

**FINAL REPORT**

# Resiliency and Vulnerability of Boreal Forest Habitat to the Interaction of Climate and Fire Disturbance Across DoD Lands of Interior Alaska

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## ABSTRACT

**Introduction and Objectives:** The overarching objective of our research was to investigate changing vegetation dynamics across boreal North America, with a focus on Department of Defense (DoD) lands of interior Alaska. We assessed observed and predicted changes in boreal tree composition through time and in a spatial context by linking field measurements with five decades of satellite observations and models. Our analyses incorporated broadscale impacts of disturbance, particularly fire, and post-disturbance vegetation succession. Our spatiotemporal analyses and modeling incorporate climate as a “press” disturbance as well as the “pulse” disturbance brought about by fire, each of which impact tree productivity and mortality. We then predicted change into the near future (20-50 years) using a combination of empirical and process-based models. We also interacted with DoD and other state and federal land managers to transfer the data products and analysis tools for their needs.

**Technical Approach:** We made extensive use of field measurements and multi-scale satellite observations, typically coupling the two in development of spatial models (maps) and change through time, while accounting for error and uncertainty. The field measurements incorporated species-specific responses to drivers and the remote sensing component addressed broader scale responses and changes in plant functional types (PFTs) including deciduous broadleaf trees, evergreen conifer trees, deciduous shrubs, and others. Two types of models were used to predict future change, informed with changes observed over recent decades. The first type included machine learning (statistical deep learning) models and the second type was a process-based model (UVAFME) that simulates a wide range of vegetation composition, structure and function in response to a suite of environmental drivers and ecosystem processes (e.g. climate, competition, fire, permafrost thaw).

**Results:** We documented wide scale change across the boreal forest ecosystems of central Alaska, as well as a broader spatial domain into Canada, over the past several decades using a diverse and extensive range of field measurements combined with multi-source remote sensing data. These were augmented with spatial models predicting future change, all with the purpose of informing management decisions. A wide range of previously unavailable data sets were documented and made available via active data archive systems that are open access. In some cases, such as data available via Google Earth Engine, these are accompanied with workflows and source code allowing updates to the data sets. We also developed an interface for launching scenarios of management actions and predicting the expected future outcomes of those actions. All of these outcomes were supported by a rich set of publications in peer-reviewed journals.

**Benefits:** We developed, in consultation and interactions with Alaskan DoD resource managers, multi-layered information that can be used in conceptually simplified management practices that incorporate directional changes in vegetation composition resulting from ongoing changes in climate combined with an increasingly severe fire disturbance. The map data products we have developed and archived can inform applied management spatially across landscapes. The approaches, tools and outcomes will benefit management efforts for DoD lands within Alaska but also have utility for applications including other land management agencies and efforts.

## TABLE OF CONTENTS

<b>LIST OF FIGURES.....</b>	<b>2</b>
<b>LIST OF TABLES.....</b>	<b>5</b>
<b>LIST OF ACRONYMS.....</b>	<b>5</b>
<b>KEYWORDS .....</b>	<b>6</b>
<b>ACKNOWLEDGMENTS .....</b>	<b>6</b>
<b>EXECUTIVE SUMMARY .....</b>	<b>7</b>
INTRODUCTION AND OBJECTIVES .....	7
TECHNICAL APPROACH.....	7
RESULTS, DISCUSSION AND IMPLICATIONS FOR FUTURE RESEARCH AND BENEFITS .....	8
<b>OBJECTIVES.....</b>	<b>15</b>
<b>TECHNICAL APPROACH.....</b>	<b>17</b>
OBJECTIVE 1: FIELD CAMPAIGNS & MEASUREMENTS .....	17
OBJECTIVE 2: REMOTE SENSING OF VEGETATION PROPERTIES & CHANGE .....	18
2.1 <i>Vegetation Cover Type Class Mapping</i> .....	18
2.2 <i>Tree Canopy Cover Density, Fractional Deciduous Cover, and Plant Functional Type Change</i> .....	19
2.3 <i>Burn Extent and Severity Mapping and Associated Post-fire Succession</i> .....	20
2.4 <i>Productivity trends &amp; precursors of mortality (“early warning signals”)</i> .....	22
OBJECTIVE 3: PREDICTIVE MODELING OF VEGETATION CHANGE .....	23
3.1 <i>Spatial Statistical / Machine Learning Models</i> .....	23
3.2 <i>Process-based Forest Demography Modeling</i> .....	25
OBJECTIVE 4: IMPLEMENTATION OF OUTCOMES WITH RESOURCE MANAGERS.....	27
<b>RESULTS AND DISCUSSION .....</b>	<b>28</b>
OBJECTIVE 1: FIELD CAMPAIGNS & MEASUREMENTS .....	28
4.1 <i>Impacts of aspen leaf miners on deciduous tree productivity</i> .....	28
4.2 <i>Impacts of fuel reduction treatments on successional trajectories</i> .....	28
4.3 <i>Linking field measurements post-fire succession with satellite estimates of composition</i> .....	29
OBJECTIVE 2: REMOTE SENSING OF VEGETATION PROPERTIES & CHANGE .....	32
5.1 <i>Vegetation Cover Type Class Mapping</i> .....	32
5.2 <i>Tree Canopy Cover Density and Fractional Deciduous Cover Change</i> .....	33
5.3 <i>Plant Functional Type Cover Change</i> .....	34
5.4 <i>Burn Extent and Severity Mapping and Associated Post-fire Succession</i> .....	37
5.5 <i>Productivity trends &amp; precursors of mortality (“early warning signals”)</i> .....	40
OBJECTIVE 3: PREDICTIVE MODELING OF VEGETATION CHANGE .....	42
6.1 <i>Spatial Statistical / Machine Learning Models</i> .....	42
6.2 <i>Process-based Forest Demography Modeling</i> .....	43
OBJECTIVE 4: IMPLEMENTATION OF OUTCOMES WITH RESOURCE MANAGERS.....	48
<b>CONCLUSIONS.....</b>	<b>54</b>
SUMMARY OF PROJECT ACCOMPLISHMENTS .....	54
SUMMARY OF OBJECTIVES AND RESEARCH OUTCOMES .....	56
<b>LITERATURE CITED .....</b>	<b>57</b>
<b>APPENDICES.....</b>	<b>61</b>

## List of Figures

**Figure 1.** Study area (yellow outline) where plant functional types were mapped, shown in context of (a) bioclimatic zones, (b) fire history, (c) field plot locations, and (d) field sampling years. Bioclimatic zones follow those of Walker et al. (2005) and Virtanen et al. (2016), and fire history is from Alaska Fire History Perimeter Polygons and Canadian National Fire Database. This figure is from Macander et al. (2022). Outcomes of the PFT mapping are presented in sections 2.2, 5.3 and 5.4.

**Figure 2.** Temporal distribution of repeatedly-measured Permanent Sample Plots (PSPs) contained in our compiled database.

**Figure 3.** Location and average aboveground biomass of forest inventory plots across DoD installations in interior Alaska

**Figure 4.** (a) Basal area increment (BAI; mean  $\pm$  SE) of living trees (solid line) from establishment to 2015 and dying trees (dashed line) from establishment to 2013 and the number of sampled trees (Sample depth; dotted line); (b) growing season climate moisture index (GS CMI; mean  $\pm$  SE) prior to the *Phyllocnistis populiella* outbreak (1945–1996); and (c) GS CMI (mean  $\pm$  SE), the maximum summer normalized difference vegetation index (NDVImax; mean  $\pm$  SE), and leaf mining (hectares of Alaska infested) during the *P. populiella* outbreak (1997–2013). In (a) and (b), dark green shading denotes when living and dying tree BAI overlapped, intermediate green shading denotes when living tree BAI was greater than dying tree BAI, and in (a) light green shading denotes the *P. populiella* outbreak.

**Figure 5.** Results of generalized linear mixed models (GLMMs) depicting the influence of (a) soil organic layer depth on deciduous (yellow points) and conifer (purple points) seedling density in thinned sites and (b) years after treatment on deciduous and (c) conifer seedling density in shearbladed sites. Shading indicates the 95% confidence interval, each point is a seedling density measurement along a transect, and significant relationships are represented by solid lines. Note that the y-axis differs across panels.

**Figure 6.** Post-fire deciduous index as a function of pre-fire deciduous index. Shapes represent different pre-fire species composition (circle=spruce, square=mixed, triangle = deciduous) and colors indicate post-fire succession trajectory (purple = thinning, blue = spruce, green = mixed, and yellow = deciduous). Black line represents generalized additive model fit with shading for the 95% confidence intervals. Pine line represents the threshold in pre-fire DI from which post-fire DI >66% is likely to emerge based on model fit. Purple line represents the threshold in pre-fire DI from which post-fire DI >66% will emerge (95% confidence) based on model fit.

**Figure 7.** Post-fire soil organic layer (SOL) depth (cm) as a function of post-fire trajectory (colors) and pre-fire class (panels). Colors indicate post-fire succession trajectory (purple = thinning, blue = spruce, green = mixed, and yellow = deciduous). The panels represent pre-fire classes (deciduous, mixed, spruce) based on deciduous index. Capital letters signify significant differences between SOL depths of post-fire trajectories within pre-fire dominance classes.

**Figure 8.** Classification of pre-fire vegetation for 1973-1992 firescars across interior Alaska using Landsat Multispectral Scanner (MSS) imagery. The black polygons outline military training lands.

**Figure 9.** Pre-fire land cover and bootstrapped land cover maps for 1995, 2005 and 2018. This example map includes the 1983 Rosie Creek Fire and the Tanana Flats Training Area.

**Figure 10.** Effect of fire age (1950 – 2018) on average change in forest canopy cover and composition between 2000 and 2015. Panel (a) average change in per-pixel deciduous fraction and tree canopy cover inside fire boundaries by fire occurrence date. Panel (b) area with small (under  $\pm 0.1$ ) and large (over  $\pm 0.1$ ) changes in deciduous fraction and tree canopy cover by three fire age classes (i) old (1950 – 1978), (ii) intermediate (1979 – 1998), and (iii) recent (1999 – 2018). Panel (c) area with small (under  $\pm 0.1$ ) and large (beyond  $\pm 0.1$ ) changes in deciduous fraction and tree canopy cover within fire scars (i) and for the boreal domain of North America (ii). Note  $\Delta$  represents change between 2000 and 2015. The grey dashed lines in a indicate the date ranges of Landsat images used in the 2000 and 2015 deciduous fraction and tree canopy cover products. The axes above and below the zero line in b indicate non-negative values.

**Figure 11.** Patterns of deciduous shrub top cover change, 1985–2020, coincident with top cover change in other plant functional types at 960 m super-pixel scale and fire history. Changes at the 960 m super-pixel scale  $\leq 1\%$  top cover are categorized as stable. 30-m pixels where change was less than the magnitude of model RMSE were set to zero before aggregation, in order to emphasize areas with higher confidence of change.

**Figure 12.** Enlargement of one panel of Figure 11 showing detail of where Conifer Tree cover increased (greens and blues) or decreased (oranges and reds). The full color key is included in Figure 11 and more specifics of change in and around DoD bases and training grounds are reported in section 5.4.

**Figure 13.** Density plots of predicted vs. observed burn depth from 100 10-fold cross validation comparisons using predictor variables relevant for (a) old fires (1940 – 1980), (b) intermediate fires (1980 – 2000), and (c) recent fires (2000 – present).

**Figure 14.** Burned area, emissions, and burn depth annual and seasonal time series across Alaska from 2001 - 2019.

**Figure 15.** Modeled burn depth for fires in interior Alaska DoD installations since 1950.

**Figure 16.** Changes in plant functional type cover (1985-2020) across DoD bases and training grounds (outlined in black) in interior Alaska. The lower right panel shows fires that occurred between 1970 and 2020. Increases in deciduous shrub cover is evident across the interior. Broadleaf and evergreen conifer tree cover also show substantial changes, although the direction of change depends on the time since fire, with initial increases in deciduous cover followed by increasing conifer cover over time.

**Figure 17.** Plant functional type weighted area per fire history class at 5-year intervals.

**Figure 18.** Heat maps showing the differences in NDVI metrics between mortality and control sites at rolling time windows of 1-5 to 1-20 years before inventory measurement and mortality thresholds varying from 0-10 percent of biomass per year. For trend and jump metrics, red colors represent where sites with tree mortality above the mortality threshold exhibited more negative mean values than control sites. For EWS metrics (AR(1), standard deviation, conditional variance, total variance, and diffusion), red colors represent conditions where sites with tree mortality above the mortality threshold exhibited greater metric values than control sites. Blue colors represent the opposite. In each case, red represents a likely detection of an early warning signal of mortality.

**Figure 19.** Density plot of model performance based on the multi-model ensemble and fully-withheld inventory sites.

**Figure 20.** Predicted changes in forest biomass by 2030 at PSP sites across boreal North America (a; aggregated into 1° grid cells) and at DoD installations within Alaska (b).

**Figure 21.** UVAFME output on total biomass difference ( $\text{tC ha}^{-1}$ ) (left) and deciduous fraction (0 – 1) difference (right) within the vicinity of Fairbanks as well as across the Tanana Valley at 2 km grid cell resolution between pre- and post-climate change conditions for the RCP 8.5 climate change scenario.

**Figure 22.** Model-simulated average aboveground biomass and deciduous fraction for an RCP 4.5 and RCP 8.5 scenario for 23 sites within interior Alaska. Shaded regions show 95% confidence intervals.

**Figure 23.** Model-simulated distributions of fire intensity ( $\text{kW m}^{-1}$ ), combustion ( $\text{kg m}^{-2}$ ), and fuel moisture (volumetric) for 23 sites in interior Alaska for historical, RCP 4.5, and RCP 8.5 climate scenarios for years 2006 through 2100. Asterisks denote significance level of Kruskal-Wallis tests (ns:  $p > 0.05$ ; \*:  $p \leq 0.05$ ). Note the log-10 scale for fire intensity.

**Figure 24.** Model-simulated distributions of fire intensity ( $\text{kW m}^{-1}$ ), combustion ( $\text{kg m}^{-2}$ ), and fuel moisture (volumetric) for simulated sites that had a greater than 50% increase in deciduous fraction (right) and for sites that had little deciduous fraction change (left) for historical, RCP 4.5, and RCP 8.5 climate scenarios for years 2006 through 2100. Asterisks denote significance level of Kruskal-Wallis tests (ns:  $p > 0.05$ ; \*:  $p \leq 0.05$ ). Note the log-10 scale for fire intensity.

**Figure 25.** Model-simulated species-specific aboveground biomass for a site near Ft. Wainwright, Alaska, showing the impact of several different treatments (conducted at stand age 100, dashed line) under current climate conditions (left) and future climate conditions (right).

**Figure 26.** UVAFME graphical user interface developed for land managers to assess the influence of different management and climate change scenarios.

## List of Tables

**Table 1.** Predictor variables used in models to estimate burn depth as a function of fire epoch.

**Table 2.** Median cross-validated  $r^2$  for models of burn depth as a function of spatial domain used for training sites and fire epoch. Note that all validation was performed using burned sites in Alaska

**Table 3.** Summary assessment of accomplished objectives.

## List of Acronyms

ABOVE – NASA’s Arctic Boreal Vulnerability Experiment  
AFSC – Alaska Fire Science Consortium  
BAI – Basal Area Increment  
BLM – Bureau of Land Management  
CAFI – Cooperative Alaska Forest Inventory  
CCDC – Continuous Classification and Detection of Change  
CMI – Climate Moisture Index  
dNBR – Difference - Normalized Burn Ratio  
DoD – Department of Defense  
GLMM – Generalized Linear Mixed Model  
GS CMI – Growing Season Climate Moisture Index  
Landsat TM – Thematic Mapper  
Landsat ETM+ – Enhanced Thematic Mapper Plus  
Landsat OLI – Operational Land Imager  
Landsat MSS – Multispectral Scanner  
LTER – Long Term Ecological Research (sites)  
NAU – Northern Arizona University  
NDVI - Normalized Difference Vegetation Index  
PFT – Plant Functional Types  
PSP – Permanent Sample Plots  
QA/QC – Quality Assurance/Quality Checks  
RCP – Representative Concentration Pathway  
SERDP – Strategic Environmental Research and Development Program  
UAS – Unmanned Airborne System  
UVAFME – University of Virginia Forest Model Enhanced

## **Keywords**

Boreal forest, composition, disturbance, fire, habitat, insects, mortality, productivity, succession

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We thank Dan Rees, in particular, for taking the time to meet with us on several occasions over the past several years, both in person and remotely, and for assisting with selection and prioritization of sampling sites, facilitating access to sites on DoD lands, and helping us to design the development of our visualization and analysis web application, and more generally to tailor our research to the needs of the DoD land management efforts in the region.

Finally, we thank the DoD SERDP program manager Kurt Preston and the members of various review panels for their constructive feedback and support, as well as the SERDP and Northern Arizona University administrative staff for their assistance, particularly Candra Dufek, Adinideen Nez, Samaneh Moeini and Stephanie Lawless.

# Executive Summary

## Introduction and Objectives

The overarching objective of our research, focused on Department of Defense (DoD) lands of interior Alaska but also across much of western boreal North America, was to assess observed in boreal vegetation composition over the past 4 decades in a spatial context by linking field measurements with satellite observations and models. Our analyses incorporate broadscale impacts of disturbance, particularly fire, and post-disturbance vegetation succession. Our spatiotemporal analyses and modeling of predicted changes incorporate climate as a “press” disturbance as well as the “pulse” disturbance brought about by fire, each of which impact tree productivity and mortality. We predicted change into the near future (20-50 years) using a combination of empirical and process-based models. We also interacted with DoD and other state and federal land managers to transfer the data products and analysis tools for their needs.

Our overarching objectives were to:

- (i) collect, analyze and spatially extend field measurements of post-disturbance trajectories of vegetation and habitat change [see *Field campaigns & measurements*].
- (ii) document changes in patterns and rates of boreal tree productivity and mortality, key drivers of habitat characteristics and ecosystem services, in relation to airborne remote sensing and time series of satellite-derived and other geospatial environmental variables [see *Remote sensing of vegetation properties & change*].
- (iii) predict near-future (30-50 year) vulnerability to changes in boreal tree composition, productivity and mortality using outcomes of the two observation-based objectives (field and remote sensing) and two approaches (statistical and process based models) [see *Predictive modeling of vegetation change*].

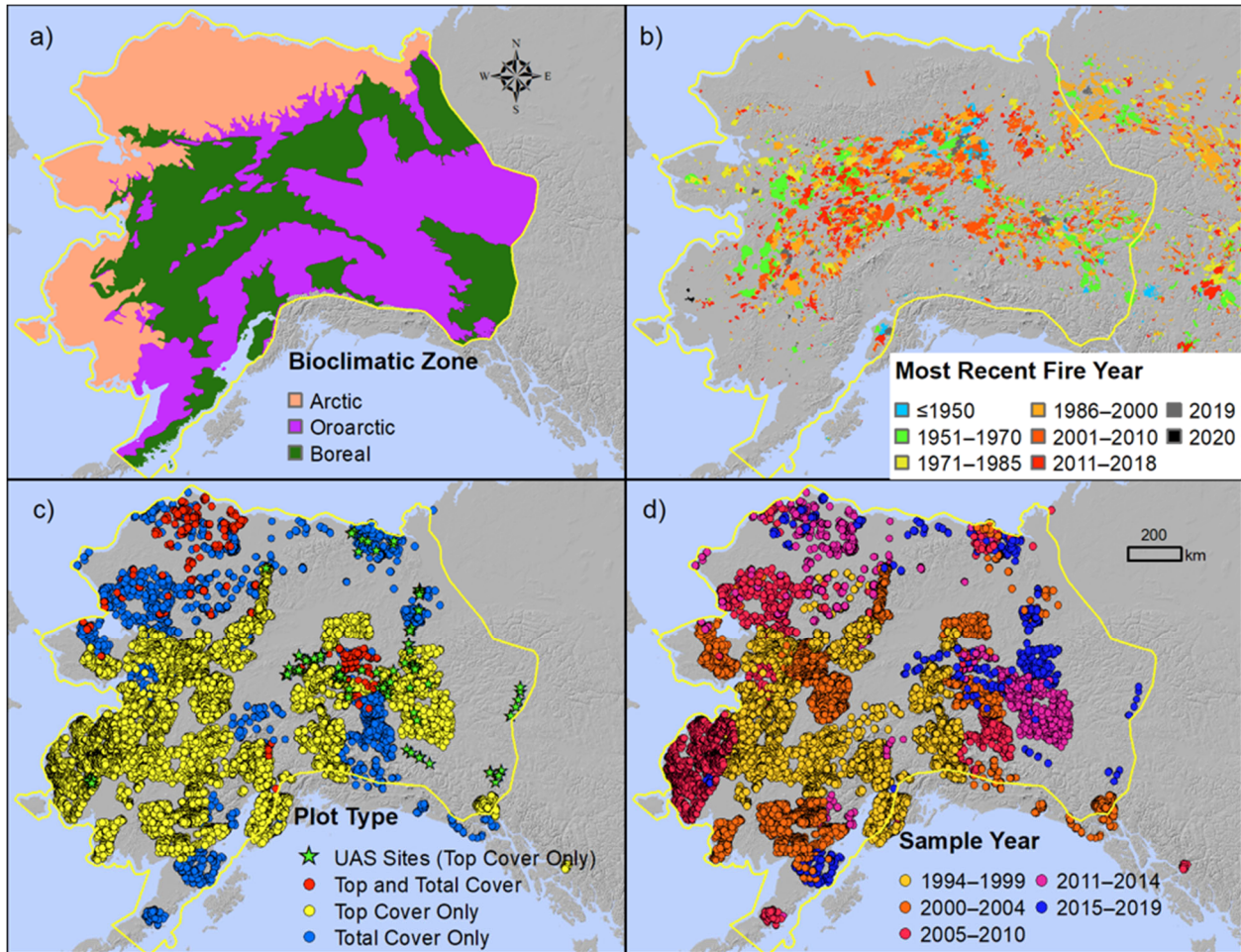
All three of these research objectives assess spatial variability in vulnerability to change, making extensive use of past, ongoing and planned field measurements, as well as remote sensing derived products, climate records, and related near-term projections.

Our final objective was more applied, i.e. (iv) to interface with DoD and other state and federal land resource managers, transferring the geospatial methodologies, analysis tools and derived data products to those who will be able to make regular use of them. This objective logically followed the development of the research objectives and data products, and we consulted with base resource managers to ensure approaches developed and data products derived are most applicable to their desired needs.

## Technical Approach

We made extensive use of field measurements (Figure 1) and multi-scale satellite observations, typically coupling the two in development of spatial models (maps) and change through time, while accounting for error and uncertainty. The field measurements incorporated species-specific responses to drivers and the remote sensing component addressed broader scale responses and changes in plant functional types (PFTs) including deciduous broadleaf trees, evergreen conifer trees, deciduous shrubs, and others. Two types of models were used to predict

future change, informed with changes observed over recent decades. The first type included machine learning (statistical deep learning) models and the second type was a process-based model (UVAFME) that simulates a wide range of vegetation composition, structure and function in response to a suite of environmental drivers and ecosystem processes (e.g. climate, competition, fire, permafrost thaw).



**Figure I.** Study area (yellow outline) where plant functional types were mapped, shown in context of (a) bioclimatic zones, (b) fire history, (c) field plot locations, and (d) field sampling years. Bioclimatic zones follow those of Walker et al. (2005) and Virtanen et al. (2016), and fire history is from Alaska Fire History Perimeter Polygons and Canadian National Fire Database. This figure is from Macander et al. (2022). Outcomes of the PFT mapping are presented in sections 2.2, 5.3 and 5.4 of our Final Report.

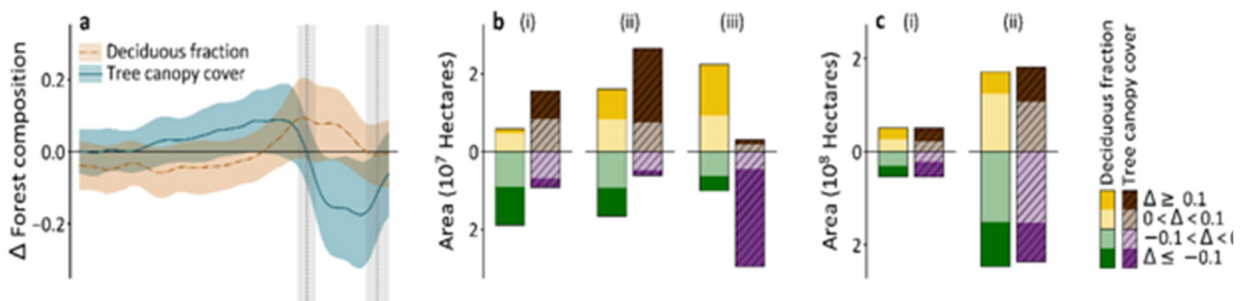
## Results, Discussion and Implications for Future Research and Benefits

Based on our analyses, results, accomplishments, outcomes and primary conclusions, as well as implications for applications, benefits and future research, we highlight the following key points:

1. Field measurement campaigns revealed (i) historic disturbance events triggered a multi-decadal growth decline that predisposed aspen to mortality during the leaf miner outbreak,

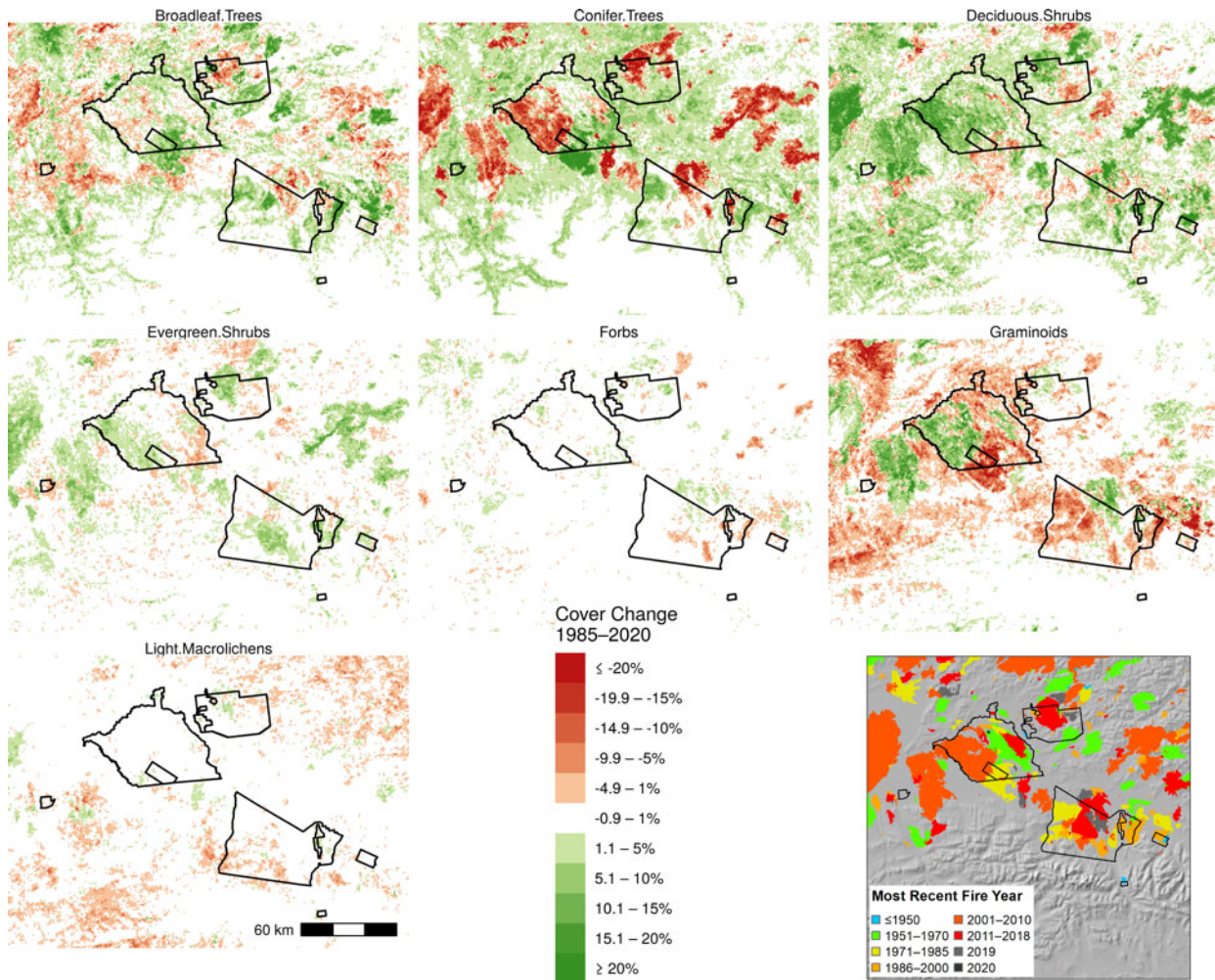
(ii) fuel reduction treatments have impacts on ecosystem characteristics that persist for decades after treatment that need to be accounted for to improve fuel treatment management protocols, designs, and fire behavior modeling, (iii) deciduous dominated forests are highly resilient to fire and even a small component of deciduous stems (~7%) in the pre-fire stand can result in a transition to deciduous dominance post-fire.

2. Vegetation Cover Type Class mapping (1975 – 2015 at 5-year intervals) showed annual land cover change in recent years (2015–present) and also provided pre-fire vegetation information for all fires in boreal Alaska between 1973–1992. This information can be further mined to assess changes in vegetation cover types pre- and post-fire, beyond the more specific assessments we conducted using more continuous proportions of vegetation cover (i.e. deciduous versus evergreen trees and shrubs) to inform management.
3. Tree Canopy Cover Density mapping with satellite imagery showed dramatic changes over large areas as a result of fire. The Landsat CCDC and Landsat MSS products we developed for vegetation classification extended and improved the tree canopy cover mapping over multiple decades.
4. Deciduous and Evergreen Vegetation Composition mapping with satellite imagery showed clear effects of time since fire and severity of burning, particularly in areas where organic soils were combusted (Figure II). The maps from this analysis are novel in that they show continuous (proportional) per-pixel cover changes at high spatial resolution (30 m) over several decades, implicitly incorporating the impacts of fire and insect disturbance. A visualization application for managers to view, interact with, and ultimately use our products for decision making was developed and is freely available here: [masseyr44.users.earthengine.app/view/decidfractreecoverserdpv1](https://masseyr44.users.earthengine.app/view/decidfractreecoverserdpv1)



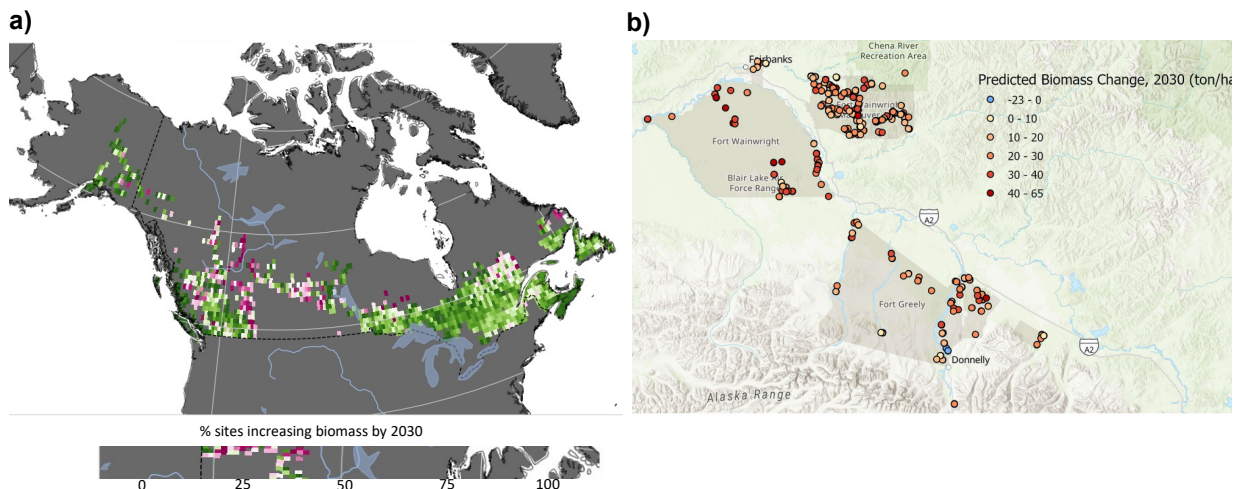
**Figure II.** Effect of fire age (1950 – 2018) on average change in forest canopy cover and composition between 2000 and 2015. Panel (a) average change in per-pixel deciduous fraction and tree canopy cover inside fire boundaries by fire occurrence date. Panel (b) area with small (under  $\pm 0.1$ ) and large (over  $\pm 0.1$ ) changes in deciduous fraction and tree canopy cover by three fire age classes (i) old (1950 – 1978), (ii) intermediate (1979 – 1998), and (iii) recent (1999 – 2018). Panel (c) area with small (under  $\pm 0.1$ ) and large (beyond  $\pm 0.1$ ) changes in deciduous fraction and tree canopy cover within fire scars (i) and for the boreal domain of North America (ii). Note  $\Delta$  represents change between 2000 and 2015. The grey dashed lines in a indicate the date ranges of Landsat images used in the 2000 and 2015 deciduous fraction and tree canopy cover products. The axes above and below the zero line in b indicate non-negative values.

5. Plant Functional Type Vegetation Composition mapping with satellite imagery allowed us to separate the deciduous and evergreen vegetation component not only tree species but also shrubs, graminoids, forbs, lichens and other PFTs. Fine-scale canopy cover data from airborne lidar and UAS data of field sites included in the models of plant functional type canopy cover added robust training data that resulted in improved maps of vegetation cover change (Figure III). A visualization application for managers to view, interact with, and ultimately use our products for decision making was developed and is freely available here: [mmaacander.users.earthengine.app/](http://mmaacander.users.earthengine.app/)



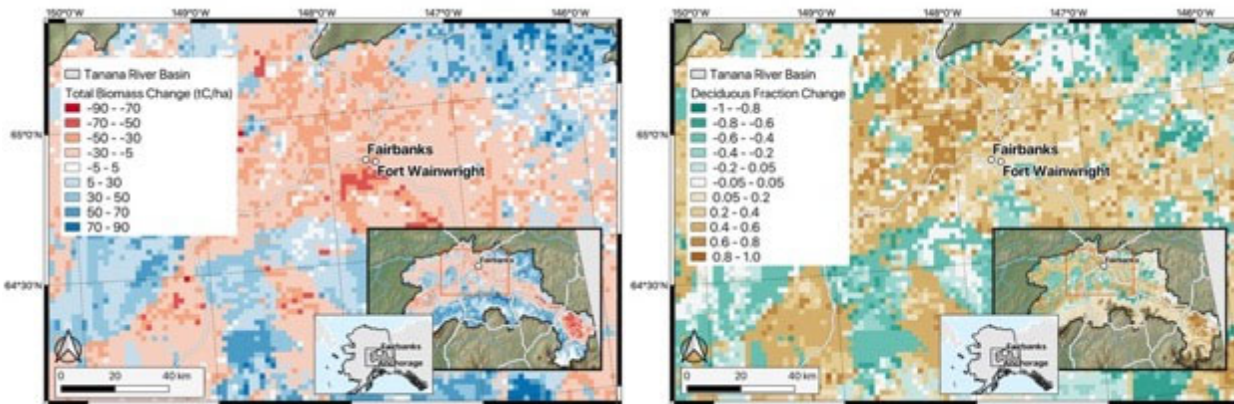
**Figure III.** Changes in plant functional type cover (1985-2020) across DoD bases and training grounds (outlined in black) in interior Alaska. The lower right panel shows fires that occurred between 1970 and 2020. Increases in deciduous shrub cover is evident across the interior. Broadleaf and evergreen conifer tree cover also show substantial changes, although the direction of change depends on the time since fire, with initial increases in deciduous cover followed by increasing conifer cover over time.

6. Combining the deciduous fraction and plant functional type cover, including older Landsat MSS-derived historical products, allowed us to characterize canopy composition changes over a 45 year record, which has never been done before across this spatial extent or as this spatial and temporal resolution.
7. Burn Severity Modeling was accomplished by leveraging an extensive database of field-measured burn severity metrics which, in turn, allowed us to derive accurate models of fire carbon emissions and burn depth that can be applied to both 'modern' (2001 and later) and historical (1940-2000) fires. Using our novel historical land cover products, we developed models of historical burn severity as a function of pre-fire vegetation class and other predictors including spectral metrics, topographic metrics, meteorological metrics, burn size, ignition date, and start-of-growing-season date. These data sets have tremendous utility for informing management decisions related to vegetation succession following fire disturbance.
8. Early Warning Signals of tree mortality were prevalent and detectable in inventory plots across Alaska and Canada using long-term remote sensing time series, but despite this our predictive models of mortality were limited in their accuracy. Prominent challenges include the stochastic nature of mortality, the relatively coarse temporal resolution of most forest inventory data, and a lack of high resolution climate forecast data for future periods.
9. Predictive models of near-future change in forest biomass from 5-25 years into the future (Figure IV) were robust and highly relevant for scientists and DoD natural resource managers. The models were highly accurate for biomass gains but less accurate for biomass losses. Nonetheless they are successfully able to distinguish between sites likely to experience biomass gains from those likely to experience losses.



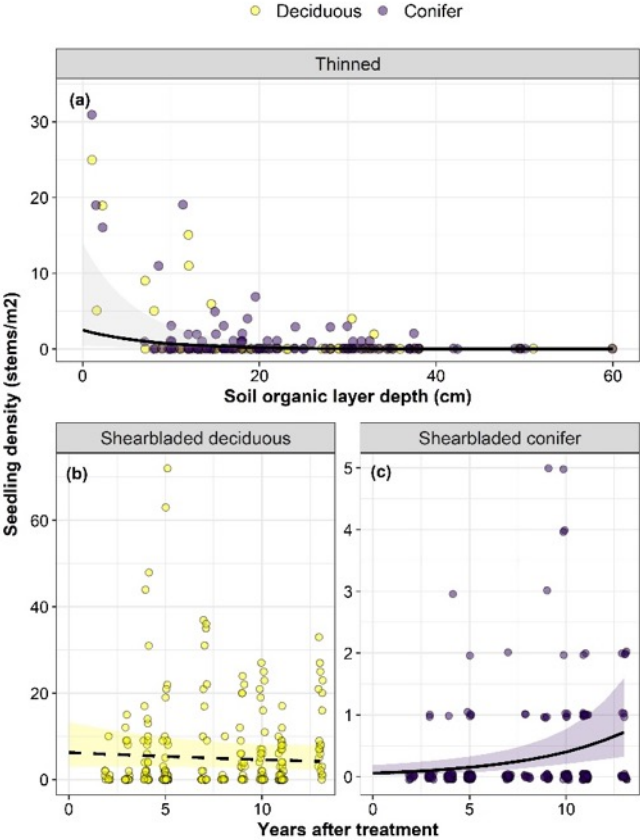
**Figure IV.** Predicted changes in forest biomass by 2030 at PSP sites across boreal North America (a; aggregated into 1° grid cells) and at DoD installations within Alaska (b).

10. Process-based models of longer-term forest change provided accurate representation of Alaskan forests and their biotic-abiotic interactions through fine-scale forest modeling. Vegetation dynamics within boreal Alaska were better represented with a process-based forest model (like UVAFME, an individual-based tree model) that includes tree- and stand-level interactions between vegetation, soils and forest fuels, wildfire, fire weather, and climate. Under scenarios of increasing temperatures and atmospheric water demand, long-term vegetation trajectories are likely to include increases in deciduous fraction and decreases in biomass, especially in drier, interior locations. Despite fuel drying and increases in lightning strikes, fire severity and intensity may decline with climate change as a result of decreasing forest biomass and fuels and increasing deciduous fraction (Figure V).

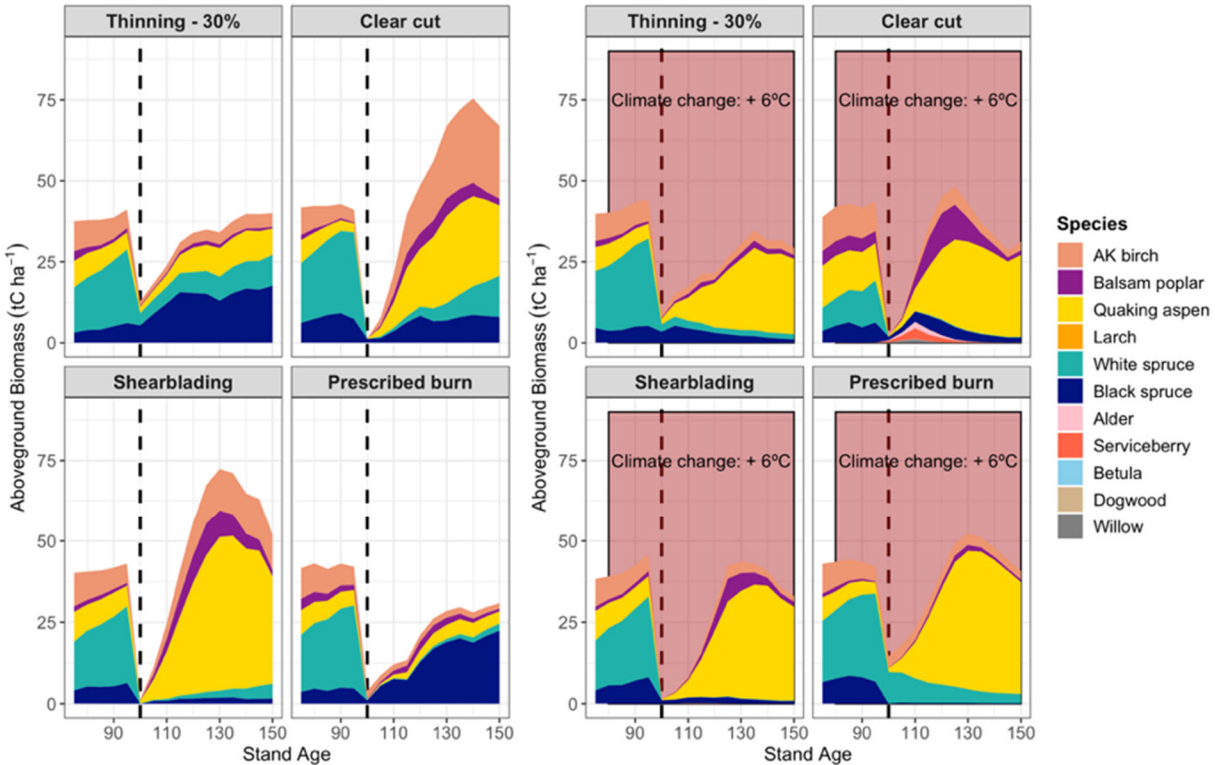


**Figure V.** UVAFME output on total biomass difference ( $\text{tC ha}^{-1}$ ) (left) and deciduous fraction (0 – 1) difference (right) within the vicinity of Fairbanks as well as across the Tanana Valley at 2 km grid cell resolution between pre- and post-climate change conditions for the RCP 8.5 climate change scenario.

11. Impacts of forest management on forest composition and structure via different management actions (i.e. thinning vs. clearcut vs. shearblading vs. controlled burns) were shown to modify the post-treatment stand composition and structure (Figure VI) which have impacts on post-treatment fuel flammability. Post-treatment stand composition and structure are also captured under scenarios of increasing temperature (Figure VII). Modifications to the post-treatment impacts could inform consideration of treatments at sites within interior Alaska, including in the context of climate change.



**Figure VI.** Results of generalized linear mixed models (GLMMs) depicting the influence of (a) soil organic layer depth on deciduous (yellow points) and conifer (purple points) seedling density in thinned sites and (b) years after treatment on deciduous and (c) conifer seedling density in shearbladed sites. Shading indicates the 95% confidence interval, each point is a seedling density measurement along a transect, and significant relationships are represented by solid lines. Note that the y-axis differs across panels.

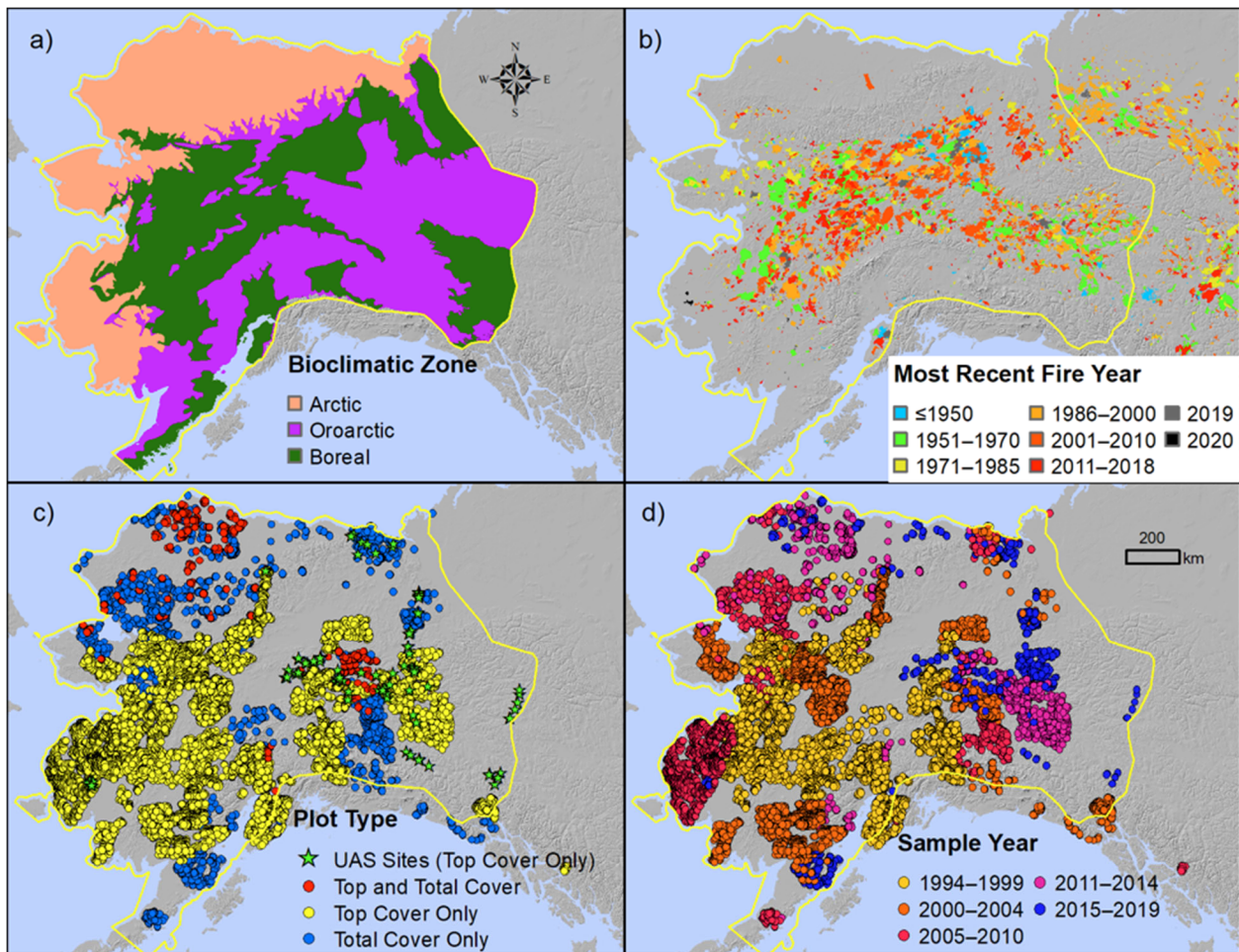


**Figure VI.** Model-simulated species-specific aboveground biomass for a site near Ft. Wainwright, Alaska, showing the impact of several different treatments (conducted at stand age 100, dashed line) under current climate conditions (left) and future climate conditions (right).

12. Implementation of outcomes with resource managers were advanced through workshops and webinars hosted by the Alaska Fire Science Consortium, with all materials (agendas, presentations, recordings, etc) available via their website ([www.frames.gov/afsc](http://www.frames.gov/afsc)). We also publicly archived data sets and developed freely available map visualization applications on Google Earth Engine for managers to view, interact with, and make use our data products. Users can quickly navigate to different DoD installations in interior Alaska (via dropdown menu) or they can roam around to other areas across Alaska and Yukon, with capabilities to zoom in and out and display different types of information. A graphical user interface was also developed to allow managers to assess the influence of simulated management actions and future climate change scenarios.

## Objectives

The overarching objective of this project was to investigate changing vegetation dynamics across Department of Defense (DoD) lands of interior Alaska, building upon prior work documenting changes in Arctic and boreal vegetation over the past three decades using multi-scale satellite observations and associated geospatial data sets and field measurements. The research is couched in a framework assessing the resiliency and vulnerability of boreal forest composition, thus in habitat, to observed changes in climate (temperature and moisture changes and variability) and related disturbance regimes, including both fire and insects. The research addresses this overarching objective using a combination of *in situ* field measurements, drone-based imaging, airborne and satellite remote sensing, and both statistical and process-based modeling. The specific areas the project focuses on encompass several DoD bases in interior Alaska (Fort Wainwright, Fort Greely, Eielson Air Force Base, and Clear Air Force Station), which include three military training areas (Tanana Flats, Yukon, and Donnelly), and the Joint Base Elmendorf-Fort Richardson near Anchorage. The analyses of change dynamics across these DoD lands leverage geographically broader research efforts across interior Alaska as well as extensive *in situ* data sets of similar boreal forest landscapes in western Canada (Figure 1).



**Figure 1.** Study area (yellow outline) where plant functional types were mapped, shown in context of

(a) bioclimatic zones, (b) fire history, (c) field plot locations, and (d) field sampling years.

Bioclimatic zones follow those of Walker et al. (2005) and Virtanen et al. (2016), and fire history is from Alaska Fire History Perimeter Polygons and Canadian National Fire Database. This figure is from Macander et al. (2022a). Outcomes of the PFT mapping are presented in sections 2.2, 5.3 and 5.4.

Our approach included three specific research objectives and a fourth objective focused on implementation. Each objective was designed to address the SERDP Resource Conservation and Climate Change program area focused on climate change vulnerability assessment of major habitats on and around DoD lands. Our first two objectives included field measurements and remote sensing, making use of multi-scale satellite image data to link changes in post-fire vegetation recovery and tree species composition change, as well as to document changes in patterns and rates of boreal tree productivity and mortality in relation to time series of satellite-derived and other geospatial environmental variables. Our third objective made use of the data products and outputs of the first two objectives coupled with the development of spatial statistical and process-based models designed to predict near-future vulnerability of boreal tree composition, productivity and mortality to changes in climate and related environmental drivers, including fire and insect disturbance. A web interface was developed to provide information useful for specific adaptive management objectives, allowing options that emphasize management priorities. By the end of the project (late July 2022) it will include a straightforward protocol for updating outputs based on new data sets and sources.

Our research objectives are summarized thus:

(i) to collect, analyze and spatially extend field measurements of post-disturbance trajectories of vegetation and habitat change [i.e. *Field campaigns & measurements*].

(ii) to document changes in patterns and rates of boreal tree productivity and mortality, key drivers of habitat characteristics and ecosystem services, in relation to airborne remote sensing and time series of satellite-derived and other geospatial environmental variables [i.e. *Remote sensing of vegetation properties & change*].

(iii) to predict near-future (30-50 year) vulnerability to changes in boreal tree composition, productivity and mortality using outcomes of the two observation-based objectives (field and remote sensing) and two approaches (statistical and process based models) [i.e. *Predictive modeling of vegetation change*].

All three of these research objectives assess spatial variability in drivers of vulnerability to change, making extensive use of past, ongoing and planned field measurements, as well as remote sensing derived products, climate records, and related near-term projections.

Our final objective was more applied, i.e. (iv) to interface with DoD and other state and federal land resource managers, transferring the geospatial methodologies, analysis tools and derived data products to those who will be able to make regular use of them. This objective logically followed the development of the research objectives and data products, and we consulted with base resource managers to ensure approaches developed and data products derived are most applicable to their desired needs.

## Technical Approach

### Objective 1: Field campaigns & measurements

This objective is focused on our fieldwork activities, which thus far have both leveraged past and ongoing data collection from other efforts (e.g. co-I Mack's SERDP project RC-2754, which sampled sites across interior Alaska that burned between the years 2004 and 2014) and NASA's Arctic Boreal Vulnerability Experiment, ABoVE (for which PI Goetz is the Science Team Lead and the other PIs had or have ABoVE projects). The measurement campaigns directly supported by this project took place in summers of 2019 and 2020 and focused on three project subtasks: (1) determining the influence of climate and insect pests on boreal tree mortality and productivity in interior Alaska, (2) addressing how successional trajectories of tree dominance, understory composition, active layer depth, and modeled surface fire behavior change over decadal timescales in fuel reduction treatments, and (3) assessing tree regeneration, conducting data analysis, and developing empirical models of post-disturbance successional trajectories. The latter has focused on identifying the drivers of post-fire deciduous tree dominance in pre-fire stands that range from entirely black spruce (the historically dominant species) to mixed spruce-deciduous and deciduous dominance. Local Alaska land managers are interested in understanding the drivers and frequency of this shift because increasing deciduous tree dominance makes forests more resistance to disturbances associated with military training activities, reduces future fire frequency and severity, and increases habitat quality for moose.

For the first of these subtasks, we combined annual measurements of tree basal area increment (BAI) from trembling aspen (*Populus tremuloides*) with long-term forest inventory data from the Cooperative Alaska Forest Inventory (CAFI). Near DoD bases in interior Alaska, we collected cores from live ('living') and disks from dead ('dying') aspen that died during the aspen leaf miner (*Phyllocnistis populiella*) outbreak (1997 – 2013). To better understand the drivers of aspen mortality, we compared growth patterns and sensitivity to climate and leaf mining of aspen that died versus survived the *P. populiella* outbreak.

For the 2<sup>nd</sup> subtask, we re-measured a network of hand-thinned and mechanically harvested ('shearbladed') fuel reduction treatments on and near DoD bases in previously black spruce-dominated stands that were treated up to ~20 years ago. To determine how these treatments change as they age, we assessed temporal trends in tree recruitment, understory composition, active layer depth, and surface rate of spread (ROS), flame length, and fireline intensity modeled using the BehavePlus (Andrews et al., 2005) fire modeling system ([www.firelab.org/project/behaveplus](http://www.firelab.org/project/behaveplus)). Fuel reduction treatments introduce a novel disturbance to boreal forests with largely unknown impacts on ecosystem characteristics. Our findings provide insight into the impacts of fuel reduction treatments on ecosystem structure and fire behavior within two decades after treatment, and thus how well the goals of reduced fire risk and increased firefighter egress are likely to be met as these treatments age without further intervention.

For the 3<sup>rd</sup> subtask under this objective, post-fire tree regeneration trajectory, we estimated pre-fire and post-fire stem density and forest composition by measuring pre-fire (burned) trees and

newly established seedlings in 204 sites that burned between the years 2004 and 2013. We used pre and post-fire deciduous fraction (DF; the proportion of deciduous stems relative to total stems) to categorize sites into one of five post-fire successional trajectory categories that are important for understanding habitat change and future successional dynamics.

## **Objective 2: Remote sensing of vegetation properties & change**

The subtasks of this objective are diverse but linked. They include mapping (i) vegetation cover type class and change, (ii) tree canopy cover density, (iii) fractional deciduous versus evergreen cover, (iv) burn extent and severity, and (v) assessments of productivity trends & precursors of mortality. We have made progress on each of these subtasks and completed some of them (those focused on initial mapping), even though refinements continue to be made.

### *2.1 Vegetation Cover Type Class Mapping*

Pre-fire vegetation is critical information to assess potential shifts in vegetation successional trajectories. To date, regional moderate resolution satellite mapping of pre-fire vegetation has started with Landsat Thematic Mapper (TM) imagery, which was available in Alaska starting in 1984, though much of Alaska had limited availability of imagery before 1999. For example, a recently released annual land cover map product was developed as part of NASA ABoVE and covers 1984–2014 (Wang et al. 2019). In cases where early imagery was insufficient for the land cover change assessment, however, the ABoVE land cover product simply extrapolates backwards from the first year with suitable data, and the year when the land cover was actually initialized is not available. We focused on extending this land cover record backwards and forwards in time to cover ~1972–2019, an increase of 17 years.

To extend land cover mapping further back in time, we compiled, calibrated, and classified a time-series composite of Landsat Multispectral Scanner (MSS) satellite imagery. The 5 MSS sensors onboard the Landsat 1-4 satellites collected data starting in 1972. Because the MSS data are of low radiometric fidelity, i.e. noisy, and data quality flags are minimal, we did not attempt to create annual or epochal (5-year interval) land cover maps. Instead, we constructed a composite for the MSS era (primarily 1972–1992) that included pre-fire only imagery for 1973–1995 fire scars. First, we performed an empirical calibration to better match top of atmosphere reflectance for the different MSS sensors to that of the Landsat 5 MSS. Then, within the bounds of 1972–1995 fire scars, we masked out imagery collected on or after the year of the fire. Finally, we calculated median reflectance for the 4 MSS bands for summer imagery (June 15–August 31) from all available pre-fire years.

To extend land cover mapping through to the present, and better document the actual years early in the record when the land cover was first mapped, we generated a new set of Continuous Classification and Detection of Change (CCDC, Zhu and Woodcock 2014) model parameters for boreal Alaska. CCDC is a temporal segmentation and time-series reflectance modeling algorithm that provides spectral predictors for land cover mapping. We improved the Wang et al. (2019) land cover type map by incorporating Landsat 8 imagery and by classifying land cover annually, rather than assuming land cover was constant within a temporal segment. We then developed scalable procedures to extrapolate the annual land cover mapping to cover recent years (currently 2015–2019), as well as prior years (1972–1992), using a bootstrapping procedure to leverage data

from the years covered by the Wang et al. (2019) map to cover additional years. Training and validation data for the forecast and backcast land cover maps were derived from carefully selected samples from the original (1985–2014) land cover map, avoiding areas with known changes.

## 2.2 Tree Canopy Cover Density, Fractional Deciduous Cover, and Plant Functional Type Change

We used Landsat satellite data from Landsat 5 TM, Landsat 7 ETM+, and Landsat 8 OLI sensors to derive deciduous fractional cover and tree canopy cover layers at 30-meter spatial resolution. While these datasets are publicly available to download through the United States Geological Survey (USGS), we used Google Earth Engine (GEE) to pre-process these data sets. We used Landsat 5, 7, and 8 Collection 1 surface reflectance data for years 1987–1997, 1998–2002, 2003–2007, 2008–2012, and 2013–2018 to derive NDVI-based median-value image composites for nominal years 1990, 2000, 2005, 2010, and 2015, respectively. The fire boundaries were obtained from Alaska Large Fire Database and Canadian National Fire Database. We trained random forest models to derive deciduous fraction layers using field samples from (1) our data sets described in under Objective 1, (2) Cooperative Alaska Forest Inventory (CAFI) (Malone et al. 2009), (3) Bonanza Creek Long Term Ecological Research (LTER) samples in Alaska (Alexander and Mack 2017), (4) permanent sample plots (PSPs) from seven Canadian provinces (Hayden et al. 1995), (5) ground sample plots from the Northwest Territories (Marshall and Baltzer 2015), and (6) Canadian National Forest Inventory plot data for sites across Canada (Gillis et al. 2005). These training data for our mapping included species-specific basal areas at each site. We converted the species-specific basal areas to deciduous fraction by taking a deciduous versus evergreen species weighted mean of the areas. The training samples used for random forest models of tree canopy cover were randomly selected from a map of global tree cover mapped for the period circa 2010 (Hansen et al. 2013). We used 30% of the ground samples that were selected to build the random forest models exclusively for model validation for both the deciduous fractional cover and tree canopy cover mapping. Parameter tuning of trained random forest models was performed by generating approximately 30 million bootstrapped random forest models to determine the best set of parameters with least error using a 3-dimensional error surface.

We identified a limitation of the deciduous fraction mapping was a lack of separation between deciduous tree fractional cover (e.g. *Populus* spp., *Betula neoalaskana*) and deciduous shrub fractional cover (e.g. *Salix* spp., *Alnus* spp, *Betula nana*). In addition, vegetation cover in early succession forest communities is generally dominated by non-tree species, and mid- to late-succession woodland or open forest communities continue to include a substantial component of non-tree taxa. To address this limitation we developed time-series of maps of top cover for 7 distinct plant functional types (PFTs) across a 1.77 x 106 km<sup>2</sup> study area in northern and central Alaska and northwestern Canada, including the military training areas. We improved on previous methods of detecting vegetation change by modeling top cover, a continuous measure of plant abundance. The PFTs collectively include all vascular plants within the study area (Conifer Trees, Broadleaf Trees, Deciduous Shrubs, Evergreen Shrubs, Graminoids, and Forbs) as well as Light Macrolichens, a nonvascular class of high importance to caribou management. To support the mapping, we applied the suite of environmental predictors (topography, phenology, climate,

and permafrost) and spectral covariates at 30 m resolution that were developed for Vegetation Cover Type Class Mapping (above). Importantly, the CCDC spectral model provides consistent predictors for midsummer and shoulder seasons across the 1985–2020 period of 30 m Landsat data. Seasonal predictors, including seasonal amplitude (range of values within the snow-free season) improve mapping of plant functional types that may be spectrally similar at midsummer.

The map models were prepared at 5-year intervals for the period 1985–2020. We integrated ground and aerial vegetation observations, and unoccupied aerial systems (UAS) maps collected from 1994–2019. Vegetation plots that only reported total foliar cover were normalized to top cover using a hierarchical approach. We assessed spatial autocorrelation of the training data and applied a spatially blocked cross-validation strategy to parameterize models and obtain unbiased estimates of model performance. We applied two gradient-boosting models (lightGBM) to map each PFT distribution based on the training data and spatial predictors. A binary probability model was applied to map PFT distribution, and a regression model was applied to map PFT abundance. The two models were combined for a final prediction of lichen cover.

The statistical modeling approach follows Nawrocki et al. (2020, 2021) with two main modifications: (i) our inner and outer cross-validation folds were spatially blocked; and (ii) spectral predictors were extracted using modeled reflectance from the year that the plot data were collected.

### *2.3 Burn Extent and Severity Mapping and Associated Post-fire Succession*

Burn severity in Alaska boreal forests, which typically experience stand-replacing crown fires, is typically governed by burn depth in organic soils and subsequent carbon emissions (Boby et al., 2010; Rogers et al., 2014). Burn depth in particular has a strong influence on post-fire recruitment and hence vegetation succession patterns (Johnstone et al., 2010a, 2010b; Baltzer et al., 2021). To model and map burn severity across fires in interior Alaska, we leveraged a recent synthesis database archived by members of our team (Walker et al., 2020), which includes site-level observations of burn depth and combustion (area-weighted carbon emissions) from over 1,000 burned plots, including 368 in interior Alaska. We built and applied statistical models of aboveground combustion, belowground combustion, and burn depth to 500m MODIS pixels mapped as burned according to a new burned area product for Alaska and Canada (Potter et al., 2022).

To do so, we related these metrics of fire severity to a variety of geospatial predictors, including those related to climate (Wang et al., 2016), topography and topographic wetness (Burns et al., 2018), soils (Hengl et al., 2017), Fire Weather Indices (Field et al., 2015), permafrost probability (Gruber, 2012), tree cover (Sexton et al., 2013), pre-fire tree species (Beaudoin et al., 2014; Ottmar et al., 2007), and remotely-sensed indices acquired from Landsat (e.g., NDVI, dNBR, Tasseled Cap Indices, and the Normalized Difference Infrared Index). We reduced these initial 75 covariates to an optimal number using Recursive Feature Elimination (Guyon et al., 2003). We then compared a suite of models, including ridge and lasso regression, linear support vector machines, polynomial support vector machines, radial support vector machines, general additive models, multivariate adaptive regression splines, random forests, and quantile random forests, as well as their ensemble prediction. After choosing a model type, we implemented a 10-fold cross validation procedure repeated 100 times using an 80–20% calibration-validation split for our

evaluation of model performance. The median  $r^2$  was chosen to represent the predictive power of a given model. Our models were developed using Landsat imagery, but due to missing imagery we then scaled modeled relationships to 500m and implemented them across the domain using 500m MODIS imagery. Finally, we derived metrics of uncertainty using a comprehensive Monte Carlo analysis with 500 simulations that incorporated uncertainty from both the field-measured combustion and random forest models, similar to techniques our research team developed in previous combustion mapping efforts (Rogers et al., 2014; Veraverbeke et al., 2015; Walker et al., 2018; Dieleman et al., 2020).

Although these models can be applied to fires that occurred during the MODIS record (2001 – present), which also contains reliable Landsat imagery for model training, our ability to model fire-induced changes in vegetation relies, in part, on our ability to characterize burn severity in fire scars that are older than the available remote sensing record. To model burn severity prior to 2001, we varied the types of predictors used, progressively older fires contain fewer types of predictor data. Specifically, fires between 1980 and 2000 in Alaska generally lack Landsat-based severity metrics, and fires older than 1980 lack Landsat-based severity metrics and information on Fire Weather Indices (Table 1). We also tested model performance when varying the distribution of training sites to either include the whole domain or just Alaska to assess if the benefits of focusing on regional-specific training data outweighed the increase in sample size achieved by including sites in Canada.

**Table 1.** Predictor variables used in models to estimate burn depth as a function of fire epoch.

Predictor variable	Early fires (1940 - 1980)	Intermediate fires (1980 – 2000)	Recent fires (2000 – present)
Soils (sand, silt, clay)	X	X	X
Topography (elevation, aspect, slope)	X	X	X
Long-term climate	X	X	X
Permafrost index	X	X	X
Ruggedness	X	X	X
Fire Weather Indices		X	X
Percent tree cover			X
Day of burn			X
Vegetation indices			X

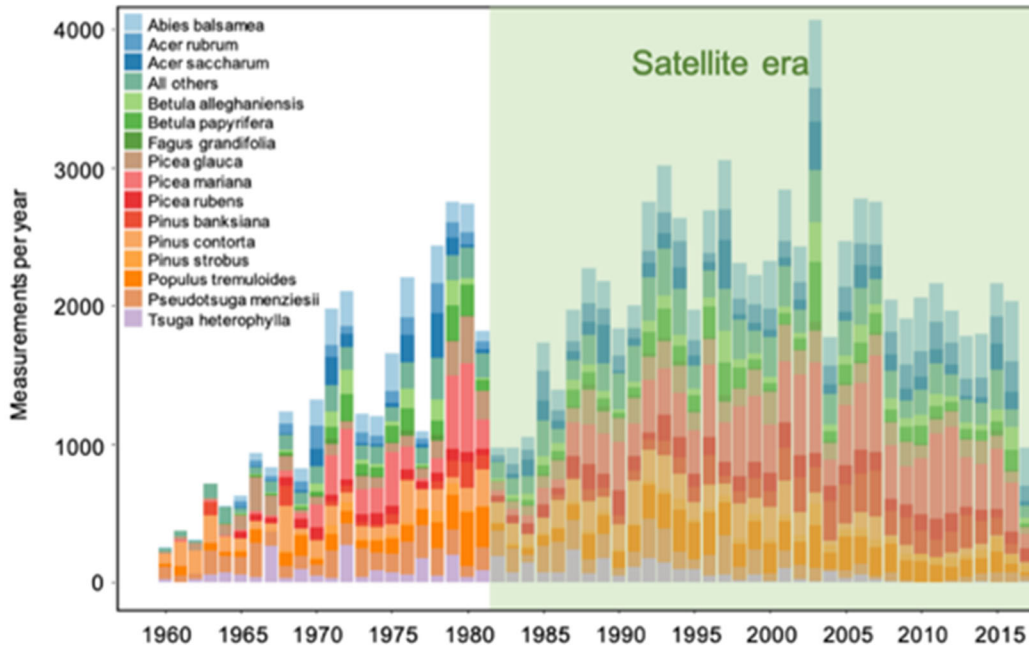
To complement these analyses and the associated fieldwork, we collected Unmanned Airborne Systems (UAS) data during late spring/early summer 2019 and 2020 to assess regeneration. In addition to UAS imagery, which covers 10s to 100s of ha, we compiled high-resolution (few meter) WorldView-2 and WorldView-3 pre- and post-fire satellite imagery for interior Alaska. The UAS and high-resolution satellite imagery provided detailed local maps to review and assess the plant functional type and deciduous fraction mapping (described earlier) used to characterize succession trajectories from fires in the historical record. We also generated data stacks from the Landsat fire history and severity time series, compiled all the dNBR fire severity data for the study area back to 1985. We collected additional *in situ* data in summer 2020 and UAS post-fire burn severity data within the 2019 Shovel Creek fire in an area with pre- and post-fire airborne lidar and high-resolution imagery (from NASA ABoVE and USGS surveys) to support calibration and validation of mapping algorithms to assess fire effects on vegetation succession.

#### 2.4 Productivity trends & precursors of mortality (“early warning signals”)

For the larger-scale remote sensing component of this Objective, we hypothesized that *early warning signals (EWS) of tree mortality in boreal forests of interior Alaska and Canada are detectable using long-term satellite-based Normalized Difference Vegetation Index (NDVI)*. Our hypothesis was confirmed by analyzing multiple EWS metrics from Landsat (5 and 7; 30 m; Ju and Masek, 2016), the Moderate Resolution Imaging Spectroradiometer (MODIS; MYD13Q1; 250 m; Didan, 2015), and the Advanced Very High Resolution Radiometer (GIMMS<sub>3g</sub>; 8 km; Pinzon and Tucker, 2014) at repeatedly-measured forest inventory plots (Permanent Sample Plots, or PSPs) in interior Alaska (the Cooperative Alaska Forest Inventory; CAFI; 612 plots aggregated into Malone et al., 2009) and Canada (the Climate Impacts on Productivity and Health of Aspen; CIPHA; Hogg et al., 2005), as detailed in Rogers et al. (2018). We have since developed a much larger database of PSPs across Alaska and Canada (Figure 2) to further explore these dynamics and develop predictive models of forest demographics (informing Objective 3.1).

We note that PSPs, as opposed to sites inventoried only once, are required to capture forest demographic processes such as mortality and changes in biomass. To develop this, we secured data sharing agreements and compiled and standardized data from Alaska and eleven Canadian provincial governments. The resulting PSP database includes site-specific information such as stand age and known disturbances, as well as site- and species-specific stem count, biomass, recruitment, growth, and mortality. Biomass-based metrics were derived using allometric equations from various sources, including Lambert et al. (2005), Ung et al. (2008), and Alexander et al. (2012). This amounts to over 25,000 unique forest plots and over 100,000 observations covering the boreal forests of North America (Figure 2). Most plots were re-measured on 10-year intervals, although a substantial fraction included more frequent measurements. A majority of observations come from the satellite era (Figure 1), enabling us to establish relationships with remote sensing indices. This database is unique in its volume of forest demographic information and is critical for our near-term predictive models of forest properties (Objective 3.1).

We then assessed the signal detection capability for site-level mortality using this comprehensive database and our EWS framework. To do so we assessed the relationships between tree mortality and preceding satellite-based EWS metrics using NDVI time series from GIMMS<sub>3g</sub>, MODIS, and Landsat. Inventory data were filtered to remove sites that were artificially treated or experienced instantaneous disturbances (i.e., non-drought and pest related disturbances such as harvest, windthrow, or fire). We derived early warning signal metrics from the NDVI record that are meant to detect a loss of resilience in a system that approaches catastrophic change (such as a mortality event), including trends, jumps, autocorrelation, standard deviation, diffusion, conditional variance, and total variance (Rogers et al., 2018). The magnitude of these EWS metrics preceding a given inventory-measured mortality level were analyzed as a function of mortality and time window for NDVI.



**Figure 2.** Temporal distribution of repeatedly-measured Permanent Sample Plots (PSPs) contained in our compiled database.

### Objective 3: Predictive modeling of vegetation change

#### 3.1 Spatial Statistical / Machine Learning Models

The subtasks of this objective include (i) site-level and (ii) spatially-gridded predictions of future changes in forest habitat composition, productivity, and mortality. Site-level predictions are developed using our PSP database across Alaska and Canada (section 2.4) and applied at DoD inventory sites in interior Alaska. The latter are being developed regionally (at ~500m resolution) as well as locally for the bases (at 30m resolution).

Our original working hypothesis was that *near-term forecasts of tree mortality are possible using long-term remote sensing time series*. To test this hypothesis, we implemented various statistical approaches to predict tree mortality 5-10 years into the future using NDVI time series. We tested varying lengths of time windows before ground plot measurements; 13 different EWS metrics from Landsat up to 20 years before a given PSP measurement (based on Rogers et al. (2018)); statistical models varying in complexity from general linear models to machine learning models; methods for sampling the distribution of mortality observations (random and stratified), and maximum versus mean growing season NDVI from Landsat.

Ultimately, these predictive models were not deemed robust enough for extrapolation and implementation at DoD installations (cross-validated  $r^2 \sim 0.1$ ). We therefore adjusted our framework to predict changes in net forest biomass as determined by forest growth, recruitment, and mortality. We note this was a slight change of scope, but that changes in net biomass are highly relevant to DoD natural resource management objectives such as training, wildfire

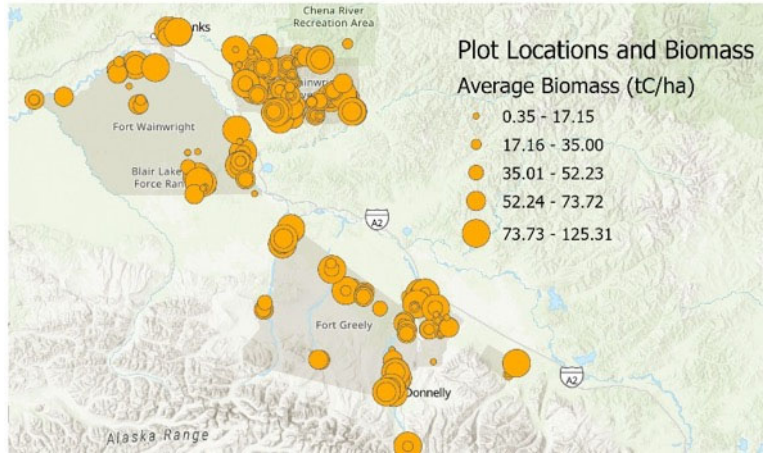
susceptibility, timber harvest, regulation compliance, wildlife habitat and conservation, and carbon sequestration (as per conversations with DoD base natural resource managers). Our hypothesis then became *near-term forecasts of forest biomass change are possible using long-term remote sensing time series and related geospatial data*.

To test this hypothesis, we integrated a suite of predictor variables known to influence forest productivity, mortality, and demographics. This included climate, soil, tree species, and permafrost predictors similar to our burn depth models (Objective 2.3), as well as EWS metrics based on Rogers et al. (2018) at varying time windows using a variety of Landsat-based vegetation indices: NDVI, moisture stress index (MSI), normalized difference infrared index (NDII), plant senescence reflectance index (PSRI), normalized difference senescent vegetation index (NDSVI), soil-adjusted total vegetation index (SAVRI), total vegetation fractional cover (TVCF), normalized burn ratio (NBR), normalized difference water index (NDWI), and the near-infrared reflectance of terrestrial vegetation ( $NIR_v$ ). These predictors were input into an Extreme Gradient Boosting regression algorithm using Python XGBoost. XGBoost was chosen because it is widely used, can tolerate missing predictors, scales well in Cloud and GPU compute environments, and outperformed the more widely-used random forest algorithm in both compute time and accuracy in our initial tests. Although XGBoost is tolerant of missing data, performance degrades as the number of NaN's increases. We therefore excluded sites with more than 50% missing data.

To ensure a completely independent test sample and to prevent overfitting we used a four-way train, validation, model test, and ensemble test split. The multiple subdivisions and strict grouping by sites ensured that test sets are fully withheld and there was no data leakage, which is a widespread problem in machine learning studies. The splitting and modelling of the data set was repeated using a less strict site and time period grouping to assess the impact of including an earlier portion of the time series for a specific site on prediction performance. We also adopted a two-stage feature selection approach for each model in our final 10-member ensemble. The first stage involves the use of a hierarchical clustering algorithm that groups the predictor variables into clusters, and then selects a feature in each cluster based on its permutation importance. This process was repeated at each level of the cluster tree until increasing the level further resulted in a degradation of model performance. To further reduce the number of predictor variables we then applied a recursive feature elimination procedure. After the final set of variables was selected, we optimized hyperparameters using a Bayesian approach.

Using a 10-member model ensemble, we performed future predictions at each PSP site by applying the models to the most recent observation. Sites whose most recent observation was greater than 30 years from the prediction end point (2025, 2030, 2035, and 2040) were excluded.

We applied our model to existing inventory plots at DoD installations in interior Alaska to facilitate operational planning. To do so, we coordinated with base managers and received access to 277 Forest Inventory and Analysis (FIA)-style plots established across the installations (Figure 3). Each plot contains four circular subplots with a radius of 24 feet, for a total of 1108 subplots. Plots were first established between 2001 and 2011. 109 plots are measured every four years and are in their 4<sup>th</sup> inventory, and 472 are measured every 10 years and are in their 3<sup>rd</sup> inventory.



**Figure 3.** Location and average aboveground biomass of forest inventory plots across DoD installations in interior Alaska.

Tree species within the sites include tamarack (*Larix laricina*), white spruce (*Picea glauca*), black spruce (*Picea mariana*), Alaska paper birch (*Betula neoalaskana*), quaking aspen (*Populus tremuloides*), and balsam poplar (*Populus balsamifera*). We calculated tree- and plot-specific biomass using allometric equations specific to Alaska and, when needed, Canada (Alexander et al., 2012; Lambert et al., 2005; Ung et al., 2008). The average biomass of the plots through time was 38.7 t ha<sup>-1</sup>.

Finally, we continue development spatially-gridded versions of these models to be applied at both a coarse scale (500 m) across the North American boreal domain, and at a fine scale (30 m) to be applied at DoD bases. We are substituting site-level observations of forest composition and biomass for gridded products, including Landsat-based tree cover and deciduous fraction estimates produced by this project (Objective 2.2). We expect to have all models finalized and shared with DoD base managers via a public webinar in the Fall of 2022 (post fire season).

### 3.2 Process-based Forest Demography Modeling

For this component of this objective, we are using a process-based model of forest demography, specifically an individual tree-based gap model called UVAFME. The model was updated and applied within interior Alaska to produce predictions of both current and future forest dynamics. The model was parameterized to over 800 testing and inventory sites, including 77 sites from the Cooperative Alaska Forest Inventory (CAFI) database (Malone, Liang, Packee, et al., 2009) and 476 sites from the Forest Inventory and Analysis (FIA) database (Burrill et al., 2018). Climate data for these site locations were obtained from the ClimateNA project (Wang et al., 2016a), the Climatic Research Unit (CRU) TS 3.26 datasets (Harris et al., 2014), WorldClim (Fick & Hijmans, 2017), and the Scenarios Network for Alaska + Arctic Planning (SNAP) database. Input topographic and soils information for each site were obtained from OpenLandMap (Hengl, 2018a, 2018b, 2018c; Hengl & Gupta, 2019) and a high-resolution (10 m) digital elevation model (Burns et al. 2018). Input species characteristics were obtained from Burns and Honkala (1990), Viereck & Little (2007), and Nikolov and Helmisaari (1992).

Despite its success in simulating Russian forests (Shuman et al., 2015, 2017), UVAFME did not previously simulate permafrost depth or freeze/thaw dynamics, and did not include species-specific interactions with litter quality and decomposition rate, which are highly important in Alaska for determining vegetation structure, biomass, composition, and overall species trajectories (Chapin et al. 2006). The model was updated for this project to include these interactions as well as an updated fire submodel to include the effect of litter characteristics and fire weather on fire intensity and individual tree mortality.

A permafrost submodel to simulate seasonal depth of thaw and its impacts on soil moisture, soil nutrients, and tree growth was added to UVAFME using equations from Bonan (1989). A moss growth submodel was also added to UVAFME based on equations from Bonan and Korzukhin (1989). An updated nutrient submodel, based equations from Pastor and Post (1985), and Bonan (1990), was created to incorporate the effects of species composition on litter quality, decomposition rate, and plant-available nitrogen.

The existing fire subroutines within UVAFME were updated to include a more mechanistic simulation of fire occurrence, intensity, and severity. These updates allow for better interaction between fuels, fire weather, fire mortality, and post-fire regrowth and are based on equations from Rothermel (1972) and Thonicke (2010). Fuels are determined based on litter inputs from the plant growth and mortality subroutines of the forest model and broken into different classes (1-hr through 1000-hr fuels). Fuel geometry (e.g. bulk density, surface area to volume, etc.) differs between these classes, and thus forest stands with differing species composition and biomass will have differing fuel characteristics. Fuel characteristics (i.e. total loading, bulk density, surface area-volume ratio, and moisture) along with fire weather characteristics (i.e. temperature, humidity, and wind speed) determine fire intensity ( $\text{kW m}^{-1}$ ), mortality of trees, and combustion of the organic layer. Ignition events are based on fire weather as well as input lightning strike frequency. Output on above- and belowground fuels consumption from the updated model agree well with observations across the region from (Walker et al., (2020)). Post-fire organic- and moss-layer depth are additionally used to influence the species-specific regeneration of seedlings, with some species (e.g. black spruce) having a greater capacity to regenerate on a deep moss/organic layer than others (e.g. aspen) (Bonan & Korzukhin, 1989). These updates to UVAFME result in better agreement with inventory data within interior AK and additionally allow for detailed interactions between vegetation composition, wildfire disturbance, and permafrost dynamics. We have additionally completed comparisons of UVAFME modeled deciduous fraction to our Landsat-based maps of deciduous fraction within Alaska produced as part of this project (Objective 2.2).

We have additionally incorporated shrub growth and mortality into the UVAFME model, which improves simulation of forest dynamics and post-fire regeneration. Data on shrub basal diameter, height, and other characteristics (Berner et al., 2015; Falster et al., 2015) were used to develop shrub-based allometric and growth equations. Comparisons to inventory measurements of shrub biomass show that the model can accurately represent shrub-tree dynamics. Finally, we implemented seed rain to adjacent grid cells within the model in order to better simulate potential species migration and biome shifts under climate change scenarios (Keane et al., 2011). Such an implementation has not been done within a model like UVAFME before and will significantly advance our understanding of how the Alaskan forests may shift in the future.

We additionally updated UVAFME to include a number of different management and fuels treatments, including thinning, trimming of ladder fuels, shearblading, logging, and controlled burns. Trees are thinned starting from the largest diameter trees first, moving to the smallest trees until the specified number of trees to thin has been met. Ladder fuels are trimmed based on a set input depth (m) to trim. Shearblading removes all trees on the plot and removes 15% (or user-specified portion) of the soil organic layer. Trees are logged based on specified inputs of number or volume of trees to log, and size and species specifications. The boles, branches, twigs, and leaves of the cut trees are removed from the stand. Controlled burns can be implemented as a surface (i.e. low intensity) or stand-replacing (i.e. high intensity) fire. Outputs from these treatments include post-treatment species composition, stand structure (tree size class<sup>-1</sup> ha<sup>-1</sup>), biomass (tC ha<sup>-1</sup>), basal area (m<sup>2</sup> ha<sup>-1</sup>), and fuel loading (kg m<sup>-2</sup>).

We developed a portable, easy-to-use application that allows users to apply the updated version of UVAFME at set locations (which have already been parameterized and tested). Users can modify which sets of sites to run, which management/climate change scenarios to use, and can modify a select number of management-related parameters.

#### **Objective 4: Implementation of outcomes with resource managers**

For this objective, our project takes a two pronged approach:

1. Direct and iterative communications with the small group of management personnel tasked with managing DoD lands in interior Alaska to ensure that project data gathering, analyses, and technology transfer activities align with their specific management needs and practices.
2. Broader communication with the regional and international management communities regarding relevant finding. For this approach the project is leveraging the outreach and technology transfer capabilities of the Alaska Fire Science Consortium, which serves fire, land, and resource managers, primarily in Alaska and Canada.

Project activities in both of these areas are expected to increase in frequency in outyears as additional results and data from field campaigns and modeling work become available. Results to date are summarized below.

## Results and Discussion

### Objective 1: Field campaigns & measurements

#### *4.1 Impacts of aspen leaf miners on deciduous tree productivity*

Our field campaigns included a focus on the novel outbreak of the aspen leaf miner (1997-2013), when forest inventory data indicate regional and dispersed aspen mortality in interior Alaska. Death in mature aspen stands opens canopies for regeneration of understory spruce and could shift successional trajectories towards spruce dominance. This would increase forest vulnerability to disturbances associated with military training, increase flammability, and reduce habitat quality for moose. Our findings reveal that aspen that died during the leaf miner outbreak were on a trajectory of decreased productivity prior to the outbreak, with productivity of ‘dying’ aspen beginning to decline nearly 50 years earlier after a severe drought followed by an infestation of the large aspen tortrix, an insect defoliator. Aspen that survived the leaf miner outbreak recovered rapidly from these historic disturbances (Figure 4). During the leaf miner outbreak both living and dying aspen exhibited a negative growth response to leaf mining but living aspen growth was also positively influenced by moisture availability while dying aspen growth was decoupled from climate. In addition, we related aspen productivity and aspen biomass growth and death to Landsat-derived maximum summer NDVI. We found that NDVI was more strongly associated with living than dying aspen productivity and aspen biomass growth than death. These results suggest that historic disturbance events predispose aspen to mortality during a novel disturbance, and that NDVI may inadequately detect dispersed insect-driven dieback of aspen in the boreal biome. These results are described in Boyd et al. (2021).

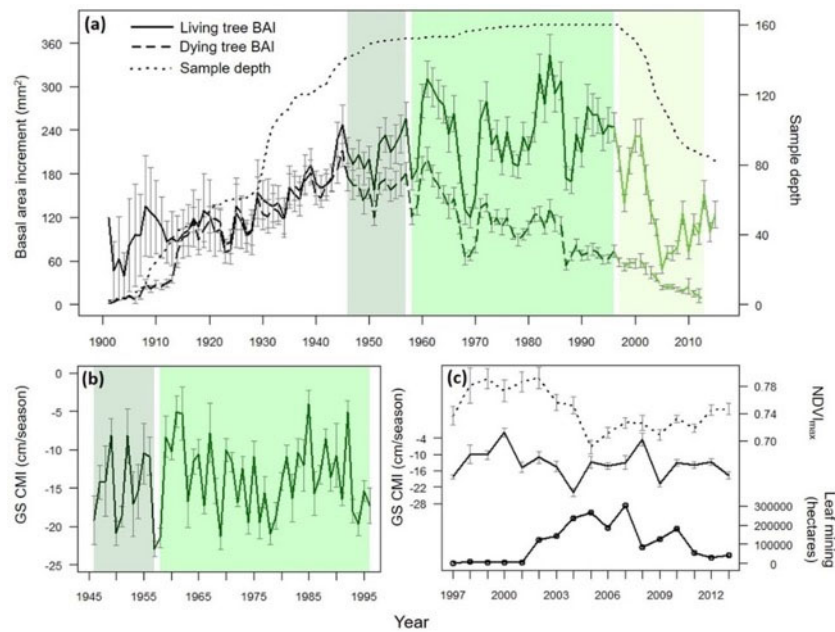
#### *4.2 Impacts of fuel reduction treatments on successional trajectories*

The second component of our field campaigns focused on the impacts of thinned and shearbladed fuel reduction treatments on successional trajectories of tree dominance, understory composition, active layer depth, and modeled surface ROS, flame length, and fireline intensity up to ~20 years post-treatment. We show that patchy disturbance to the soil organic layer in thinned treatments promoted conifer and deciduous tree recruitment. As recruitment largely occurred initially after thinning, management that removes conifer seedlings could reinforce a deciduous trajectory in this treatment. In shearbladed areas conifer seedling density increased slowly over time but these sites had 20 times more deciduous tree seedlings, indicating this treatment is following a deciduous-dominated trajectory (Figure 5). Thinning did not modify understory composition whereas grasses and shrubs increased in dominance in shearbladed treatments over time. In both treatments active layer depth, an indication of permafrost degradation, increased over time but was 1.3 times greater in shearbladed than thinned treatments. This suggests that thinned instead of shearbladed treatments should be implemented in areas of ice-rich permafrost to limit permafrost degradation and subsidence. Predicted surface fire behavior did not capture our quantified temporal changes in shearbladed understory composition, highlighting limitations of the basic fuel models and need to collect additional fuels-specific data to more accurately model fire behavior in this treatment. Lastly, whether treatments reduced modeled ROS, flame length, and fireline intensity depended on the fuel model used for an untreated black spruce stand, pointing towards uncertainties about treatment

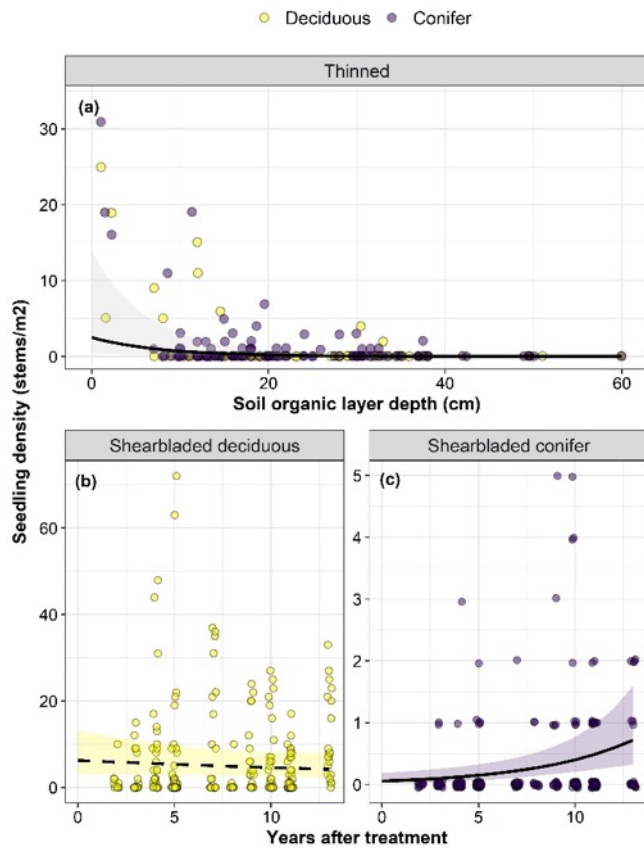
effectiveness at reducing surface fire behavior. Overall, our findings indicate that fuel reduction treatments have long-term impacts on ecosystem structure and fuel accumulation. To enhance the design, management protocols, and fire behavior predictions in fuel reduction treatments these factors need to be accounted for.

#### 4.3 Linking field measurements post-fire succession with satellite estimates of composition

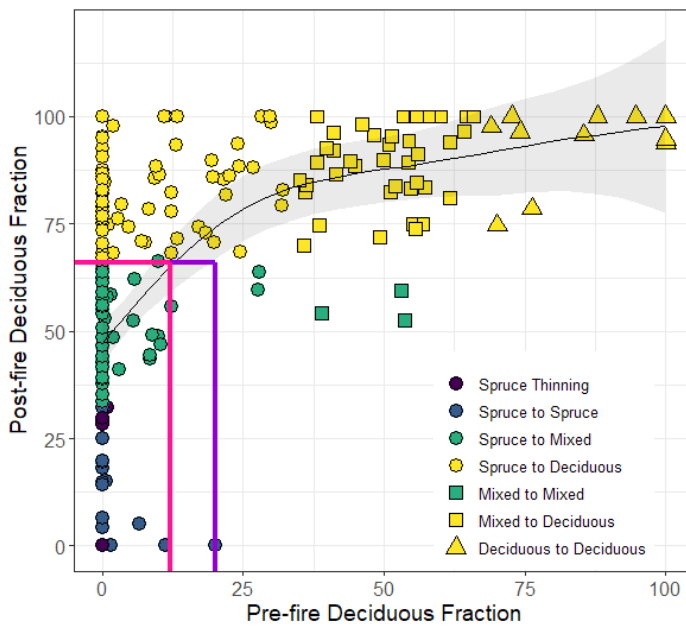
The third component of this objective focused on linking remote sensing analyses of forest composition (fraction of biomass that is deciduous) with field measurements, focusing on understanding the patterns and drivers of spruce versus deciduous dominance of post-fire successional trajectories. We found that if stands had >12% pre-fire deciduous index (DI; relative density plus relative biomass of deciduous trees or seedlings divided by two and multiplied by 100) then they were likely to transition to deciduous dominance (i.e., post-fire DI was >66%) (Figure 6; pink line). If stands had >20% pre-fire DI, then post-fire stands were exclusively deciduous dominated based on confidence intervals of fitted relationships (Figure 6; purple line). Pre-fire spruce stands (157 sites) were most likely to transition to deciduous dominance (67 sites) or mixed spruce-deciduous (51 sites). Pre-fire deciduous dominated stands exclusively self-replaced (35 out of 35 sites). The majority of mixed stands (40 out of 43) transitioned to deciduous dominance, with the remaining sites remaining mixed spruce-deciduous dominance post-fire.



**Figure 4.** (a) Basal area increment (BAI; mean  $\pm$  SE) of living trees (solid line) from establishment to 2015 and dying trees (dashed line) from establishment to 2013 and the number of sampled trees (Sample depth; dotted line); (b) growing season climate moisture index (GS CMI; mean  $\pm$  SE) prior to the *Phyllocnistis populiella* outbreak (1945–1996); and (c) GS CMI (mean  $\pm$  SE), the maximum summer normalized difference vegetation index (NDVI<sub>max</sub>; mean  $\pm$  SE), and leaf mining (hectares of Alaska infested) during the *P. populiella* outbreak (1997–2013). In (a) and (b), dark green shading denotes when living and dying tree BAI overlapped, intermediate green shading denotes when living tree BAI was greater than dying tree BAI, and in (a) light green shading denotes the *P. populiella* outbreak.



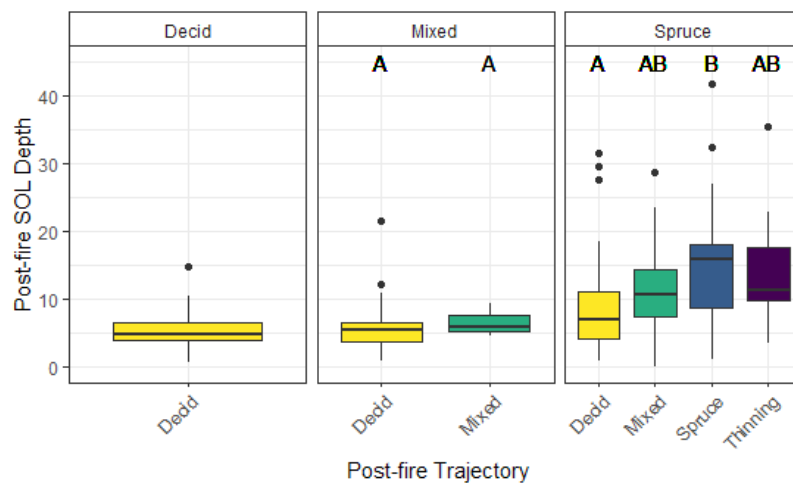
**Figure 5.** Results of generalized linear mixed models (GLMMs) depicting the influence of (a) soil organic layer depth on deciduous (yellow points) and conifer (purple points) seedling density in thinned sites and (b) years after treatment on deciduous and (c) conifer seedling density in shearbladed sites. Shading indicates the 95% confidence interval, each point is a seedling density measurement along a transect, and significant relationships are represented by solid lines. Note that the y-axis differs across panels.



**Figure 6.** Post-fire deciduous index as a function of pre-fire deciduous index. Shapes represent different pre-fire species composition (circle=spruce, square=mixed, triangle = deciduous) and colors indicate post-fire succession trajectory (purple = thinning, blue = spruce, green = mixed, and yellow = deciduous). Black line represents generalized additive model fit with shading for the 95% confidence intervals. Pine line represents the threshold in pre-fire DI from which post-fire DI >66% is likely to emerge based on model fit. Purple line represents the threshold in pre-fire DI from which post-fire DI >66% will emerge (95% confidence) based on model fit.

In examining soil organic layer (SOL) depth of post-fire trajectories within the same pre-fire class, the only difference we observed was between spruce transitioning to deciduous dominance and spruce remaining spruce (Figure 7). Specifically, spruce stands that remained spruce had an average post-fire SOL of depth of 14.9 cm, which was significantly higher than spruce stands that transitioned to deciduous dominance (8.4 cm).

Regardless of pre-fire class, post-fire SOL depth did not differ among post-fire trajectories of mixed or deciduous dominance with average post-fire SOL depths of 10.4 and 7.3 cm, respectively (Figure 7). Our results reveal the presence of deciduous trees in the post-fire stand strongly impacts post-fire successional trajectories, with a threshold of 12% DI resulting in post-fire deciduous dominance. This is due to the presence of deciduous trees in the pre-fire stand providing a bud bank for asexual regeneration that facilitates rapid and prolific post-fire colonization. However, even with no deciduous stems present pre-fire (97 sites), almost 30% of spruce dominated stands transitioned to deciduous dominance post-fire, highlighting the importance of deciduous seed availability and favorable seedbeds (i.e., thin SOL) for the establishment of alternative deciduous trajectories. Taken together our results suggest that with continued intensification of wildfire, spruce stands are likely to shift to alternative post-fire successional trajectories of deciduous dominance and once deciduous trees establish their post-fire regeneration strategies will reinforce deciduous dominance.



**Figure 7.** Post-fire soil organic layer (SOL) depth (cm) as a function of post-fire trajectory (colors) and pre-fire class (panels). Colors indicate post-fire succession trajectory (purple = thinning, blue = spruce, green = mixed, and yellow = deciduous). The panels represent pre-fire classes (deciduous, mixed, spruce) based on deciduous index. Capital letters signify significant differences between SOL depths of post-fire trajectories within pre-fire dominance classes.

Publications:

Boyd, M. A., Berner, L. T., Foster, A. C., Goetz, S. J., Rogers, B. M., Walker, X. J., and Mack, M. C. (2021). *Historic declines in productivity portend trembling aspen death during a contemporary leaf miner outbreak in Alaska*. *Ecosphere*. 12: e03569. doi.org/10.1002/ecs2.3569

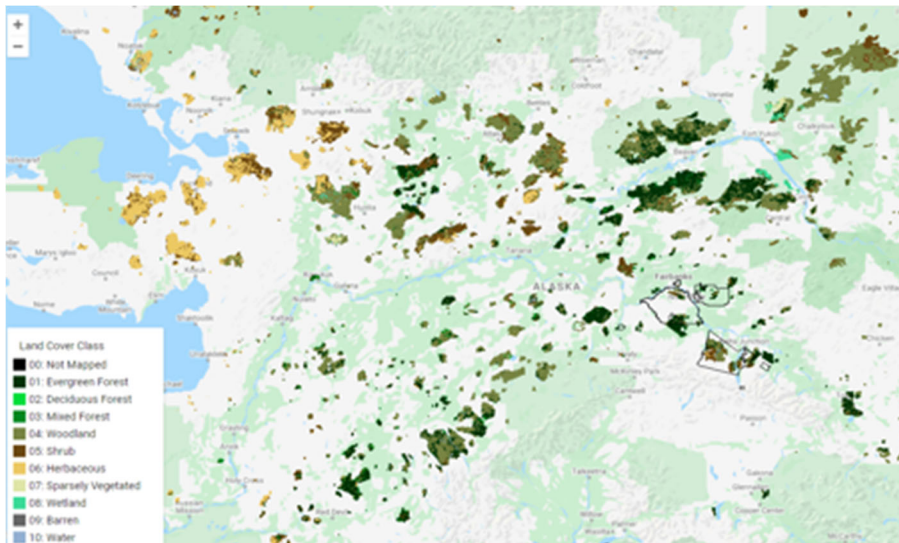
Boyd, M. A., Berner, L. T., Doak, P., Goetz, S., Rogers, B., Wagner, D., Walker, X., Mack, M. C. (2019). *Impacts of climate and insect herbivory on productivity and physiology of trembling aspen (Populus tremuloides) in Alaskan boreal forests*. *Environmental Research Letters*. 14: 085010. doi.org/10.1088/1748-9326/ab215f

Boyd, M. A., Walker, X. J., Barnes, J., Celis, G., Goetz, S.J, Johnstone, J.F., Melvin, A.M., Saperstein, L., Schuur, E.A.G., Mack, M. C. (in review). *Decadal impacts of wildfire fuel reduction treatments on ecosystem structure and fire behavior in Alaskan boreal forests*. Forest Ecology and Management. Preprint available at [dx.doi.org/10.2139/ssrn.4102858](https://dx.doi.org/10.2139/ssrn.4102858)

## Objective 2: Remote sensing of vegetation properties & change

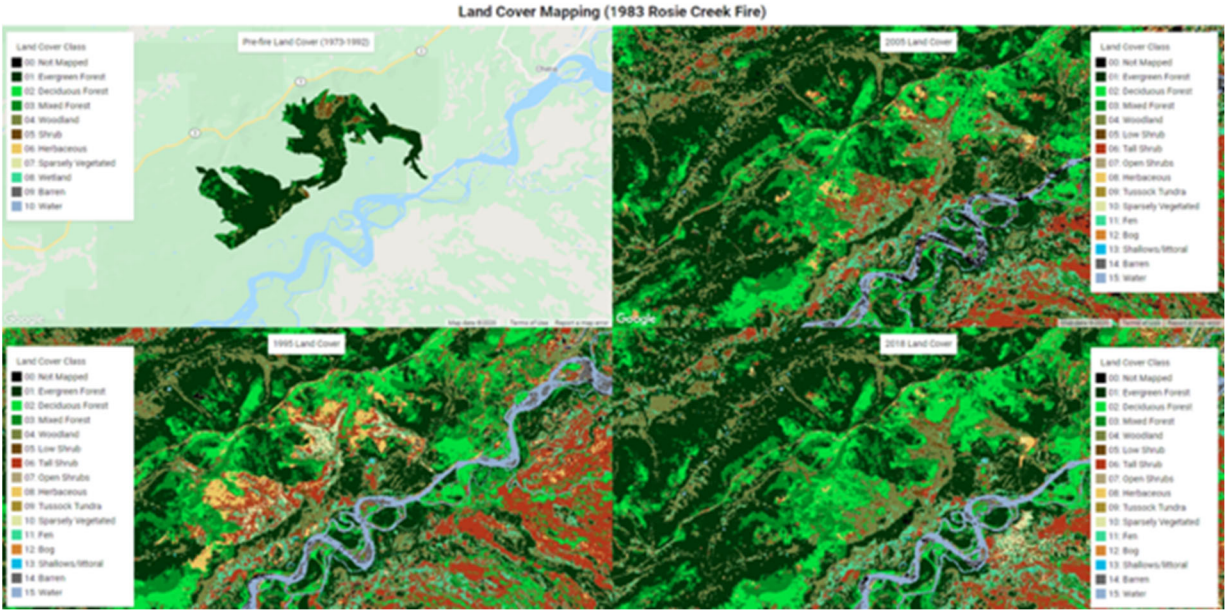
### 5.1 Vegetation Cover Type Class Mapping

The analysis of pre-fire Landsat MSS imagery extends the historical record of pre-fire vegetation by a decade or more. The empirical intercalibration of Landsat MSS 1–5 resulted in a radiometrically consistent spectral composite of pre-fire conditions and a classification of pre-fire vegetation in the 1973–1992 fire scars (Figure 8), providing new information for areas that burned several decades ago. Similarly, the land cover record extended to cover recent years (currently 2015–2020) provides up to date information on current land cover and extends the time period of tracking post-fire succession patterns. For example, a comparison of the pre-fire land cover map for the 1983 Rosie Creek fire and modeled land cover for 3 post-fire years (Figure 9) depicts the history of land cover change and vegetation succession. The bootstrap procedure we developed allows extension of land cover mapping to a historical record of nearly 5 decades, from the 1970s through to the present.



**Figure 8.** Classification of pre-fire vegetation for 1973-1992 fire scars across interior Alaska using Landsat Multispectral Scanner (MSS) imagery. The black polygons outline military training lands.

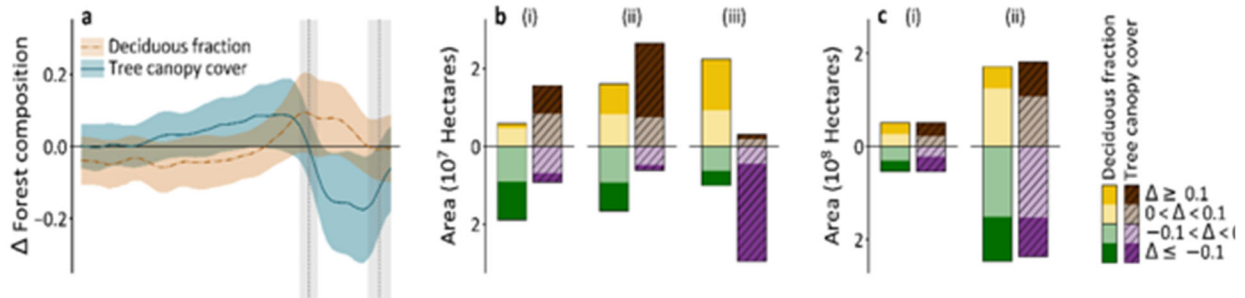
These land cover maps for 1972–2020 were compiled to create a complete annual time-series stack that is being made available through our visualization and analysis web application (Objective 4.0). The data were also exported to be made available for download on a public data portal, the Oak Ridge National Laboratory (ORNL) Distributed Active Center (DAAC) (Macander et al. 2022b *in prep*; Appendix 3).



**Figure 9.** Pre-fire land cover and bootstrapped land cover maps for 1995, 2005 and 2018. This example map includes the 1983 Rosie Creek Fire and the Tanana Flats Training Area.

*5.2 Tree Canopy Cover Density and Fractional Deciduous Cover Change*

There were substantial temporal changes in forest composition and tree cover resulting from fires over the period 1950 – 2018 (Figure 10). Because the majority of the total burned area occurred in recent (1999 – 2018) to intermediate (1979 – 1998) fire age ranges, a majority of the area with deciduous fraction increase occurred in those fire scars. In contrast, evergreen canopy mostly increased inside the intermediate and old (1950 – 1978) fire boundaries. Large overall tree canopy cover declines in recent fire scars are caused by high-severity fires killing mostly evergreen conifer forests, and those fires with more severe burning have increased deciduous cover. More generally, most of the tree regrowth in burn scars occurred in the intermediate to old fires, and this was true of both evergreen and deciduous cover (Figure 10b), which is consistent with our field observations capturing the time it takes for trees to establish and grow post-fire. We have developed a visualization tool of these cover and composition maps to allow land managers to see changes through time at their bases and training grounds. A link is provided below under results for objective 4.



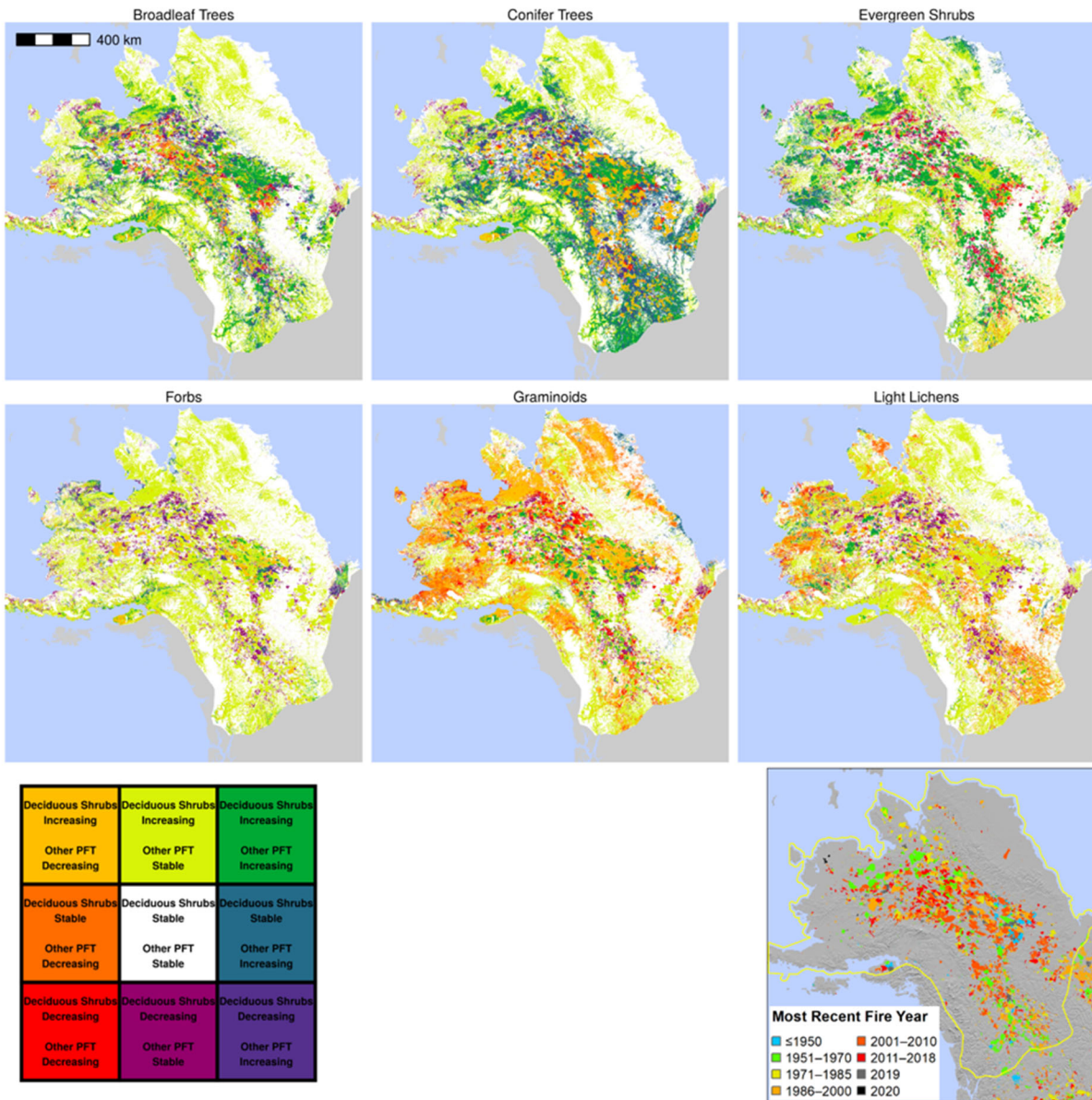
**Figure 10.** Effect of fire age (1950 – 2018) on average change in forest canopy cover and composition between 2000 and 2015. Panel (a) average change in per-pixel deciduous fraction and tree canopy cover inside fire boundaries by fire occurrence date. Panel (b) area with small (under  $\pm 0.1$ ) and large (over  $\pm 0.1$ ) changes in deciduous fraction and tree canopy cover by three fire age classes (i) old (1950 – 1978), (ii) intermediate (1979 – 1998), and (iii) recent (1999 – 2018). Panel (c) area with small (under  $\pm 0.1$ ) and large (beyond  $\pm 0.1$ ) changes in deciduous fraction and tree canopy cover within fire scars (i) and for the boreal domain of North America (ii). Note  $\Delta$  represents change between 2000 and 2015. The grey dashed lines in a indicate the date ranges of Landsat images used in the 2000 and 2015 deciduous fraction and tree canopy cover products. The axes above and below the zero line in b indicate non-negative values.

### 5.3 Plant Functional Type Cover Change

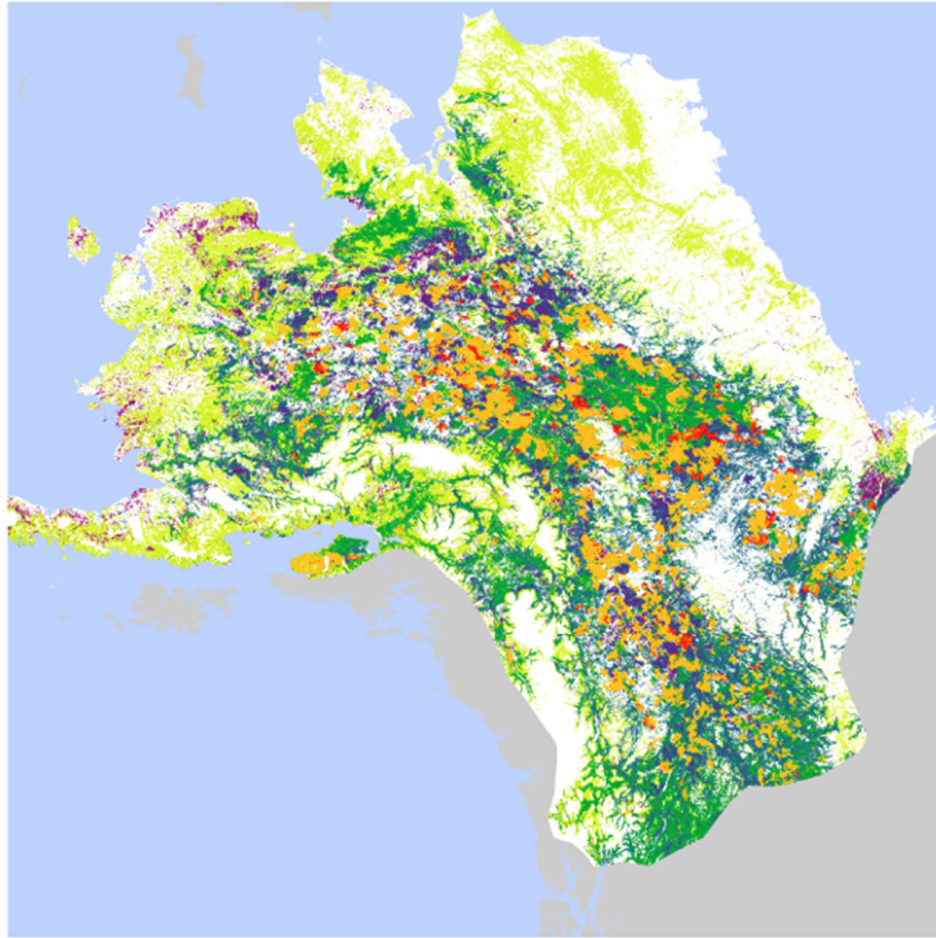
Our PFT cover change mapping across all of Alaska and Yukon between 1985 and 2020 identified net increases in deciduous shrubs ( $66 \times 10^3 \text{ km}^2$ ), evergreen shrubs ( $20 \times 10^3 \text{ km}^2$ ), broadleaf trees ( $17 \times 10^3 \text{ km}^2$ ), and conifer trees ( $16 \times 10^3 \text{ km}^2$ ), and net decreases in graminoids ( $-40 \times 10^3 \text{ km}^2$ ) and light macrolichens ( $-13 \times 10^3 \text{ km}^2$ ), with similar patterns across Arctic, Oroarctic, and Boreal bioclimatic zones (Figures 1, 11, 12). Model performance was assessed using spatially blocked, nested 5-fold cross-validation with overall root mean square errors ranging from 8.3–19.0%. Most net change occurred as succession or plant expansion within areas undisturbed by recent fire, though PFT top cover change also clearly resulted from fire disturbance. These maps have important applications for assessment of surface energy budgets, permafrost changes, nutrient cycling, and wildlife habitat, management and movement analysis.

Our paper reporting on the plant functional type mapping was published in *Environmental Research Letters* (Macander et al. 2022a). The outcomes were also presented to an audience of 80+ participants on 8 March 2022 at an Alaska Center for Climate Assessment and Policy (ACCAP) webinar entitled *Time-series maps reveal widespread change in plant functional type cover across arctic and boreal Alaska and Yukon* (linked [here](#)).

The map data products have been submitted to and will be available through the ORNL DAAC ([doi.org/10.3334/ORNLDAAC/2032](https://doi.org/10.3334/ORNLDAAC/2032)). The data are also be available through our visualization and analysis web application (section 4).



**Figure 11.** Patterns of deciduous shrub top cover change, 1985–2020, coincident with top cover change in other plant functional types at 960 m super-pixel scale and fire history. Changes at the 960 m super-pixel scale  $\leq 1\%$  top cover are categorized as stable. 30-m pixels where change was less than the magnitude of model RMSE were set to zero before aggregation, in order to emphasize areas with higher confidence of change.



**Figure 12.** Enlargement of one panel of Figure 11 showing detail of where Conifer Tree cover increased (greens and blues) or decreased (oranges and reds). The full color key is included in Figure 11 and more specifics of change in and around DoD bases and training grounds are reported in section 5.4 below.

#### Publications:

Macander, M. J., Nelson, P., Nawrocki, T. W., Frost, G. V., Orndahl, K. M., Palm, E. C., Wells, A. F., Goetz, S. J. (2022a). *Time-series maps reveal widespread change in plant functional type cover across arctic and boreal Alaska and Yukon*. Environmental Research Letters. doi.org/10.1088/1748-9326/ac6965

Macander, M.J. and P.R. Nelson (2022c). *Modeled Top Cover by Plant Functional Type over Alaska and Yukon, 1985-2020*. ORNL DAAC, Oak Ridge, Tennessee, USA. doi.org/10.3334/ORNLDAAC/2032

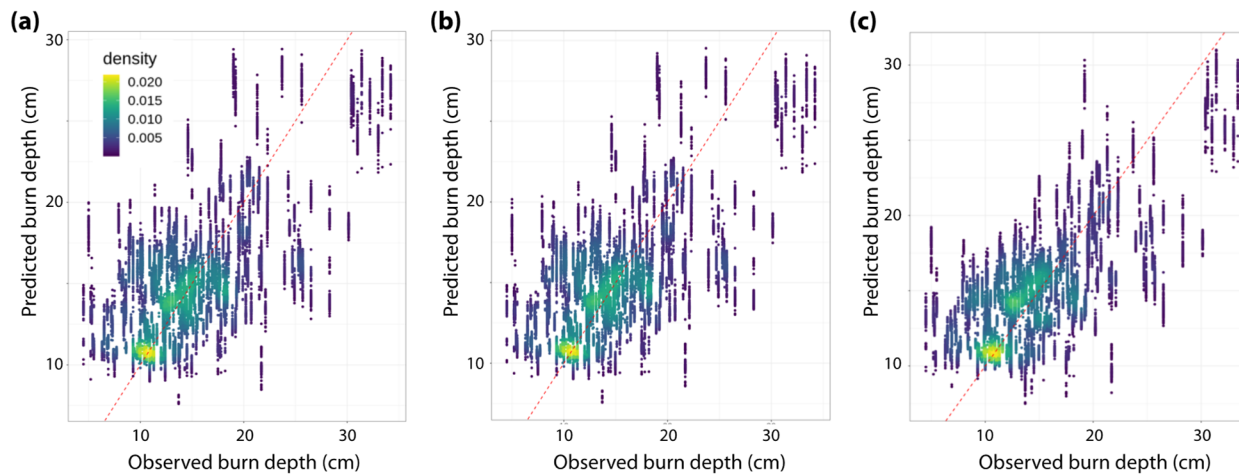
Massey, R., Rogers, B. M., Berner, L. T., Cooperdock, S., Mack, M. M., Walker, X. J. & Goetz, S. J. (in revision). *Changes in forest composition and associated biophysical climate feedbacks across boreal North America*. Nature Climate Change. A preprint is available here: [www.researchsquare.com/article/rs-1209150/v1](http://www.researchsquare.com/article/rs-1209150/v1)

#### 5.4 Burn Extent and Severity Mapping and Associated Post-fire Succession

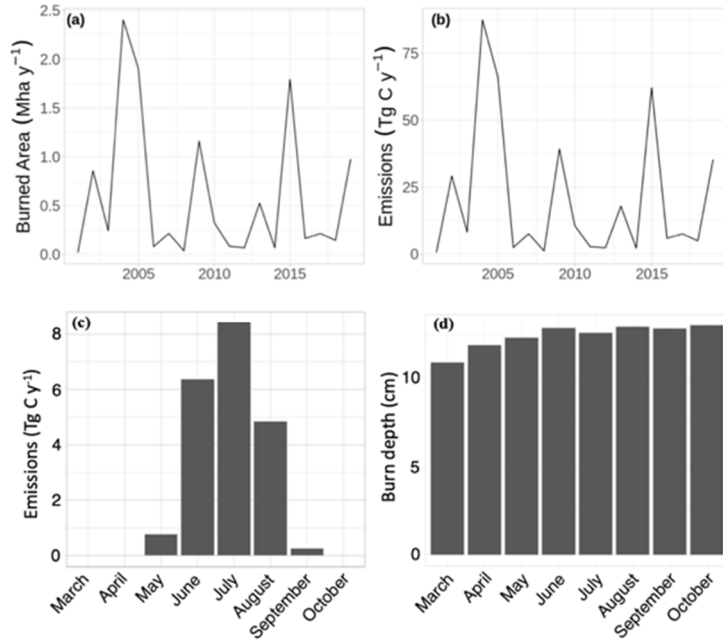
Across the suite of statistical models employed, a ranger random forest performed best for our aboveground combustion, belowground combustion, and burn depth models, with median cross-validated  $r^2$  values of 0.46, 0.25, and 0.53, respectively. Our retrospective burn depth modeling resulted in smaller but still acceptable  $r^2$  values ( $\sim 0.4$ ) for fires in the historical record (pre-2001). Models trained exclusively on Alaska sites performed slightly better than models trained on data from the entire domain (Alaska and western Canada), indicating that regional relationships in burn depth dynamics are important. Importantly, models for each fire epoch were able to estimate the full range of burn depth values in an unbiased fashion (Figure 13).

**Table 2.** Median cross-validated  $r^2$  for models of burn depth as a function of spatial domain used for training sites and fire epoch. Note that all validation was performed using burned sites in Alaska.

Fire epoch	Alaska domain	Alaska and Canada domain
Old (1940 – 1980)	0.40	0.39
Intermediate (1980 – 2000)	0.40	0.39
Recent (2000 – present)	0.50	0.48

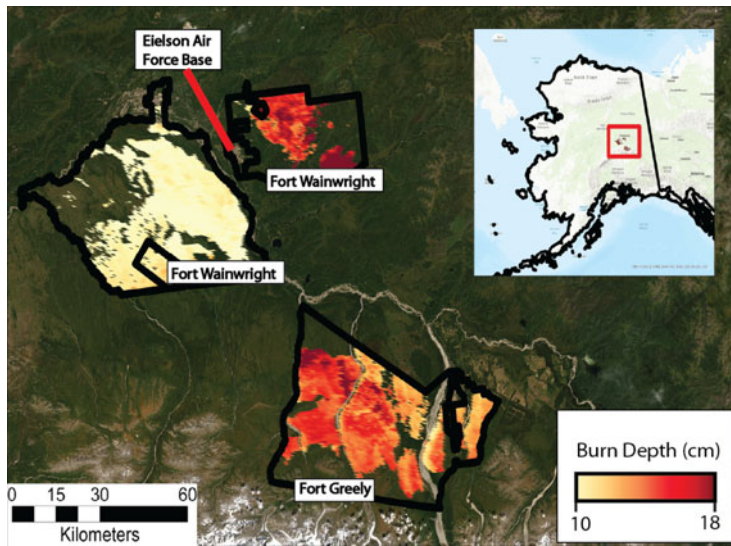


**Figure 13.** Density plots of predicted vs. observed burn depth from 100 10-fold cross validation comparisons using predictor variables relevant for (a) old fires (1940 – 1980), (b) intermediate fires (1980 – 2000), and (c) recent fires (2000 – present).



**Figure 14.** Burned area, emissions, and burn depth annual and seasonal time series across Alaska from 2001 - 2019.

Major fire years and carbon emissions were observed in Alaska during 2004, 2005 and 2015 (Figure 14). Emissions peaked in July, although mean burn depth steadily increased across the fire season. Across the time series, Alaska averaged 0.59 Mha  $y^{-1}$  of burned area, 20.7 Tg C  $y^{-1}$  of wildfire carbon emissions, 12.5 cm burn depth, and 3.44 kg C  $m^{-2}$  combusted. Although fires were common across DoD installations in interior Alaska, depth of burn varied considerably within and among fire events (Figure 15).

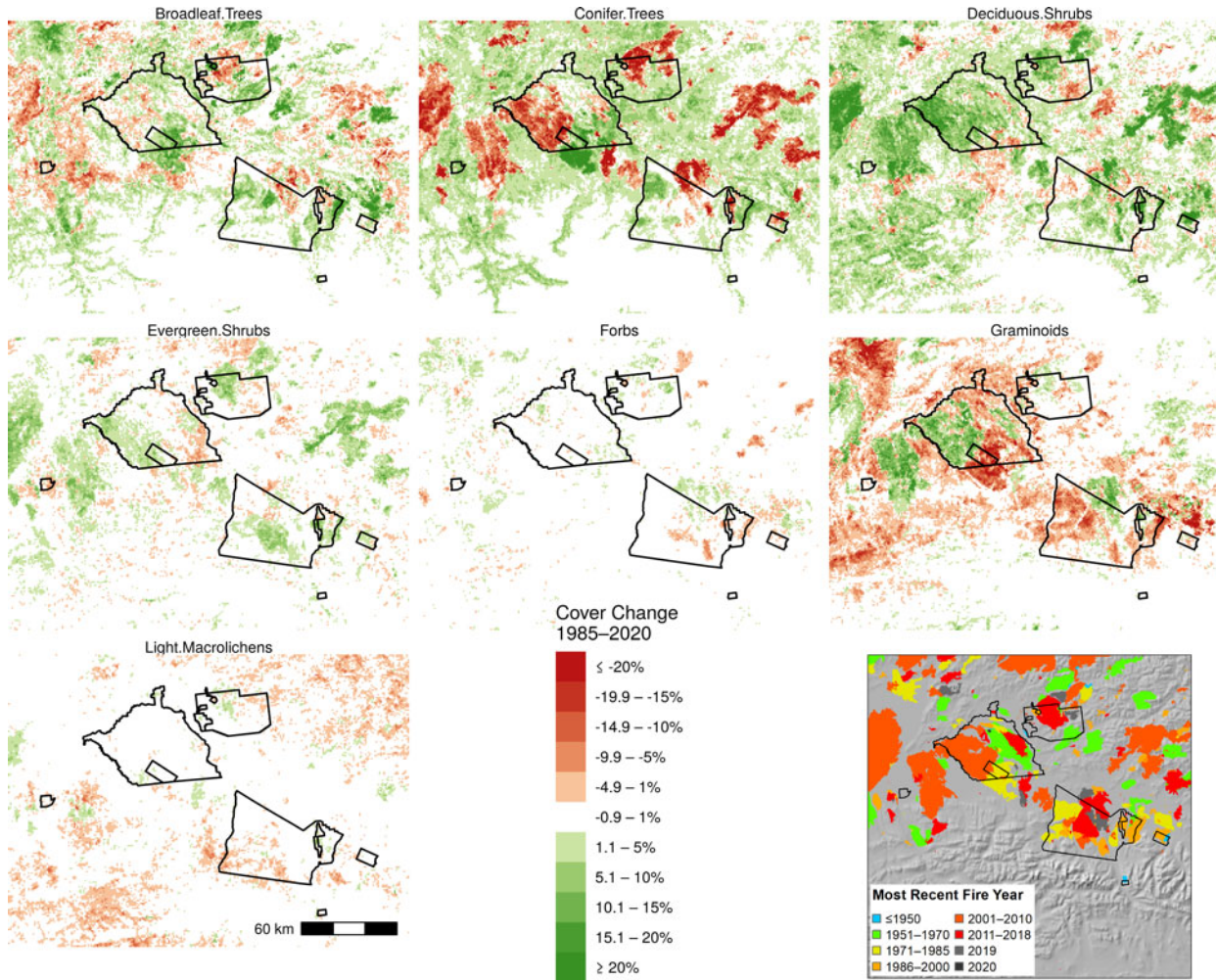


**Figure 15.** Modeled burn depth for fires in interior Alaska DoD installations since 1950.

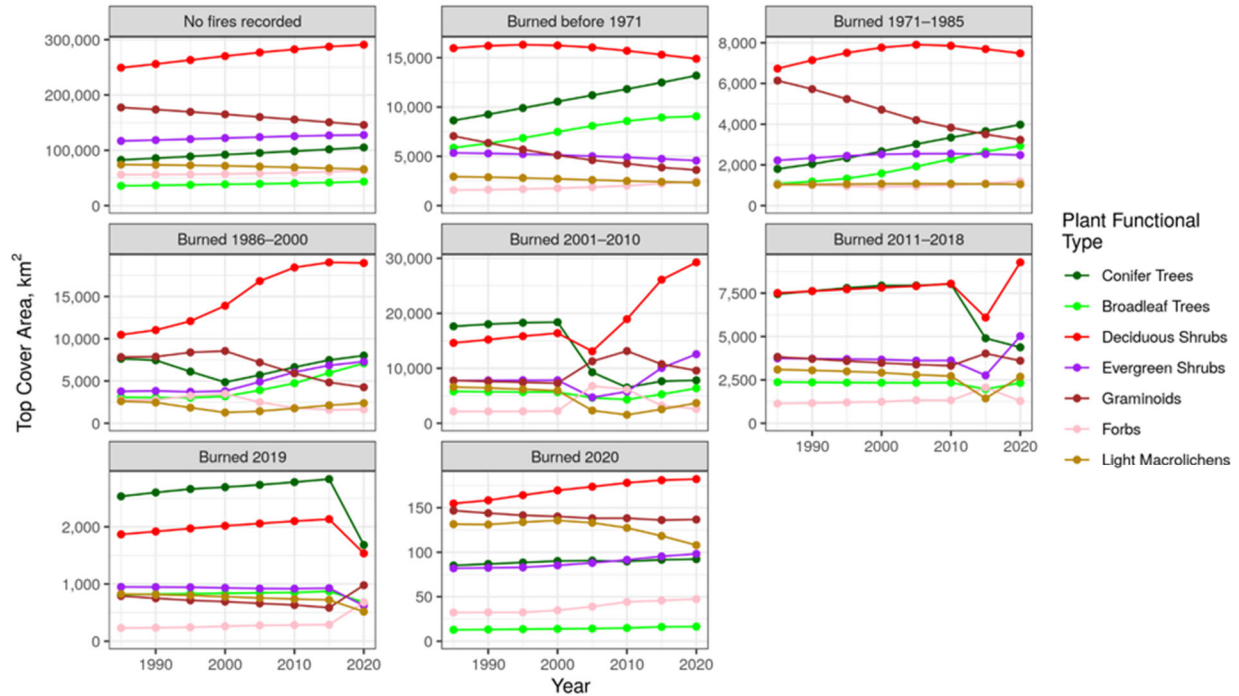
In addition to these novel results, the Landsat CCDC modeled reflectance has proven to be a reliable source of post-snowmelt / pre-greenup reflectance at landscape to regional scales, and thus a valuable data source for consistently mapping landcover change and trajectories of plant functional type change related postfire vegetation succession (as described in the previous section and more below). The UAS imagery, covering 10s to 100s of ha, also proved valuable for linking the field measurements of vegetation composition to the satellite imagery, as has high-resolution WorldView-2 and WorldView-3 pre- and post-fire satellite imagery.

Moreover, the development of the pre-fire vegetation land cover (Figure 9), the deciduous fraction maps (Figure 10) and the plant functional type change maps (Figures 11-12) allowed us to characterize vegetation succession from fires in the historical record (Figures 16-17). Our analyses show that across years, deciduous fraction is higher in areas that were dominated by deciduous trees before the fire, which is consistent with our field measurements of deciduous composition changes pre- and post-fire (Figure 6). The wide range in deciduousness at each

stage allowed us to map the areas that shifted more or less from their pre-fire conditions, and relate these patterns to burn severity, climate and landscape patterns (Macander et al. 2022a, Massey et al. in revision). Separation of the deciduous signal between broadleaf forest and deciduous shrub categories (Figures 11-12 and 16-17) allowed further discrimination of changes from pre- and post-fire conditions.



**Figure 16.** Changes in plant functional type cover (1985-2020) across DoD bases and training grounds (outlined in black) in interior Alaska. The lower right panel shows fires that occurred between 1970 and 2020. Increases in deciduous shrub cover is evident across the interior. Broadleaf and evergreen conifer tree cover also show substantial changes, although the direction of change depends on the time since fire, with initial increases in deciduous cover followed by increasing conifer cover over time.



**Figure 17.** Plant functional type weighted area per fire history class at 5-year intervals.

### Publications:

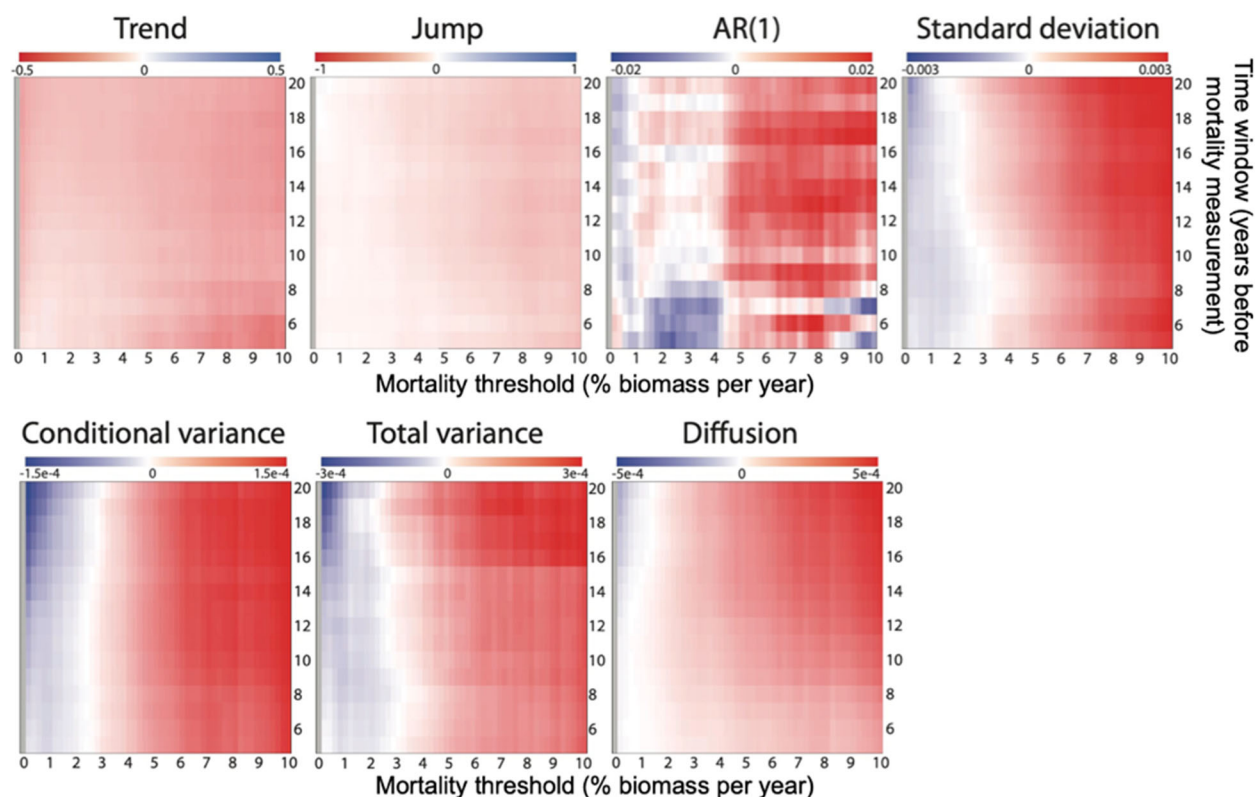
Potter, S., Cooperdock, S., Walker, X. J., Veraverbeke, S., Mack, M. C., Goetz, S. J., Baltzer, J. L., Bourgeau-Chavez, L., Burrell, A., Dieleman, C. M., French, N., Hoy, E. E., Jenkins, L., Johnstone, J. F., Kane, E. S., Natali, S., Randerson, J. T., Turetsky, M. R., Whitman, E., Wiggins, E., and Rogers, B. M. (2022). *Burned area and carbon emissions across northwestern boreal North America from 2001 - 2019*, Biogeosciences. Available at [www.biogeosciences.net](http://www.biogeosciences.net)

Potter, S., Solvik, K., Erb, A., Goetz, S.J., Johnstone, J.F., Mack, M.C., Randerson, J.T., Román, M.O., Schaaf, C.L., Turetsky, M.R., Veraverbeke, S., Walker, X.J., Wang, Z., Massey, R., Rogers, B.M. (2020). *Climate change decreases the cooling effect from post-fire albedo in boreal North America*. *Global Change Biology* 26:1592-1607. doi.org/10.1111/gcb.14888

Rogers, B., Balch, J.K., Goetz, S.J., Lehmann, C.E.R., Turetsky, M. (2020). *Focus on changing fire regimes: Interactions with climate, ecosystems, and society*. *Environmental Research Letters*, 15:030201. doi/10.1088/1748-9326/ab6d3a

### 5.5 Productivity trends & precursors of mortality (“early warning signals”)

In order to address our working hypothesis that early warning signals (EWS) of tree mortality in boreal forests of interior Alaska and Canada are detectable using long-term satellite-based NDVI, we assessed the strength of relationships between tree mortality derived from our comprehensive PSP database and EWS metrics derived from Landsat, MODIS, and AVHRR NDVI time series. Results confirmed the relationships shown in Rogers et al. (2018), but generally with stronger correlations and patterns due to the order of magnitude larger sample size of PSPs (Figure 18). Because 30 m Landsat data can be directly related to site-level information,



**Figure 18.** Heat maps showing the differences in NDVI metrics between mortality and control sites at rolling time windows of 1-5 to 1-20 years before inventory measurement and mortality thresholds varying from 0-10 percent of biomass per year. For trend and jump metrics, red colors represent where sites with tree mortality above the mortality threshold exhibited more negative mean values than control sites. For EWS metrics (AR(1), standard deviation, conditional variance, total variance, and diffusion), red colors represent conditions where sites with tree mortality above the mortality threshold exhibited greater metric values than control sites. Blue colors represent the opposite. In each case, red represents a likely detection of an early warning signal of mortality.

products are generated at a spatial resolution commensurate with management decisions, and Landsat-based EWS metrics consistently displayed stronger relationships with tree mortality compared to MODIS and AVHRR, we decided to use only Landsat-derived EWS metrics for the predictive models in Objective 3.

These results are consistent with our related analyses of temporal changes in vegetation productivity derived from time series of Landsat imagery over the past few decades (Berner et al. 2022). Those results show boreal forest areas with declining productivity (based on spectral vegetation indices) primarily occurred in the climatically warmest margins of both the boreal forest biome and major forest types (e.g., evergreen conifer forests), especially in densely treed areas where summers became warmer and drier.

Publications:

Berner, L. T. & Goetz, S. J. (2022). *Satellite observations document trends consistent with a boreal forest biome shift*. *Global Change Biology*. 32: 3275–3292, doi.org/10.1111/gcb.16121

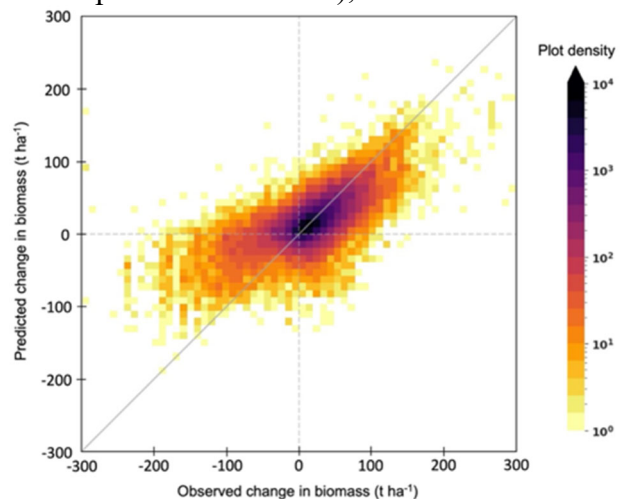
### Objective 3: Predictive modeling of vegetation change

#### 6.1 Spatial Statistical / Machine Learning Models

Our original attempts to predict tree mortality within 5-10-year windows using NDVI time series from preceding years and decades were largely unsuccessful (cross-validated  $r^2 \sim 0.1$ ), or at least not robust enough for extrapolation and implementation at DoD installations. Although we were able to clearly detect early warning signals of mortality in these NDVI time series, there was high variance and overlapping distributions of EWS metrics between plots with high and low mortality, despite significant differences in the means. Adding to this, the 5-10-year re-measurement interval in the PSP plots introduced uncertainty as to the timing of mortality and dampened mortality signals (due to the need to average across many years). This phenomenon is highlighted by the fact that our models performed substantially better ( $r^2 = 0.38$ ) when implemented on the CIPHA data set, which is a relatively small PSP database (75 sites) but one of the few with annual re-measurements.

We therefore adjusted our modeling framework to predict changes in net forest aboveground biomass (AGB), which includes mortality as well as recruitment and growth, and resulted in much-improved model performance. Our 10-member model ensemble was able to predict changes in biomass with an ensemble  $r^2$  of 0.46 in the fully-withheld test sets, and, importantly, was able to predict the direction of change (increases or decreases in biomass) correctly 82% of the time (Figure 19). Our feature selection approach reduced an initial 2301 variables to between 44 and 74 without any loss in model performance. We also note that similar models allowed to train on portions of a given site's observation time series (but not the portion being withheld for cross-validation) performed better with an  $r^2$  of 0.62. This indicates improved performance if our models are being applied to sites with repeat measurements available for training.

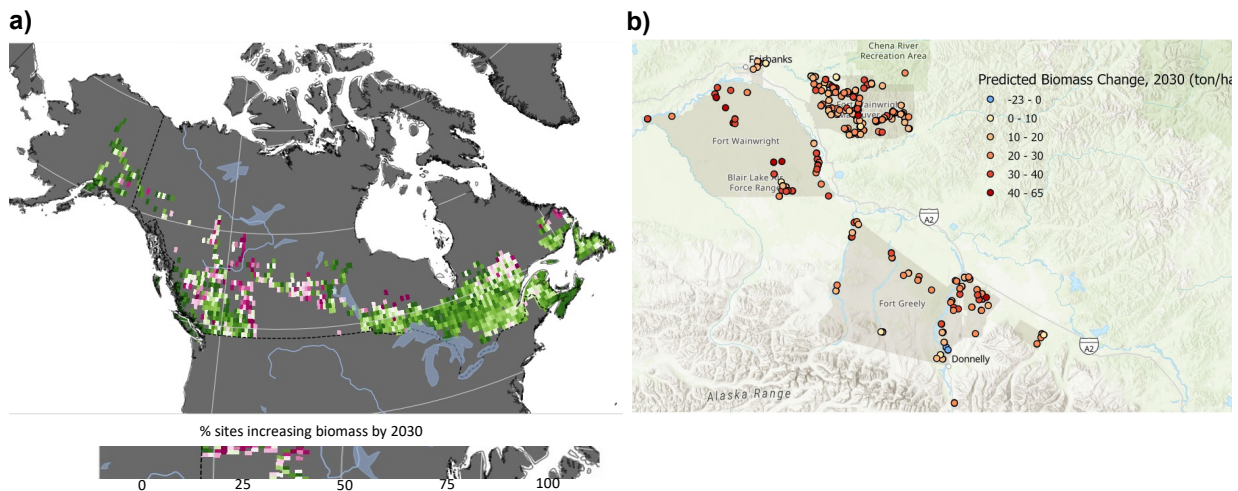
Initial biomass at the beginning of a prediction window was the most important predictor variable, followed by observation gap (the length of the prediction window), and initial stem density. Initial biomass was negatively correlated with  $\Delta\text{AGB}$ , whereas both the observation gap and the initial stem density showed strong positive correlations. These findings are in line with expectations, as younger forests accrue biomass more quickly than mature forests, the larger intervals allow for more biomass gain. The most important species variable was the dominance of black spruce, which showed a negative correlation with  $\Delta\text{AGB}$ . The most important climate variable was the temperature difference between the hottest and coldest month, where smaller temperature differences ( $<30^\circ\text{C}$ ) had a positive influence on biomass gain and larger temperature differences ( $>30^\circ\text{C}$ ) had a negative effect. When considered as groups,



**Figure 19.** Density plot of model performance based on the multi-model ensemble and fully-withheld inventory sites.

forest inventory variables had a mean permutation importance of 0.85, followed by climate (0.28), species (0.11), remotely-sensed vegetation metrics and early warning signals (0.10; although these were particularly important for capturing mortality, or negative changes in biomass), soli properties (0.03), and finally permafrost-related variables (0.0001).

When predicting into the future across boreal North America, biomass increases were predicted at 77% of sites by 2030 (Figure 20a). The most consistent losses are predicted for sites in the southern boreal regions of Alberta, Saskatchewan, and British Columbia. However, even in regions with a majority fraction of sites predicted to increase in biomass, there are sites with predicted losses. We also applied this 10-member ensemble to the 277 DoD inventory sites across interior Alaska installations (Figure 20b). These sites had a mean initial AGB of 38.7 t ha<sup>-1</sup> and our models predicted variable responses in AGB changes 2030; roughly 95% of inventory sites are expected to continue to gain biomass by 2030, and the remaining are exhibiting signals associated with near-term tree mortality and biomass losses. These predictions are being handed off to DoD managers via a short summary, and we continue to develop a Google Earth Engine application to view results. We note that our models are not designed to predict forest losses resulting from disturbances such as wildfire or pest outbreaks.



**Figure 20.** Predicted changes in forest biomass by 2030 at PSP sites across boreal North America (a; aggregated into 1° grid cells) and at DoD installations within Alaska (b).

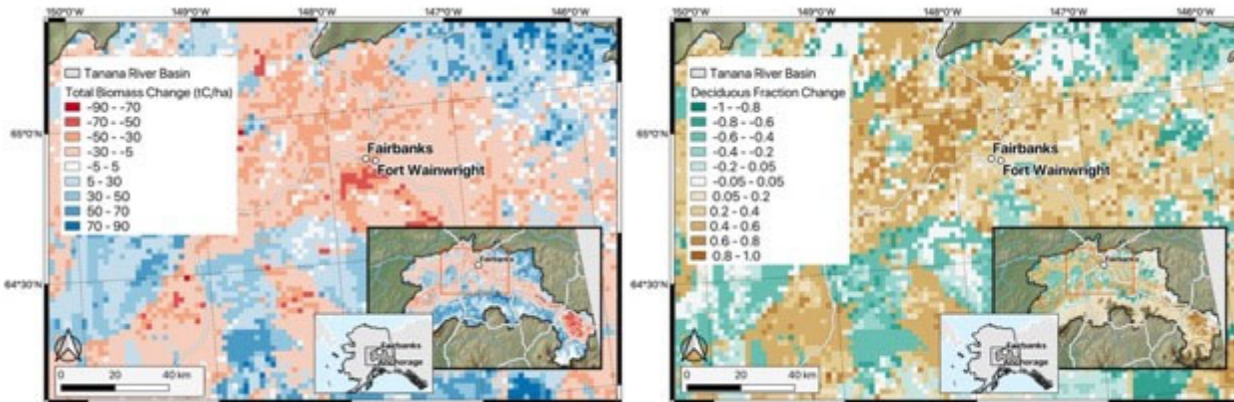
Publications:

Burrell, A., Cooperdock, S., Goetz, S. J., Berner, L. T., Foster, A., Hember, R. A., Mack, M. C., Massey, R., Walker, X. J., and Rogers, B. M., *The predictability of near-term forest biomass changes in boreal North America*, *Global Change Biology* (in review).

*6.2 Process-based Forest Demography Modeling*

Following validation, climate change simulations were conducted across the entire Alaskan Yukon River basin (at 2 km cell resolution) using output from a CMIP 5 5-model average for the RCP 8.5 scenario (Leonawicz et al., 2015). Results indicate the potential for changing biomass and species composition under increasing temperatures and increasing precipitation (Figure 21),

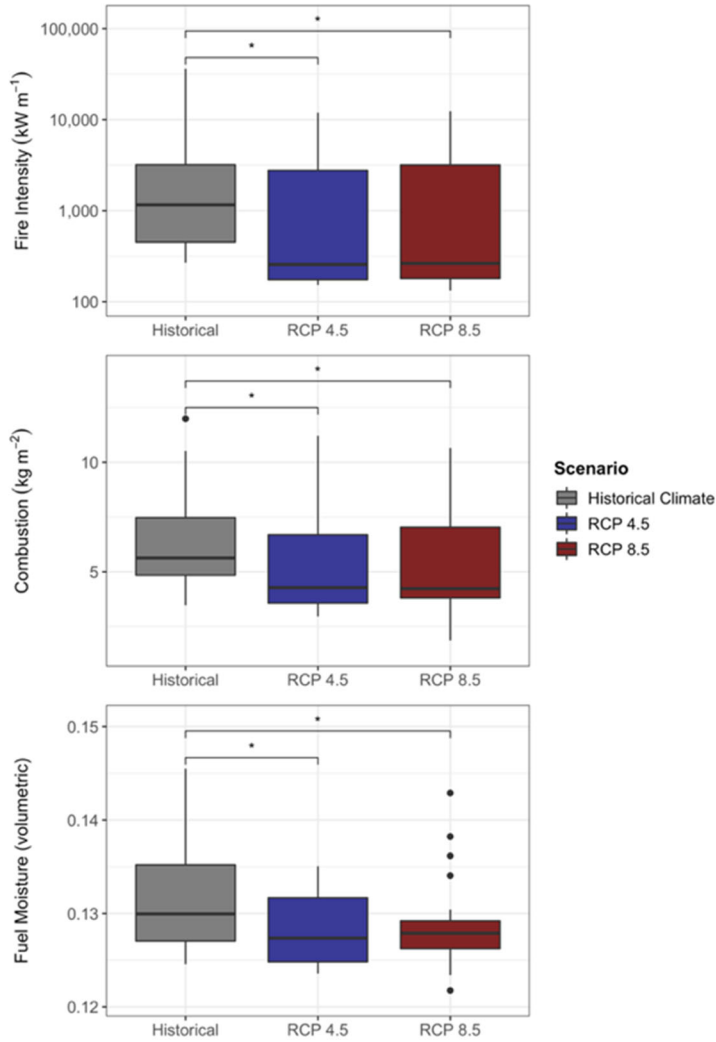
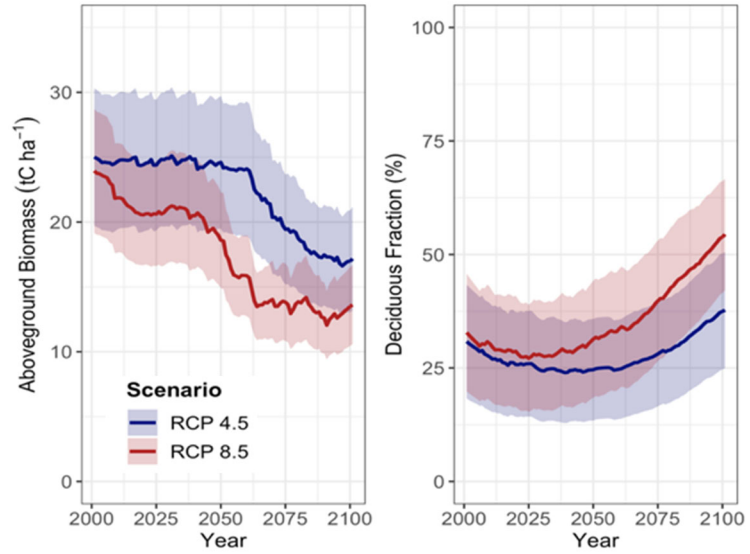
with some areas of black spruce dominance shifting to white spruce dominance, and other areas of white spruce dominance shifting to deciduous dominance. Increases in deciduous dominance were highest in areas with large increases in atmospheric aridity and large decreases in soil moisture, highlighting the importance of accurate portrayal of drought response across varying tree species and ages. In particular, the relative effects of atmospheric demand and soil moisture on plant moisture stress is of key importance for future predictions.



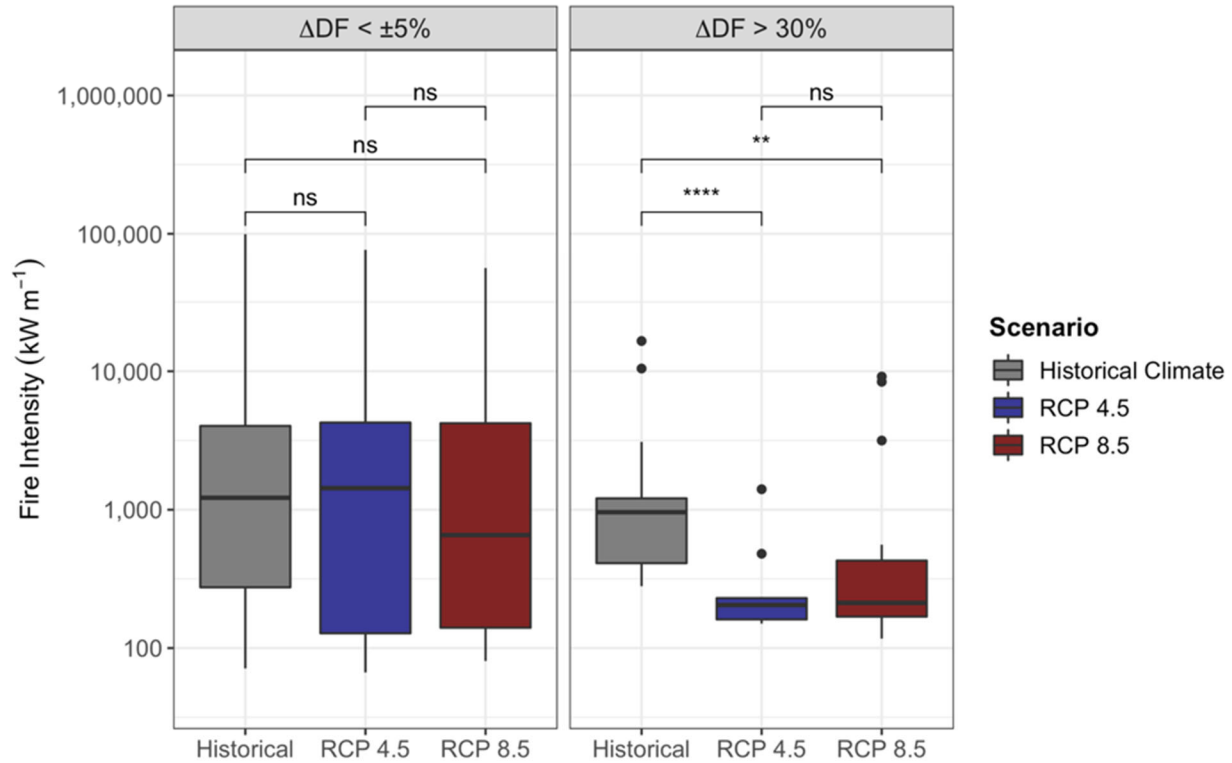
**Figure 21.** UVAFME output on total biomass difference ( $\text{tC ha}^{-1}$ ) (left) and deciduous fraction ( $0 - 1$ ) difference (right) within the vicinity of Fairbanks as well as across the Tanana Valley at 2 km grid cell resolution between pre- and post-climate change conditions for the RCP 8.5 climate change scenario.

We additionally applied the model at sites in interior Alaska to investigate potential future fire regimes given the predicted trajectories in biomass and deciduous fraction, which are likely to feed back to impacts on forest fuels (Krawchuk et al., 2006). We performed a climate change application to predict how forest biomass, species composition, and fire regimes (e.g. intensity, probability, and flammability) may shift under changing climate. These results indicate the importance of dynamic vegetation and fuels when predicting future forest and wildfire conditions. Simulated vegetation response to shifting climate differed based on physiographic condition, with drier sites showing overall decreases in biomass, and wetter sites showing overall increases in biomass with climate change (Figure 22), as in our simulations across all of interior Alaska (Figure 21). A similar pattern is seen with changing fire intensity across different physiographic conditions: drier sites, which also tended to have a higher deciduous fraction and greater decreases in biomass (Figure 23), had lower fire intensity with climate change as compared to wetter sites (Figures 24). This decline in fire intensity was strongest at sites where deciduous fraction increase was greatest, indicating that while fuel drying may be important, and did occur at these sites, the bottom-up, negative feedback on fuel loading and geometry outweighed the increasing flammability from drying fuels and increased lightning strike frequency.

**Figure 22.** Model-simulated average aboveground biomass and deciduous fraction for an RCP 4.5 and RCP 8.5 scenario for 23 sites within interior Alaska. Shaded regions show 95% confidence intervals.

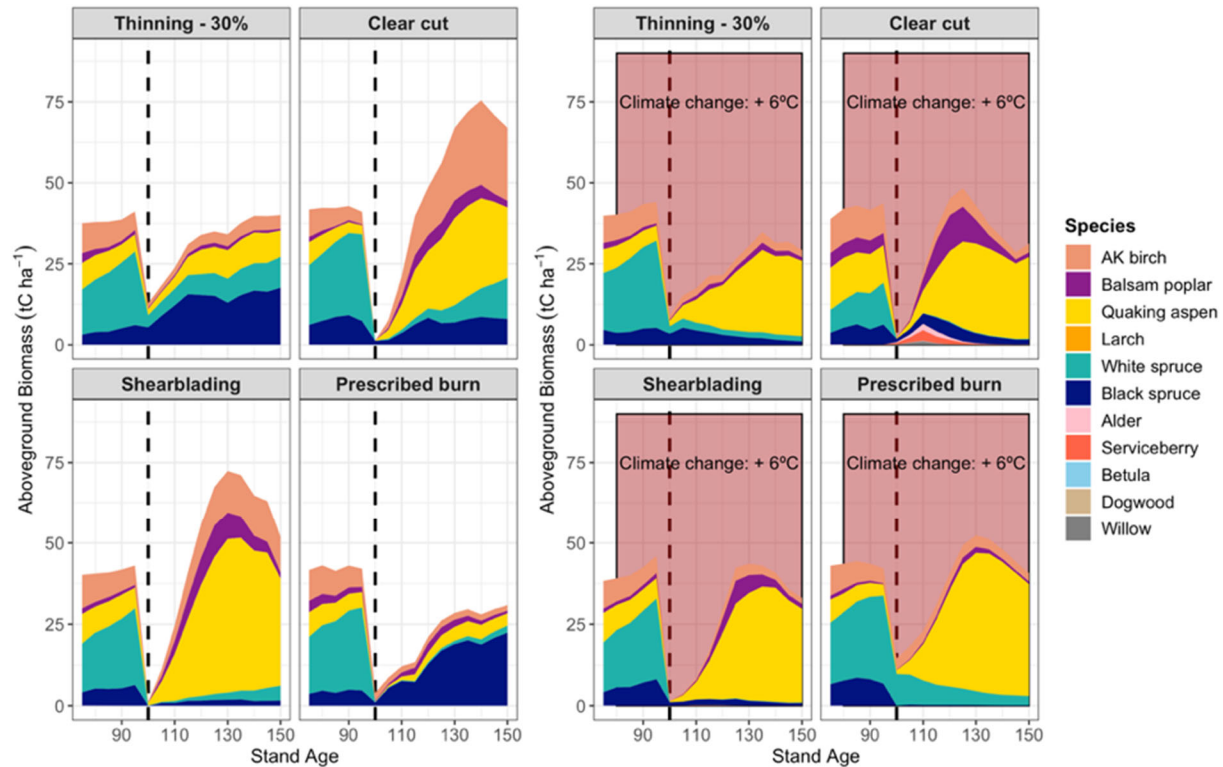


**Figure 23.** Model-simulated distributions of fire intensity ( $\text{kW m}^{-1}$ ), combustion ( $\text{kg m}^{-2}$ ), and fuel moisture (volumetric) for 23 sites in interior Alaska for historical, RCP 4.5, and RCP 8.5 climate scenarios for years 2006 through 2100. Asterisks denote significance level of Kruskal-Wallis tests (ns:  $p > 0.05$ ; \*:  $p \leq 0.05$ ). Note the log-10 scale for fire intensity.



**Figure 24.** Model-simulated distributions of fire intensity ( $\text{kW m}^{-1}$ ), combustion ( $\text{kg m}^{-2}$ ), and fuel moisture (volumetric) for simulated sites that had a greater than 50% increase in deciduous fraction (right) and for sites that had little deciduous fraction change (left) for historical, RCP 4.5, and RCP 8.5 climate scenarios for years 2006 through 2100. Asterisks denote significance level of Kruskal-Wallis tests (ns:  $p > 0.05$ ; \*:  $p \leq 0.05$ ). Note the log-10 scale for fire intensity.

Finally, we simulated various management treatments at forest stands within the DoD training areas (e.g. Fort Wainwright) under historical and future climate conditions to determine the impact on these treatments and how the forest response to treatments may change in the future (Figure 25). We found the treatment type and parameters were a strong driver of post-treatment species composition and biomass, with shearblading causing a higher post-treatment deciduous fraction than thinning, clear cutting, or prescribed burns. However, these effects were modified under scenarios of increasing temperature, with a failure of black spruce regeneration following a prescribed burn under a  $6^{\circ}\text{C}$  increase in temperature.



**Figure 25.** Model-simulated species-specific aboveground biomass for a site near Ft. Wainwright, Alaska, showing the impact of several different treatments (conducted at stand age 100, dashed line) under current climate conditions (left) and future climate conditions (right).

Our findings further understanding of vegetation-climate-wildfire interactions as well as how different management and fuels treatments will interact with changing climate, vegetation, and wildfire regimes. They provide a powerful means to assess how interacting effects of climate, fire intensity and burn severity can be incorporated into fuels management and likely future trajectories of vegetation composition.

#### Publications:

Foster, A.C., Shuman, J.K., Rogers, B.M., Walker, X.J., Mack, M.C., Bourgeau-Chavez, L.L., Veraverbeke, S., & Goetz, S.J. (2022). *Bottom-up drivers of future fire regimes in western boreal North America*. Environmental Research Letters, 17, 025006. doi.org/10.1088/1748-9326/ac4c1e.

Foster, A. C., Armstrong, A. H., Shuman, J. K., Shugart, H. H., Rogers, B. M., Mack, M. C., Goetz, S. J., Ranson, K. J. (2019). *Importance of tree- and species-level interactions with wild fire, climate, and soils in interior Alaska : Implications for forest change under a warming climate*. Ecological Modelling, 409:108765. doi.org/10.1016/j.ecolmodel.2019.108765

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

Raiho, A.M., Nicklen, E.F., Foster, A.C., Roland, C.A., & Hooten, M.B. (2021). *Bridging implementation gaps to connect large ecological datasets and complex models*. *Ecology and Evolution*, 11(24), 18271-18287. doi.org/10.1002/ece3.8420.

Shugart, H. H., Foster, A. C., Wang, B., Druckenbrod, D., Ma, J., Lerdau, M., Saatchi, S., Yang, X., & Yan, X. (2020). *Gap models across micro- to mega-scales of time and space: Examples of Tansley's ecosystem concept*. *Forest Ecosystems*, 7(14). doi.org/10.1186/s40663-020-00225-4

#### **Objective 4: Implementation of outcomes with resource managers**

As noted earlier (section 2.3) this objective is focused on transferring the geospatial methodologies, analysis tools and derived data products to resource managers within DoD as well as other state, provincial and federal agencies. This was done (and continues to be done) through a combination of workshops and webinars, all available on the Alaska Fire Science Consortium website ([www.frames.gov/afsc](http://www.frames.gov/afsc)) which is hosted the Fire Research and Management Exchange System ([www.frames.gov](http://www.frames.gov)). AFSC also hosts relevant reports, presentations and publications in a searchable [reference database](#) on their website, and hosts [recordings](#) of science talks from the workshops. By informing and working with managers we anticipate increased likelihood that the science will be incorporated into future strategies and mitigation planning.

In the very first week of our project (July 2018), even before contracts were in place, several of our project team visited Fort Wainwright to meet with the base Natural Resources Coordinator (Dan Rees) and some of his colleagues (Natural Resource Planning Branch Chief Matt Sprau and Training Area coordinator Josh Buzby). Six members of our group took advantage of the fact they were already in Alaska to visit some of field sites where Dan and his colleagues are working, including one of three experiment/demonstration areas for different forest thinning treatments. We discussed field measurement protocols and also reviewed a presentation of what the project is about. Since we had provided the overview as part of the post-selection coordination activities they had already reviewed it before the visit. Much of the conversation centered around active vegetation management, whether it be shearblading, thinning, hydro-axing, etc. Their interest in changing vegetation successional trajectories relates primarily to encouraging landscapes that require less maintenance while maintaining training value or firebreak quality (e.g. stopping or delaying spruce recruitment in firebreaks). Some of the discussion about thinning treatments related to tradeoffs that effectively reduce fire spread (e.g. reducing fuel loads also opens sites up to more sun and drying).

Additional field visits took place on following days, including to intensive insect management stands, recently burned sites, and more typical boreal forest vegetation types. The base resource managers were interested in intensive treatments of small but high-value spruce stands that are important for cover and concealment in training. In this context we also discussed use of drones to augment field sampling both on and off military lands to inform the objectives linking field plots to landscape scale forest habitat mapping and change assessments. Since that initial contact we have had several in person and virtual (telecon) meetings with these and a broader array of resource managers to which our project is highly relevant.

In March 2020, we provided a update via a Zoom video conference, which was recorded and is available here: [vimeo.com/403815862/3f7869fc08](https://vimeo.com/403815862/3f7869fc08).

Discussion topics at these meetings included:

- exploring the use of different platforms for displaying and summarizing remotely sensed data on forest composition changes;
- evidence for vegetation change related to fire history, including decreasing overall forest cover and increasing deciduous forest, shrublands, fens, and sparse vegetation in the area of interest;
- advances in modeling species composition and flammability following fuels treatments (managers noted that results largely coincide with their anecdotal experience);
- appropriate metrics for evaluating flammability following fuels treatments;
- modeling various types of fuel treatments to evaluate cost-effectiveness, longevity, and effects on permafrost;
- ways to make models easily accessible for management use;
- management utility of vulnerability assessment tools.

In addition to the land managers listed in the acknowledgements section at the beginning of this report, the following project team members participated:

Project Researchers:

Melissa Boyd (Research Staff, Northern Arizona University)  
Arden Burrell (Postdoctoral Research, Woods Hole Research Center)  
Adrianna Foster (Postdoctoral Research, Northern Arizona University)  
Scott Goetz (Professor, Northern Arizona University)  
Matt Macander (Senior Scientist, ABR Inc.)  
Michelle Mack (Professor, Northern Arizona University)  
Richard Massey (Postdoctoral Research, Northern Arizona University)  
Kyoko Okano (PhD student, Northern Arizona University)  
Brendan Rogers (Associate Scientist, Woods Hole Research Center)  
Xanthe Walker (Senior Research Associate, Northern Arizona University)

Alaska Fire Science Consortium (AFSC @ UAF):

Zav Grabinski (Science Communication Specialist)  
Randi Jandt (Fire Ecologist)  
Alison York (Coordinator)

The managers were most interested in our work related to fuel treatments and resulting fire danger. We discussed results from Mack's RC 2754 field study of fuel reduction management treatments and the results of that and our RC18-1183 project with respect to their application for understanding future forest composition. Land managers were enthusiastic about applying lessons learned from fieldwork to the predictive modeling of vegetation change (described above, and more below) to generate longer time-scale predictions of forest composition in fuel manipulations.

These discussion topics were also shared and discussed with land managers from agencies such as the US Fish and Wildlife Service, National Park Service, and Alaska Department of Fish and Game who are and have been involved in implementing fuel reduction treatments in Alaska. There was also particular interest in the relevance of our project related to post-fire vegetation composition changes, which strongly influences flammability, and our modeled changes in forest biomass, which impacts fuel loads. Based on these discussions, we worked with the project team and relevant managers to discuss development of additional products and outreach mechanisms.

In March 2021 project members Scott Goetz and Adrianna Foster presented results from the project at the Alaska Fire Science Consortium Spring Fire Science Workshop, convened online in association with the Alaska Interagency Spring Fire Management Operations meeting. The workshop had 157 participants from at least 18 agencies involved in wildland fire management issues in Alaska, including US Forest Service, Bureau of Land Management, National Park Service, US Fish and Wildlife Service, Bureau of Indian Affairs, US Geological Survey, NASA, Alaska Division of Forestry, Alaska Department of Fish and Game, Alaska Department of Environmental Conservation, municipal emergency managers, tribal non-profits, and universities. The presentation, titled *Past, Present and Future Boreal Forest Responses to Climate and Fire Disturbance across Interior Alaska*, was recorded and is available along with links to other presentations, the workshop agenda, background information, and related literature at the following website: [www.frames.gov/event/573652](http://www.frames.gov/event/573652).

In April 2021 project members Michelle Mack and Melissa Boyd presented the results of the fuel reduction treatment field campaign at the Alaska Society of American Foresters (AKSAF) annual meeting. Also in April 2021, project members Michelle Mack and Brendan Rogers presented their results in an online workshop focused on fire management at the Yukon Flats National Wildlife Refuge, and interacted with a variety of managers interested in our project. Their presentations, in a session about carbon emissions, vegetation conversion, and using fire management to keep permafrost protected and carbon in the ground was organized by the Alaska Fire Science Consortium (Zav Grabinski, Randi Jandt, Alison York) and Northern Latitudes Partnership in partnership with U.S. Fish and Wildlife Service. The workshop, entitled *Improving Wildfire Management Decision-making for the Yukon Flats National Wildlife Refuge*, focused on a specific permafrost-rich landscape that also experiences an active fire regime, and brought together a total of 46 participants (researchers, managers, tribal members, and adjacent landowners) to explore new decision-making frameworks for fire management based on the best available science. The vision of the workshop was to increase persistence and resilience of desired habitats, while considering integrated impacts on local communities.

The workshop had four primary goals:

1. gain a better understanding of how wildland fire affects refuge landscapes, wildlife habitat, and carbon dynamics;
2. understand how wildfire emissions affect human health and investigate potential mitigations;
3. understand if, and how, current fire management approaches and tools might be used to address concerns about the effects of fire on habitat, permafrost, carbon dynamics, and human health: and

4. using what we know about wildland fire in the boreal forest, climate change, and the availability of current tools, proceed with fire management planning and engaging with others over the next few years.

All materials for the workshop, including links to the presentations, the workshop agenda, background information, and literature can be found here: [www.frames.gov/event/574183](http://www.frames.gov/event/574183).

In October 2021 project members from the Alaska Fire Science Consortium highlighted findings from our project before the Alaska Interagency Fall Fire Review, attended virtually by over 100 representatives and practitioners from state, federal and tribal management fire and land management agencies across the state.

In March 2022 project members from the Alaska Fire Science Consortium highlighted findings at from our project (along with related research) at the Spring Fire Operations meeting, again attended virtually by over 100 representatives and practitioners representing state, federal and tribal fire and land management agencies across the state. Research findings and related management implications were summarized and reinforced with a [bullet-list style handout](#) for attendees. The documented changes in forest composition and striking transformation occurring in permafrost across the region were received with great interest and generated many questions, along with requests for publications and data (particularly Macander et al. 2022a,c).

Also in March 2022 project member Matt Macander presented findings on changes in plant functional types across Alaska, based on core research from this project, to the Interagency Arctic Research Policy Committee group. This [webinar](#), hosted by University of Alaska-Fairbanks ACCAP, was well attended (with representation from several Alaska organizations as well as international arctic participation) and considerable interest was expressed in the work and ways to expand inferences to particular management units.

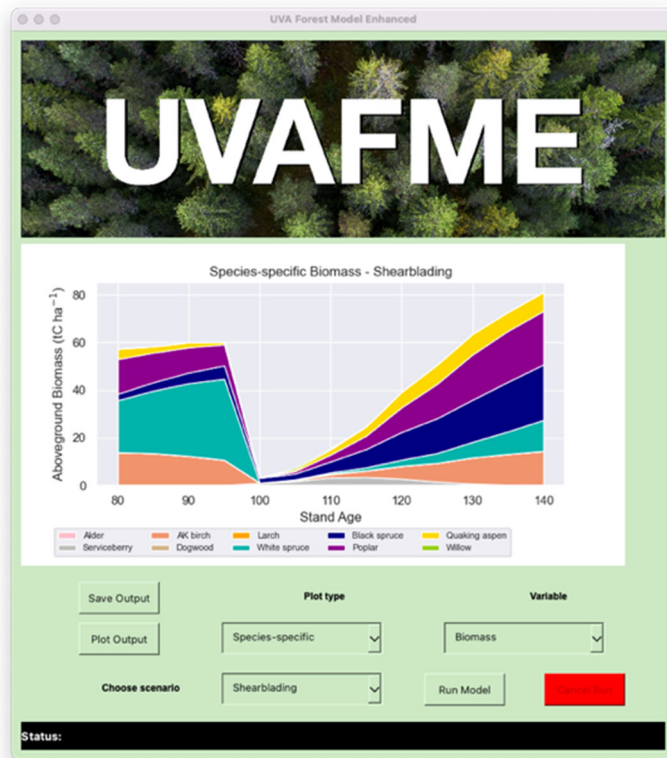
After some postponements due to the Covid pandemic we resumed in-person / hybrid meetings with a “research to operations” (RTO) workshop on 12-13 May 2022 (led by the AK Fire Science Consortium project members York & Jandt) in conjunction with the 8<sup>th</sup> NASA ABoVE Science Team meeting (led by project PI Goetz). We gathered leadership from Alaska state and federal agencies to discuss new science findings and how best to apply them in fire and land management. At this workshop managers connected directly with scientists in breakout sessions, expressed their problems and discussed barriers to operational application of new science. Over 50 people attended each day and written proceedings are in process. As a result of the meetings managers realized that mapping products of permafrost and active layer distribution and condition will be key to future land management planning, including military training plans. Also, there was considerable interest and discussion of the land cover change identified in the study. Project team member Macander again highlighted our plant functional type data products as new sources of data for making important distinctions relevant to management decision making (e.g. identifying areas with high continuity of black spruce tree cover likely to have high fire risk). All materials for the RTO workshop, including links to the presentations, the workshop agenda, background information, and literature can be found here: [www.frames.gov/event/557648](http://www.frames.gov/event/557648). Another outcome of the workshop was a frank discussion on the barriers to applying new science findings in decision-making, particularly in a world where

managers and resource specialists from both government and non-governmental agencies feel bombarded and overwhelmed with information. Survey data (from separate AFSC projects) show that managers continue to need targeted assistance in applying new research results and tools to a particular decision context, and that scientists benefit from similar support in understanding management issues relevant to their work. The ability to focus and refine questions, and the ability to distill specific custom management implications from a plethora of scientific papers is critical, and this has been the main job of the Alaska Fire Science Consortium as a collaborator in our project. The AFSC will remain available on an ongoing basis to continue assisting managers as they incorporate and apply these findings in future.

Specific key products and outreach mechanisms that we have advanced are summarized here:

- We have developed multiple data visualization applications for managers to view, interact with, and ultimately use our products for decision making. One such application based on our 30m time series of deciduous fraction across Alaska, developed using Google Earth Engine: [masseyr44.users.earthengine.app/view/decidfractreecoverserdpv1](https://masseyr44.users.earthengine.app/view/decidfractreecoverserdpv1) This application allows users view changes in deciduous fraction, tree cover, and simultaneously view a recent high-resolution image of the area of interest. We also developed a similar capability to view plant functional type (PFT) vegetation composition via the same GEE platform: [mmacander.users.earthengine.app](https://mmacander.users.earthengine.app) and another is nearing completion to visualize the near-term gridded aboveground forest biomass predictions. Users can quickly navigate to different DoD installations in interior Alaska (via dropdown menu) or they can roam around to other areas across Alaska and Yukon, with capabilities to zoom in and out and display different types of vegetation cover. We integrated feedback from managers and anticipate these applications may be useful for decisions related to fuel treatments and flammability as assessing vegetation recovery in areas that have been managed / treated in the past.
- We continue to implement a similar capability for spatial predictions of our statistically-based predictive model of aboveground forest biomass at inventory sites across DoD installations in interior Alaska, which will also be available as a GEE App. The May 2022 RTO workshop did not have the DoD base managers we've been working with available and in attendance (it was in in-person only meeting) so we will follow up via a Fall 2022 webinar to further describe the results and discuss potential use for predicting changes in forest biomass / fuels post-treatment.
- We also implemented relevant management treatment scenarios in our UVAFME modeling and have developed a visualization and analysis web application with a graphical user interface (GUI) for managers to interact with in testing various scenarios for their planning and management efforts. We have implemented fuels management schemes, such as thinning and shearblading, into the forest modeling scenarios (Figure 25). These allow managers to test potential outcomes of various fuels treatments and their impacts on future stand composition, soil and fuel characteristics, and flammability. To facilitate manager's use of this deliverable, we have GUI that runs the UVAFME model on any operating system (Figure 26). Managers are able to choose locations to run, different scenarios and input variables, and select other options from dropdown menus. They can then view output graphs and save processed output to various files. We will provide another virtual demo in Fall 2022 to ensure managers can operate the GUI / model (and also to further showcase the GEE data visualization apps). This will be

facilitated by the comprehensive documentation, code and example inputs for the forest model available on GitHub ([uvafme.github.io](https://uvafme.github.io)). Specific documentation for the GUI is being made available in a separate but linked GitHub repository.



**Figure 26.** UVAFME graphical user interface developed for land managers to assess the influence of different management and climate change scenarios.

## Publications and Outreach Materials

Jandt, R, and York, A. 2021. Alaska Burning: *Wildfire is Transforming Alaska and Amplifying Climate Change*. Scientific American 325, 4, 42-49 (October 2021) doi:10.1038/scientificamerican1021-4

## Conclusions

### Summary of Project Accomplishments

Based on our analyses, our accomplishments include the following:

- Field measurement campaigns revealed (i) historic disturbance events triggered a multi-decadal growth decline that predisposed aspen to mortality during the leaf miner outbreak, (ii) fuel reduction treatments have impacts on ecosystem characteristics that persist for decades after treatment that need to be accounted for to improve fuel treatment management protocols, designs, and fire behavior modeling, (iii) deciduous dominated forests are highly resilient to fire and that even a small component of deciduous stems (~7%) in the pre-fire stand can result in a transition to deciduous dominance post-fire.
- Vegetation Cover Type Class mapping (1975 – 2015 at 5-year intervals) showed annual land cover change in recent years (2015–present) and also provided pre-fire vegetation information for all fires in boreal Alaska between 1973–1992. This information could be further mined (as we are now doing) to assess changes in vegetation cover types pre- and post-fire, beyond the more specific assessments we conducted using continuous proportions of vegetation cover (i.e. deciduous versus evergreen trees and shrubs) to inform management.
- Tree Canopy Cover Density mapping with satellite imagery showed dramatic changes over large areas as a result of fire. The Landsat CCDC and Landsat MSS products we developed for vegetation classification extended and improved the tree canopy cover mapping over multiple decades.
- Deciduous and Evergreen Vegetation Composition mapping with satellite imagery showed clear effects of time since fire and severity of burning, particularly in areas where organic soils were combusted. These maps are novel in that they show continuous (proportional) per-pixel cover changes at high spatial resolution (30 m) over several decades, implicitly incorporating the impacts of fire and insect disturbance. A visualization application for managers to view, interact with, and ultimately use our products for decision making was developed and is freely available here: [masseyr44.users.earthengine.app/view/decidfractreecoverserdpv1](https://masseyr44.users.earthengine.app/view/decidfractreecoverserdpv1)
- Plant Functional Type Vegetation Composition mapping with satellite imagery allowed us to separate the deciduous and evergreen vegetation component not only tree species but also shrubs, gramminoids, forbs, lichens and other PFTs. Fine-scale canopy cover data from airborne lidar and UAS data of field sites included in the models of plant functional type canopy cover added robust training data that resulted in improved maps of vegetation cover change. A visualization application for managers to view, interact with, and ultimately use our products for decision making was developed and is freely available here: [mmaacander.users.earthengine.app/](https://mmaacander.users.earthengine.app/)
- Combining the deciduous fraction and plant functional type cover, including older Landsat MSS-derived historical products, allowed us to characterize canopy composition changes over a 45 year record, which has never been done before across this spatial extent or as this spatial and temporal resolution.
- Burn Severity Modeling was accomplished by leveraging an extensive database of field-measured burn severity metrics which, in turn, allowed us to derive accurate models of

fire carbon emissions and burn depth that can be applied to both 'modern' (2001 and later) and historical (1940-2000) fires. Using our novel historical land cover products, we developed models of historical burn severity as a function of pre-fire vegetation class and other predictors including spectral metrics, topographic metrics, meteorological metrics, burn size, ignition date, and start-of-growing-season date. These data sets have tremendous utility for informing management decisions related to vegetation succession following fire disturbance (and we are already pursuing that in follow-on work).

- Early Warning Signals of tree mortality were prevalent and detectable in inventory plots across Alaska and Canada using long-term remote sensing time series, but despite this our predictive models of mortality were limited in their accuracy. Prominent challenges include the stochastic nature of mortality, the relatively coarse temporal resolution of most forest inventory data, and a lack of high resolution climate forecast data for future periods.
- Predictive models of near-future change in forest biomass from 5-25 years into the future (Figure 20) were robust and highly relevant for scientists and DoD natural resource managers. The models were highly accurate for biomass gains but less accurate for biomass losses. Nonetheless they are successfully able to distinguish between sites likely to experience biomass gains from those likely to experience losses.
- Process-based models of longer-term forest change provided accurate representation of Alaskan forests and their biotic-abiotic interactions through fine-scale forest modeling. Vegetation dynamics within boreal Alaska were better represented with a process-based forest model (like UVAFME, an individual-based tree model) that includes tree- and stand-level interactions between vegetation, soils and forest fuels, wildfire, fire weather, and climate. Under scenarios of increasing temperatures and atmospheric water demand, long-term vegetation trajectories are likely to include increases in deciduous fraction and decreases in biomass, especially in drier, interior locations. Despite fuel drying and increases in lightning strikes, fire severity and intensity may decline with climate change as a result of decreasing forest biomass and fuels and increasing deciduous fraction.
- Impacts of forest management on forest composition and structure via different management actions (i.e. thinning vs. clearcut vs. shearblading vs. controlled burns) were shown to modify the post-treatment stand composition and structure (Figure 5) which have impacts on post-treatment fuel flammability. Post-treatment stand composition and structure are also captured under scenarios of increasing temperature (Figure 25). Modifications to the post-treatment impacts could inform consideration of treatments at sites within interior Alaska, including in the context of climate change.
- Implementation of outcomes with resource managers were advanced through workshops and webinars hosted by the Alaska Fire Science Consortium, with all materials (agendas, presentations, recordings, etc) available via their website ([www.frames.gov/afsc](http://www.frames.gov/afsc)). We also archived data sets (see list in appendices) and developed freely available map visualization applications on Google Earth Engine for managers to view, interact with, and make use our data products. Users can quickly navigate to different DoD installations in interior Alaska (via dropdown menu) or they can roam around to other areas across Alaska and Yukon, with capabilities to zoom in and out and display different types of vegetation cover. A graphical user interface was also developed to allow managers to assess the influence of simulated management actions and future climate change scenarios.

## Summary of Objectives and Research Outcomes

**Table 3.** Summary assessment of accomplished objectives. Associated references to cited peer-reviewed publications and archived data products can be found in the Appendices.

<b>Objective</b>	<b>Status</b>	<b>Publications / Data Sets / Outreach</b>
1: Field campaigns & measurements	Completed	Boyd et al. (2019; 2021a-d; in review)
2.1: Landcover type mapping	Completed	Macander et al. (2020, 2022b)
2.2: Tree canopy cover density and fractional deciduous and plant functional type cover	Completed	Macander et al. (2022a,c) Massey et al. (in revision) Montesano et al. (2022)
2.3: Burn extent and severity mapping and associated vegetation succession	Completed	Potter et al. (2021; 2022a-b) Rogers et al. (2020)
2.4: Productivity trends and mortality precursor assessments	Completed	Berner & Goetz (2022) Rogers et al. (2020)
3.1 & 3.2: Predict near-future vulnerability to change in habitat composition, productivity, and tree mortality.	Completed	Burrell et al. (in review) Foster et al. (2019; 2022) Mekonnen et al. (2019)
4: Implementation of outcomes with resource managers	Completed and Ongoing	Jandt & York (2021); <a href="http://www.frames.gov/afsc">www.frames.gov/afsc</a> ; Google Earth Engine visualization apps; UVAFME model GUI interface

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## Appendices

### Appendix 1: Scientific/Technical Publications

- Berner, L. T. & Goetz, S. J. (2022). *Satellite observations document trends consistent with a boreal forest biome shift*. *Global Change Biology*. 32: 3275–3292, doi.org/10.1111/gcb.16121
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- Boyd, M. A., Berner, L. T., Doak, P., Goetz, S., Rogers, B., Wagner, D., Walker, X., Mack, M. C. (2019). *Impacts of climate and insect herbivory on productivity and physiology of trembling aspen (Populus tremuloides) in Alaskan boreal forests*. *Environmental Research Letters*. 14: 085010. doi.org/10.1088/1748-9326/ab215f
- Boyd, M. A., Walker, X. J., Barnes, J., Celis, G., Goetz, S.J, Johnstone, J.F., Melvin, A.M., Saperstein, L., Schuur, E.A.G., Mack, M. C. *Decadal impacts of wildfire fuel reduction treatments on ecosystem structure and fire behavior in Alaskan boreal forests*. *Forest Ecology and Management* (in review). Preprint available at dx.doi.org/10.2139/ssrn.4102858
- Burrell, A., Cooperdock, S., Goetz, S. J., Berner, L. T., Foster, A., Hember, R. A., Mack, M. C., Massey, R., Walker, X. J., and Rogers, B. M., *The predictability of near-term forest biomass changes in boreal North America*, *Global Change Biology* (in review).
- Foster, A.C., Shuman, J.K., Rogers, B.M., Walker, X.J., Mack, M.C., Bourgeau-Chavez, L.L., Veraverbeke, S., & Goetz, S.J. (2022). *Bottom-up drivers of future fire regimes in western boreal North America*. *Environmental Research Letters*, 17, 025006. doi.org/10.1088/1748-9326/ac4c1e.
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- Macander, M. J., Nelson, P., Nawrocki, T. W., Frost, G. V., Orndahl, K. M., Palm, E. C., Wells, A. F., Goetz, S. J. (2022a). *Time-series maps reveal widespread change in plant functional type cover across arctic and boreal Alaska and Yukon*. *Environmental Research Letters*. doi.org/10.1088/1748-9326/ac6965
- Massey, R., Rogers, B. M., Berner, L. T., Cooperdock, S., Mack, M. M., Walker, X. J., & Goetz, S. J. *Changes in forest composition and associated biophysical climate feedbacks across boreal North America*. *Nature Climate Change* (in revision). Preprint available at: www.researchsquare.com/article/rs-1209150/v1
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Potter, S., Cooperdock, S., Walker, X. J., Veraverbeke, S., Mack, M. C., Goetz, S. J., Baltzer, J. L., Bourgeau-Chavez, L., Burrell, A., Dieleman, C. M., French, N., Hoy, E. E., Jenkins, L., Johnstone, J. F., Kane, E. S., Natali, S., Randerson, J. T., Turetsky, M. R., Whitman, E., Wiggins, E., and Rogers, B. M. (2022). *Burned area and carbon emissions across northwestern boreal North America from 2001 - 2019*, Biogeosciences. Available at [www.biogeosciences.net](http://www.biogeosciences.net)

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Raiho, A.M., Nicklen, E.F., Foster, A.C., Roland, C.A., & Hooten, M.B. (2021). *Bridging implementation gaps to connect large ecological datasets and complex models*. *Ecology and Evolution*, 11(24), 18271-18287. [doi.org/10.1002/ece3.8420](https://doi.org/10.1002/ece3.8420).

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Shugart, H. H., Foster, A. C., Wang, B., Druckenbrod, D., Ma, J., Lerdau, M., Saatchi, S., Yang, X., & Yan, X. (2020). *Gap models across micro- to mega-scales of time and space: Examples of Tansley's ecosystem concept*. *Forest Ecosystems*, 7(14). [doi.org/10.1186/s40663-020-00225-4](https://doi.org/10.1186/s40663-020-00225-4)

## Appendix 2: Archived data

Boyd, M. A., Berner, L. T., Foster, Adrianna. C., Goetz, S. J., Rogers, B. M., Walker, X. J., Mack, M. C. and Bonanza Creek LTER (2021a). *Annual aspen growth (basal area increment; BAI) of 84 aspen that were alive and 76 that were dead when sampled in 2016 from 22 plots (eight sites) that are a part of the Cooperative Alaska Forest Inventory (CAFI)*, doi.org/10.6073/pasta/4041316bc68a6d5f5f9252c9ef92fed4.

Boyd, M. A., Berner, L. T., Foster, Adrianna. C., Goetz, S. J., Rogers, B. M., Walker, X. J., Mack, M. C. and Bonanza Creek LTER (2021b). *Annual maximum summer NDVI (NDVImax) at 22 plots (8 sites) that are a part of the Cooperative Alaska Forest Inventory (CAFI) from 1986 - 2015.*, doi.org/10.6073/pasta/17dd18c0a4f0e9c807c0220dd519313d.

Boyd, M. A., Berner, L. T., Foster, Adrianna. C., Goetz, S. J., Rogers, B. M., Walker, X. J., Mack, M. C. and Bonanza Creek LTER (2021c). *Seasonal climate data (growing season, spring, fall/winter, and previous growing season) at an annual resolution for eight sites from the Cooperative Alaska Forest Inventory (CAFI) from 1945 - 2013.*, doi.org/10.6073/pasta/08d8211791b22ce66ba611c64cc30d0e.

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Walker, X. J., Baltzer, J. L., Bourgeau-Chavez, L. L., Day, N. J., De Groot, W. J., Dieleman, C., Hoy, E. E., Johnstone, J. F., Kane, E. S., Parisien, M. A., Potter, S., Rogers, B. M., Turetsky, M. R., Veraverbeke, S., Whitman, E. and Mack, M. C. (2020). *Synthesis of Burned and Unburned Forest Site Data, AK and Canada, 1983-2016*, ORNL DAAC, doi:10.3334/ORNLDAAAC/1744.

### Appendix 3: Assessment of photo-interpreted ecotypes and land cover time-series maps

We utilized photo-interpreted ecotypes from 20 systematically distributed sample grids (Douglas et al. 2016) to assess our time-series land cover maps. The grids included 100 points each and were interpreted for 3 time-steps, based on high-resolution imagery. The interpretations from the middle (1978–1980) and recent (2006–2011) epochs were overlaid on the corresponding year from our annual 1972–2020 land cover time-series.

Ecotypes were crosswalked to the 15-class AboVE land cover legend (Wang et al. 2019). There were no ecotypes that crosswalked to the Woodland, Open Shrub, Sparsely Vegetated, and Shallows/Littoral land cover classes; of these, Woodland was the only commonly mapped land cover class. For this comparison, Woodland was merged with the Evergreen Forest land cover class.

The photo-interpretation was applied over a 10-m diameter circle for tree and shrub ecotypes; and at the point location only for meadow and tundra types (Douglas et al. 2016). When a mixture of ecotypes was observed within the 10-m circle, the ecotype at the point location was identified.

The most abundant photo-interpreted classes for both epochs were Evergreen Forest, Low Shrub, Deciduous Forest, and Mixed Forest. Tall Shrub, Fen, and Bog were moderately abundant. There was high agreement for the Evergreen Forest class in both epochs (Tables 4-5 below), with an 69% F1 score (which balances user's and producer's accuracy). Deciduous Forest had an F1 score of 54% for the 1978–1980 epoch, but 24% for the 2006–2011 epoch. Barren was uncommon and had an F1 score of >57% in both epochs. Other classes had poor agreement in both epochs (<29%). Overall agreement was 43% and 35% for the middle and recent epochs, respectively. There was high confusion between Tall and Low Shrub, and (especially for the recent epoch) between Deciduous Forest and Tall Shrub. The photo-interpreted Fen class was nearly always mapped as Tall Shrub. These results highlight the importance of scale and identify challenges in distinguishing among woody broadleaf and productive wetland graminoids with moderate resolution optical imagery.

Douglas, T.A., Jorgenson, M.T., Brown, D.N., Hiemstra, C.A., Liljedahl, A.K., Downer, C., Pradhan, N., Marchenko, S., Campbell, S., Senseman, G. and Olson, K. (2016). *Addressing the Impacts of Climate Change on US Army Alaska with Decision Support Tools Developed Through Field Work and Modeling*. US Army Cold Regions Research and Engineering Laboratory Fort Wainwright United States.

**Table 4.** Comparison of photo interpreted points and project-derived Landsat MSS land cover, 1978–1980.

		Precision (User's Accuracy) (%)	Recall (Producer's Accuracy) (%)	F1 (%)	EF	DF	MF	WL	LS	TS	OS	HE	TT	SV	FE	BO	SH	BA	WA	Row Total
1	Evergreen Forest	67.2	71.5	69.3	510	21	91	0	98	12	0	1	0	0	0	22	0	2	2	759
2	Deciduous Forest	55.7	52.6	54.1	12	162	76	0	16	8	0	0	0	0	6	11	0	0	0	291
3	Mixed Forest	22.0	23.3	22.6	127	39	58	0	26	10	0	0	0	0	3	0	0	1	0	264
4	Woodland	NA	NA	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Low Shrub	71.8	16.2	26.4	12	5	2	0	79	10	0	0	0	0	0	2	0	0	0	110
6	Tall Shrub	7.0	33.7	11.6	23	75	16	0	197	29	0	10	0	0	56	6	0	0	0	412
7	Open Shrub	NA	NA	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	Herbaceous	0.0	0.0	NA	0	0	0	0	32	2	0	0	0	0	0	0	0	0	0	34
9	Tussock Tundra	NA	NA	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10	Sparsely Vegetated	0.0	NA	NA	1	1	0	0	0	2	0	0	0	0	0	0	0	5	0	9
11	Fen	0.0	0.0	NA	28	5	6	0	41	13	0	1	0	0	0	1	0	0	0	95
12	Bog	NA	0.0	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Shallows/Littoral	NA	NA	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	Barren	68.8	57.9	62.9	0	0	0	0	0	0	0	0	0	0	0	0	0	11	5	16
15	Water	NA	0.0	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Column Total				713	308	249	0	489	86	0	12	0	0	65	42	0	19	7	1990
	Overall Accuracy	42.7																		
	Kappa	28.3																		

**Table 5.** Comparison of photo interpreted points and Wang et al. (2019) land cover map for the period 2006–2011.

		Precision (User's Accuracy) (%)	Recall (Producer's Accuracy) (%)	F1 (%)	EF	DF	MF	WL	LS	TS	OS	HE	TT	SV	FE	BO	SH	BA	WA	Row Total
1	Evergreen Forest	67.3	71.6	69.4	495	45	127	0	37	14	0	0	0	0	4	10	0	2	1	735
2	Deciduous Forest	32.2	18.5	23.5	3	46	82	0	2	6	0	0	0	0	3	0	0	1	0	143
3	Mixed Forest	32.1	14.3	19.8	60	27	45	0	2	4	0	0	0	0	2	0	0	0	0	140
4	Woodland	NA	NA	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Low Shrub	57.9	16.9	26.1	17	3	9	0	66	8	0	2	0	0	0	9	0	0	0	114
6	Tall Shrub	6.3	22.9	9.9	33	108	30	0	144	27	0	6	0	0	54	26	0	1	0	429
7	Open Shrub	0.0	NA	NA	3	0	1	0	1	0	0	0	0	0	0	0	0	1	0	6
8	Herbaceous	4.9	23.5	8.2	0	5	7	0	16	9	0	4	0	0	3	35	0	1	1	81
9	Tussock Tundra	0.0	NA	NA	1	0	0	0	8	2	0	0	0	0	0	21	0	0	0	32
10	Sparsely Vegetated	0.0	NA	NA	6	0	3	0	34	27	0	2	0	0	0	8	0	2	1	83
11	Fen	2.8	8.3	4.2	72	15	11	0	81	20	0	2	0	0	6	3	0	1	0	211
12	Bog	NA	0.0	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Shallows/Littoral	0.0	NA	NA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1
14	Barren	57.1	57.1	57.1	1	0	0	0	0	1	0	1	0	0	0	0	0	12	6	21
15	Water	100.0	16.7	28.6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2
	Column Total				691	249	315	0	391	118	0	17	0	0	72	112	0	21	12	1998
	Overall Accuracy	35.2																		
	Kappa	21.4																		