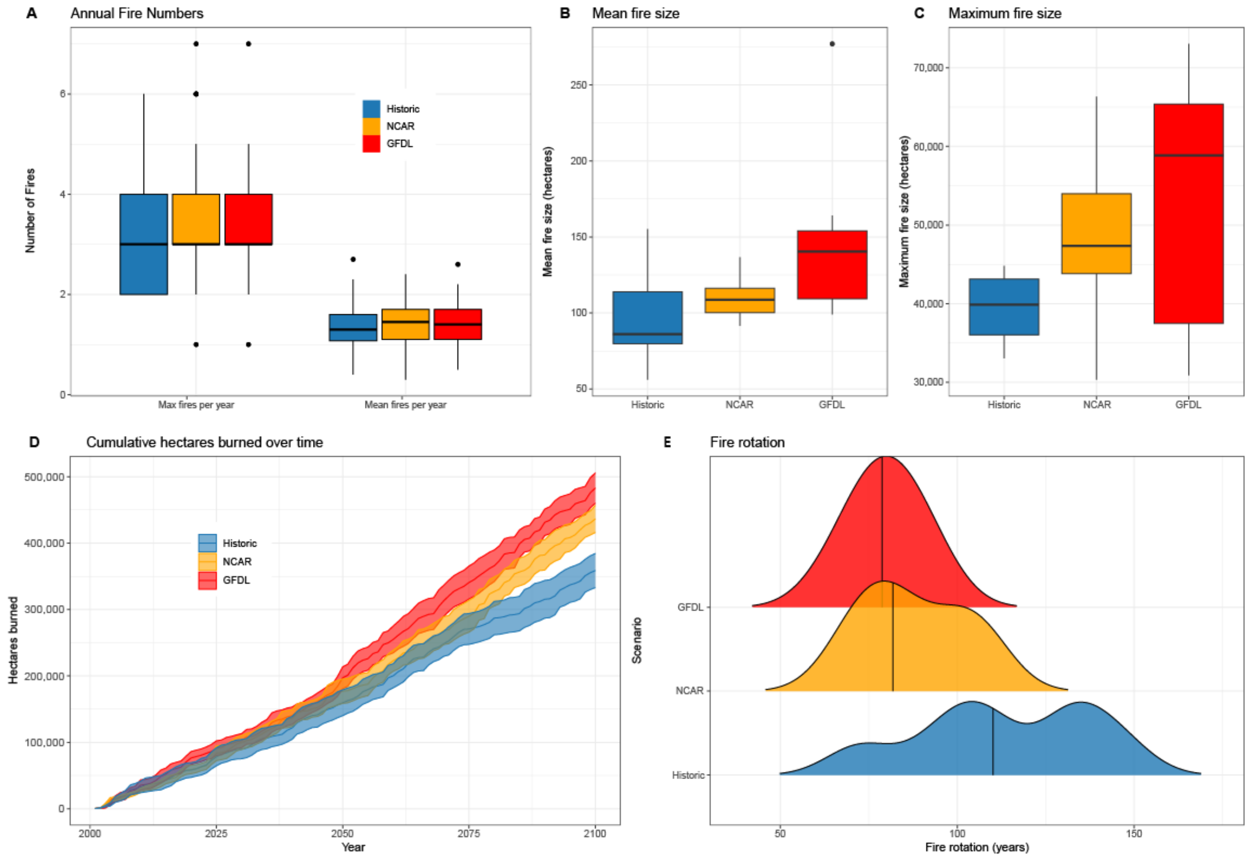


Figure 4: Changes in the fire regime of boreal Alaska through multiple aspects of fire activity by climate scenario: cumulative hectares burned (a), fire rotation (b), the annual number of fires (c), mean fire size (d), and maximum fire size (e). Ribbons in the Cumulative area burned represent stand error.

Conifers, the dominant forest type at the beginning of the simulation (~70% coverage), declined on the landscape by at least 20% throughout all the climate scenarios (Figure 5). This dynamic between conifers and hardwoods under historic climate conditions saw an exacerbated shift under future climate change, notably in the Future GFDL scenario. By the end of the simulations, conifer presence as a percentage of the landscape plummeted to about 25% (NCAR) and 20% (GFDL) of the landscape, while hardwoods surged to almost 75% and 80% respectively.

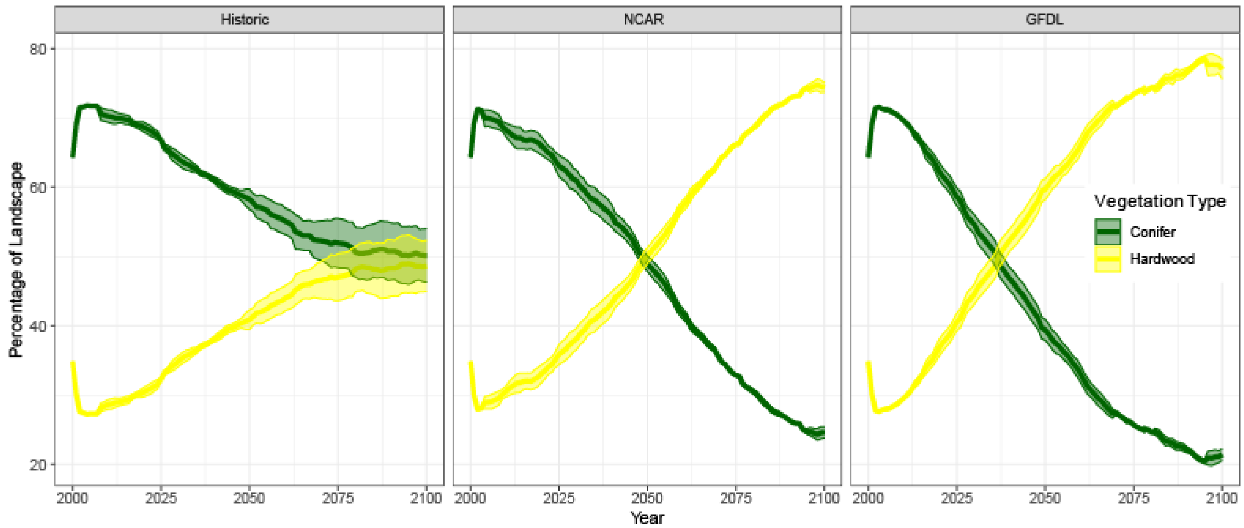


Figure 5: Tree coverage by functional type (conifer and hardwood) shown as a percentage of the landscape through the simulation period and by climate scenario. Ribbons represent stand error.

Given that maps of permafrost are not accurate at the scale of our simulations, we validated permafrost at the start of the simulation by comparing our map of permafrost to forest type with a spatial correlation index (Figure 6). We found that permafrost was present primarily in areas with coniferous forest coverage. Model agreement between the presence/absence of permafrost and vegetation type was relatively high (R^2 = 0.85). The biomass of specific modeled species can be found in Appendix Figure 1.

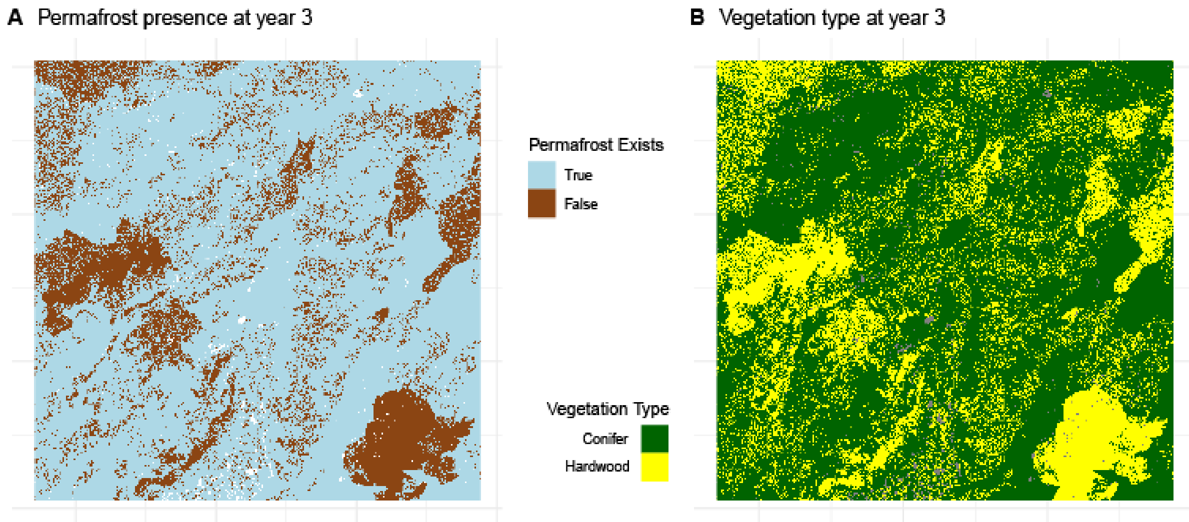


Figure 6: Initial condition maps of permafrost presence at 3m depth (A) and vegetation functional groups of conifer and hardwood tree-dominated cells (B) at year 3 of the simulation. Year 3 was chosen because the calculation of permafrost requires 2 consecutive years.

Belowground trends

Soil temperature profiles showed minimal differences between scenarios in the first decade of the simulation; climate change conditions were only 0.25 °C warmer in the top meter of soil (Figure 7). Temperatures of all scenarios converged at around 10 m depth, averaging below zero. By the end of the century, significant divergence occurred between the climate scenarios. Under historic conditions, there was a half a degree of cooling, while Future NCAR and GFDL warmed, the latter by approximately 3 and 6 °C, respectively, at the near-surface. It is not until around 30 and 40 m that both future forcings drop to below freezing.

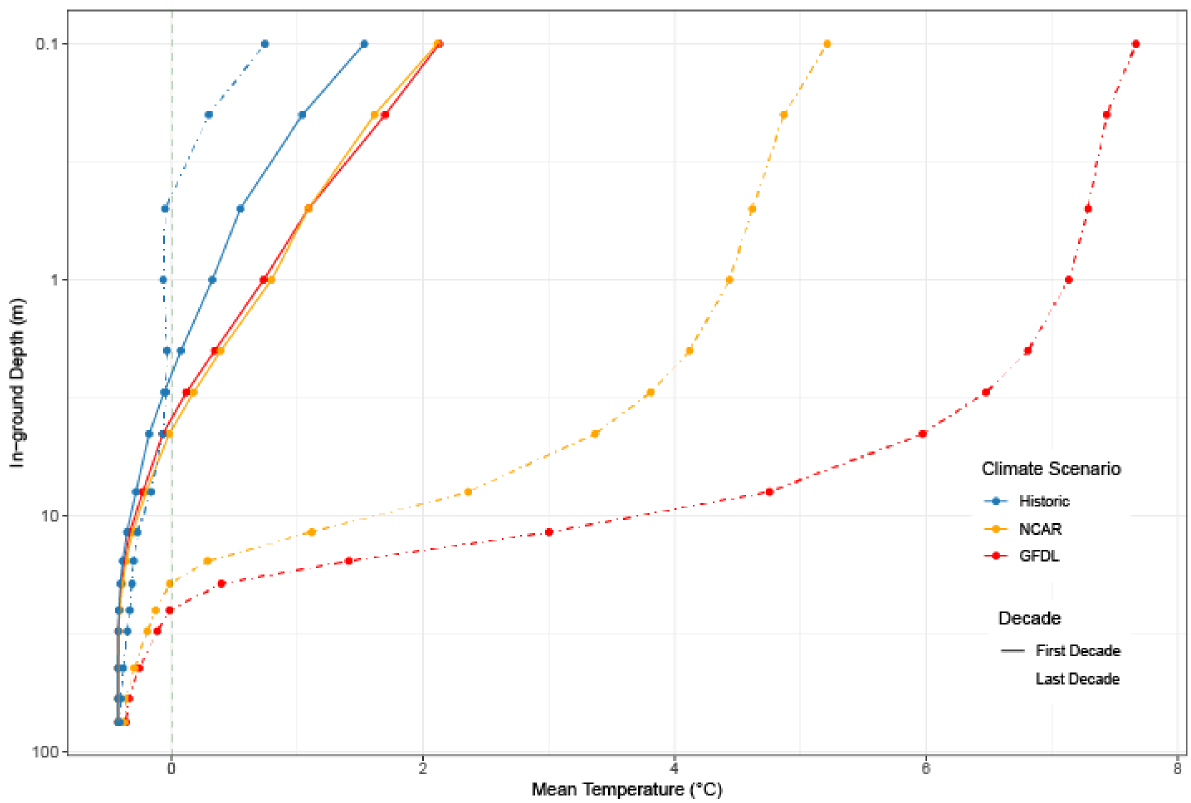


Figure 7: Soil temperature by depth profile down to 75 m, showing average first (solid line) and last (dashed line) decade mean soil temperatures by climate scenario.

Depth profiles for soil moisture showed minimal differences between historic and NCAR scenarios in the first decade, with GFDL having 8% higher VWC at the soil surface (Figure 8). All scenarios followed similar patterns of decreasing moisture with depth, converging at a depth of approximately 6 m. Historic conditions during the final decade were similar to initial levels of VWC at 10 cm depth. However, at 1-3 m of depth, VWC levels were lower than in the first decade, and then higher VWC levels were past 3 m down to 6 m. NCAR and GFDL decreased VWC by 10 and 20%, respectively, at shallow depths by the end of the decade, but deeper than 2 m, consistently moister with depth than the first decade, with GFDL around 2% drier than NCAR.

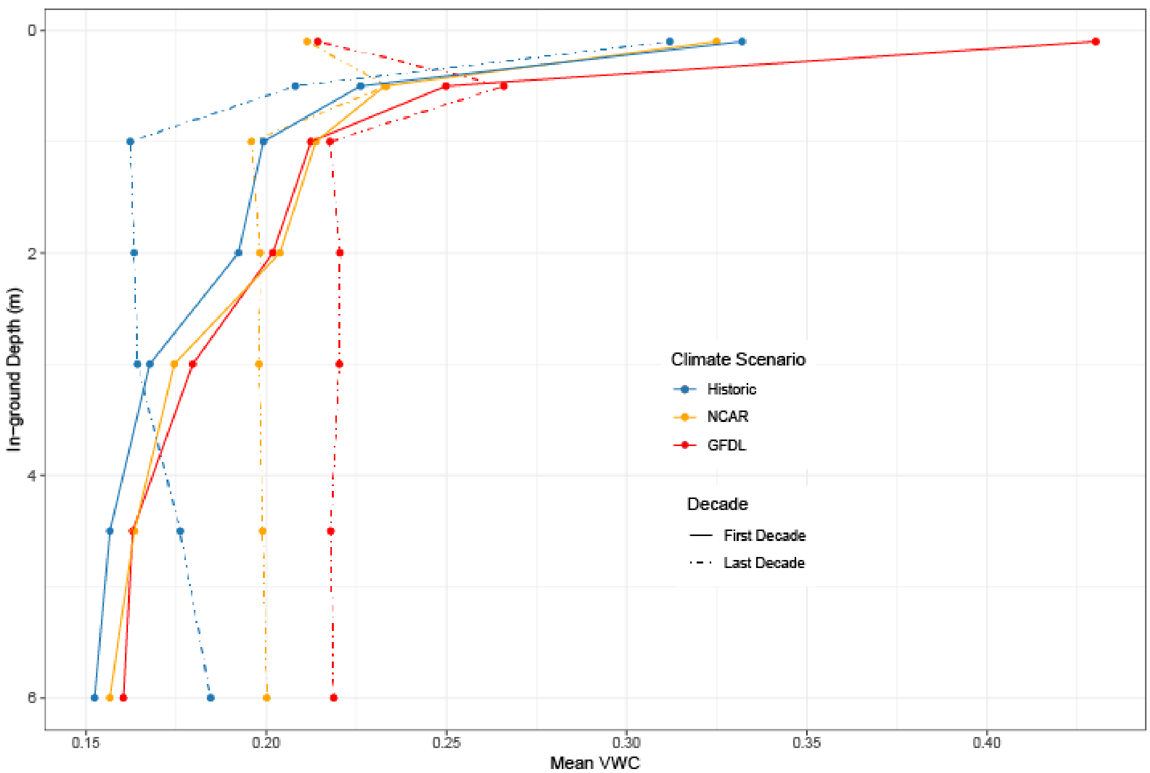


Figure 8: Soil moisture by depth profile down to 6 m, showing average first (solid line) and last (dashed line) decade mean VWC by climate scenario.

Declines in landscape permafrost coverage at the near surface (up to 3 m depth) were seen at all depth intervals and across climate scenarios (Figure 9). At 1 m below the surface, presence under historic forcing began around 50%, rapidly declining in the first 10 years to nearly 10% before variably oscillating between 5% and 20% for the rest of the simulation with a slight increase in the rate of percent over time (Figure 9a). Future forcing saw lower initial presence of permafrost with NCAR forcing, beginning at approximately 12% and declining to nearly 0% around 2060. GFDL, with a higher initial landscape coverage at 40%, declined the quickest, reaching 0% around 2012.

At 2m depth, initial permafrost coverage on the landscape was similar between scenarios. Historic forcing again declined till the year 2025 before stabilizing between 15% and 40% on the landscape (Figure 9b). The NCAR scenario, with the quickest initial decline, slowed this rate around 2010, effectively disappearing from the landscape at this depth just before 2060. Under the GFDL climate, coverage declined consistently, reaching 0% around the year 2015.

Permafrost at 3m depth initially covered 60% of the landscape across all scenarios, with declines commencing within the first few decades (Figure 9c). Historic climate conditions saw permafrost levels stabilize after 25 years, oscillating between 20 and 40% on the landscape. Future NCAR and GFDL diverged after two decades; NCAR's permafrost declined more gradually, with GFDL reaching near zero just past the 25-year mark. NCAR's more moderate warming and precipitation rates allowed permafrost persistence until nearly 75 years into the simulation.

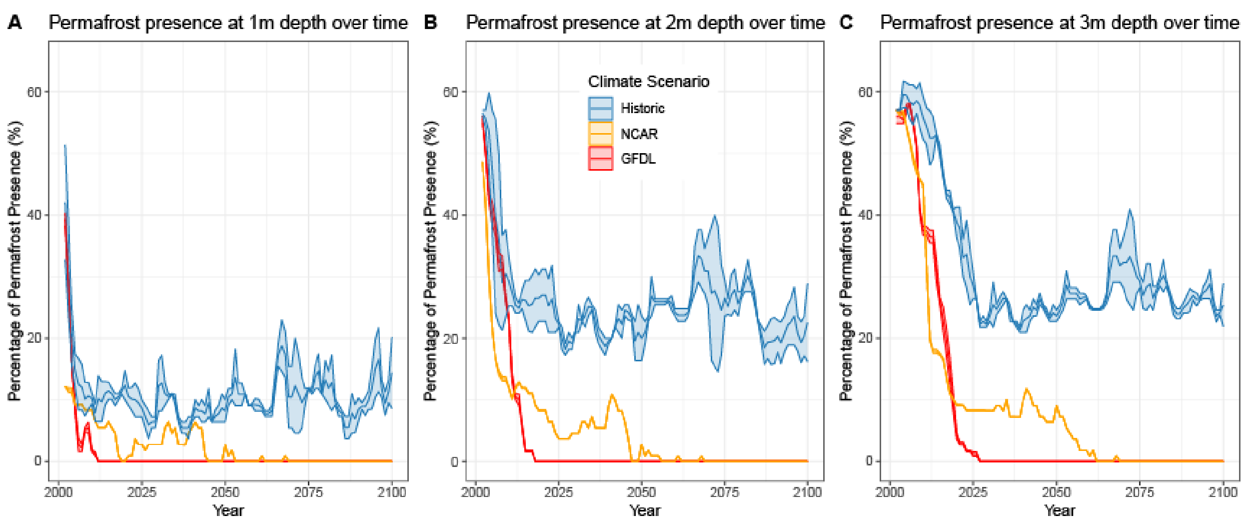


Figure 9: Permafrost presence (as a percentage of landscape) at 1 m (a), 2 m (b), and 3 m (c) depths through the simulation period and by climate scenario. Ribbons represent stand error.

The results of the ALD simulations indicate an exacerbated deepening of the seasonally thawing thickness under future climate change compared to our baseline climate (Figure 10). Showing an increased average of around ALD of 2 m, historic climate conditions increase this depth slowly till the end of the century. Under moderate warming with NCAR, average depths increase rapidly, ending the simulation period approximately 18 m deeper than historic (22 m total). The substantial increase in this thawing thickness was seen under GFDL climate conditions, with ALD nearly 24 m deeper on the landscape on average than baseline (28m total).

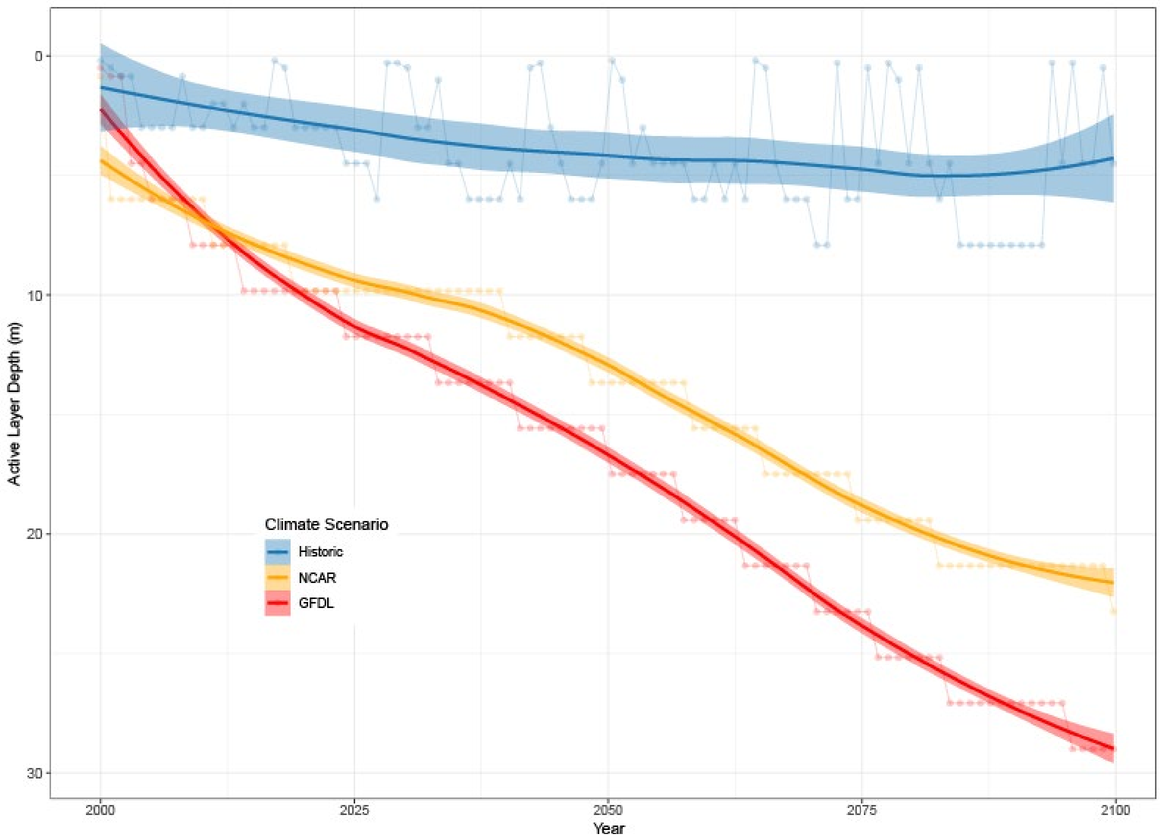


Figure 10: Mean landscape active layer depth over the simulation period by climate scenario. Error bars represent 95% confidence intervals.

Running a linear regression through the simulation period to show the rate of change in ALD returned a rate of 3.4 cm/year under a historic climate. This rate increased to a rate of 18.3 cm/year and 25.9 cm/year under NCAR and GFDL climate change forcing.

Table 1: Rates of increase in ALD by climate scenario

Climate scenario	Rate of thaw (cm/year)
Historic	3.4
NCAR	18.3
GFDL	25.9

Soil temperature and moisture dynamics by vegetation type

Soils under historic forcing showed little temperature change during the three decades following the post-fire, with soil under conifers and hardwoods staying just above and below freezing, respectively (Figure 11a). This stability after disturbance was similar in the NCAR scenario, with conifers just below 2°C and hardwoods warmer at around 3.5°C. Under the GFDL scenario, soil temperatures under conifers and hardwoods start at 3.5°C and 6°C each, warming a degree in the 30 years following fire.

While soil temperature levels were similar between vegetation types under historic forcing and diverged with more intense climate change scenarios, the opposite was seen for soil moisture, which had greater differences under historic than under the GFDL future climate scenario (Figure 11b). Soil moisture under a historic climate saw substantial differences between vegetation types, with conifers maintaining higher VWC and hardwoods slightly drying in the 30 years post-fire (Figure 11b). Under future NCAR, these trends were reversed, with the moister soil under conifers declining overall by almost 2% with drier but more stable conditions under hardwood vegetation. GFDL forcing soil moisture under both vegetation types is similar in the decades after fire, with conifers fostering slightly higher levels of VWC yet declining at a faster rate.

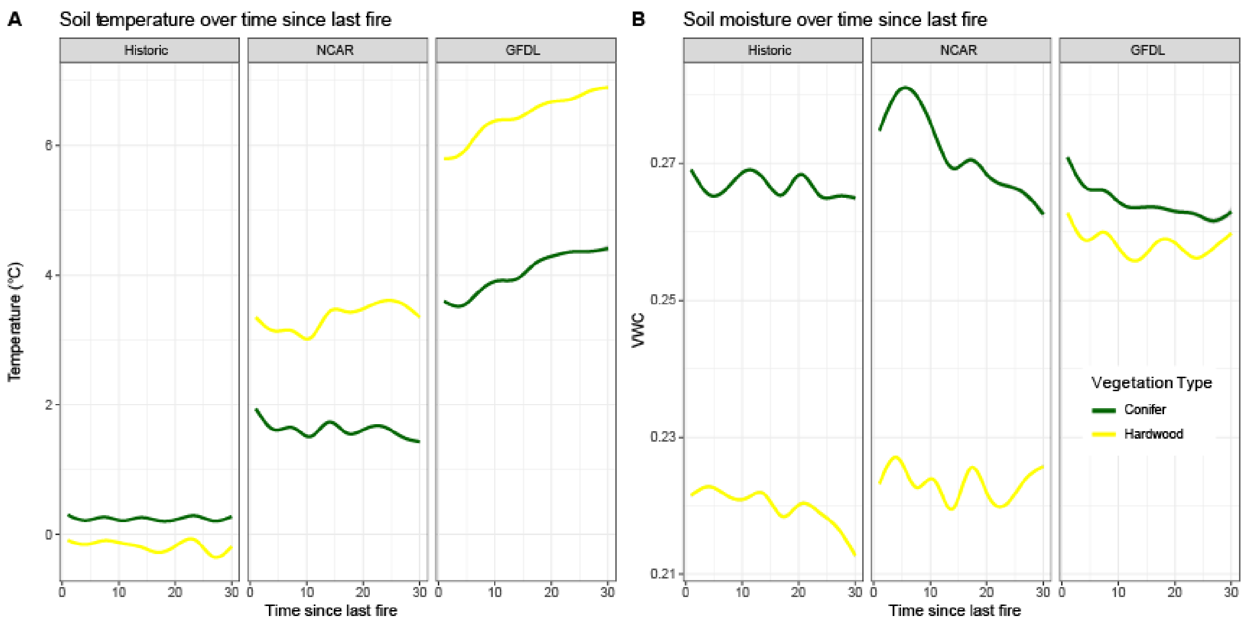


Figure 11: Soil temperature (a) and moisture (b) at 1 m depth over time since last fire colored by vegetation type and grouped by climate scenario. Ribbons represent stand error.

At a soil depth of 0.5 m, soil temperatures for both conifers and hardwoods oscillated around 0°C under historical climate conditions, with low variability (Figure 12a). However, under future climate change, soil temperatures increased, especially with GFDL. By the end of the simulation, areas dominated by hardwoods warmed by an additional 2 °C compared to conifers.

Under historic conditions, soil moisture (VWC) levels for conifers were relatively constant over time, while hardwoods exhibited slight drying (Figure 12b). Under future forcing, conifers saw similar decreases in VWC by scenario, initially higher than historic, but ending lower. Under hardwoods, moisture trends for NCAR matched historic, while GFDL saw a downward trend. The future GFDL scenario began at approximately 10% higher than others but dropped significantly in the simulation's first 25 years before a more stable decline, continuing to maintain higher levels than both historic and NCAR scenarios throughout the century.

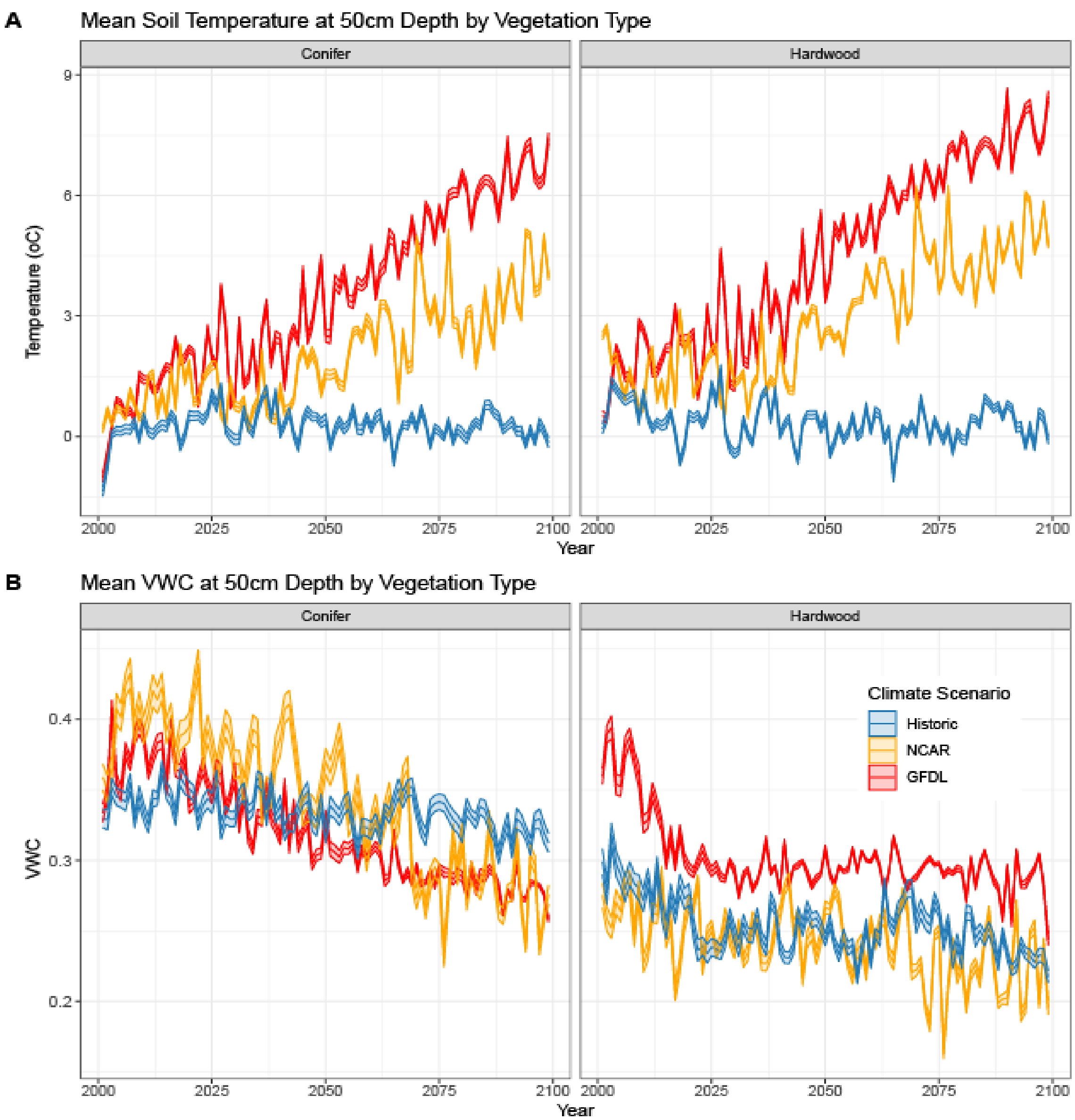


Figure 12: Soil temperature (a) and VWC (b) time series split by vegetation functional group and climate scenario. Ribbons represent stand error.

Our analysis of effect sizes shows that climate scenario, climate region, vegetation type, and age (or time since last disturbance) exert differential impacts on soil temperature and VWC (Table 1). Climate change scenario emerged by far as the predominant factor affecting soil temperature, with an effect size of 0.38 ηp^2. Climate region also played a significant role, with a smaller yet notable effect size of 0.05 ηp^2. Vegetation type and age had lesser but still measurable impacts on soil temperature, with effect sizes of 0.03 ηp^2 and 0.01 ηp^2, respectively.

*Table 2: Results of relative effect sizes on soil temperatures and VWC showing factorial ANOVA partial eta squares. Large effect size = ***, medium = **, small = *.*

Factor	**Soil temperature η_p^2**	**VWC η_p^2**
Climate Scenario	0.38***	0.07**
Climate Region	0.05*	0.19***
Vegetation Type	0.03*	0.12**
Vegetation Age	0.01*	0.04*

The effect sizes of experimental variables on soil moisture diverged from that of soil temperature, pointing towards distinct interactions between climatic factors and soil attributes. The climate scenario retained the highest effect size at 0.19 η_p^2 for VWC, underscoring its influence, while climate region and vegetation type effect sizes of 0.12 η_p^2 and 0.07 η_p^2, respectively, indicated significant contributions to soil moisture variability. Interestingly, vegetation age had a more pronounced impact on VWC than on soil temperature, suggesting that factors like forest structure, biomass, root systems, and ground cover might be more integral to soil moisture than to temperature dynamics.

DISCUSSION

Boreal resilience is profoundly affected by the interactions among increasing temperature and precipitation, changing fire regimes, and vegetation shifts. These findings highlight the importance of incorporating these dynamic feedbacks into broader ecological and climate strategies to better predict and manage the impacts of climate change on these critical ecosystems. Addressing these challenges requires a nuanced understanding of both the ecological and climatic variables at play and concerted efforts to integrate these findings into broader ecological and climate strategies.

Key insights

(1) Permafrost completely thawed under climate change by 2025 (GFDL) and 2060 (NCAR)

Permafrost under historical conditions shows an initial decline, then stabilizes, oscillating between 20% and 40% coverage at 3 m depth. This partial thaw suggests that 'historical' conditions already embody some effects of anthropogenic climate change even under late 20th-century 1970-2000 climate or a point towards a state of disequilibrium in our baseline period. Under future climate change, permafrost presence at the near-surface (3 m) experiences a steep decline over time on the landscape, leading to a total loss by 2060 (NCAR) and 2025 (GFDL), respectively. At shallower depths (1 m and 2 m), coverage across scenarios saw similar trends with steeper initial declines, stabilizing at lower percentages on the landscape. Similarly, landscape mean ALD increased by 16 m and 22 m under future climate change, greater than the increase observed under historic forcing. The rate of ALD increase under NCAR GFDL reaches as high as 18.3 cm/year and 25.9 cm/year, starkly contrasting with the 3.4 cm/year observed under historic climate, highlighting the profound impact of enhanced warming and precipitation changes. Ground-truthing in the region shows that current permafrost depths are still within 1 m in many areas, implying the GFDL climate forcing may be too aggressive. This points towards trends of permafrost degradation under the NCAR, the more modest of the RCP 8.5 scenarios, as possibly being more accurate.

(2) Higher future soil temperatures and moisture decline across vegetation types post-fire

As climate scenarios intensify, particularly under the GFDL model, we observed a notable divergence in soil temperatures, resulting from shifts in vegetation type and increased temperature and precipitation. This shift leads to higher soil temperatures under hardwood dominance, particularly noted in the decades following fire disturbances, where hardwood areas show rapid warming trends. Interestingly, while soil temperature responses to vegetation type become more pronounced under severe climate change scenarios, the patterns of soil moisture show an inverse trend. Under future climate change, the differences in soil moisture between vegetation types converge, unlike the significant differences between the types under historic forcing. Under the GFDL scenario, despite starting with higher moisture levels, both conifers and hardwoods experience similar rates of moisture decline, highlighting a uniform response to increased temperatures and altered precipitation patterns.

(3) Climate scenario and region drive soil temperature and moisture, respectively

Our findings reveal that variations in soil temperature are predominantly influenced by the overarching climate scenarios, while regional climatic variations (bioclimatic zones) exert a more pronounced impact on soil moisture. The disproportionate influence of climate scenarios on soil temperature stems from its role in defining broader atmospheric conditions, such as air temperature and precipitation patterns, which directly affect soil thermal regimes. In contrast, regional climatic variations influencing soil moisture may relate to more localized factors, such as topography, soil type, and localized weather patterns, which can vary significantly within different bioclimatic zones. These regional differences can lead to varied water retention capacities and evapotranspiration rates, thus affecting soil moisture levels more distinctly than temperature.

Future of boreal forests in a changing climate

The boreal forests of the interior of Alaska, nestled between the Alaska and Brooks Mountain ranges, showcase a patchwork mosaic of various vegetation types responding to environmental and topographic features of the landscape. Despite a limited species diversity, dominated by relatively few species of coniferous and hardwood trees and shrubs, the vegetation here has an extensive influence back on the landscape. Understanding and projecting this crucial aspect of boreal forest is then critical for understanding the implications of a changing climate and fire regime on global carbon cycling and permafrost thaw (Jafarov et al., 2013).

The resilience of boreal forests in the face of climate change is intricately tied to the stability of permafrost, which serves as a critical component of the forest's foundational structure and health. Here, we show that permafrost diminishes under all scenarios, with the most severe thawing under future NCAR and GFDL conditions leading to its disappearance near-surface within the next century. Changes in permafrost coverage and shifts towards conifer dominance even under historic forcing point towards to possibilities or a mix of them: (1) A state of disequilibrium under our historic climate forcing where boreal forest conditions are already beginning to shift; this shift is further exacerbated by future climate change. This is similar to findings in other studies where historic climate conditions still led to significant ecological changes (Serra-Diaz et al., 2018). And (2) substantial thaw in the first few decades in our scenarios is due to issues with parametrization or model functionality. This could include higher rates of soil conductivity during the summer, too little modeled snow interception from trees, or overly dried soil conditions at the surface. Differences in the timing of surface thawing on the landscape heavily depend on top-down climate forcing orchestrating ecological dynamics and the mechanisms within the DGS model framework. This thaw, though, is not only influenced by the marked increase in air temperatures and precipitation (particularly as rain) but by the not-unrelated substantial changes in fire regimes and shifts in vegetation type from coniferous to less insulative hardwood species, which exacerbate permafrost vulnerability.

The increased frequency and size of fires, particularly evident under the GFDL scenario, introduce significant heat into the soil, exacerbating permafrost thaw and altering vegetation patterns. The transition from coniferous to hardwood dominance affects the landscape's capacity to insulate permafrost effectively and impacts the forest's carbon sequestration capabilities. Additionally, the convergence of post-fire soil moisture levels under future climate scenarios, as observed in our study, suggests a potential homogenization of soil conditions across different vegetation types. This could diminish existing distinct ecological niches between coniferous and hardwood forests, potentially impacting biodiversity and forest structure. As hardwood species exhibit different phenological responses and rooting depths, they may adapt differently to increased temperatures and drier soil conditions, potentially affecting their growth rates, water uptake efficiency, and overall ecosystem services. Questions remain about whether increases in hardwood dominance will sustain itself longer than the simulation period presented in this study, given drier projected soil conditions. Given higher water requirements, there is potential for negative feedback interactions and a return to an increased coniferous presence on the landscape or a decrease in tree vegetation overall.

The soil temperature profile plays a pivotal role in defining the presence and stability of permafrost, affecting microbial activity, decomposition rates, and overall nutrient cycling. (Jorgenson et al 2010). As our results indicate, increasing soil temperatures correlate with decreased moisture levels, especially at shallow depths where permafrost was previously stable. This interaction between rising temperatures and diminishing moisture levels is crucial as it not only facilitates the degradation of permafrost but also impacts the hydrological dynamics essential for forest stability. The dynamics presented in this study are particularly critical as they suggest a nuanced interaction between soil properties and vegetation types under changing climatic conditions. As soil properties are each affected by different climate drivers, models like LANDIS-II are needed to carefully consider regional and scenario-specific inputs to accurately predict changes in boreal landscapes.

The thawing of permafrost has significant global implications, particularly through the release of carbon and methane from decomposing organic materials previously trapped in frozen soil (Schuur et al., 2009). This process underscores the critical role of permafrost in the global carbon cycle and its potential to exacerbate global warming (Hayes et al., 2011; Yuan et al., 2012). The dynamics between climate, fire regimes, and vegetation types are complex, pointing towards interrelated feedbacks seen in other studies (Johnstone et al., 2016; ref). The feedback mechanisms from permafrost thaw, coupled with other changes in boreal forests, are likely to drive substantial transformations in forest structure and function.

Comparison with other modeling studies in boreal Alaska

Our research findings contribute to the growing body of literature on the impacts of climate change on boreal ecosystems, aligning with several key studies and offering new insights into the dynamics of soil temperature, moisture, and vegetation shifts. Consistent with other studies (Johnstone et al., 2011; Young et al., 2016; Mekonnen et al., 2019), our findings predict increased fire size and frequency across boreal ecosystems due to climate change. These forecasts of fire on the boreal landscape indicate a fire regime altered from the one that has been in place for millennia.

Our analysis demonstrates trends similar to those observed in Mann et al. (2012), Jorgenson et al. (2015), Mekonnen et al. (2019), and Mack et al. (2021) studies concerning the future shifts in vegetation from conifer- to hardwood-dominated landscapes. Under historic forcing, the decline in coniferous coverage to around 50% can be seen as the result of either the landscape responding to modern climate with a lag, or the model parameterization results in more deciduous, or some combination of the two. As boreal forests experience shifts from coniferous to hardwood species, we observe corresponding changes in soil temperature and moisture levels. Hardwoods, which generally provide less ground insulation than conifers, lead to increased soil temperature fluctuations and accelerated moisture depletion.

Our permafrost estimates for the current century under GFDL forcing showed premature disappearance compared to other studies on the landscape. However, compared with Pastick et al. (2015), our estimates of permafrost coverage at 1 m under the NCAR forcing align with their permafrost probability projections around 50% and under 20% at mid and end-century, respectively. This similarly aligns with the results of Jafarov et al. (2012), who simulated permafrost at 2 m depth, also till the end of the 21st century. These studies also use GIPL 2.0 or decision and regression trees informed by remote sensing to predict substantial thawing within the next century in interior boreal Alaska. Additionally, estimates of permafrost thaw by the International Panel on Climate Change predict a decrease in permafrost volume (top 3 meters) of 90% by 2100 with 3° C temperature increases, somewhat aligning with our estimates of complete thaw by this time. Anderson et al. (2020), who compared eight models of soil moisture in permafrost regions, saw that projected conditions depended greatly on model type. Our results agreed with four of these models (CLM, TEM, ORCHIDEE, and UWVIC) that simulated drying conditions to the end of the century. However, a careful comparison of this study and others is needed to account for differences in scale, model capabilities, and climate forcing.

Limitations and future research

Although we calibrated soil temperatures at five depths at multiple field sites (Lucash et al., 2023) and found a high correlation between permafrost and forest type, we could not validate future trends in permafrost with observed data. With no continuously updated wall-to-wall permafrost map in this discontinuous region, permafrost model validation was limited for our future estimates. Additionally, the lack of precise depth and temperature profiles for permafrost also constrained our ability to validate these key outputs fully. Another challenge is our model's capacity to comprehensively capture all aspects of the boreal ecosystem. While LANDIS-II effectively simulates vegetation dynamics and fire regimes, it does not fully incorporate the intricate interactions within the soil, such as microbial activities crucial for emission estimates from permafrost thaw. Moreover, detailed hydrological processes such as a water table or lateral flow, crucial for a complete ecosystem simulation, are also not integrated within the SHAW model. For this reason, lowlands sites with poor drainage are not accurately simulated (Marshall et al, 2021). Furthermore, the LANDIS-II framework does not simulate feedback processes such as the input of greenhouse gasses into the atmosphere from wildfire and release from permafrost thaw. With the higher probability of a lightning-ignited wildfire in boreal forests with warming (Hessilt et al., 2022), this increase was also not reflected in the model over time. Additionally, while socioeconomic factors and human influence are pivotal in many ecological studies, they were not incorporated into our simulations. With little land management occurring in the region, the effects of the construction of infrastructure, such as roads and buildings that have been shown to affect permafrost, are not simulated (Jiang et al., 2020).

Future research will extend this modeling work to a larger landscape, enhancing the simulation of spatial variability and interactions within boreal ecosystems, including a detailed focus on talik layers and organic matter such as mosses crucial for permafrost dynamics. Participating in a model intercomparison project with other researchers in Alaska, other ecosystem models with differences in scale, levels of vegetation representation, and modeled processes will be used to understand boreal forest landscape dynamics better.

Novel modeling approach

This study is among the first to apply the LANDIS-II DGS extension, integrating GIPL 2.0 within a spatial interactive, process-based forest model. This integration facilitates a comprehensive analysis of both above-ground and below-ground ecological dynamics, marking a pioneering application of the DGS extension for landscape studies in boreal forests. Unlike previous studies that often utilize physics-based heat flux models to examine permafrost dynamics in isolation or vegetation models focused solely on fire and vegetation shifts, this study captures the interactive effects of vegetation changes, fire regimes, and heat inputs into the soil on permafrost stability. By simulating the complex interplay between these factors, our model provides a more realistic representation of how above-ground disturbances influence spatial permafrost thawing patterns. Additionally, the model's capability to handle soil moisture and temperature across many depths up to 75m offers a nuanced view of how these variables interact spatially and temporally, further enhancing our understanding of boreal forest ecosystems under changing climatic conditions.

CONCLUSION

This study, leveraging the advanced and novel capabilities of the DGS extension of the LANDIS-II model extension, which couples permafrost (at ~55 depths down to 75m), soil moisture (~20 depths down to 6 m), species-level succession, and wildfire offers a detailed glimpse into the future of boreal landscapes under the stress of further anthropogenic climate change. Our simulations over the next century depict the disappearance of permafrost at the near-surface by mid-century with a rapid increase in ALD catalyzed by profound changes in soil temperature and moisture dynamics. Additionally, striking shifts from coniferous to hardwood deciduous and shrub-dominated vegetation are seen, driven by an escalation in wildfire disturbance. Baseline ecosystem stability under future climate scenarios is disrupted, with soil temperatures rising and moisture levels declining markedly, particularly in burned areas transitioning from coniferous to less insulative hardwood coverage.

The projected disappearance of permafrost has critical implications for the global carbon cycle and the regional hydrology of boreal forests. As permafrost thaws, previously trapped organic carbon is released, accelerating global warming in a feedback loop that further threatens these and other ecosystems worldwide.

WORKS CITED:

Abramoff, R. Z., Davidson, E. A., & Finzi, A. C. (2017). A parsimonious modular approach to building a mechanistic belowground carbon and nitrogen model. *Journal of Geophysical Research: Biogeosciences, 122*(9), 2418–2434. https://doi.org/10.1002/2017JG003796/FORMAT/PDF

AKCCS. (2019). *Alaska Vegetation and Wetland Composite Map.* https://accscatalog.uaa.alaska.edu/dataset/alaska-vegetation-and-wetland-composite

Apps, M. J., Kurz, W. A., Luxmoore, R. J., Nilsson, L. O., Sedjo, R. A., Schmidt, R., Simpson, L. G., & Vinson, T. S. (1993). Boreal forests and tundra. *Water Air Soil Pollut., 70*, 39–53.

Beck, P. S., Goetz, S. J., Mack, M. C., Alexander, H. D., Jin, Y., Randerson, J. T., & Loranty, M. M. (2011). The impacts and implications of an intensifying fire regime on Alaskan boreal forest composition and albedo. *Global Change Biology, 17*(9), 2853-2866.

Begét, J. E., Stone, D., & Verbyla, D. L. (2006). Regional overview of interior Alaska. In Alaska's Changing Boreal Forest (pp. 12–20)

Baillargeon, N., Natali, S. M., Rogers, B. M., Treharne, R. (2022). Review of Permafrost Science in IPCC's AR6 WG1. *Woodwell Climate Research Center*, www.woodwellclimate.org/review-of-permafrost-science-in-ipccs-ar6-wg1/

Ben-Shachar M, Lüdecke D, Makowski D (2020). effectsize: Estimation of Effect Size Indices and Standardized Parameters. Journal of Open Source Software, 5(56), 2815. doi: 10.21105/joss.02815

Berner, L. T., Alexander, H. D., Loranty, M. M., Ganzlin, P., Mack, M. C., Davydov, S. P., & Goetz, S. J. (2015). Biomass allometry for alder, dwarf birch, and willow in boreal forest and tundra ecosystems of far northeastern Siberia and north-central Alaska. *Forest Ecology and Management*, 337, 110–118. https://doi.org/10.1016/j.foreco.2014.10.027

Bieniek, P. A., Bhatt, U. S., Walsh, J. E., Rupp, T. S., Zhang, J., Krieger, J. R., & Lader, R. (2016). Dynamical Downscaling of ERA-Interim Temperature and Precipitation for Alaska. *Journal of Applied Meteorology and Climatology*, 55(3), 635–654. https://doi.org/10.1175/JAMC-D-15-0153.1

Boulanger, Y., Arseneault, D., Boucher, Y., Gauthier, S., Cyr, D., Taylor, A. R., Price, D. T., & Dupuis, S. (2019). Climate change will affect the ability of forest management to reduce gaps between current and presettlement forest composition in southeastern Canada. *Landscape Ecology, 34*, 159-174.

Brandt, J. P. (2009). The extent of the North American boreal zone. *Environmental Reviews, 17*(NA), 101–161. https://doi.org/10.1139/a09-004

Chapin, F. S., Callaghan, T. V., Bergeron, Y., et al. (2004). Global change and the boreal forest: thresholds, shifting states or gradual change? *Ambio, 33*, 361–365.

Chapin, F. S., Trainor, S. F., Cochran, P., Huntington, H., Markon, C., McCammon, M., McGuire, A. D., & Serreze, M. (2014). Ch. 22: Alaska. In J. M. Melillo, Terese (T. C.) Richmond, & G. W. Yohe (Eds.), *Climate Change Impacts in the United States: The Third National Climate Assessment* (pp. 514-536). U.S. Global Change Research Program.

Cleve, K. V., & Viereck, L. (1983). A comparison of successional sequences following fire on permafrost-dominated and permafrost-free sites in interior Alaska. *Permafrost: Proc. 4th Int. Conf. (Fairbanks, AK)* (pp. 1286–91). Washington, DC: National Academy Press.

Douglas, T. A., Turetsky, M. R., & Koven, C. D. (2020). Increased rainfall stimulates permafrost thaw across a variety of Interior Alaskan boreal ecosystems. *npj Climate and Atmospheric Science, 3*, 28. https://doi.org/10.1038/s41612-020-0130-4

Ebel, B. A., Koch, J. C., & Walvoord, M. A. (2019). Soil physical, hydraulic, and thermal properties in interior Alaska, USA: Implications for hydrologic response to thawing permafrost conditions. *Water Resources Research, 55*(5), 4427-4447.

Euskirchen, E. S., Bennett, A. P., Breen, A. L., Genet, H., Lindgren, M. A., Kurkowski, T. A., & Rupp, T. S. (2016). Consequences of changes in vegetation and snow cover for climate feedbacks in Alaska and northwest Canada. *Environmental Research Letters, 11*(10), 105003. https://doi.org/10.1088/1748-9326/11/10/105003

Fisher, J. P., Estop-Aragonés, C., Thierry, A., et al. (2016). The influence of vegetation and soil characteristics on active-layer thickness of permafrost soils in boreal forest. *Global Change Biology, 22*, 3127–3140.

Flerchinger, G. N. (2000). The Simultaneous Heat and Water (SHAW) Model: Technical Documentation.

Fryer, J. L. (2014). Fire regimes of Alaskan black spruce communities. Fire Effects Information System. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fire Sciences Laboratory (Producer). Available: www.fs.usda.gov/database/feis/fire_regimes/AK_black_spruce/all.html

GeoMAC. (2019). Historic Perimeters Combined 2000-2018. U.S. Geological Survey. https://data-nifc.opendata.arcgis.com/datasets/nifc::historic-perimeters-combined-2000-2018/about

GeoMAC. (2020). Historic Perimeters 2019, U.S. Geological Survey. https://data-nifc.opendata.arcgis.com/datasets/nifc:historic-perimeters-2019/about

Greene, D. F., Macdonald, S. E., Haeussler, S., et al. (2007). The reduction of organic-layer depth by wildfire in the North American boreal forest and its effect on tree recruitment by seed. *Canadian Journal of Forest Research, 37*, 1012–1023.

Hansen, W. D., Foster, A., Gaglioti, B., Seidl, R., & Rammer, W. (2023). The Permafrost and Organic LayEr module for Forest Models (POLE-FM) 1.0. Geoscientific Model Development, 16(7), 2011-2036. https://doi.org/10.5194/gmd-16-2011-2023

Hayes, D. J., McGuire, A. D., Kicklighter, D. W., Gurney, K. R., Burnside, T. J., & Melillo, J. M. (2011). Is the northern high-latitude land-based CO2 sink weakening? *Global Biogeochemical Cycles, 25*, GB3018.

Helbig, M., Pappas, C., & Sonnentag, O. (2016). Permafrost thaw and wildfire: Equally important drivers of boreal tree cover changes in the Taiga Plains, Canada. *Geophysical Research Letters, 43*(4), 1598–1606. https://doi.org/10.1002/2015gl067193

Hessilt, T. D., Abatzoglou, J. T., Chen, Y., Randerson, J. T., Scholten, R. C., van der Werf, G., & Veraverbeke, S. (2022). Future increases in lightning ignition efficiency and wildfire occurrence expected from drier fuels in boreal forest ecosystems of western North America. *Environmental Research Letters, 17*(5), 054008. https://doi.org/10.1088/1748-9326/ac6311

Higuera, P. E., Brubaker, L. B., Anderson, P. M., et al. (2009). Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. *Ecological Monographs, 79*, 201–219.

Hollingsworth, T. N., Johnstone, J. F., Bernhardt, E. L., & Chapin, F. S. (2013). Fire severity filters regeneration traits to shape community assembly in Alaska's boreal forest. *PLOS ONE*.

Hoecker, T. J., & Turner, M. G. (2022). A short-interval reburn catalyzes departures from historical structure and composition in a mesic mixed-conifer forest. *Forest Ecology and Management, 504*. https://doi.org/10.1016/j.foreco.2021.119814

IPCC. *Climate Change 2023: Synthesis Report*. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, H. Lee and J. Romero (eds.)]. (2023) IPCC, Geneva, Switzerland, pp. 35-115, doi: 10.59327/IPCC/AR6-9789291691647.

Jafarov, E. E., Marchenko, S. S., & Romanovsky, V. E. (2012). Numerical modeling of permafrost dynamics in Alaska using a high spatial resolution dataset. *The Cryosphere, 6*(3), 613–624. https://doi.org/10.5194/tc-6-613-2012

Jafarov, E. E., Romanovsky, V. E., Genet, H., McGuire, A. D., & Marchenko, S. S. (2013). The effects of fire on the thermal stability of permafrost in lowland and upland black spruce forests of interior Alaska in a changing climate. *Environmental Research Letters, 8*(3), 035030. https://doi.org/10.1088/1748-9326/8/3/035030

Johnstone, J. F., Chapin, F. S. (2006). Fire interval effects on successional trajectory in boreal forests of northwest Canada. *Ecosystems, 9*, 268–277.

Johnstone, J. F., Chapin, F. S., Hollingsworth, T. N., et al. (2010). Fire, climate change, and forest resilience in interior Alaska. *Canadian Journal of Forest Research, 40*, 1302–1312.

Johnstone, J. F., Hollingsworth, T. N., Chapin, F. S., & Mack, M. C. (2020). Changes in fire regime break the legacy lock on successional trajectories in Alaskan boreal forest. *Global Change Biology, 26*(3), 1640-1652.

Johnstone, J. F., Rupp, T. S., Olson, M., et al. (2011). Modeling impacts of fire severity on successional trajectories and future fire behavior in Alaskan boreal forests. *Landscape Ecology, 26*, 487–500. https://doi.org/10.1007/s10980-011-9574-6

Johnstone, J. F., et al. (2016). Changing disturbance regimes, ecological memory, and forest resilience. *Frontiers in Ecology and the Environment, 14*(7), 369–378. https://doi.org/10.1002/fee.1311.

Jones, L. D. H. J. B., Adams, W. R. B. P. C., & Petrone, K. C. (2006). Watershed hydrology and chemistry in the Alaskan Boreal forest: the central role of permafrost. In F. S. Chapin, et al. (Eds.), *Alaska's changing boreal forest* (pp. 269-302). Oxford University Press.

Jorgenson, M. T., Marcot, B. G., Swanson, D. K., Jorgenson, J. C., & DeGange, A. R. (2015). Projected changes in diverse ecosystems from climate warming and biophysical drivers in northwest Alaska. *Climatic Change, 130*(2), 131–144. https://doi.org/10.1007/s10584-014-1302-1

Jorgenson, M. T., Romanovsky, V., Harden, J., et al. (2010). Resilience and vulnerability of permafrost to climate change. *Canadian Journal of Forest Research, 40*, 1219–1236.

Jorgenson, T., Yoshikawa, K., Kanevskiy, M., Shur, Y., Romanovsky, V., Marchenko, S., Grosse, G., Brown, J., & Jones, B. (2008). Permafrost characteristics of Alaska - 2008 Shapefile. University of Alaska Fairbanks, Institute of Northern Engineering; University of Alaska Fairbanks, Geophysical Institute; International Permafrost Association; U.S. Geological Survey. Retrieved from https://catalog.northslopescience.org/dataset/1725

Kasischke, E. S., Verbyla, D. L., Rupp, T. S., McGuire, A. D., Murphy, K. A., Jandt, R., Barnes, J. L., Hoy, E. E., Duffy, P. A., Calef, M., & Turetsky, M. R. (2010). Alaska's changing fire regime: implications for the vulnerability of its boreal forests. *Canadian Journal of Forest Research, 40*, 1313–1324.

Kobayashi, H., Ikawa, H., & Suzuki, R. (n.d.). I, Ver. 3-5, AmeriFlux AMP, (Dataset).

Kobayashi, H., Ikawa, H., & Suzuki, R. (2019). *AmeriFlux BASE US-Prr Poker Flat Research Range Black Spruce Forest* (Dataset).

Krause, C & Lemay, A. (2022). Root adaptations of black spruce growing in water-saturated soil. Canadian Journal of Forest Research. 52(5): 653-661. https://doi.org/10.1139/cjfr-2021-0310

Kurkowski, T. A., Mann, D. H., Rupp, T. S., & Verbyla, D. L. (2008). Relative importance of different secondary successional pathways in an Alaskan boreal forest. *Canadian Journal of Forest Research, 38*, 1911–1923.

Lader, R., Walsh, J. E., Bhatt, U. S., & Bieniek, P. A. (2017). Projections of Twenty-First-Century Climate Extremes for Alaska via Dynamical Downscaling and Quantile Mapping.

Journal of Applied Meteorology and Climatology, 56(9), 2393–2409. https://doi.org/10.1175/JAMC-D-16-0415.1

Loranty, M. M., Lieberman-Cribbin, W., Berner, L. T., Natali, S. M., Goetz, S. J., Alexander, H. D., & Kholodov, A. L. (2016). Spatial variation in vegetation productivity trends, fire disturbance, and soil carbon across arctic-boreal permafrost ecosystems. Environmental Research Letters, 11(9), 095008. doi:10.1088/1748-9326/11/9/095008

Lucash, M. S., & Scheller, R. M. (2021). *LANDIS-II Climate Library v4.2 User Guide*.

Lucash, M. S., Marshall, A. M., Weiss, S. A., McNabb, J. W., Nicolsky, D. J., Flerchinger, G. N., Link, T. E., Vogel, J. G., Scheller, R. M., Abramoff, R. Z., & Romanovsky, V. E. (2023). Burning trees in frozen soil: Simulating fire, vegetation, soil, and hydrology in the boreal forests of Alaska. *Ecological Modelling, 481*, 110367.

Lynch, J. A., Clark, J. S., Bigelow, N. H., et al. (2002). Geographic and temporal variations in fire history in boreal ecosystems of Alaska. *Journal of Geophysical Research: Biogeosciences, 107*, 8152.

Mack, M. C., Schuur, E. A. G., Bret-Harte, M. S., Shaver, G. R., & Chapin, F. S. (2011). Ecosystem carbon storage in arctic tundra reduced by long-term nutrient fertilization. *Nature, 461*(7263), 389-392.

Mack, M. C., Walker, X. J., Johnstone, J. F., Alexander, H. D., Melvin, A. M., Jean, M., & Miller, S. N. (2021). Carbon loss from boreal forest wildfires offset by increased dominance of deciduous trees. Science, 372(6539), 280–283. doi:10.1126/science.abf3903

Mann, D. H., Rupp, T. S., Olson, M. A., & Duffy, P. A. (2012). Is Alaska's boreal forest now crossing a major ecological threshold? *Arctic, Antarctic, and Alpine Research, 44*(3), 319–331. https://doi.org/10.1657/1938-4246-44.3.319

Marchenko, S., Romanovsky, V., & Tipenko, G. (2008). Numerical modeling of spatial permafrost dynamics in Alaska. Proceedings of the Ninth International Conference on Permafrost, 29, 1125–1130.

Marshall, A. M., Link, T. E., Flerchinger, G. N., & Lucash, M. S. (2021). Importance of parameter and climate data uncertainty for future changes in boreal hydrology. *Water Resources Research, 57*(8), e2021WR029911. https://doi.org/10.1029/2021WR029911

McConnell, N. A., Turetsky, M. R., McGuire, A. D., Kane, E. S., Waldrop, M. P., & Harden, J. W. (2013). Controls on ecosystem and root respiration across a permafrost and wetland gradient in interior Alaska. *Environmental Research Letters, 8*(4), 045029.

Mekonnen, Z. A., Riley, W. J., Randerson, J. T., et al. (2019). Expansion of high-latitude deciduous forests driven by interactions between climate warming and fire. *Nature Plants, 5*, 952–958. https://doi.org/10.1038/s41477-019-0495-8

Menne, M. J., Durre, I., Vose, R. S., Gleason, B. E., & Houston, T. G. (2012). An Overview of the global historical climatology network-daily database. *Journal of Atmospheric and Oceanic Technology,* 29(7), 897–910. https://doi.org/10.1175/JTECH-D-11-00103.1

MTBS. Direct download. Monitoring Trends in Burn Severity (MTBS). Retrieved from https://www.mtbs.gov/direct-download

National Cooperative Soil Survey. NCSS Soil Characterization Database (Lab Data Mart). Available online.

Nelson, F. E., Anisimov, O. A., & Shiklomanov, N. I. (2001). Subsidence risk from thawing permafrost. *Nature, 410*, 889–890.

Nicolsky, D. J., Romanovsky, V. E., Panda, S. K., et al. (2017). Applicability of the ecosystem type approach to model permafrost dynamics across the Alaska North Slope. *Journal of Geophysical Research: Earth Surface, 122*(1), 50–75. https://doi.org/10.1002/2016JF003852

Nicolsky, D. J., Romanovsky, V. E., Panteleev, G. G., & Geopl, A. (2009). Estimation of soil thermal properties using in-situ temperature measurements in the active layer and permafrost. *Cold Regions Science and Technology, 55*, 120–129. https://doi.org/10.1016/j.coldregions.2008.03.003

Osterkamp, T. E., Viereck, L., Shur, Y., Jorgenson, M. T., Racine, C., Doyle, A., & Boone, R. D. (2000). Observations of thermokarst and its impact on boreal forests in Alaska, USA. *Arctic, Antarctic, and Alpine Research, 32*, 303–15.

Pan, Y., Birdsey, R. A., Phillips, O. L., & Jackson, R. B. (2013). The Structure, Distribution, and Biomass of the World's Forests. *Annual Review of Ecology, Evolution, and Systematics, 44*(1), 593–622. https://doi.org/10.1146/annurev-ecolsys-110512-135914

Pastick, N. J., Jorgenson, M. T., Wylie, B. K., Nield, S. J., Johnson, K. D., & Finley, A. O. (2015). Distribution of near-surface permafrost in Alaska: Estimates of present and future conditions. *Remote Sensing of Environment, 168*, 301–315. https://doi.org/10.1016/j.rse.2015.07.019

Porter, C., et al. (2023). *ArcticDEM, Version 4.1*. https://doi.org/10.7910/DVN/3VDC4W

Potter, C., & Hugny, C. (2020). Wildfire effects on permafrost and soil moisture in spruce forests of interior Alaska. *Journal of Forestry Research, 31*(2), 553-563.

R Core Team (2021). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/.

Roland, C. A., Schmidt, J. H., Winder, S. G., Stehn, S. E., & Nicklen, E. F. (2019). Regional variation in interior Alaskan boreal forests is driven by fire disturbance, topography, and climate. *Ecological Monographs, e01369*. https://doi.org/10.1002/ecm.1369

Scheller, R. M., Domingo, J. B., Sturtevant, B. R., Williams, J. S., Rudy, A., Gustafson, E. J., & Mladenoff, D. J. (2007). Design, development, and application of LANDIS-II, a spatial landscape simulation model with flexible temporal and spatial resolution. *Ecological Modelling, 201*, 409–419.

Scheller, R. M. and D.J. Mladenoff. 2004. A forest growth and biomass module for a landscape simulation model, LANDIS: Design, validation, and application. Ecological Modelling 180: 211-229.

Scheller, R., et al. (2019). A landscape model of variable social-ecological fire regimes. *Ecological Modelling, 401*, 85–93. https://doi.org/10.1016/j.ecolmodel.2019.03.022

Scheffer, M., Hirota, M., Holmgren, M., Van Nes, E. H., & Chapin, F. S. (2012). Thresholds for boreal biome transitions. *Proceedings of the National Academy of Sciences, 109*(52), 21384–21389. https://doi.org/10.1073/pnas.1219844110

Schuur, E. A. G., & Mack, M. C. (2018). Ecological Response to Permafrost Thaw and Consequences for Local and Global Ecosystem Services. *Annual Review of Ecology, Evolution, and Systematics, 49*(1), 279–301. https://doi.org/10.1146/annurev-ecolsys-121415-032349

Serra-Diaz, J. M., Maxwell, C., Lucash, M. S., Scheller, R. M., Laflower, D. M., Miller, A. D., & Thompson, J. R. (2018). Disequilibrium of fire-prone forests sets the stage for a rapid decline in conifer dominance during the 21st century. *Scientific Reports, 8*(1). https://doi.org/10.1038/s41598-018-24642-2

Shabaga, J. A., Bracho, R., Klockow, P. A., et al. (2022). Shortened fire intervals stimulate carbon losses from heterotrophic respiration and reduce understorey plant productivity in boreal forests. *Ecosystems*. https://doi.org/10.1007/s10021-022-00761-w

Short, K. C. (2021). Spatial wildfire occurrence data for the United States, 1992-2018 [FPA_FOD_20210617] (5th ed.).

Sturm, M., Schimel, J., Michaelson, G., et al. (2005). Winter biological processes could help convert arctic tundra to shrubland. *Bioscience, 55*, 17–26.

Taylor, P. C., Cai, M., Hu, A., et al. (2013). A decomposition of feedback contributions to polar warming amplification. *Journal of Climate, 26*, 7023–7043.

Ueyama, M., Iwata, H., & Harazono, Y. (n.d.-a). *AmeriFlux BASE US-Fcr Cascaden Ridge Fire Scar, Ver. 2-5, AmeriFlux AMP*, (Dataset).

Ueyama, M., Iwata, H., & Harazono, Y. (n.d.-b). *AmeriFlux BASE US-Uaf University of Alaska, Fairbanks* (Dataset). https://doi.org/https://doi.org/10.17190/AMF/1480322

Ueyama, M., Iwata, H., & Harazono, Y. (2018a). *AmeriFlux BASE US-Rpf Poker Flat Research Range: Succession from fire scar to deciduous forest, Ver. 6-5, AmeriFlux AMP*, (Dataset). . https://doi.org/https://doi.org/10.17190/AMF/1579540

Ueyama, M., Iwata, H., & Harazono, Y. (2018b). *AmeriFlux BASE US-Uaf University of Alaska, Fairbanks, Ver. 9-5, AmeriFlux AMP,* (Dataset). https://doi.org/https://doi.org/10.17190/AMF/1480322

Ueyama, M., Iwata, H., & Harazono, Y. (2019a). *AmeriFlux AmeriFlux US-Rpf Poker Flat Research Range: Succession from fire scar to deciduous forest* (Dataset). https://doi.org/https://doi.org/10.17190/AMF/1579540128

Ueyama, M., Iwata, H., & Harazono, Y. (2019b). *AmeriFlux BASE US-Fcr Cascaden Ridge Fire Scar* (Dataset). https://doi.org/https://doi.org/10.17190/AMF/1562388

Urban, D. L. (2005). Modeling Ecological Processes Across Scales. Ecology, 86(8), 242–242. https://doi.org/10.1111/j.1525-139X.1993.tb00152.x

USDA-Forest Service. (2018). PNW-FIA Interior Alaska Database. https://www.fs.usda.gov/pnw/tools/pnw-fia-interior-alaska-database

USGS. (2020a). *Alaska 2 Arc-second Digital Elevation Models (DEMs).* https://data.usgs.gov/datacatalog/data/USGS:4bd95204-7a29-4bd4-acce-00551ecaf47a

USGS. (2020b). *LANDFIRE 2020 Fuel Characteristic Classification System (FCCS) AK 2022 Capable Fuels*. https://landfire.gov/metadata/lf2020/AK/LA22_FCCS_220.html

Viereck, L., van Cleve, K., Chapin, F. S., Hollingsworth, T., & Ruess, R. (2010). Vegetation Plots of the Bonanza Creek LTER Control Plots: Species Percent Cover (1975 - 2009): Vol. BNZ:174 (Issue http://www.lter.uaf.edu/data/data-detail/id/174). Bonanza Creek LTER - University of Alaska Fairbanks.

Weiss, S.A., Marshall, A.M., Hayes, K.R. et al. (2023). Future transitions from a conifer to a deciduous-dominated landscape are accelerated by greater wildfire activity and climate change in interior Alaska. Landscape Ecology 38, 2569–2589 https://doi.org/10.1007/s10980-023-01733-8

Wolken, J. M., Hollingsworth, T. N., Rupp, T. S., Chapin, F. S., Trainor, S. F., Barrett, T. M., & Yarie, J. (2011). Evidence and implications of recent and projected climate change in Alaska's forest ecosystems. *Ecosphere, 2*(11), art124. https://doi.org/10.1890/es11-00288.1

Young, A. M., Higuera, P. E., Duffy, P. A., & Hu, F. S. (2016). Climatic thresholds shape northern high-latitude fire regimes and imply vulnerability to future climate change. *Ecography, 40*(5), 606–617. https://doi.org/10.1111/ecog.02205

Yuan, F. M., Yi, S. H., McGuire, A. D., Johnson, K. D., Liang, J. J., Harden, J. W., Kasischke, E., & Kurz, W. A. (2012). Assessment of historical boreal forest carbon dynamics in the Yukon river basin: relative roles of climate warming and fire regime changes. *Ecological Applications, 22*, 2091–2109.

Zambrano-Bigiarini, M., & Rojas, R. (2018). hydroPSO: Particle Swarm Optimisation, with Focus on Environmental Models. R package version 0.5-1. https://doi.org/DOI:10.5281/zenodo.1287350

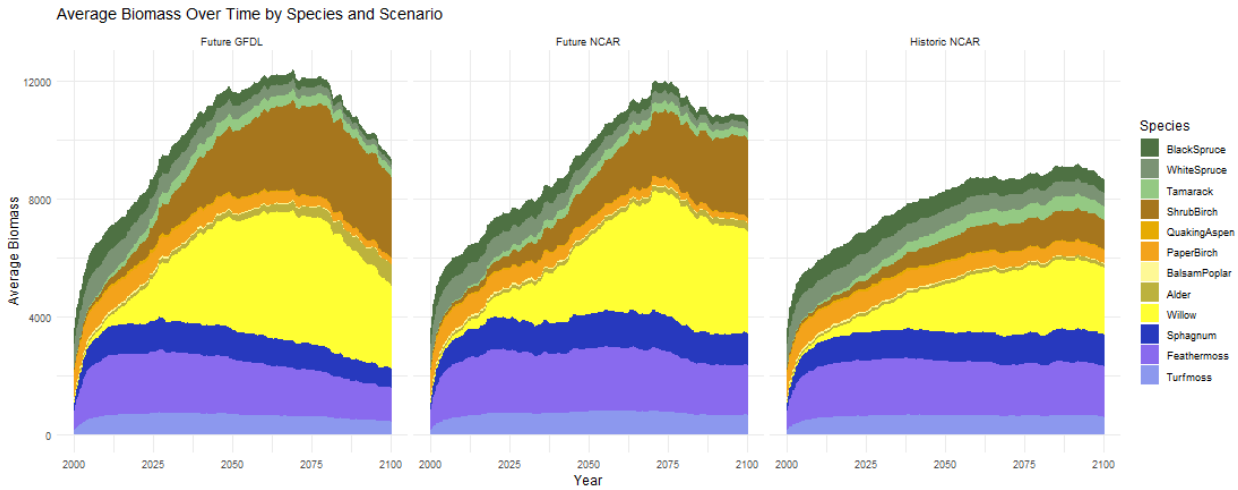
Zasada, J. C., Sharik, T. L., & Nygren, M. (1992). The reproductive process in boreal forest trees. In H. H. Shugart, R. Leemans, & G. B. Bonan (Eds.), *A Systems Analysis of the Global Boreal Forest* (pp. 85–125). Cambridge University Press.

APPENDIX

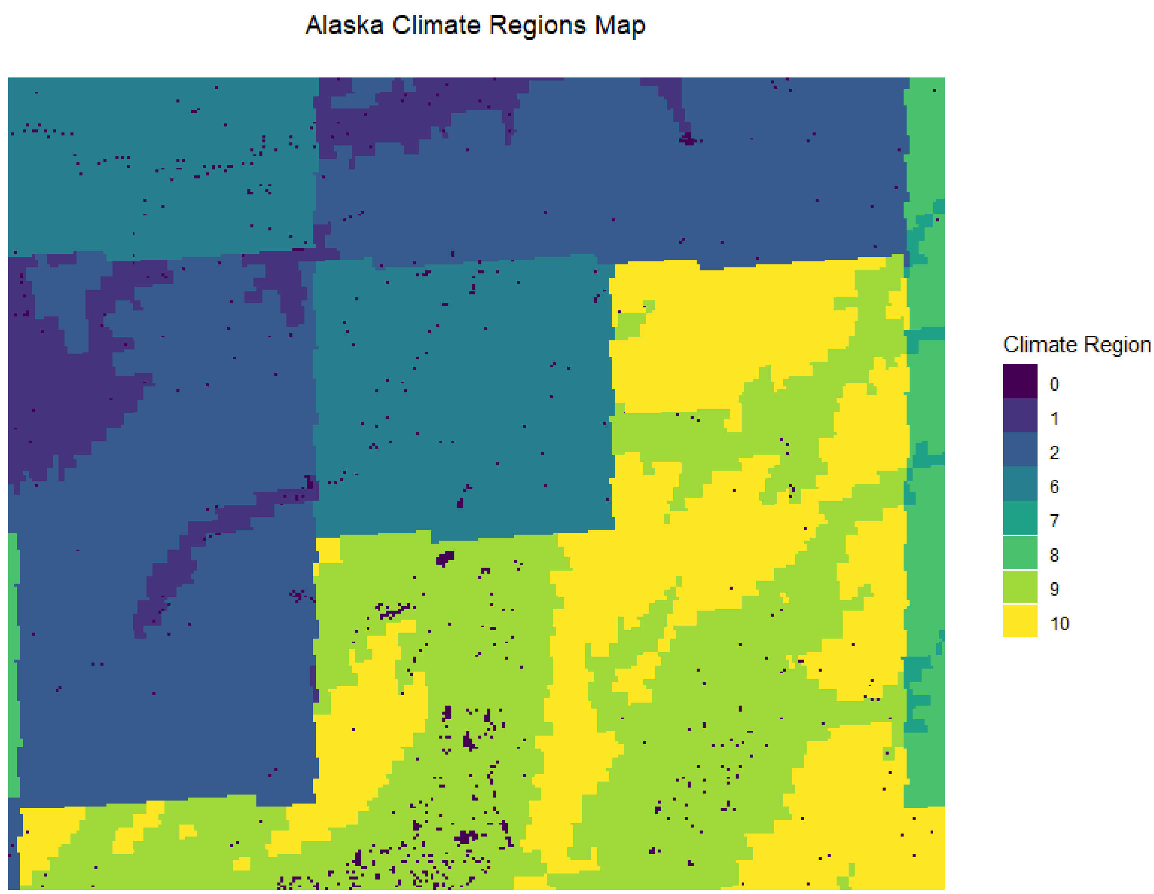
Focal Species

Appendix Table 2: Vegetation species modeled. Conifers in yellow, broadleaf hardwood trees/shrubs in green, mosses in blue.

Scientific Names	**Common Names**
Picea mariana	Black Spruce
Picea glauca	White Spruce
Larix laricina	Tamarack, Larch
Betula neoalaskana	Alaska Paper Birch, Resin Birch
Populus tremuloides	Quaking Aspen
Populus balsamifera	Balsam Poplar
Salix spp.	Willow
Alnus spp.	Alder
Betula nana	Dwarf Birch
Sphagnum spp.	Sphagnum Peatmoss
Feathermoss functional group: *Hylocomium* spp., *Pleurozium* spp., *Thuidium* spp., *Kindbergia* spp., *Brachythecium* spp.	Feathermoss
Turfmoss functional group: *Bryum* spp., *Mnium* spp., *Polytrichum* spp.	Turfmoss



Appendix Figure 1: Species biomass over time by climate scenario



Appendix Figure 2: Climate regions of interior boreal Alaskan landscape