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Article

Predicting the Unpredictable: Predicting Landcover in Boreal Alaska and the Yukon Including Succession and Wildfire Potential

Monika P. Calef [1,*], Jennifer I. Schmidt [2], Anna Varvak [3,†] and Robert Ziel [4]

[1] Environmental Studies, Soka University of America, Aliso Viejo, CA 92656, USA
[2] Institute of Social and Economic Research, University of Alaska Anchorage, Anchorage, AK 99508, USA
[3] Math/Science, Soka University of America, Aliso Viejo, CA 92656, USA
[4] Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, USA
[*] Correspondence: mcalef@soka.edu; Tel.: +1-001-949-480-4323
[†] Retired.

Abstract: The boreal forest of northwestern North America covers an extensive area, contains vast amounts of carbon in its vegetation and soil, and is characterized by extensive wildfires. Catastrophic crown fires in these forests are fueled predominantly by only two evergreen needle-leaf tree species, black spruce (*Picea mariana* (Mill.) B.S.P.) and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.). Identifying where these flammable species grow through time in the landscape is critical for understanding wildfire risk, damages, and human exposure. Because medium resolution landcover data that include species detail are lacking, we developed a compound modeling approach that enabled us to refine the available evergreen forest category into highly flammable species and less flammable species. We then expanded our refined landcover at decadal time steps from 1984 to 2014. With the aid of an existing burn model, FlamMap, and simple succession rules, we were able to predict future landcover at decadal steps until 2054. Our resulting land covers provide important information to communities in our study area on current and future wildfire risk and vegetation changes and could be developed in a similar fashion for other areas.

Keywords: boreal forest; wildfire; interior Alaska; Yukon; machine learning model

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1. Introduction

The boreal forest of Alaska and western Canada covers an extensive area, is partially underlain by permafrost, contains vast amounts of carbon in its soils and vegetation, and is home to only very few tree species. This area is also characterized by frequent and extensive wildfires, especially crown fires, which are integral to the ecology of this biome, since they rejuvenate cold, wet sites by thawing the underlying permafrost, provide nutrients, and reset succession [1–3]. Annual area burned varies widely from year to year and has been linked to large-scale climate teleconnections but is ultimately a result of available dry fuels, ignition by lightning or people, and weather conducive to fire spread [4–7]. While people ignite many fires near their towns and roads, these fires do not generally contribute much to overall area burned [8–10].

The population of Alaska has increased more than five times since 1950 (US Census) leading to extensive development into the highly flammable wildland–urban interface (WUI) thereby drastically increasing people's exposure to risk of catastrophic losses. Communities are faced with burning structures, air pollution, and loss of subsistence foods and ecosystem services [11,12] as well as projected wildfire response costs of around USD 1.1–2.1B from 2006 through 2100 in Alaska [13]. The simplest prevention of future loss is to limit development in hazardous zones [14]. However, this requires communities to identify areas most prone to hazards such as wildfire, permafrost collapse, and flooding.

While the boreal forest of Interior Alaska has evolved with frequent wildfires for the past 4000 years [15], plant response to fire depends on the species' flammability, ability to resprout or reseed quickly, and fire severity and return interval. Recovery after fire is usually lead by graminoids and herbaceous plants, followed by deciduous shrubs and trees such as quaking aspen (*Populus tremuloides* Michx.) and paper birch (*Betula papyrifera* Marsh.) and eventually by slower-growing evergreen trees [16]. Both more severe fires that remove much of the soil organic layer [17,18] and more frequent fires [19] seem to inhibit full evergreen recovery and lead to a greater post-fire abundance of deciduous shrubs and trees.

Temperatures in Alaska have been warming twice as fast as the global average since the mid-20th century [20]. A detailed analysis of Alaskan climate trends from 1920–2012 indicates underlying warming and drying which is confounded by large interannual variability, as well as larger climate patterns such as the Pacific Decadal Oscillation (PDO) and Pacific-North American (PNA) [4,21]. Projections indicate that Alaska is likely to warm by 4.4–5.6 °C in the Interior by 2050 [22], which is not accompanied by increases in precipitation. Several remote sensing-based analyses have tried to understand recent forest responses to this changing climate [23–26]. These studies found areas of greening mostly due to shrub expansion into tundra and browning in the forests of Interior Alaska. A decrease in NDVI occurs immediately after fire but can also be associated with insect defoliators, dry conditions, and mid- and late successional changes from deciduous to evergreen dominance [23,27]. There is concern that recent and predicted changes in climate as well as increase in fire extent, frequency, and severity will lead to a biome shift away from especially black spruce (*Picea mariana* (Mill.) B.S.P.)-dominated ecosystems [18,26,28–30].

Understanding these vegetation and wildfire changes and their impacts on human risk exposure requires detailed and frequent landcover datasets. Yet very few such datasets are available. The National Land Cover Datasets [31] mostly focus on the conterminous US but are available for Alaska for 2001, 2011, and 2016 [32]. Unfortunately, they do not extent to Canada. The North American Land Change Monitoring Systems [33] is only available for three years (2005, 2010, and 2015) and contains a unique 'urban and built-up' class [34]. The landcover with the largest spatial and temporal extent in the Western Arctic is based on NASA's Arctic-Boreal Vulnerability Experiment (ABoVE) [35]. ABoVE included a major field campaign with the purpose to provide a "better understanding of the vulnerability and resilience of ecosystems and society to this changing environment" in the Western Arctic of North America [36]. The resulting 31-year landcover data, based on LANDSAT data, landcover training data, and very high resolution imagery, provide a 15-class land cover dataset at 30 m resolution from 1984 to 2014 [35]. However, just like NLCD and NALCMS, the ABoVE classification includes only a single evergreen forest category for the entire domain.

We wanted to understand forest changes at decadal increments from 1984 to 2054 near three major towns in the western North American boreal zone in order to aid these communities with wildfire exposure assessment and planning. Therefore, (1) we further refined the singular "evergreen forest" category in the existing ABoVE land cover dataset to distinguish between evergreen tree species with different flammability and then expanded this refined classification across four historic decadal instances from 1984 to 2014. (2) We predicted future vegetation and wildfire occurrence at decadal intervals to expand our landcover data until 2054 by including future fire modeling and succession.

2. Materials and Methods

2.1. Study Areas

We chose three major communities in the far north of the western boreal zone as study areas, Fairbanks and Anchorage, Alaska, USA, and Whitehorse, Yukon, Canada (Figure 1). The Fairbanks and Whitehorse study areas are much larger than the Anchorage area (Table 1). The Anchorage study area has the largest proportion of developed area: 9% of the study area according to the 2016 NLCD [34] and the largest population.

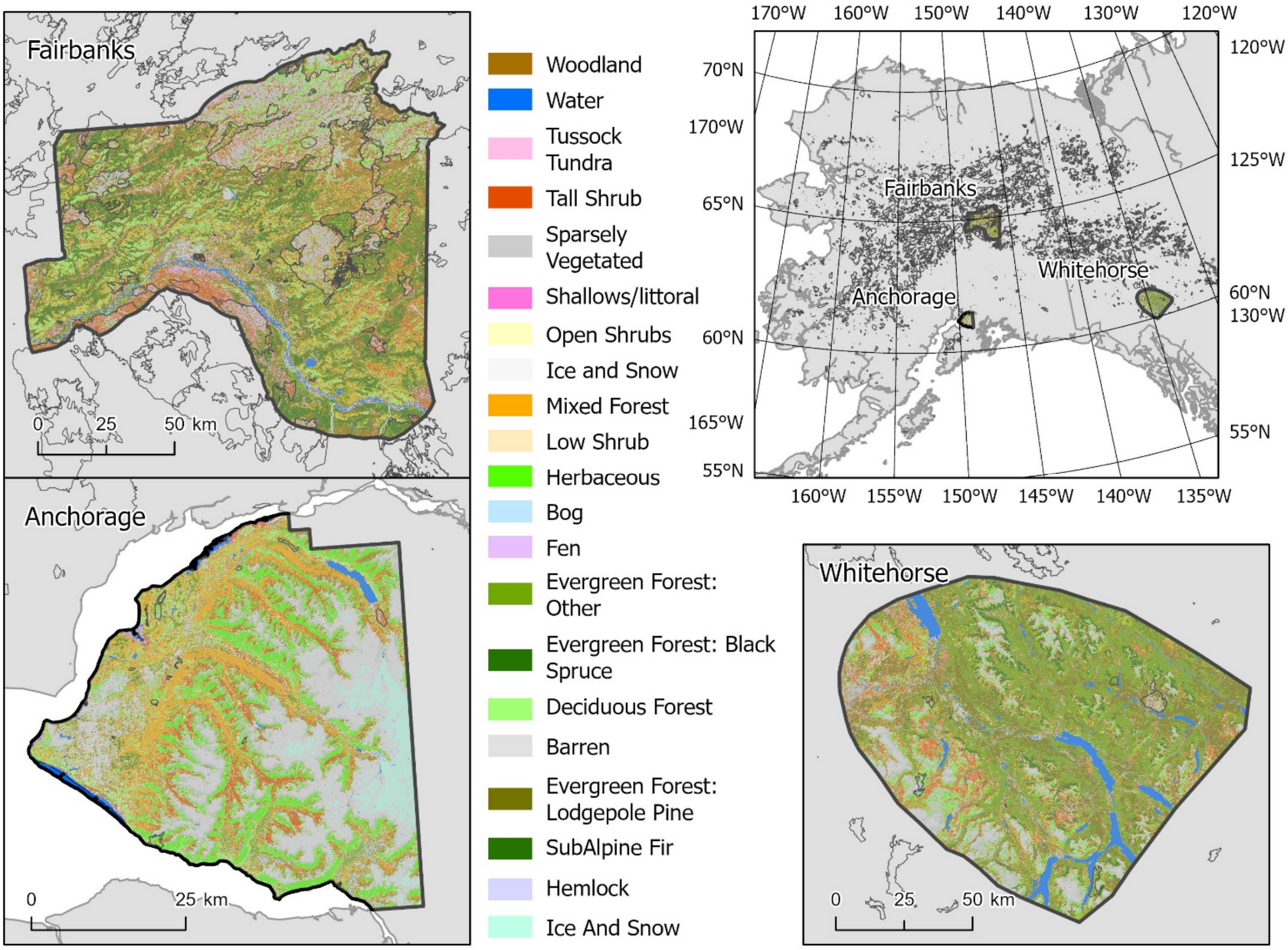


Figure 1. The three study areas in the western boreal zone. Vegetation is shown for 2014. *Evergreen Forest: Black Spruce* is only found in Fairbanks and Anchorage; *Hemlock* is only found in Anchorage; and *SubAlpine Fir* and *Evergreen Forest: Lodgepole Pine* are only found in Whitehorse. Thin gray outlines delineate fire perimeters for 1980 to 2019 in Alaska and from 1980 to 2022 in the Yukon.

The Anchorage study area near the southern coast consists mostly of the Municipality of Anchorage (MOA), the most populous city in Alaska. Most of the human development in the MOA is located along the western and southern coastline, while the rest of the area is mountainous and inaccessible. Only 28% of the land is covered by forest consisting mostly of paper birch, quaking aspen, balsam poplar (*Populus balsamifera* L. subsp. *Balsamifera*), and white spruce (*Picea glauca* (Moench) Voss s.l.) [37]. These species prefer well-drained, permafrost-free sites [38]. White spruce is a fire avoider that regenerates from seeds after fire [29] while the deciduous tree species are much less flammable, regenerate via suckering and seeds, and are often found in early successional stages [39]. Black spruce and mountain hemlock (*Tsuga mertensiana* (Bong.) Carriere) are less common. Black spruce generally grows on cold soils shaded from the sun, which are also poorly drained, nutrient poor, and acidic [38,40]. Black spruce is a highly flammable fire embracer with semi-serotinous cones that fuels severe crown fires [40–42]. It generally self-replaces after fire. Mountain hemlock grows near the treeline, is fire-sensitive, and regenerates from seeds after fire [43]. Due to the proximity of the ocean, this study area receives plentiful rainfall, 417 mm a year, (NOAA 1991–2020 normals), and fire is infrequent.

The Fairbanks study area (Table 1) is located in Interior Alaska and includes the majority of the Fairbanks North Star Borough (FNSB) which is home to the town of Fairbanks. Study area boundaries are similar to the FNSB but were adjusted to include areas most relevant to the communities impacted by wildfire [44]. This area is covered by extensive boreal forest dominated by black spruce on poorly drained acidic soils (usually also containing permafrost) in valley bottoms and on northern slopes. White spruce, trembling aspen, and birch are found at warmer, well-drained sites on south-facing slopes [39,40,45,46]. This study area experiences extensive wildfires almost every year; 30% of its area has burned since 1984.

Whitehorse is the capital of the Yukon, Canada, and is located east of the Rocky Mountains. The study area boundaries were drawn to capture surrounding communities and wildfire activity that could encroach especially from the south. Dominant tree species include mostly white spruce and lodgepole pine (*Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm.) on well-drained sites, trembling aspen on warm sites, and subalpine fir (*Abies lasiocarpa* (Hook.) Boivin) and paper birch on finer textured soils [47,48]. Much like black spruce, lodgepole pine is a highly flammable fire embracer sustaining crown fires. The species is still expanding its range migrating northward in northwestern Canada but has not yet reached Alaska [49]. Subalpine fir is fire sensitive and regenerates from seeds after fire. Other less common tree species include balsam poplar and black spruce on some wetlands. This study area has hardly burned for several decades, and there is concern that flammability is becoming critically high.

Table 1. Population, size, and area burned from 1984 to 2021 for the three study areas. Note that the Alaska fire perimeter database [34] includes fires > 100 ha prior to 1988 and fires > 10 ha since; the Yukon fire perimeter database [35] includes fires > 200 ha until 1997 and smaller fires especially near communities since. Population data are given for 2021 [50,51].

Study Area	Population	Area (km^2)	Area Burned (km^2, %)
Anchorage, AK	288,121	2703.84	18.43, 0.68
Fairbanks, AK	95,593	13,822.02	4190.75, 30.32
Whitehorse, YK	31,913	12,305.27	102.85, 0.84

2.2. Landcover Modeling

We developed the following major landcover modeling approaches for each of the three study sites:

1. A refinement of ABoVE's *Evergreen Forest* category into different types of needle leaf species relevant to wildfire potential using several predictors in a compound modeling approach for the year with the best cross-reference data. We then applied this refined model to existing ABoVE data for the remaining years of 1984, 1994, 2004, and 2014 and used a succession sequence based on analyses of existing ABoVE data to simulate recovery after fire disturbance.
2. A future wildfire and vegetation prediction approach that used the historic fire record as reference, Monte Carlo simulations to represent expected future area burned, FlamMap's Burn Probability module to randomly identify future large fire locations and perimeters, and succession rules derived from ABoVE data to guide burned area revegetation.

2.2.1. Refinement of the ABoVE Classification

Starting with one annual ABoVE dataset in each study area, we reclassified the evergreen forest category into more detailed vegetation classes based on the species' wildfire response using a compound modeling approach that incorporates machine learning where better information was not available. The start year was chosen based on available cross-reference vegetation data such as Community Wildfire Protection Plans (CWPP) [44,52] or a vegetation inventory dataset [53].

We started with Fairbanks, splitting the 2004 evergreen forest category into black spruce and white spruce as identified on the 2005 CWPP by the Fairbanks North Star Borough within the boundaries of the CWPP extent (which was restricted to the borough boundary) [44]. Within this area, we developed and trained a gradient boosted decision tree machine learning model using the XGBoost package (version 1.0.1) in R (version 3.6.3, https://xgboost.ai/, accessed 1 June 2022) [54–56] on black spruce locations. We could then use this model to extrapolate black spruce locations to the Evergreen Forest category throughout the entire study area. All remaining evergreen pixels were classified as white spruce.

For Anchorage, we used the 2004 CWPP [52] data to identify hemlock locations in the entire study area and then reclassified the rest of the 2004 evergreen forest pixels as white and black spruce with a new gradient boosted decision tree machine learning model.

For Whitehorse, we first identified subalpine fir locations on a 5 k vegetation inventory dataset [53] from 2012 which covered approximately 2/3 of our study area. Outside the area of overlap, a minimum elevation of 1200 m was used based on a statistical analysis of mean elevation of subalpine fir pixels, which is also confirmed by species observations [53]. All evergreen pixels in the 2014 ABoVE landcover which identified as subalpine fir were reclassified accordingly. Then, we trained a new gradient boosted model on lodgepole pine locations in the same 5 k inventory dataset, which allowed us to extrapolate to the rest of the study area. All remaining other evergreen forest pixels were classified as white spruce.

Once the machine learning models were developed for the year with vegetation training data, they could be propagated to the evergreen forest category in ABoVE landcovers for all remaining decadal time steps (1984, 1994, 2004, and 2014) and domains following two rules:

1. If the pixel remains classified as evergreen forest, then the modeled classification remains the same.
2. If the pixel's ABoVE classification changes to the evergreen forest category, then we use the trained machine learning model to refine that category.

We only applied minor additional corrections; e.g., the 2014 Fairbanks dataset did not include the impact of a very large fire the previous year; therefore, we reclassified evergreen forest pixels within the fire perimeter as sparsely vegetated. In addition, some pixels classified as herbaceous prior to 2014 were classified as deciduous forest in 2014 without any indication of an earlier disturbance or a successional response during the 30-year period. Inspection of current and historical satellite imagery by members of our group studying permafrost loss determined this earlier classification of areas as herbaceous was an error and the 2014 deciduous classification was more appropriate (Dmitry Nicolsky and Louise Farquharson, personal communication). We revised herbaceous pixels in earlier decades (29% in 1984, 25% in 1994, and 11% in 2004) to deciduous forest when they were classified as such in 2014 and lacked wildfire activity to better represent actual vegetation.

2.2.2. Model Predictors, Testing, and Validation

After substantial exploratory analysis, we settled on the following predictors that were available for our study areas. Additionally, four-fold cross-validation on training data identified the parameters, which boosted performance, as measured by area under the ROC curve (AUC-ROC):

- (For all three study areas) Topology: elevation, aspect (split into north–south and east–west components), and slope;
- (For all three study areas) Climate (averages for ten years prior to the year of interest from CRU 4.0 [57,58]: growing season (MJJA) temperature, growing season precipitation, summer temperature (JJA), and winter temperature (DJF);
- (For Anchorage and Fairbanks) Wetland status using NWI GEN data [59];
- (For Fairbanks) Time since last fire for the year of interest from the Alaska large perimeter database (https://fire.ak.blm.gov/ (accessed on 1 January 2023)) and Canadian National Fires Database [60];
- (For Fairbanks) Soil information from the SSURGO database [59]: annual water storage, groundwater water pH, and topsoil pH.

To spatially de-correlate the data, the dataset was divided into multiple spatial rectangles (about a thousand per each geographical study area), and then 20%–25% of those rectangles were randomly assigned as test data. The remaining data were used for model training and were randomly assigned into several groups for cross-validation in tuning model parameters.

Like a random forest machine learning method, XGBoost is an ensemble learning algorithm that combines predictions from multiple decision trees. Whereas a random forest builds independent decision trees and uses bagging to aggregate the results from the decision trees, XGBoost uses a form of gradient boosting, where each additional decision tree is built to correct the prediction errors of the previous trees. This should result in a model with better performance [45]. To prevent overfitting, each decision tree is shallow and trained on a random subset of the training data. We have chosen to use the XGBoost model rather than a random forest because the R XGBoost package is significantly faster in training its models and can result in better model performance.

For each of the three locations, we thus arrived at a nonparametric model, which takes as inputs values corresponding to the independent variables described above and outputs a number between 0 and 1 which represents a weighted "vote" between the aggregate of the decision trees.

Since we wanted to use our models to give a binary result (e.g., whether or not the observation is "black spruce" or "other evergreen"), it is necessary to establish a particular cutoff for the resulting output. The cutoff for each model was determined to maximize the F1-score, which is the harmonic mean between precision and recall, which we chose to balance the tradeoff between the positive predictive value and the sensitivity of the model.

After the models were trained and the cutoffs were established, we measured each model's performance by area under the receiver operating characteristic curve (AUC-ROC) by comparing true positive rate with false positive rate for different cutoffs. For Fairbanks, we additionally calculated the area under the curve for precision and recall (AUCPR). We then created the confusion matrices on test data and used them to determine precision and recall of each model.

2.2.3. Succession Model

To determine future changes to the landscape, we needed to develop general successional rules based on ecological knowledge of the boreal forest [1,61] and exploration of the 31-year ABoVE dataset. While not all sites follow the same pathway at the same speed, a detailed analysis of vegetation changes across the ABoVE data record combined with published information and expert knowledge allowed us to derive general transition rates and pathways for our study areas which are explained in more detail in the Appendix A (Figures A1–A3 and Table A1).

There were three main reasons to use the existing literature in addition to the ABoVE data. First, data become more limited as we go back in time, especially for vegetation types less prone to burning 10 years after a fire. Therefore, we combined data-driven results with current knowledge to develop informed succession rules. Second, during our data analysis we observed that fires in the early 1980s occurred in the ABoVE dataset prior to them actually occurring (for example, 1986 burns were recorded in 1984). Third, the fire perimeter boundaries for Alaska often include unburned areas (i.e., inclusions). This in addition to edge effects can affect the results from the ABoVE analysis. The resulting rules were reviewed by ecologists and fire experts in Alaska and Canada and further fine-tuned. The final succession rules were then applied to burned areas to determine landcover type after disturbance.

The Fairbanks study area experienced the most landcover change due to extensive wildfires. Since the Anchorage study area experienced essentially no disturbance, vegetation was assumed to be persistent. The succession pathway for Whitehorse is similar to the others, except for the addition of sub-alpine fir and lodgepole pine categories. The ABoVE data from the Fairbanks area were analyzed in three ways to understand succession and guide our model. We calculated the change in vegetation composition based on the time since the last fire irrespective of the vegetation type prior to burning (Figure A1). Then, we identified the vegetation type in the year prior to a wildfire (i.e., pre-fire) and tracked the composition of vegetation within each pre-fire vegetation type after a wildfire (Figure A3). Previous research indicates that pre-fire vegetation is important for post-fire succession [1,18,62]. Lastly, we created a chord graph using the statistics software R's circlize package v. 4.15 [63] to visualize flows among vegetation types between 1984 and 2014. These results along with expert opinion were used to develop succession rules based on pre-fire vegetation type and time since last fire. When predicting future landcover, vegetation was assumed to remain the same between time steps unless there was enough time since the last fire that succession would be expected by the model or the pixels burned.

2.2.4. Future Fire Disturbance and Landcover

We utilized the 72-year record (1950–2021) of wildfire history within the Fairbanks area to understand recent trends in area burned. While there is much variability in annual area burned and the record is less reliable further back in time, the area burned seems to be increasing [64]. We calculated the 10-year moving sum of annual area burned and number of wildfires (Figure 2). Figure 2 identifies two notable departures in decadal area burned, based on extreme fire seasons of 1957, 1958, and 2004. Otherwise, decadal totals were much less variable. Both the elevated decadal totals that included the 2004 season and the elevated norms after 2014 suggest increasing areas burned and thus the impact of climate change. We used this historic trend of decades with extraordinary area burned separated by three decades with less area burned to guide assertions of future area burned totals for Fairbanks.

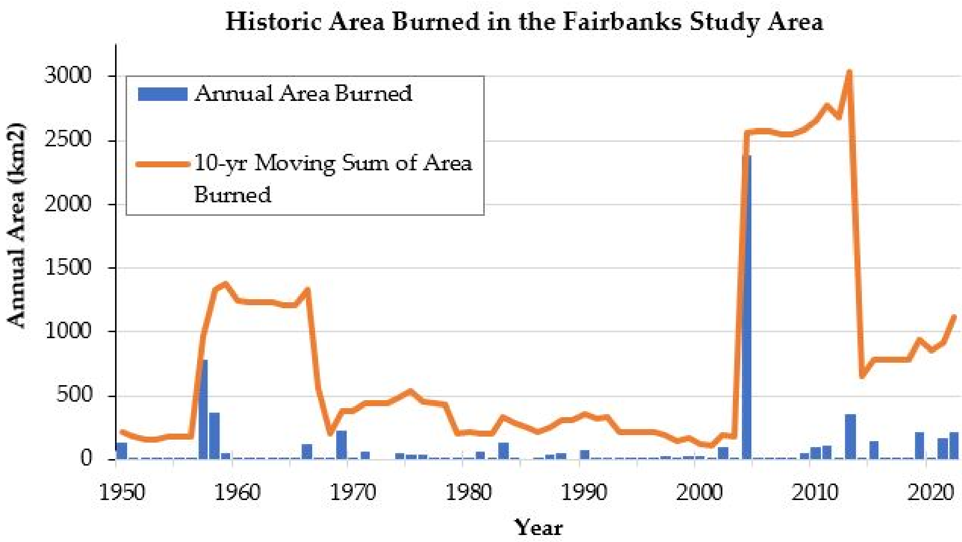


Figure 2. Historic area burned in the Fairbanks study area. Area burned (in km^2) is shown annually (blue bars) and as a 10-year moving sum (orange line).

This history of 10-year cumulative sums (63 in total) of annual area burned were used in a Monte Carlo simulation consisting of 100,000 iterations to randomly cumulate ten years of area burned and estimate future decadal projections. The decadal number of large fires has not varied nearly as much (n = 20–32) as the total area burned over the historic record in Fairbanks. As such, we assumed little increase in the number of ignitions (kept around 25 except for the last decade which was set to 30) and attributed most of the variability in area burned to increased fire sizes. Most of the increase in area burned was reserved for one extreme decade of area burned anticipated 2045–2054.

With these assertions for the number of large fires and total area burned for each succeeding decade, we used the fire simulation model FlamMap [65] to simulate individual fire perimeters that meet those expectations. FlamMap is a fire mapping and analysis system used in fire management that calculates fire behavior independently for each cell. It cumulates spread rates and fire line directions over specified time periods to produce burned areas and perimeters. Calculations are based on land cover and terrain characteristics converted to a FlamMap fuelscape, and we tuned the model by its ability to match historic fire perimeters. Like similar fire behavior modeling systems such as BehavePlus [66,67], FARSITE [68], and NEXUS [69,70], FlamMap uses the Rothermel surface fire spread model [71–73]. FlamMap combines this fuelscape with flammability parameters consisting of fuel moistures and wind speeds responsible for large fire growth. The Burn Probability module starts with a specified number of randomly ignited fires and produces burned area perimeters for each specified ignition. Though there is no way to predict the accurate location and size of individual future fires, we utilized FlamMap to elicit a representative distribution of simulated fire perimeters that provides a picture of future impact to the landscape based on our expectations for each of the specified future decadal totals for ignitions and total area burned.

Subsequent to those decadal disturbance depictions, the landscapes were modified using our succession rules before modeling the next decade's disturbances and successional progressions.

Since wildfires played a minor role in the other two study areas with <1% burned from 1984 to 2021 in each (Table 1), we concluded that it was not useful to simulate significant reductions in wildfire hazard and exposure based on unreferenced increases in area burned in future decades. Instead, because large catastrophic impacts are plausible and need to be planned for, we used simulated wildfire perimeters from FlamMap simulations to suggest where and how wildfires in the Wildland Urban Interface (WUI) around Anchorage and Whitehorse may impact those communities. For those communities, landscape, and therefore wildfire hazard, changes were estimated primarily with succession rules applied to other noted disturbances, such as planned fuel treatments and major insect and disease impacts.

3. Results

3.1. Refined ABoVE Classification

Using our approach, we were able to develop consistent and comparable landcover datasets for our three study areas across four decades that provided the forest details necessary to distinguish evergreen forest types with significantly different wildfire behavior (Figure 3).

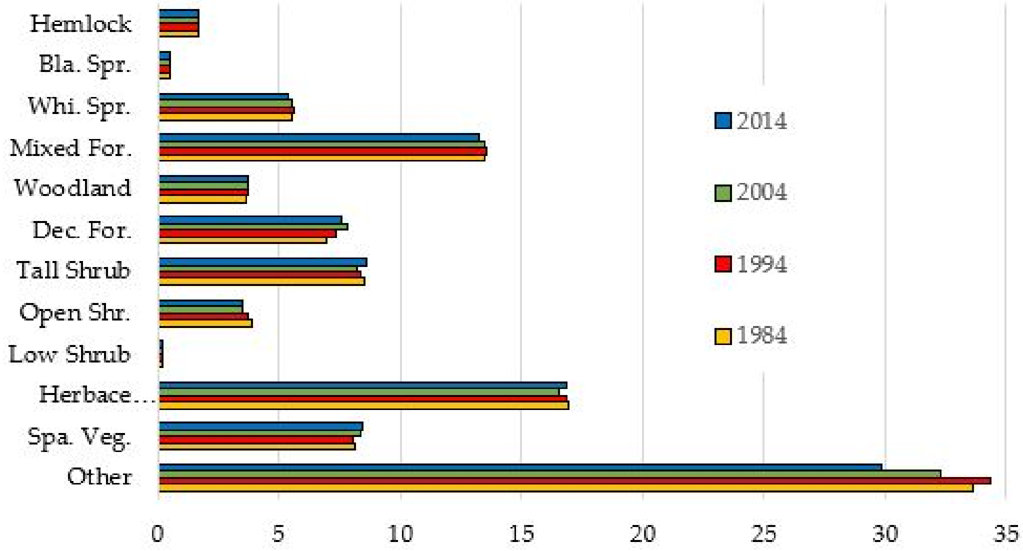
Nearly 70% of the Anchorage study area contains non-forest landcover (Figure 3a, Table A2a). The predominant forest types are mixed forest (13% of the study area in 2014), deciduous forest (8%), and white spruce (5%). The presence of highly flammable black spruce is low (0.52%) though concentrated adjacent to several developed areas. Overall landcover change is barely noticeable through the four decades despite some spruce beetle mortality in the area.

In contrast, the Fairbanks study area (Figure 3b, Table A2b) is dominated by woodland (20% in 2014) followed by black spruce (19%). This study area is predominantly covered by trees as is indicated by the distribution of mixed forest (9%), deciduous forest (9%), and white spruce forest (8%). The landscape changed through the four decades. For example, 14% of 1984 evergreen forests, 19% of woodlands, and 18% of deciduous forest were converted to other landcover types by 2014. The distribution of sparsely vegetated land and low and tall shrubs increased dramatically, indicating disturbance.

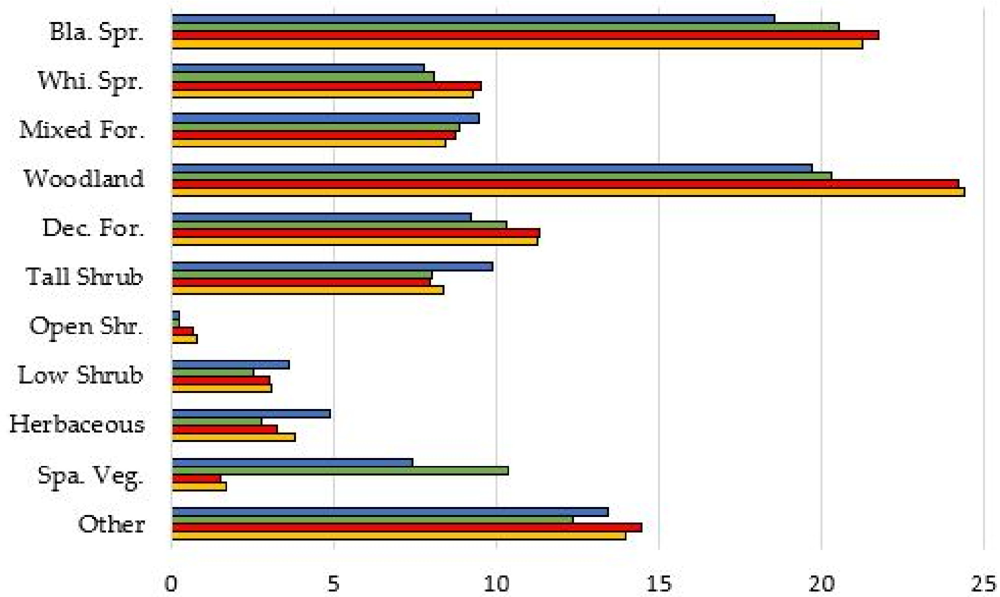
The Whitehorse study area (Figure 3c, Table A2c) is dominated by white spruce forest (29% in 2014) followed by lodgepole pine forest (13%). Subalpine fir accounts for only 6%. From 1984 to 2014, there seems to be general vegetation recovery as herbaceous, sparsely vegetated, and barren landcover types are decreasing, while all forest types, as well as tall and low shrubs, are increasing.

3.2. Model Validation

Overall, the models were sufficiently accurate. Table 2 shows the confusion matrices for the three study areas followed by statistics in Table 3. AUC-ROC was 0.88 for Anchorage, 0.77 for Fairbanks, and 0.86 for Whitehorse. AUCPR for Fairbanks was 0.89. The Fairbanks model had the highest true positive rate probably due to the high number of black spruce pixels on which the model could be trained (Table 3). For example, for observations that are actually black spruce, the model correctly identified them 84% of the time and misclassified only 16% of them. For observations that are not black spruce, the model correctly identified them 52% of the time and misclassified 48% of them. In contrast, Anchorage had a large proportion of true negatives because only 0.5% of the study areas included black spruce for model training and testing.

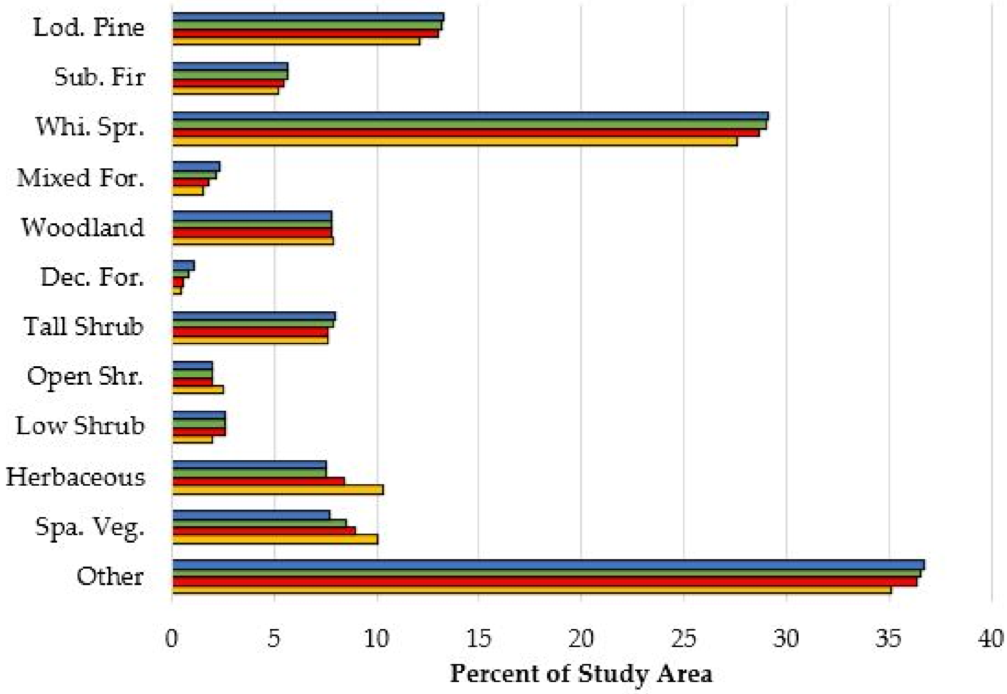


(**a**)



(**b**)

Figure 3. *Cont.*



(**c**)

Figure 3. Landcover from 1984 to 2014 in the (**a**) Anchorage, (**b**) Fairbanks, and (**c**) Whitehorse study areas. Units are given as the percent of study area. Here Bla. Spr. = Black Spruce, Whi. Spr. = White Spruce, Mixed For. = Mixed Forest, Dec. For. = Deciduous Forest, Open Shr. = Open Shrubs, Spa. Veg. = sparsely vegetated, Lod. Pine = Lodgepole Pine, and Sub. Fir = Subalpine Fir. Other includes barren, bog, fen, NA, shallows/littoral, tussock tundra, and water.

Table 2. Confusion matrix. Here, 1 = black spruce for Anchorage and Fairbanks, and 1 = lodgepole pine in Whitehorse. A value of 0 represents other evergreens which are mostly white spruce.

	Anchorage		**Fairbanks**		**Whitehorse**	
	Actual					
Predicted	**0**	**1**	**0**	**1**	**0**	**1**
0	38,665	1635	130,139	108,045	571,058	111,373
1	2356	815	118,907	572,700	75,964	177,110

Table 3. Statistics based on the Confusion Matrix.

Statistic	**Anchorage**	**Fairbanks**	**Whitehorse**
Accuracy	90.8%	75.6%	80.0%
True positive	33.3%	84.1%	61.4%
False positive	66.7%	15.9%	38.6%
True negative	94.3%	52.3%	88.3%
False negative	6.1%	91.4%	13.3%
Precision	25.7%	82.8%	70.0%
Recall	33.3%	84.1%	61.4%

3.3. Succession Model

The analysis of ABoVE data yielded information on vegetation recovery based on pre-fire vegetation type (Figure 4). Pre-fire vegetation was important for determining post-fire succession with distinct vegetation compositions among the different vegetation types (Figure A3). Therefore, the derived post-fire succession rules were based on pre-fire vegetation at 5-year increments for each study area (Table 4). In general, the first 5–10 years are frequently sparsely vegetated followed by succession into shrubs (Figure A2). Deciduous forest returns 16 years after fire; mixed forest and woodland can take 20–30 years to recover; and evergreen forests do not return for >30 years with the exception of lodgepole pine, which could reestablish after 20 years ([1,58] and Jill Johnstone, personal communication). Our chord graph visualization supports the transition of flammable evergreen and woodland pixels into other landcover types over the 31 years within the Fairbanks area (Figure 5).

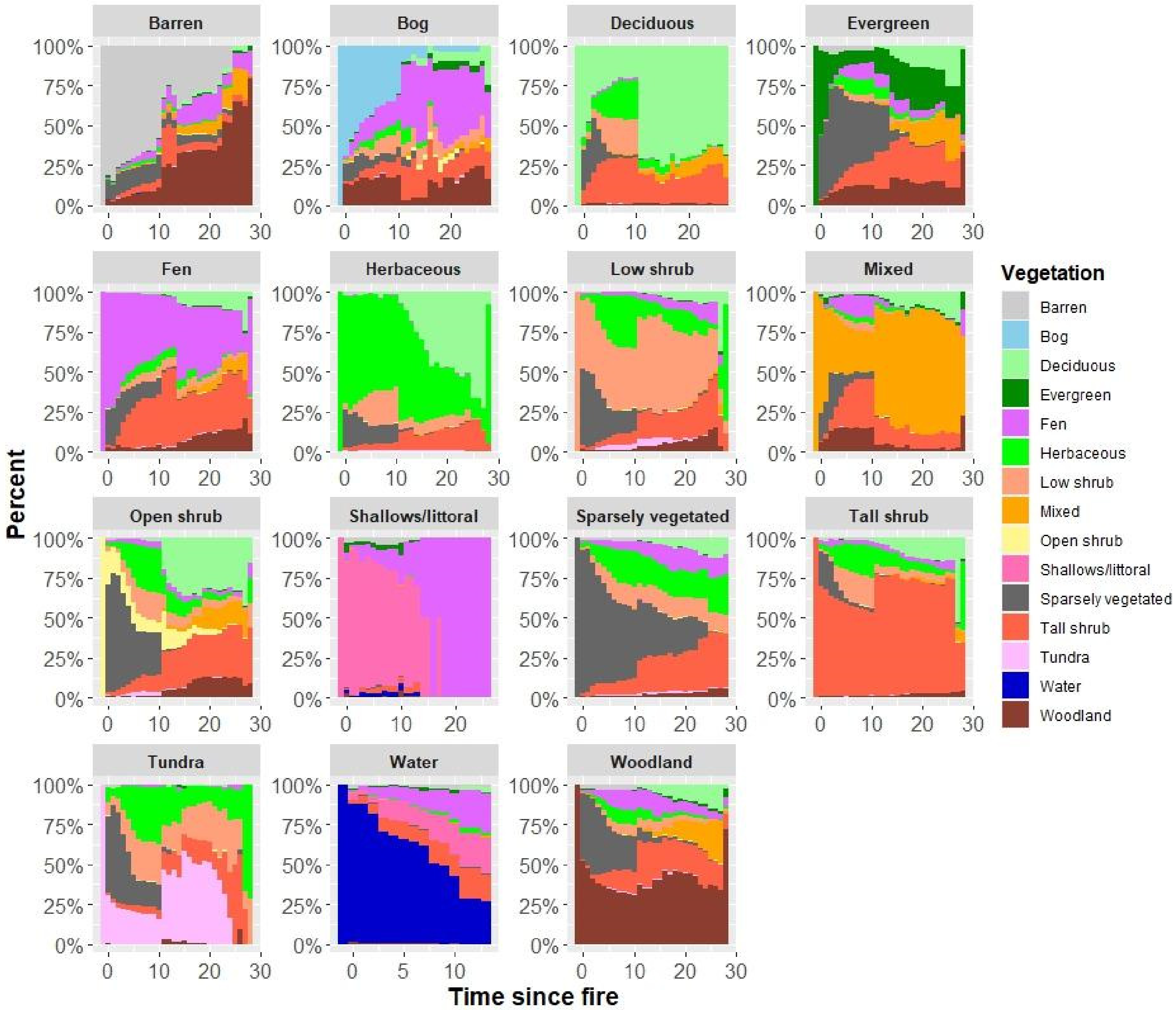


Figure 4. Vegetation changes after fire (year 0) in the Fairbanks study area based on ABoVE data and organized by pre-fire vegetation type. Only burns between 1985 and 2021 were used. Pre-fire vegetation for burns after 2014 was assumed to be the same as 2014 counts. Actual pixel counts decrease with time since fire and are provided in Figure A3.

Table 4. Vegetation succession rules after fire based on analysis of ABoVE data, literature review, and expert feedback for (**a**) Anchorage and Fairbanks and (**b**) Whitehorse. For example, if a black spruce pixel burns, it is classified at sparsely vegetated for the following 10 years, then becomes tall shrub, and after 30 years is again recognizable as a black spruce pixel. Mixed forest and Lodgepole ine (only in Whitehorse) recover after 20 years, and deciduous forest recovers after 15. Woodland recovery can take 20 or 30 years depending on pre-fire vegetation and location (Alaska versus Yukon). Hemlock (only in Anchorage) recovers after 30 years. Only landcover types that are undergoing succession are shown here. Abbreviations used are Bla. Spr. = Black Spruce Forest, Spr. For. = Other Spruce Forest, Mix. For. = Mixed Forest, Dec. For. = Deciduous Forest, Open Shr. = Open Shrubs, Sha./lit. = shallows/littoral, and Spa. Veg. = Sparsely Vegetated. For more detail on how this table was derived, see Appendix A.

(a)

Pre-Fire Vegetation	**Postfire Vegetation Recovery in 5-Year Increments**					
	0–5 Years	**6–10 Years**	**11–15 Years**	**16–20 Years**	**21–30 Years**	**>31 Years**
Hemlock	Spa. Veg.	Low shrub	Tall shrub	Tall shrub	Tall shrub	Hemlock
Bla. Spr.	Spa. Veg.	Spa. Veg.	Tall shrub	Tall shrub	Tall shrub	Bla. Spr.
Spr. For.	Spa. Veg.	Low shrub	Tall shrub	Tall shrub	Tall shrub	Spr. For.
Mixed forest	Low shrub	Tall shrub	Tall shrub	Tall shrub	Mix. For.	Mix. For.
Woodland	Spa. Veg.	Spa. Veg.	Open Shr.	Open Shr.	Woodland	Woodland
Dec. For.	Low shrub	Tall shrub	Tall shrub	Dec. For.	Dec. For.	Dec. For.
Open shrubs	Spa. Veg.	Open Shr.	Open Shr.	Dec. For.	Dec. For.	Dec. For.
Sha./lit.	Sha./lit.	Sha./lit.	Sha./lit.	Sha./lit.	Fen	Fen
Spa. Veg.	Spa. Veg.	Spa. Veg.	Spa. Veg.	Spa. Veg.	Tall shrub	Tall shrub

(b)

Pre-Fire Vegetation	**Postfire Vegetation Recovery in 5-Year Increments**					
	0–5 Years	**6–10 Years**	**11–15 Years**	**16–20 Years**	**21–30 Years**	**>31 Years**
Lodgepole pine	Spa. Veg.	Low shrub	Tall shrub	Tall shrub	Lodgepole Pine	Lodgepole Pine
Sub-alpine fir	Spa. Veg.	Spa. Veg.	Spa. Veg.	Low shrub	Low shrub	Sub-alpine fir
Spr. For.	Spa. Veg.	Low shrub	Tall shrub	Tall shrub	Tall shrub	Spr. For.
Mixed forest	Low shrub	Tall shrub	Tall shrub	Tall shrub	Mix. For.	Mix. For.
Woodland	Spa. Veg.	Herbaceous	Herbaceous	Open Shr.	Open Shr.	Woodland
Dec. For.	Low shrub	Tall shrub	Tall shrub	Dec. For.	Dec. For.	Dec. For.
Open shrubs	Spa. Veg.	Open Shr.	Open Shr.	Open Shr.	Open Shr.	Woodland
Sha./lit.	Sha./lit.	Sha./lit.	Sha./lit.	Sha./lit.	Fen	Fen
Spa. Veg.	Spa. Veg.	Spa. Veg.	Spa. Veg.	Spa. Veg.	Woodland	Woodland

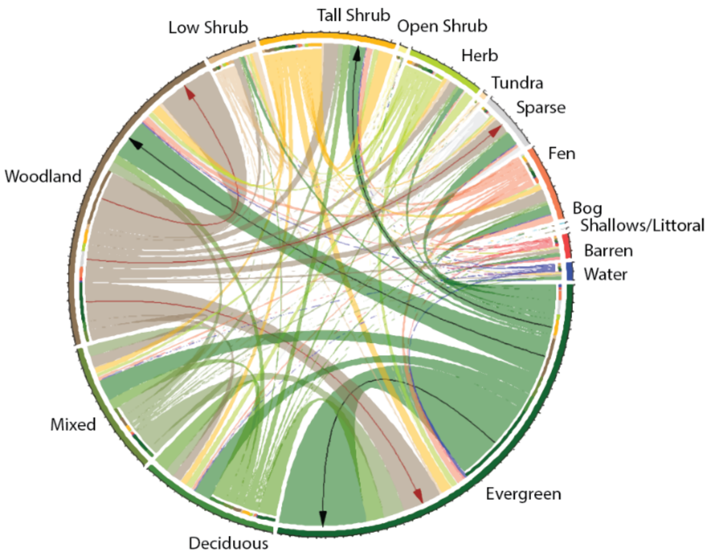


Figure 5. Landcover change from 1984 to 2014 in the Fairbanks study area. In this chord diagram, the size of each wedge indicates the proportion of the landscape and lines across the middle indicate transitions; 1984 landcover is set back from the edge, and arrows indicate change through time.

3.4. Future Fire Disturbance and Landcover

We were unable to draw relationships to climate trends through 2060 that could inform changes in flammability or fuel characterizations that would produce the anticipated increase in burned area using fire behavior modeling tools such as FlamMap. At the same time, there is indication in the historic fire record that suggests important trends are already manifest. The historic trends suggest that large departures in annual burned area totals for Fairbanks have occurred in both 1958/59 and in 2004, something less than 50 years apart. This is likely due to the maturation of boreal spruce forests in the intervening period [74]. The burned area in 2004 and its impact on decadal totals is much larger than for the earlier period. Also, burned area totals since 2014 have shown a marked increase from earlier periods as well.

Figure 6a shows the plotted distribution of those 100,000 instances. The simulation suggested a bimodal distribution with two distinctly different ranges analogous to the historic trend: a lower distribution with median decadal area burned of approximately 1000 km^2 that occurred in 80% of the simulations and a second, higher, and distinct range of exceptional decadal burned area totals with a median of approximately 4000 km^2 that occurred in the remaining 20% of simulations. Assuming the near future is not drastically different from the past, we let these two probable yet distinctly different scenarios serve as the basis for our four future simulated decadal area burned totals. The simulation runs were guided by the 1000 km^2 estimate for the first three decades (2014–2023, 2024–2033, and 2034–2043). The 4000 km^2 total was used to guide the simulated total for the final decade (2044–2053). These simulated totals are shown in Figure 6b alongside the historic decadal area burned total and demonstrate conformance to the historic trend, as well as the suggestion of climate-based increase. With now nine of the ten years of the 2014–2023 decade passed, the first projected decadal total is nearly complete and is very close to our Monte Carlo estimate.

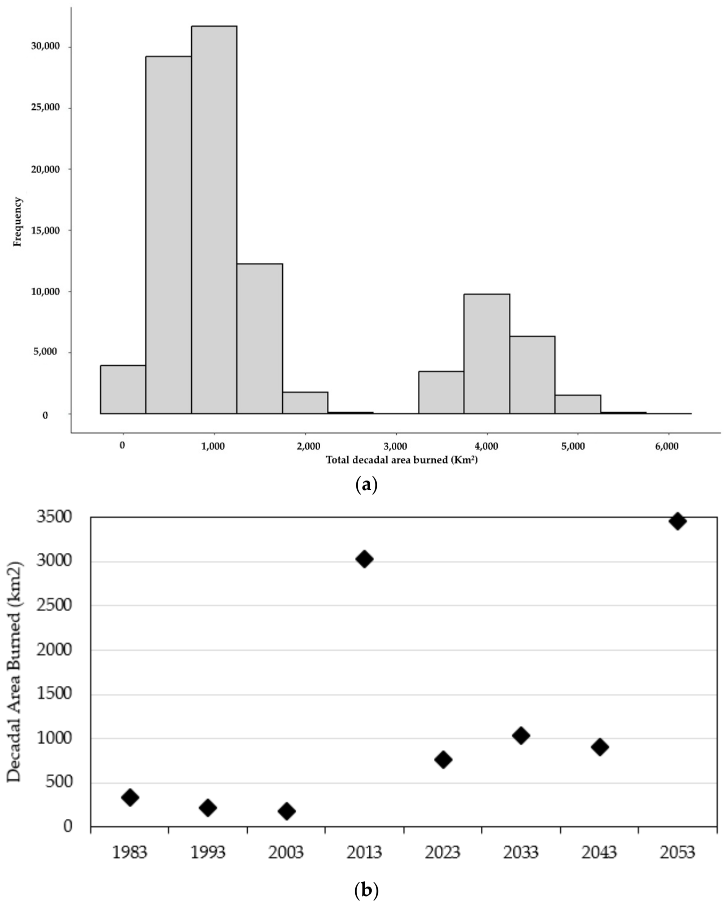


Figure 6. Area burned trends for the Fairbanks study area. (**a**) Results of 100,000 Monte Carlo simulations of decadal area burned (in km^2) based on random combination of historic annual area burned from the period 1950–2021. Here, frequency represents the number of simulations. (**b**) Historic (1974 to 2022) and simulated (2023–2053) decadal area burned (in km^2), years on the *x*-axis indicate when the decade ended, so 1983 includes area burned from 1974 to 1983.

We realize that our simulated fire perimeters are only one possible version of the future, but they give us a probable estimate of where the fires might be and how much area might burn. We know from historic fire analysis that many forest stands identified with a high wildfire exposure have actually burned recently. We can also see in Figure 7 that our model recognizes that some of the tall shrub area northeast of Fox, which burned in a massive wildfire in 2004, will start to be flammable again sometime within the next decade as indicated by the two smaller fire perimeters.

The landcover composition changed very little in the Anchorage study area over the years (Figure 8a). The Fairbanks study area will continue to experience the most change in landcover (Figure 8b, Table A3a). Evergreen and deciduous forests will decline in upcoming decades, which becomes more drastic during the high intensity fire decade preceding 2054. Mixed forest and woodland will expand slightly from 2024 to 2044 but suffer reductions by 2054. Many trees are replaced by low and tall shrubs by 2044. After the intense fire decade, tall shrubs will dominate 24% of the landscape, followed by woodland (15%) and sparsely vegetated (13%). In 2054, black spruce will cover 47% of its 2014 extent and 41% of its 1984 extent. White spruce will be reduced to 49% and 41% of its respective 2014 and 1984 extent. Forests will no longer dominate the Fairbanks landscape in 2054 when they will account for only 27% with an additional 15% of woodland (compared to 45% and 20% in 2014, respectively). The Whitehorse study area will continue its conversion of sparsely vegetated, tall, and open shrub to mostly woodland, white spruce, and mixed forest (Figure 8c, Table A3c). However, overall landscape change is minimal.

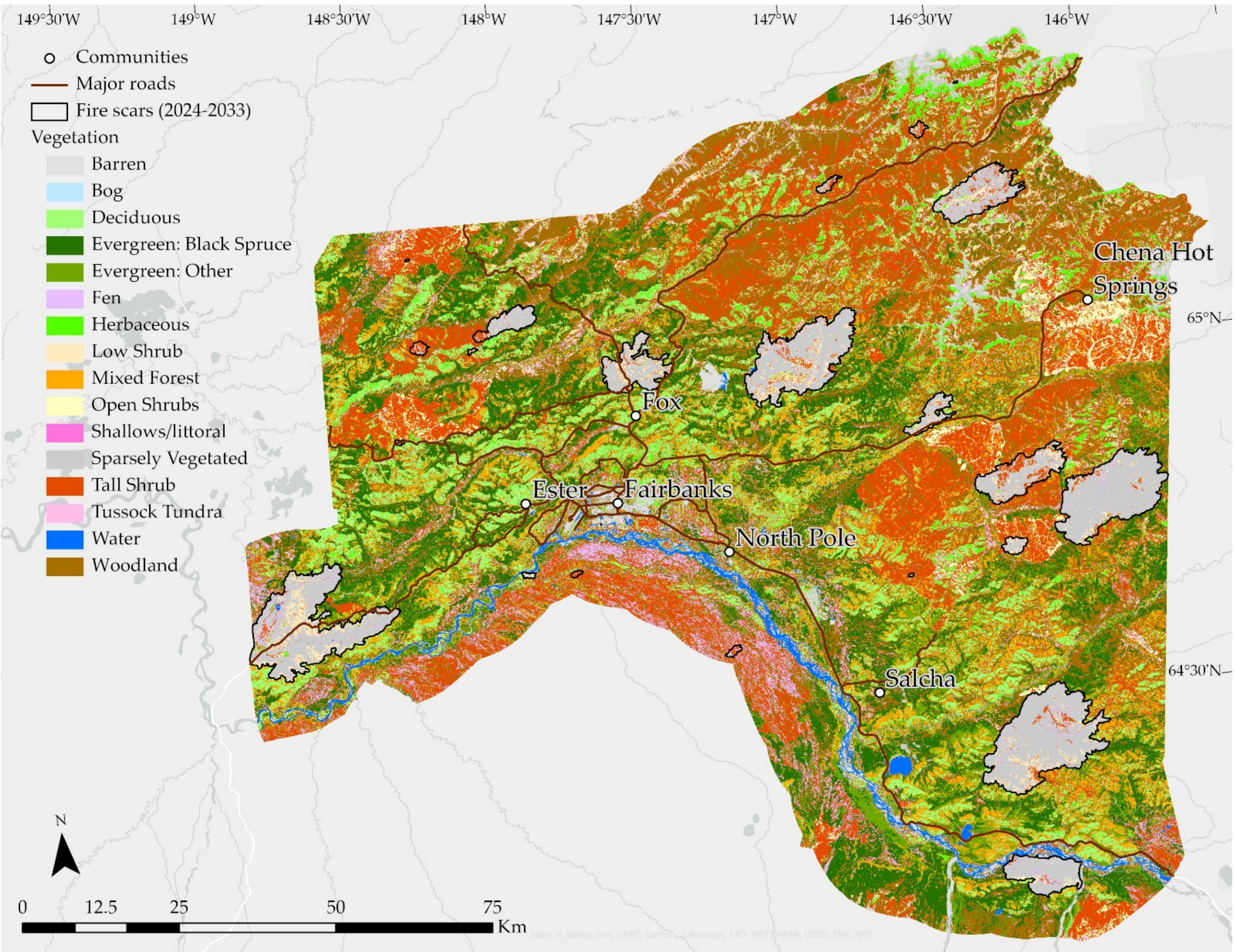
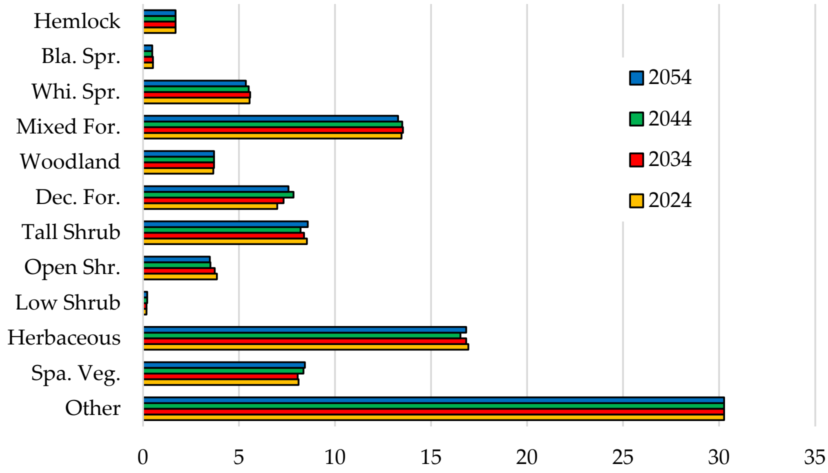
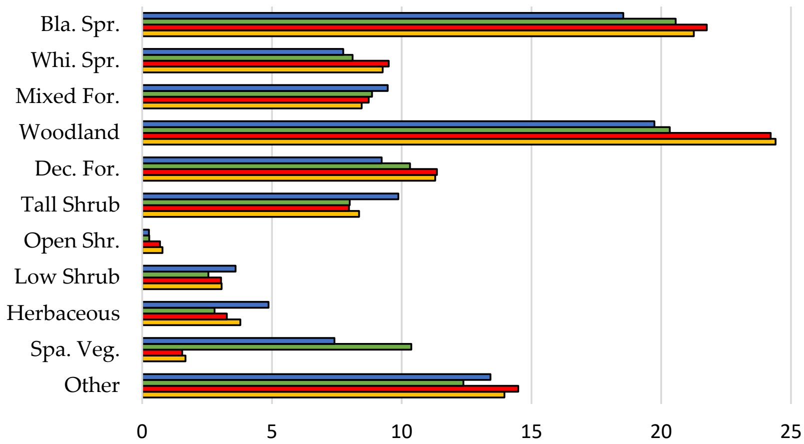


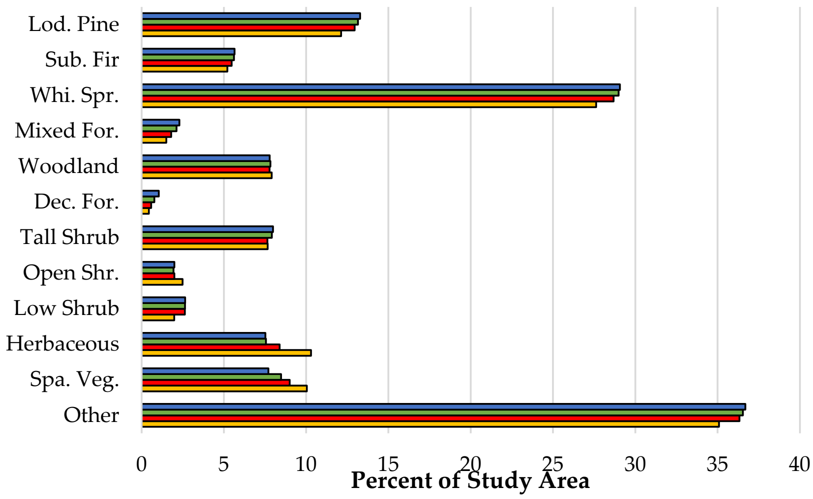
Figure 7. 2034 landcover for Fairbanks with 2024–2033 modeled fire perimeters.



(**a**)



(**b**)



(**c**)

Figure 8. Predicted future landcover in the (**a**) Anchorage, (**b**) Fairbanks, and (**c**) Whitehorse study areas. Units are given as percent of study area. Here, Bla. Spr. = Black Spruce, Whi. Spr. = White Spruce, Mixed For. = Mixed Forest, Dec. For. = Deciduous Forest, Open Shr. = Open Shrubs, Spa. Veg. = sparsely vegetated, Lod. Pine = Lodgepole Pine, and Sub. Fir = Subalpine Fir. Other includes barren, bog, fen, NA, shallows/littoral, tussock tundra, and water.

4. Discussion

In this study, we set out to create consistent landcover datasets for our three study areas at decadal increments. We then projected landcover into the future to better understand wildfire exposure for communities across eight decades.

4.1. Historic Land Cover and Succession

Ecosystems in boreal Alaska and western Canada are responding to recent changes in climate as well as the fire cycle. Several remote sensing analyses of unburned forest areas at various scales and resolutions ranging from 1980 to 2014 indicate that while the majority of the forest biome is stable or going through succession as expected [26,27,30,75], our analysis of ABoVE time series data confirms that the majority of the forest in our study still appears to be following historic succession pathways at the landscape scale.

However, there are indications of change along the northern and southern border, as well as in the eastern portion of Interior Alaska [26,27,30,75]. There, "browning" of forest pixels has been detected, indicating a decrease in NDVI or ecosystem productivity. Studies that include recent fires [24,27,29,76] describe an ecosystem shift from evergreen to deciduous forest which might have starting around 1990 [28].

The Fairbanks study area in Interior Alaska is dominated by forest and woodland (accounting for nearly 75% of the study area in 1984), contains the most highly flammable black spruce forest (21% in 1984), and experienced extensive wildfires (30% of the study area burned between 1984 and 2021). This led to a notable decrease in forest and woodland between 1984 and 2014 when they accounted for only 65% of the study area, while sparsely vegetated area increased by 84%. The chord diagram (Figure 5) visualizes this "flow" of evergreen and woodland pixels to other landcover types.

Several studies have discussed this shift to alternate succession trajectories as more frequent wildfires can prevent black spruce recovery when there is not enough recovery time [18,28,29]. White spruce regeneration might be impeded by moisture stress and higher temperatures at dry sites [77,78], while potentially encroaching on sites where permafrost is melting [78]. While the general assumption is a replacement of evergreen forest with deciduous, a tree-ring study from Interior Alaska found decreasing growth trends for aspen since the 1950s with sharper reductions during insect defoliation events, while recent birch growth also was slightly lower than the 20th century mean [77]. Our landcover analysis shows decreases in deciduous forest in the Fairbanks study area by 18% between 1984 to 2014.

Whitehorse is our second-most forested study area, where forests and woodlands accounted for nearly 55% of landcover in 1984 and increased to 59% in 2014, while herbaceous and sparsely vegetated landcover types decreased. This indicates general vegetation recovery and occurred in the near absence of fires, though some flammable vegetation was removed via fuel treatment. Anchorage contains the largest urban area and the highest population despite being the smallest study area. It had the least amount of forest and woodland cover in 1984 (32%) and experienced essentially no change in landcover. Wildfires were also essentially absent due to a moister climate and less flammable vegetation.

While needle-leaf trees are generally more flammable than deciduous species, being able to differentiate the major evergreen tree species based on their flammable vastly improves fire model predictions and thus risk assessment for communities. Since our study areas extended across two countries and three sites, a lack of widely available predictor data would have been problematic for a more static empirical model. Instead, our machine learning model was able to incorporate available data but also interpolate when data were insufficient. This was a critical ability for a model in a study such as ours where available data rarely covered the entire study area. Additionally, choosing a decision tree model over a random forest model, which would have been similar, vastly increased model processing speed. Overall, model accuracy could possibly have been improved by incorporating more predictors than the climate, soils, and topographic information we used, but after a year spent searching for and testing additional datasets, these datasets covered most of our study areas, were at an appropriate resolution, and seemed most robust.

4.2. Future Fire Disturbance and Landcover

Flammap [65] is a well-established fire behavior mapping and analysis program that calculates fire behavior cell-by-cell in a GIS environment. Since the model simulates fire spreading through surface fuels, it helps identify areas most at risk of burning and therefore at priority for fuel treatment or similar hazard reduction measure. For example, it was used to assess the impact of fuel loads and topography on fire in California montane forest [79], pre- and post-fire fuel treatment in Utah [72], and the burn potential of fire refugia in the Eastern Canadian mixed forest [80]. Using flammability settings based on our refined ABoVE landcover types, FlamMap could be used to predict areas likely to burn in the near future in our study areas. Our assumption of increased wildfire in the last decade of our prediction was based on historic incidence of high fire decades and matches predictions of climatic wildfire thresholds that will result in larger areas burned in the future [81–83].

Our model predicts a continued conversion of forests to non-forests in the highly flammable Fairbanks study area. This includes evergreen, deciduous, and mixed forest, while woodland remains essentially the same and results in a landscape where tall shrubs, woodland, and sparsely vegetated account for 52% of the area by 2054. While there are several predictions of conversions of evergreen forests to deciduous and some reduction in forest altogether in an impeding major ecological shift [28,30,84], concrete details on the speed of this conversion or the actual area are lacking.

We realize that our simulated future firescars are only one possible version of the future, but they provide a realistic estimate of where future fires are likely, based on flammability of the landscape and how much area might burn. We know from historic fire analysis that many forest stands identified with a high wildfire exposure have actually burned recently. We can also see in Figure 7 that our model recognizes that some of the tall shrub area northeast of Fox which burned in a massive wildfire in 2004 will start to be flammable again sometime within the next decade as indicated by the two smaller firescars. Otherwise, direct comparison of model results with other people's simulations is nearly impossible due to vast differences in study areas and temporal and spatial resolution. Balshi et al. [81] predicted a doubling of area burned from 1991–2000 to 2041–2050 which is much lower than our numbers in Figure 6, which indicates a roughly fourfold increase in area burned. Simulations with ALFRESCO indicated that annual area burned would increase "markedly" after 2010 [28]. McCoy [83] predicted a doubling in area burned in the central Yukon by 2069 based on projected fire weather. But since our predictions are based on current vegetation, its flammability, and past fire history, not future climate, our estimates are not comparable.

By refining and expanding ABoVE landcover datasets beyond their temporal coverage, our modeling approach resulted in a consistent and sufficiently detailed land cover datasets for our three study areas from 1984 to 2054 that identified evergreen forest stands with different flammability. This provides critical information for communities and agencies preparing for climate-related hazards who will have to adapt to increased fire risk, exposure, and costs in the boreal zone [85].

This, in turn should eventually reduce available fuel and thus fires [86]. Additionally, defoliation-causing insects and disease seem to be spreading and intensifying in some areas [87]. These changes will be associated with carbon losses, but eventually, the lower flammability of deciduous ecosystems should stabilize the wildfire regime [86,88].

5. Conclusions

We developed a unique approach to landcover modeling in the western North American boreal forest by combining multiple models to fill the data gap at the appropriate level of detail and temporal and spatial extent. Resulting landcovers can be used to determine wildfire risks from 1984 to 2054 in our three study areas and will provide critical planning tools to affected communities. Our relatively simple modeling approach could serve as a blueprint for similar efforts elsewhere.

Author Contributions: Conceptualization, J.I.S.; methodology, M.P.C., J.I.S., A.V. and R.Z.; software, M.P.C., J.I.S., A.V. and R.Z.; formal analysis, J.I.S., A.V. and R.Z.; investigation, M.P.C., J.I.S., A.V. and R.Z.; resources, M.P.C., J.I.S., A.V. and R.Z.; data curation, M.P.C., J.I.S., A.V. and R.Z.; writing—original draft preparation, M.P.C.; writing—review and editing, M.P.C., J.I.S., A.V. and R.Z.; visualization, M.P.C., J.I.S., A.V. and R.Z.; supervision, J.I.S.; project administration, J.I.S.; funding acquisition, J.I.S. and M.P.C. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The landcover layers, as well as the R scripts presented in this study, are openly available in https://osf.io/vr93u/ (accessed on 1 February 2023).

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Appendix A

Deriving general succession rules required a thorough analysis of AboVE data in multiple steps. We also used fire history between 1950 and 2020 while our analysis of pre-fire vegetation effects was limited to fires between 1985 and 2014. Fairbanks was the only study area with extensive wildfire activity with over 23% of the study area burnt in 2004 and subsequent impacts on the vegetation composition. To build a vegetation succession model, we used the ABoVE dataset to explore how the vegetation changed over time (Figure A1). We then reorganized this information into proportion of pixels for each year before and after fire by vegetation type (Figure A2). This then allowed us to show how vegetation changed after fire based on pre-fire vegetation (Figure A3). Pre-fire vegetation is the vegetation identified in the year prior to burning. Areas that burned were primarily woodland (35%) and evergreen (28%) followed by tall shrub (9%) and fen (6%). All other vegetation types accounted for less than 5% of the area burned.

In order to identify the dominant vegetation type at each 5-year increment following disturbance, we plotted distribution of vegetation types after fire (Table A1). Our analysis indicates that sparse vegetation dominates the landscape during the first 5 years after a wildfire. Even though woodland that burned tended to return to woodland immediately after a fire, we believe it would be more realistic to transition to sparsely vegetated, then open shrubs, and back to woodland. Information in this table was then simplified into Table 4. Lessons learned from the ABoVE data were also compared with the literature and vetted by plant ecologists and wildfire experts in Alaska and Canada to develop rules for succession.

Detailed landcover data resulting from our modeling efforts for each decadal timestep are given in Table A2 (1984 to 2014) and Table A3 (predicted future vegetation for 2024 to 2054).

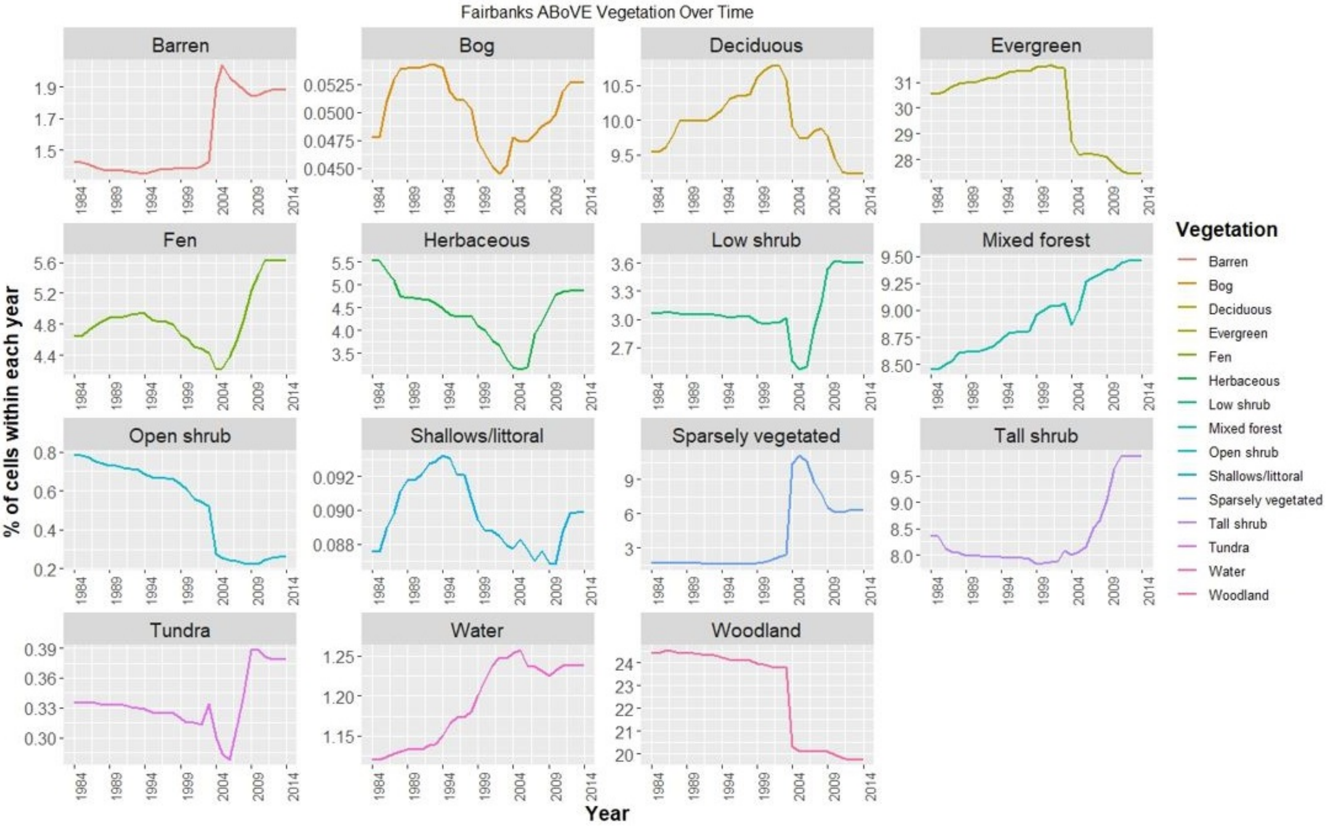

Figure A1. Changes in land cover in the Fairbanks study area as identified in ABoVE by year.

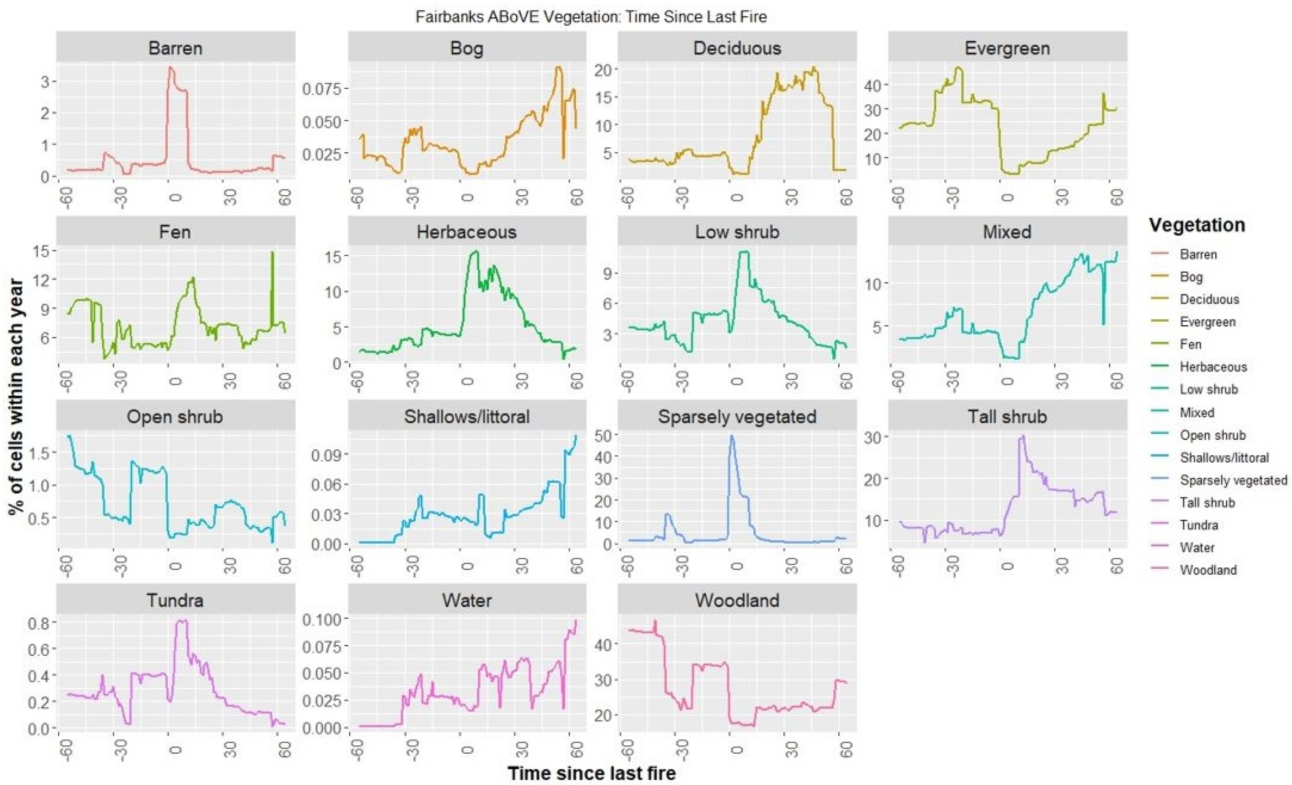

Figure A2. Changes in land cover in the Fairbanks study area as identified in ABoVE pixels of time since the last fire.

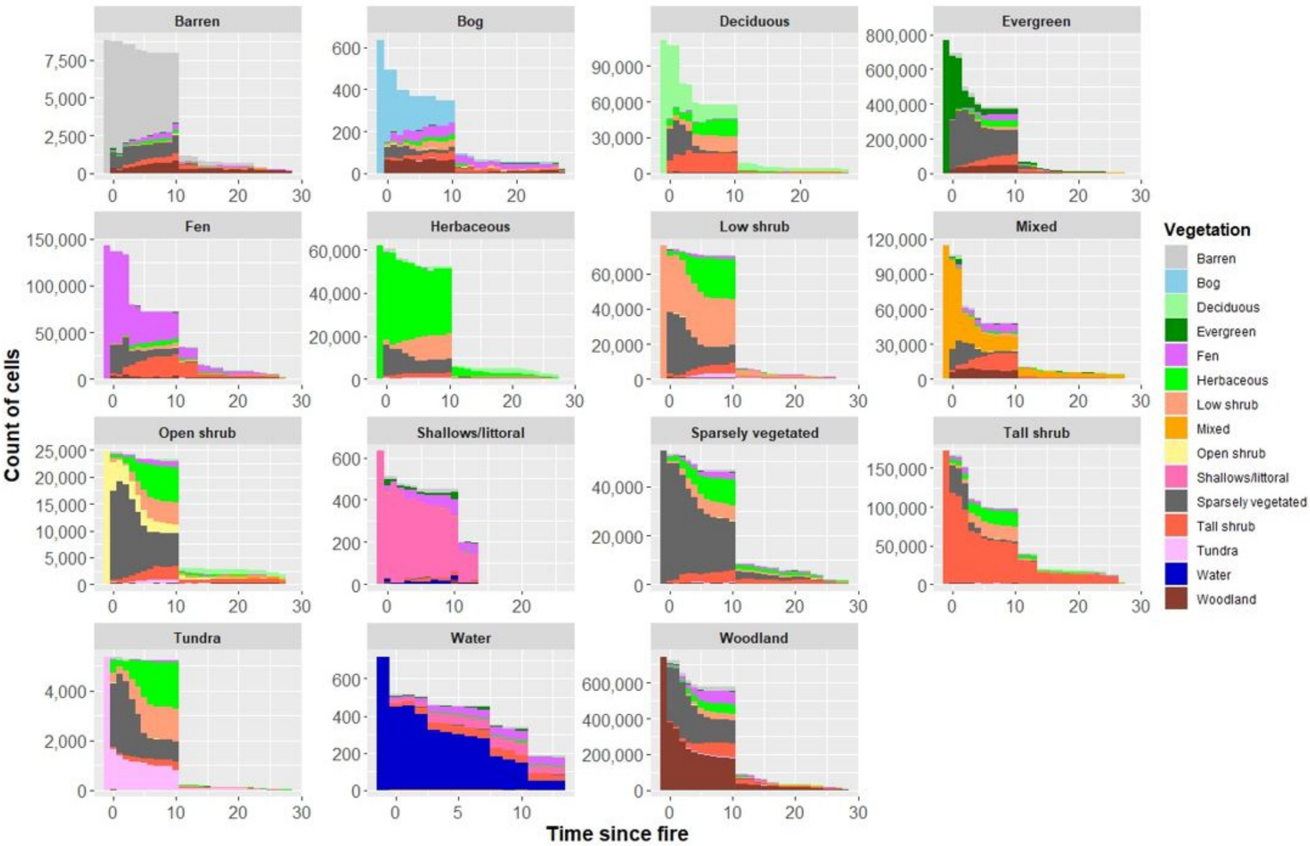

Figure A3. Cell counts of the vegetation present after a fire based on pre-fire vegetation type. Only burns between 1985 and 2021 were used. Pre-fire vegetation for burns after 2014 was assumed to be the same as 2014 counts.

Table A1. Landcover type by time since last fire in the Fairbanks study area using the 1984–2014 ABoVE vegetation dataset and the Alaska wildfire dataset from 1950 through 2021 (https://fire.ak.blm.gov/ (accessed on 1 January 2023)). Numbers are given as a percent of pixels at each time step. Bold text indicates the dominant vegetation. If vegetation types are within 2 percent of each other, they are considered co-dominant.

	Time Since Last Fire													
Vegetation	**0**	**5**	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**	**64**
Barren	3	3	3	0	0	0	0	0	0	0	0	0	1	1
Bog	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Deciduous	2	1	1	8	12	17	16	17	16	19	16	13	2	2
Evergreen	15	4	3	8	8	8	13	14	15	18	**23**	**24**	**29**	31
Fen	5	9	10	10	7	7	7	7	6	5	7	7	7	6
Herbaceous	4	14	16	10	13	9	9	7	5	3	3	3	2	2
Low shrub	3	10	11	8	6	5	5	4	4	3	2	2	2	2
Mixed	3	1	1	6	8	10	9	10	12	13	11	12	12	14
Open shrub	0	0	0	0	0	0	1	1	1	0	0	0	1	0
Shallows/littoral	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Sparsely vegetated	**40**	**27**	**21**	3	1	1	1	0	0	0	1	1	2	2
Tall shrub	6	13	16	**24**	**22**	**20**	17	17	17	15	15	17	12	12
Tundra	0	1	1	1	0	0	0	0	0	0	0	0	0	0
Water	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Woodland	19	18	17	**22**	**21**	**22**	**22**	**22**	**24**	**22**	**22**	**22**	**30**	29

Table A2. Landcover change through time in the (**a**) Anchorage, (**b**) Fairbanks, and (**c**) Whitehorse study areas. Area units are given in km^2 and percent and are based on 30 m pixels.

(a)	1984		1994		2004		2014	
Vegetation	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
Barren	592	21.89	589	21.78	591	21.86	589	21.78
Bog	0	-	0	-	0	-	0	-
Deciduous Forest	189	6.99	198	7.32	212	7.84	205	7.58
Evergreen Forest: Black Spruce	14	0.52	14	0.52	13	0.48	13	0.48
Evergreen Forest: White Spruce	150	5.55	151	5.58	149	5.51	145	5.36
Fen	13	0.48	14	0.52	13	0.48	14	0.52
Hemlock	46	1.7	46	1.7	46	1.7	46	1.7
Herbaceous	458	16.94	455	16.83	447	16.53	455	16.83
Low Shrub	5	0.18	5	0.18	6	0.22	6	0.22
Mixed Forest	364	13.46	366	13.54	365	13.5	359	13.28
NA	158	5.84	158	5.84	158	5.84	158	5.84
Open Shrubs	104	3.85	101	3.74	95	3.51	94	3.48
Shallows/littoral	2	0.07	3	0.11	2	0.07	2	0.07
Sparsely Vegetated	219	8.1	218	8.06	226	8.36	228	8.43
Tall Shrub	231	8.54	227	8.39	222	8.21	232	8.58
Tussock Tundra	1	0.04	1	0.04	2	0.07	2	0.07
Water	57	2.11	56	2.07	56	2.07	56	2.07
Woodland	99	3.66	100	3.7	100	3.7	100	3.7
(b)	**1984**		**1994**		**2004**		**2014**	
Vegetation	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
Barren	196	1.42	186	1.35	263	1.9	260	1.88
Bog	7	0.05	7	0.05	7	0.05	7	0.05
Deciduous Forest	1561	11.29	1570	11.36	1426	10.32	1275	9.23
Evergreen Forest: Black Spruce	2939	21.26	3008	21.76	2842	20.56	2563	18.54
Evergreen Forest: White Spruce	1281	9.27	1313	9.5	1121	8.11	1071	7.75
Fen	641	4.64	683	4.94	583	4.22	777	5.62
Herbaceous	522	3.78	451	3.26	386	2.79	673	4.87
Low Shrub	423	3.06	420	3.04	353	2.55	498	3.6
Mixed Forest	1169	8.46	1207	8.73	1225	8.86	1308	9.46
NA	2	0.01	2	0.01	2	0.01	2	0.01
Open Shrubs	108	0.78	95	0.69	38	0.27	36	0.26
Shallows/littoral	12	0.09	13	0.09	12	0.09	12	0.09
Sparsely Vegetated	231	1.67	213	1.54	1434	10.37	1024	7.41
Tall Shrub	1155	8.36	1101	7.97	1106	8	1364	9.87
Tussock Tundra	46	0.33	45	0.33	42	0.3	52	0.38
Water	155	1.12	159	1.15	173	1.25	171	1.24
Woodland	3374	24.41	3348	24.22	2810	20.33	2728	19.74
(c)	**1984**		**1994**		**2004**		**2014**	
Vegetation	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
Barren	707	5.75	650	5.28	634	5.15	624	5.07
Bog	0	0	0	0	0	0	1	0.01
Deciduous Forest	54	0.44	71	0.58	96	0.78	129	1.05
Evergreen Forest: Lodgepole Pine	1492	12.13	1593	12.95	1618	13.15	1634	13.28
Evergreen Forest: White Spruce	3399	27.62	3529	28.68	3567	28.99	3578	29.07
Fen	212	1.72	292	2.37	295	2.4	314	2.55
Herbaceous	1267	10.3	1032	8.39	930	7.56	926	7.52
Low Shrub	244	1.98	324	2.63	325	2.64	326	2.65
Mixed Forest	184	1.5	221	1.8	261	2.12	283	2.3
NA	7	0.06	7	0.06	7	0.06	7	0.06

Table A2. *Cont.*

(c)	1984		1994		2004		2014	
Vegetation	**km^2**	%	**km^2**	%	**km^2**	%	**km^2**	%
Open Shrubs	307	2.49	245	1.99	239	1.94	245	1.99
Shallows/littoral	17	0.14	19	0.15	20	0.16	20	0.16
Sparsely Vegetated	1236	10.04	1107	9	1044	8.48	949	7.71
Subalpine Fir	641	5.21	674	5.48	691	5.62	695	5.65
Tall Shrub	942	7.66	941	7.65	975	7.92	983	7.99
Tussock Tundra	40	0.33	57	0.46	52	0.42	47	0.38
Water	583	4.74	586	4.76	588	4.78	588	4.78
Woodland	973	7.91	957	7.78	964	7.83	959	7.79

Table A3. Predicted future landcover in the (**a**) Anchorage, (**b**) Fairbanks, and (**c**) Whitehorse study areas. Area units are given in km^2 and are based on 30 m pixels.

(a)	2024		2034		2044		2054	
Vegetation	**km^2**	%	**km^2**	%	**km^2**	%	**km^2**	%
Barren	588	21.73	588	21.73	588	21.73	588	21.73
Bog	0	0	0	0	0	0	0	0
Deciduous Forest	204	7.55	205	7.58	205	7.58	205	7.58
Evergreen Forest: Black Spruce	13	0.47	13	0.47	13	0.47	13	0.47
Evergreen Forest: White Spruce	144	5.32	144	5.32	144	5.32	144	5.32
Fen	14	0.52	14	0.52	14	0.52	14	0.52
Hemlock	46	1.68	46	1.68	46	1.68	46	1.68
Herbaceous	454	16.78	454	16.78	454	16.78	454	16.78
Low Shrub	8	0.3	7	0.25	8	0.29	8	0.29
Mixed Forest	357	13.2	358	13.25	359	13.27	359	13.27
NA	157	5.8	157	5.8	157	5.8	157	5.8
Open Shrubs	94	3.47	94	3.46	94	3.46	94	3.46
Shallows/littoral	2	0.08	2	0.08	2	0.08	2	0.08
Sparsely Vegetated	227	8.41	227	8.4	227	8.4	227	8.4
Tall Shrub	235	8.67	234	8.66	233	8.61	233	8.61
Tussock Tundra	2	0.06	2	0.06	2	0.06	2	0.06
Water	56	2.07	56	2.07	56	2.07	56	2.07
Woodland	100	3.68	100	3.69	100	3.69	100	3.69
(b)	**2024**		**2034**		**2044**		**2054**	
Vegetation	**km^2**	%	**km^2**	%	**km^2**	%	**km^2**	%
Barren	193	1.39	193	1.39	193	1.39	193	1.39
Bog	7	0.05	7	0.05	7	0.05	7	0.05
Deciduous Forest	1322	9.56	1334	9.65	1290	9.33	1081	7.82
Evergreen Forest: Black Spruce	2282	16.51	1953	14.13	1742	12.61	1192	8.62
Evergreen Forest: White Spruce	906	6.55	796	5.76	719	5.2	527	3.81
Fen	628	4.54	628	4.54	628	4.55	629	4.55
Herbaceous	390	2.82	390	2.82	390	2.82	390	2.82
Low Shrub	487	3.52	525	3.8	515	3.73	1058	7.65
Mixed Forest	1222	8.84	1254	9.08	1281	9.27	971	7.03
NA	1	0.01	1	0.01	1	0.01	1	0.01
Open Shrubs	1019	7.38	202	1.46	272	1.96	355	2.57
Shallows/littoral	12	0.09	12	0.08	11	0.08	11	0.08
Sparsely Vegetated	958	6.93	919	6.65	840	6.08	1761	12.74
Tall Shrub	2075	15.01	2536	18.35	3004	21.73	3297	23.86
Tussock Tundra	43	0.31	43	0.31	43	0.31	43	0.31
Water	171	1.24	171	1.24	171	1.24	171	1.24
Woodland	2104	15.22	2857	20.67	2712	19.63	2133	15.43

Table A3. *Cont.*

(c) Vegetation	2024 km^2	2024 %	2034 km^2	2034 %	2044 km^2	2044 %	2054 km^2	2054 %
Barren	623	5.06	623	5.06	623	5.06	623	5.06
Bog	1	0.01	1	0.01	1	0.01	1	0.01
Deciduous Forest	129	1.05	131	1.06	130	1.06	128	1.04
Evergreen Forest: Lodgepole Pine	1641	13.33	1639	13.32	1644	13.36	1644	13.36
Evergreen Forest: White Spruce	3557	28.91	3566	28.98	3573	29.04	3590	29.18
Fen	313	2.54	313	2.54	313	2.54	313	2.54
Herbaceous	928	7.54	928	7.54	927	7.53	926	7.53
Low Shrub	326	2.65	327	2.66	327	2.65	325	2.64
Mixed Forest	283	2.30	283	2.30	283	2.30	285	2.32
NA	4	0.03	4	0.03	4	0.03	4	0.03
Open Shrubs	249	2.03	244	1.99	245	1.99	243	1.98
Shallows/littoral	20	0.17	20	0.17	20	0.16	20	0.16
Sparsely Vegetated	950	7.72	927	7.54	922	7.49	922	7.49
Subalpine Fir	692	5.62	692	5.62	692	5.62	694	5.64
Tall Shrub	998	8.11	1008	8.19	1002	8.14	984	8.00
Tussock Tundra	47	0.38	47	0.38	47	0.38	47	0.38
Water	588	4.78	588	4.78	588	4.78	588	4.78
Woodland	956	7.77	962	7.82	964	7.84	966	7.85

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