Post-fire successional analysis of vegetation in the 2019 Swan Lake Burn - Kenai National Wildlife Refuge

Final Report: 2019 Swan Lake Fire Burned Area Rehabilitation Plan, as amended.

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Abstract

The comparison of vegetation and fuel characteristics among recently burned habitats with different fire histories helps monitor ecological trend and potentially predict change in analogous systems. The Alaska Center for Conservation Science in cooperation with the US Fish and Wildlife Service resampled 21 permanent vegetation plots in Alaska's Kenai National Wildlife Refuge, which burned in the 2019 Swan Lake and earlier fires to explore how burn history may have influenced the severity of the most recent burn, the composition and structure of the extant plant community, and the successional direction of vegetation recovery.

For plots assessed two years following the Swan Lake Fire, fire frequency and severity appear to be the primary drivers of current site condition, with substrate condition and pre-fire canopy composition exerting the greatest influence over successional trajectory. Plots in the Mystery Creek area that had not burned since a 1947 wildfire burned more severely in 2019 than plots that burned both in 1947 and by prescribed fire in 1999 or 2002, supporting a lower diversity of plant species and a less complex vegetation structure. Two plots that burned in the southern portion of the Swan Lake Fire perimeter during drier conditions had burned in a 1996 wildfire and, two years post fire, were populated primarily by herbs and non-vascular plants.

With respect to successional trajectory, plots with a severely burned substrate tended to support a greater density of herbaceous plants, broadleaf shrubs, seedlings, and trees that differed from the dominant species prior to the Swan Lake Fire, whereas plots with a less severely burned substrate tended to be recolonized by resprouting shrubs and the largely deciduous tree canopy species that were dominant before the fire.

Based on these associations, we suggest that severe substrate burns and/or more frequent fire may result in a prolonged mid-successional stage characterized by broadleaf tree and shrub species. Further, that these habitats are more likely to divert from their pre-fire successional trajectory, especially if subjected to an additional disturbance event prior to the reestablishment of a coniferous phase. Alternatively, less severely burned substrates where duff, rhizomes, rootstocks and seed are preserved may provide both the propagule source and microsite protection for the eventual reestablishment of the pre-fire forest type.

This work highlights the potential role of prescribed fire in mitigating the severity of subsequent wildfire and promoting the growth of browse species in the boreal ecoregion. This dataset is also of interest as an example of the decreasing fire return interval expected from climate change. While more frequent fire may prolong a mid-successional phase rich in broadleaf browse species, this near-term enrichment of wildlife habitat may come at the expense of greater ecosystem resilience.

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Introduction

Alaska ecosystems are adapted to and depend on fire, but land and fire managers are concerned about observed and predicted increases in severe fire weather and fire occurrence (Veraverbeke et al. 2017, Gabrinski, and McFarland 2020, Yu et al. 2021), ecological effects of short-interval reburns (Brown and Johnstone 2012, Hayes and Buma 2021), and observed and predicted shifts from coniferous to deciduous forests with implications for carbon storage and wildlife habitat (Baltzer et al. 2021, Macander et al. 2022). Fires on the Kenai National Wildlife Refuge (KNWR or Refuge), located in Southcentral Alaska (Figure 1), are primarily initiated by lightning or unplanned human ignitions) but prescribed fire has also been used as a land management tool. Wildfires within the Refuge are relatively common, occurring at an average return interval of 89 years in black spruce (*Picea mariana*) forest (SD ± 43 years, DeVolder 1999). Forests dominated by white (*Picea glauca*) and Lutz (*Picea x lutzii*) spruce have longer fire return intervals ranging with a mean fire interval between 400 – 600 years (Berg and Anderson 2006). The forested lowlands of the Kenai Peninsula, especially those dominated by black spruce, are fire susceptible, and have burned with some regularity since the early 1800s owing in part to climatic amelioration at the end of the Little Ice Age as well as the advent of European settlement (ca. 1828) (DeVolder 1999).

To measure the effects of fire on fuel loading and vegetation, and by extension to promote the effective management of fire-susceptible lands in the Refuge, KNWR staff established permanent vegetation plots following Fire Monitoring Handbook (FMH) protocols (USDOI 1992). Permanent plots were located to capture information from different fire events with a total of 71 plots established within the Refuge between 1994 and 2001. Each of these plots was sampled at establishment; subsets of plots were resampled in 1999 (Windy Point) and 2004 (Windy Point and Mystery Creek) following natural or prescribed fire events (Bowser and Berg 2005).

In 2021, The Alaska Center for Conservation Science (ACCS) partnered with US Fish and Wildlife Service (USFWS) to resample a set of permanent plots that had been burned by the 2019 Swan Lake Fire. Our primary objective was to capture baseline information on fire severity and post-fire vegetation and fuels characteristics. However, because there are few monitoring plots in Alaska with pre-fire data that have burned during a prescribed fire and a subsequent wildfire (Little et al. 2018, Jandt et al. 2019) the data collected have extended value in the context of climate change and anticipated reduction in fire return interval and the effect of fuels management.

Notable wildfires affecting the resampled set of permanent plots include an unmapped 1849 fire (De Volder 1999), the large, stand-replacing 1947 Kenai and 2019 Swan Lake fires, and the more localized 1996 Hidden Creek Fire (Alaska Interagency Coordination Center database, https://fire.ak.blm.gov/predsvcs/maps.php). Prescribed burns affecting the permanent plots resampled here were set in 1999 (Unit IV) and 2002 (Units V and VI) in the Mystery Creek area. Wildfires and prescribed burns intersecting the perimeter of the 2019 Swan Lake fire are presented in Table 1 and Figure 1.

Table 1. List of wild and prescribed fires intersecting the perimeter of the 2019 Swan Lake Fire, Kenai National Wildlife Refuge, Alaska.

Incident Name	Fire Year	Discovery Date	Out Date	Type	Area (ha)	Area (ac)
Unnamed	1849	NA*	NA	Wild	8251	20389
Kenai	1947	June 3, 1947	NA	Wild	128727	318091
Engineer Lake	1963	July 6, 1963	NA	Wild	79	196
Russian River	1969	June 14, 1969	July 25, 1969	Wild	826	2041
Pipeline	1974	August 22, 1974	August 29, 1974	Wild	1210	2989
Skilak Lake Unit I	1984	NA	NA	Prescribed	421	1040
Skilak Lake Road II	1987	NA	NA	Prescribed	766	1893
Pothole Lake	1991	May 19, 1991	October 31, 1991	Wild	3729	9214
Hidden Creek	1996	May 11, 1996	August 21, 1996	Wild	2089	5161
Juneau Lake	1997	June 25, 1997	August 1, 1997	Wild	4	9
Mystery Creek Burn Unit IV	1999	NA	NA	Prescribed	177	438
Unnamed	2001	June 28, 2001	August 17, 2001	Wild	282	698
Unnamed	2001	June 28, 2001	August 17, 2001	Wild	4	10
Mystery Creek Burn Unit V	2002	NA	NA	Prescribed	241	597
Mystery Creek Burn Unit VI	2002	NA	NA	Prescribed	246	608
Kenai River Trail	2004	July 5, 2004	August 13, 2004	Wild	19	46
Card Street	2015	June 15, 2015	December 10, 2015	Wild	3591	8875
East Fork	2017	June 15, 2017	December 7, 2017	Wild	411	1016
Swan Lake	2019	June 5, 2019	December 5, 2019	Wild	67656	167182

NA – Not Available

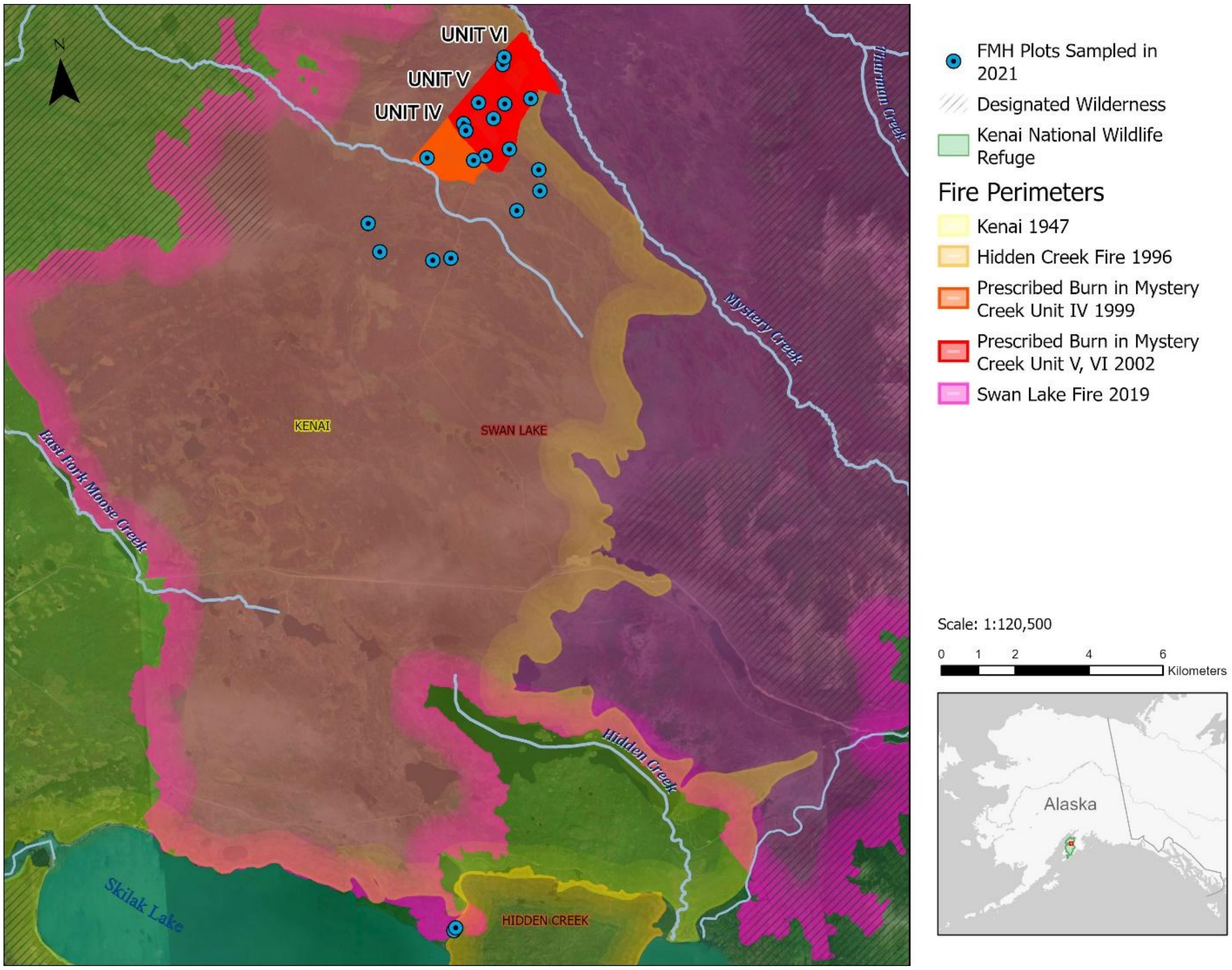

Figure 1. Fire perimeters symbolized by year and locations of plots resampled in 2021, Kenai National Wildlife Refuge, Alaska.

Of the 21 plots resampled in 2021, 19 are located in or proximal to the Mystery Creek Burn Unit, and two are located on the northern shore of Skilak Lake within the perimeter of the 1996 Hidden Creek burn (Figure 2). Due to their locations and selection for prescribed burning, plots have been burned two or three times with periods between fires ranging from 17 to 72 years. All of the plots included in our analysis burned in the 2019 Swan Lake Fire, however one of the plots in Mystery Creek was incompletely burned, and the two Hidden Creek plots did not burn until later in the season after an extended drying period. Plot establishment, resampling events and fire history is summarized in Table 2.

Fuels, Fire Weather, and Fire Behavior

When the Mystery Creek FMH plots were established within the 1947 Kenai Fire perimeter between 1994-1996, the area was vegetated by continuous stands of black spruce with scattered Alaska birch (*Betula neoalaskana*) and quaking aspen (*Populus tremuloides*), all presumably less than 50 years old. Different from the Mystery Creek plots, white spruce was a significant component of the Hidden Creek stands burned in 1996 (DeVolder 1999). Hidden Creek FMH plots were established after the fire so no pre-fire data are available.

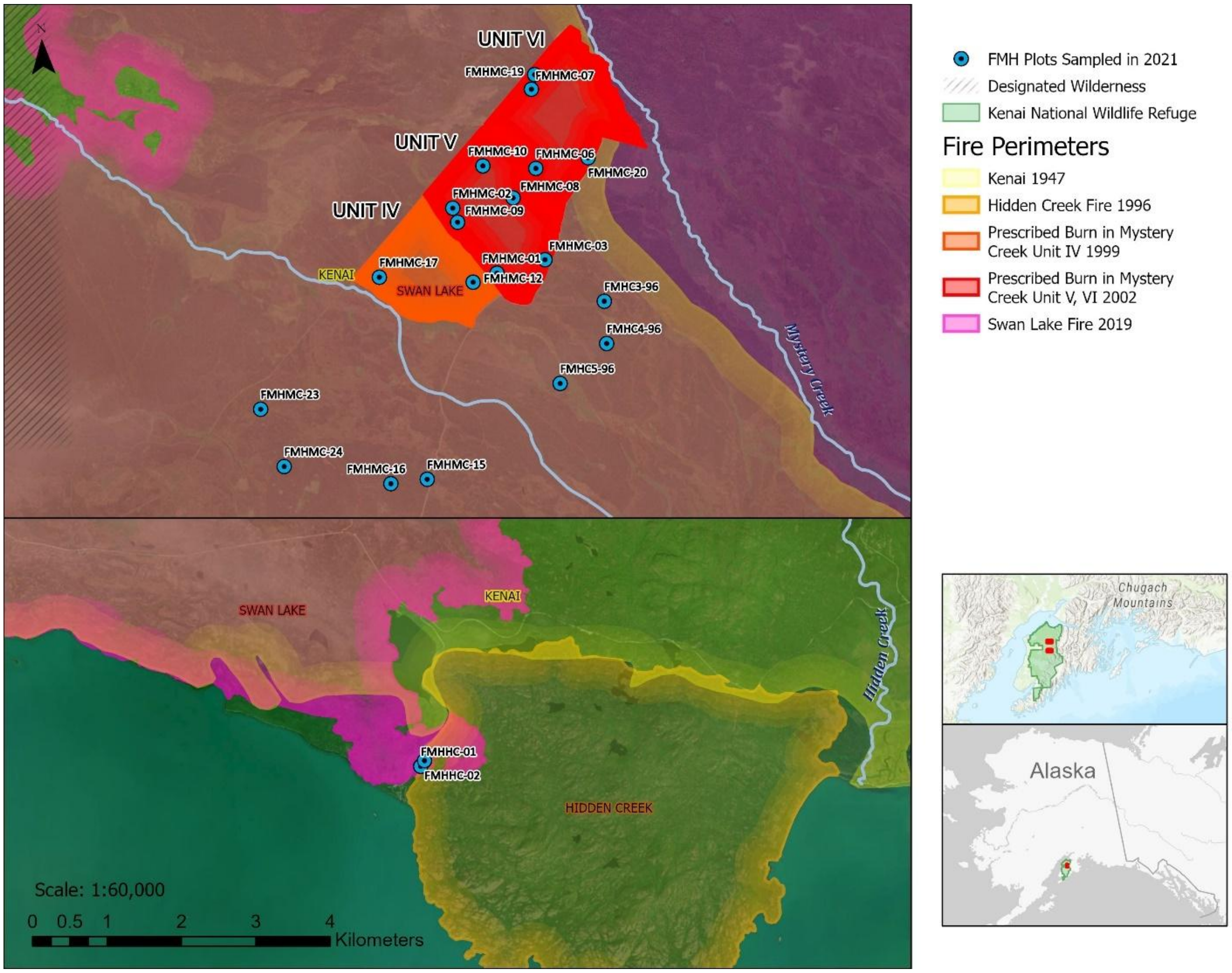

Figure 2. Prescribed burn units and locations of plots resampled in 2021, Kenai National Wildlife Refuge, Alaska.

Prior to the prescribed burns in Mystery Creek burn units V and VI, existing vegetation was described as lowland black spruce forest with trees between 2.4 – 12.2 meters (8 – 40 feet) tall and the forest floor composed predominantly of feather mosses (*Hylocomium splendens, Pleurozium schreberi*, and *Ptilium crista-castrensis*) with some sphagnum moss (*Sphagnum* spp.). The depth of pre-burn forest floor material (litter, moss, lichen, and duff combined) ranged from 10.9 – 18.3 cm (4.3 to 7.2 inches) (Olson et al. 2003). McLean (2002) described the burn unit as follows: "Scattered throughout the burn area are 4-inch diameter birch and pockets of over mature, larger aspen. Understory consists of tree spruce and heavily browsed birch, willow, and aspen trees. Ground cover includes Labrador tea, shrub-lichen, sparse herbs and feathermosses. Bluejoint reedgrass (*Calamagrostis canadensis)* is present and will be a primary carrier of fire in those areas, if cured. There are several large grassy openings in Unit V, more so than in Unit VI. There are also pockets of jackstraw accumulation of dead-down spruce poles, approximately 15 tons per acre".

Table 2. Establishment dates and fire years for FMH plots resampled in 2021.

Plot ID	Burn Unit	Established Date	Resample Date (2004)	Resample Date (2021)	1849 (wild)	1947 (wild)	1996 (wild)	1999 (prescribed)	2002 (prescribed)	2019 (wild)	Plot CBI	Burn History Category
FMHMC-03	Mystery Creek V	May 19, 1994	June 7, 2004	August 15, 2021		Y			Y	partial	1.194	wild/prescribed
FMHMC-01	Mystery Creek V	May 13, 1994	June 4, 2004	August 15, 2021		Y			Y	Y	1.421	wild/prescribed/wild
FMHMC-02	Mystery Creek V	May 16, 1994	June 3, 2004	July 16, 2021		Y			Y	Y	2.289	wild/prescribed/wild
FMHMC-06	Mystery Creek VI	June 14, 1994	June 9, 2004	July 14, 2021		Y			Y	Y	1.869	wild/prescribed/wild
FMHMC-07	Mystery Creek VI	June 16, 1994	June 14, 2004	July 12, 2021		Y			Y	Y	1.985	wild/prescribed/wild
FMHMC-09	Mystery Creek V	June 22, 1994	June 10, 2004	July 15, 2021		Y			Y	Y	1.694	wild/prescribed/wild
FMHMC-10	Mystery Creek V	June 23, 1994	June 18, 2004	July 19, 2021		Y			Y	Y	1.768	wild/prescribed/wild
FMHMC-12	Mystery Creek IV	June 27, 1994	NA	August 12, 2021		Y		Y		Y	2.056	wild/prescribed/wild
FMHMC-19	Mystery Creek VI	August 2, 1994	June 15, 2004	July 12, 2021		Y			Y	Y	2.274	wild/prescribed/wild
FMHMC-20	Mystery Creek VI	August 5, 1994	June 2, 2004	July 13, 2021		Y			Y	Y	1.365	wild/prescribed/wild
FMHC3-96	Mystery Creek	July 10, 1996	NA	August 14, 2021	Y	Y				Y	2.271	wild/wild
FMHC4-96	Mystery Creek	July 11, 1996	NA	August 14, 2021	Y	Y				Y	2.528	wild/wild
FMHC5-96	Mystery Creek	July 16, 1996	NA	August 14, 2021	Y	Y				Y	2.556	wild/wild
FMHHC-01	Hidden Creek Burn	July 17, 1997	NA	July 20, 2021			Y			Y	2.564	wild/wild
FMHHC-02	Hidden Creek Burn	August 19, 1997	NA	July 20, 2021			Y			Y	2.576	wild/wild
FMHMC-08	Mystery Creek V	June 20, 1994	June 16, 2004	July 14, 2021		Y			partial	Y	2.728	wild/wild
FMHMC-15	Mystery Creek V	July 12, 1994	NA	August 15, 2021		Y				Y	2.521	wild/wild
FMHMC-16	Mystery Creek III	July 13, 1994	NA	August 12, 2021		Y				Y	2.183	wild/wild
FMHMC-17[1]	Mystery Creek IV	July 18, 1994	NA	August 12, 2021		Y		Y[2]		Y	2.263	wild/prescribed/wild
FMHMC-23	Mystery Creek III	August 16, 1994	NA	August 13, 2021		Y				Y	2.25	wild/wild
FMHMC-24	Mystery Creek III	August 17, 1994	NA	August 13, 2021		Y				Y	2.5	wild/wild

NA – Not Applicable

[1]FMHMC-17 was prescribed burned in 1998, but the burn was patchy, and the plot was not resampled until 2021

Eleven plots located in the Mystery Creek Burn Unit were burned by USFWS between 1998 – 2002. One plot received a patchy burn in 1998, one was burned in 1999, and the remaining nine were burned in 2002. Prescribed burns are intentionally ignited under weather parameters (temperature, relative humidity, wind speed and direction) specific to burn and safety objectives. They are often conducted under conditions that are not conducive to large fire growth in order to reduce the probability of escaping control. Burning in Units V and VI was initiated June 22 and completed by July 4, 2002. Objectives of the burn were to reduce black spruce crown fire hazard, reduce fine fuel loading by 70%, shift plant communities to lower seral stages to benefit wildlife, particularly moose, and to provide a partial fuel break between Refuge lands and the community of Sterling (McClean 2002). The intent was to expose pockets of mineral soil over at least 5% of the units to encourage proliferation of deciduous tree and shrubs and also to leave 10 – 30% of the units unburned to serve as wildlife cover (McClean 2002).

At the time of burning, humidity ranged from 44 to 49%, temperature ranged from 64 to 71°F and average wind speed was 1 to 2 miles per hour. The depth of post-fire forest floor material ranged from 3.5 to 5.6 cm (1.4 to 2.2 inches), equivalent to a reduction of 23 to 28%. The percent of blackened forest floor post-fire ranged from 72 to 93% (Olsen et al. 2003). When the plots were resurveyed in 2004, the area was characterized by blackened, partially burned duff, little brush, and blackened, standing black spruce poles (Bowser and Berg 2005).

The Swan Lake Fire was ignited by lightning on June 5, 2019 and burned 67,656 hectares (167,182 acres) over 146 days. The fire started about 13 km (8 miles) west of the northwest corner of Unit IV in black spruce forest, but many different plant communities burned including white/Lutz spruce forest, alpine tundra, and mountain hemlock (*Tsuga mertensiana*). Weather conditions varied throughout the fire's long duration, including temperatures that exceeded previously recorded maximums, below average precipitation, and a dry cold front accompanied by strong winds in mid-August that resulted in 13,355 hectares (33,000 acres) of fire growth in two days. A fire progression map is provided in Figure 3.

Little information is available about the Hidden Creek burn plots. They were sampled one year after the fire and were not revisited prior to 2021. Data sheets from 1997 indicate that, Hidden Creek FMHHC-01 was dominated by white spruce and Alaska birch prior to the fire and FMHHC-02 was dominated by black spruce. Most trees were killed in 1996. Two other plots established in the Hidden Creek burn that were not reburned by Swan Lake Fire were also in white spruce and birch forest.

Canadian Forest Fire Danger Rating System (CFFDRS) fire weather codes and indices are useful for interpreting and comparing potential fire behavior based on weather inputs. The Buildup Index (BUI) indicates the total amount of fuel available for burning and characterizes seasonal severity (Ziel 2015). It is based on the moisture content of the moderately deep, loosely compacted organic layer and the more compact organic layer below it. The Fire Weather Index (FWI) incorporates the BUI, fine fuel moisture, and winds to indicate fire intensity potential and extreme fire behavior potential. BUI and FWI values were generally higher during the 2002 Mystery Creek prescribed burn than when the Swan Lake Fire reburned this area.

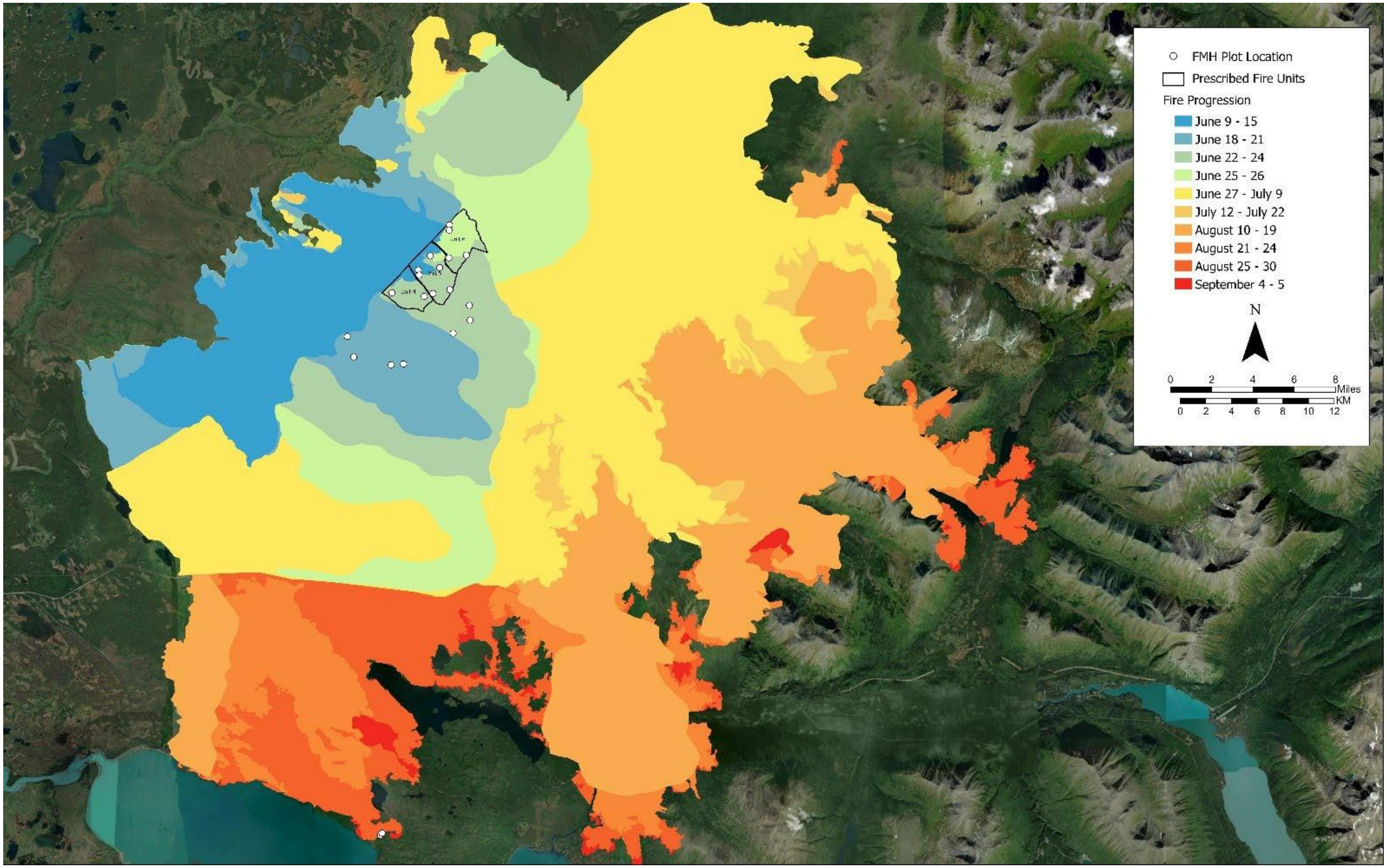

Figure 3. Progression of Swan Lake Fire relative to FMH plot location. A burnout was conducted June 17-18 from the access road north northeast of the Mystery Creek burn units to protect pipeline infrastructure to the east, potentially slowing spread of the fire into the units.

The KNWR Remote Automated Weather Station (RAWS), located 1.1 km (0.7 miles) south of plot FMHMC-16, provided weather data in 2002 and 2019. The Swan Lake Fire burned near the Mystery Creek FMH plots from approximately June 13 – 26, 2019 (Figure 3). BUI was Moderate on June 13, High between June 14 – 23, and Very High between June 24 – 26 (Table 3, https://akff.mesowest.org/). The BUI was Extreme when the fire reached the Hidden Creek FMH plots south of the Sterling Highway August 28 – 29. FWI was considered Moderate when the fire was near the Mystery Creek plots for all but the last four days when it was considered High. In comparison, FWI was extreme, with a value of 46, when winds pushed the fire across the Sterling Highway on August 18.

During the 2002 prescribed burn, BUI was largely High or Very High, reaching Extreme values the last 3 days of burning. FWI was also in the High or Very High class for 10 days and reached a maximum on June 30 when the smoldering fire flared up, with torching and spotting that ignited Unit VI (Olson et al. 2003).

Table 3. Threshold values for interpreting BUI and FWI fire weather indices.

Index	Low	Moderate	High	Very High	Extreme
BUI	0 – 39.9	40 – 59.9	60 – 89.9	90 – 109.9	110+
FWI	0 – 8.9	9 – 17.9	18 – 27.9	28 – 34.9	35+

Methodology

We prioritized plots that had burned in the 2019 Swan Lake Fire, had a history of multiple burns, and could be accessed by foot for resampling. In order to reduce search time, KNWR staff relocated and flagged some plots prior to the sampling event; plots that could not be located were dropped from the sample. Of the total 44 FMH plots identified for potential sampling, 14 plots could not be relocated and an additional 9 were not within walking distance of roads; the remaining 21 plots were resampled (Appendices A, C; Figures1, 2).

Plot Sampling

We developed a modified sampling methodology to reduce sampling time and better align with post-fire and treatment monitoring methods used elsewhere within KNWR and National Park Service units in Alaska as described in Barnes et al. (2020). General modification to the FMH protocol (USDOI 2003) includes use of a circular rather than rectangular plot design, two rather than four fuels transects, and the Composite Burn Index (CBI) (Key and Benson 2006, Barnes and Hrobak 2020) rather than burn severity points. Point-intercept methods for estimating plant cover followed Morton et al. (2006) for the KNWR Long-Term Monitoring Program (LTEMP) rather than those documented in Barnes et al. (2020).

All FMH plots were previously established and monumented by KNWR crews following FMH methods (USDOI 1992). Of this original memorialization, we used the center point, marked by a 1.5 m tall fence post, and two of the four fuels transect origins, marked by rebar stakes. The revised plot geometry is a 10-m radius circular plot (Figure 4) encompassing two 20-m perpendicular transects oriented N-S and E-W relative to true north (using current declination compass settings 15.18˚ E). Total plot area is 314.2 m^2 or 0.08 acre.

Plot Metadata

At each plot, we recorded percent terrain slope and aspect in degrees from true north. We also took a standard set of photos capturing views along the transects and the ground surface condition. We used the geospatial coordinates and elevation data archived for each permanent plot instead of recollecting this information on site. The methods used to quantify plant species abundance and diversity, seedling, shrub, and tree density and morphology, downed woody debris (i.e., fuels) volume, and fire severity are detailed in the following sections.

Vegetation and Substrate Percent Cover

We collected line point intercept (LPI) data at each plot to estimate the cover of vegetation and substrate type following methods developed by Morton and others (2006). Using a laser pointer mounted to a rigid, 2 m rod we sampled along two orthogonal 20 m transects, recording the substrates and species types intersected by the vertical projection of the laser. Readings were taken at 0.5 m intervals, for a total of 80 sampling points per plot. For plants, we collected intercept data within the height categories of 0-1 m, 1-2 m, and > 2 m. Regardless of how many times the laser pointer intersected a given plant taxon at a sampling point (e.g., overlapping leaves of a live tree), the taxon was only recorded once per height category. We recorded both vascular and non-vascular

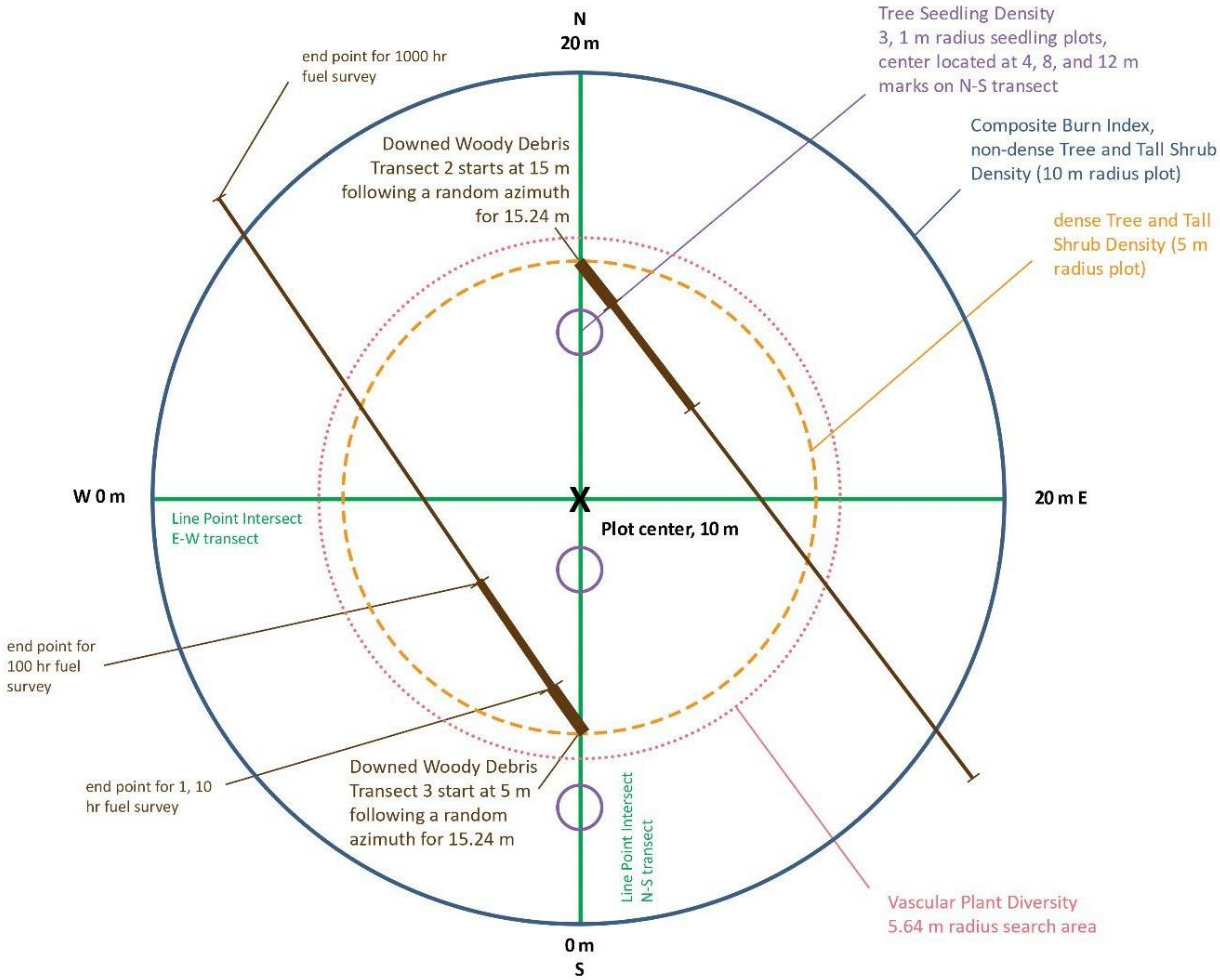

Figure 4. Plot schematic showing point intercept lines, example fuels transects, and search areas for species diversity, seedlings, tall shrubs and trees, and assessed area for composite burn index.

plant species; dead plant material was not recorded unless the plant had died during the growing season due to senescence. We categorized substrates as mineral soil, organic soil (duff), litter (including wood <2.5 cm in diameter), wood (>2.5 cm in diameter), or rock (>1.3 cm maximum dimension), with duff differentiated from litter by having no recognizable plant parts.

Vascular Plant Diversity

To fully capture the vascular plant species richness for each plot and to maintain consistency with vegetation protocols used elsewhere in KNWR (e.g., Morton et al. 2006), we recorded the presence of all vascular taxa within a 5.64 m radius of the plot center.

Tree Seedling Morphology and Density

We measured tree seedling morphology and density following methods developed by Barnes and others (2020) to capture the nascent species composition and status of forest regeneration. Regardless of age, a seedling is defined as a tree species with height less than 1.37 m (i.e., breast height) where tree species are defined in accordance with Viereck and Little (2007). We tallied all live seedlings in 1-m radius subplots centered at the 4 m, 8 m, and 12 m points on the north-south transect. We further categorized seedlings by species and life stage where life stage was categorized as:

- resprouts defined as new growth from older root stock (e.g., Alaska birch basal sprouts, aspen suckers),
- immature, defined as new plants from seeds less than 10 cm tall, and
- mature, defined as new plants or growth greater than 10 cm tall

Unless noted otherwise, the term "seedling" will hereafter include all three categories.

Tall Shrub Morphology and Density

We calculated tall shrub density to further inform the successional trajectory of the plot and to quantify the abundance of moose browse. We included all shrub species greater than 1.0 m tall where shrub species are defined in accordance with Viereck and Little (2007). For less dense stands we tallied all individuals within the 10 m radius plot. In dense stands with more than 15 tall shrubs within 5 m of the plot center, we tallied only the individuals within the 5 m radius subplot (Figure 4). We further categorized tall shrubs by species and life stage where life stage was categorized as:

- resprouts, defined as new growth from older root stock,
- mature, defined as an individual with less than 50% of their biomass dead,
- decadent, defined as individuals with more than 50% of their biomass dead, and
- dead, defined as individuals with no sign of living material.

We also recorded the average height of each shrub species within the 5 or 10 m radius search area.

Tree Morphology and Density

We collected data on tree morphology and density following methods developed by Barnes and others (2020) to monitor trends in stand structure, composition, and health as well as to provide data inputs to model crown fire potential. We calculated tree density by recording the number of trees by species, diameter at breast height (DBH) size class (<5, 5.1-10, 10.1-15, 15.1-23, > 23 cm), and status (i.e., live, dead, diseased/insect damaged) within 10 m of the plot center. We did not include individuals less than breast height nor dead trees leaning at an angle of less than 45° from the ground. We pulled small, leaning trees upright to see if they met the 1.37 m height threshold. In dense stands with more than 15 trees within 5 m of the plot center, we tallied only the individuals within the 5 m radius subplot (Figure 4).

To summarize tree morphologies at the plot level, we measured two live trees representing each species and DBH size class. Again, trees were defined as individuals taller than breast height (i.e., 1.37 m). We preferentially selected trees proximal to the plot center and recorded their location information (azimuth and distance from plot center) for future reference. To estimate tree basal area, crown bulk density, and stand height at the plot level, we measured DBH, total height, crown radius, and height to dead and live ladder fuels and main crown base for the selected conifers.

Because deciduous trees do not typically support ladder fuels and their foliage is less flammable than that of coniferous trees, we measured only height and DBH for deciduous species.

Downed Woody Debris Volume

Dead wood is important in carbon and nutrient cycles and serves as habitat for microorganisms, plants, insects, and wildlife (Boulanger and Sirois 2006), but it can be a problem for fire management. Fire can smolder for extended periods in large diameter logs, allowing it to persist during wetter periods and spreading when conditions dry. Coarse woody debris also increases the difficulty of suppression and can increase burn severity as heat sustained in logs is transferred to the soil. We inventoried downed woody debris to evaluate its availability to sustain future fire following the methods developed by Brown (1974) and described in Barnes et al. (2020). Different from the original FMH methods we limited our resurvey to two fuels transects rather than four, preferentially selecting transects 2 and 3 if we could find the stakes located at the 15 and 5 m marks on the north-south transect, respectively. Each transect extended 15.24 m along its original random azimuth assigned at plot establishment and listed in Appendix B. Downed woody debris was classified by its timelag category (1, 10, 100, and 1,000-hour), which corresponds to the time required for the fuels to lose approximately 63% of their moisture content. We tallied downed woody debris proceeding from 0 m to a set distance determined by the diameter of the material (Table 4, Figure 4). For logs over 7.6 cm (1,000-hour fuels), we recorded the species, diameter, and quality of the wood (i.e., rotten or solid). We also recorded the average percent slope of the ground along the fuels transect. Along each transect, we included downed woody debris crossing the tape within 1.8 m of the ground surface; stumps were included if they were uprooted and not covered by the substrate. We did not include herbaceous material, parts of standing trees, cones, bark, or leaves, woody material buried more than halfway into the substrate at the point of interception with the transect, or woody material with a central axis running parallel to (i.e., not crossing) the transect.

Table 4. Transect survey lengths for fuel diameter classes.

Fuel Class	Fuel Diameter (in)	Fuel Diameter (cm)	Transect length (ft)	Transect length (m)
1-hr fuels	0-0.25	0-0.6	6	1.8
10-hr fuels	0.25-1	0.6-2.5	6	1.8
100-hr fuels	1-3	2.5-7.6	12	3.7
1000-hr fuels	>3	>7.6	50	15.2

Burn Severity

We assessed burn severity at each plot to inform correlations to fire return interval and post-fire fuel and vegetation characteristics. Using the CBI developed by Key and Benson (2006) and modified for Alaska by Hrobak and Barnes (2020), we assigned a severity index ranging from 0 (unburned) to 3 (severely burn) for five strata (Table 5). Different from Hrobak and Barnes (2020), we limited our fire severity assessment area to a 10 m radius circle rather than 15 m to match the extent covered by the line point intercept transects. Lastly, we added a moss/lichen species composition/relative abundance component to the substrate section to lower the severity index for incompletely burned plots where species composition is similar to pre-fire conditions despite lower relative abundance.

Table 5. Strata assessed in the composite burn index (CBI) methodology.

Stratum	Description	Ranked Components
A	Substrates - light, medium and heavy fuels, duff, soil, rock, non-vasculars	Litter/ light fuel consumption, duff consumption, medium and heavy fuel consumption, change in soil and rock cover and color, change in moss/lichen consumption and relative abundance
B	Herbs, Low Shrubs, and Trees Less than 1 m	Percent foliage altered, frequency of living foliage, colonizers, species composition and relative abundance
C	Tall Shrubs >1 meter and Trees 1-2 m	Foliage altered, frequency of living plants, change in cover of colonizers, species composition, and relative abundance
D	Intermediate Trees (subcanopy, pole-sized) 2-8 m	Percent change in crown volume of green (unaltered), black (torched), brown (scorched/girdled), and dead foliage, char height
E	Big Trees (upper canopy, dominant, codominant) >8 m	Percent change in crown volume of green (unaltered), black (torched), brown (scorched/girdled), and dead foliage, char height

The cumulative combustion of surface organic layers by successive fires is not captured by the CBI method, complicating the assessment of burn severity after multiple fires especially when considering ecosystem effects and emissions. Measurements of organic layer thickness prior to prescribed burns and post-fire in 2004 and 2021 can help tease apart the effects of individual fires despite the use of different methodologies. Litter (including live and dead mosses and lichens) and duff depth were recorded on surface fuel transects during plot establishment and two years after the prescribed burn; burn severity was measured at the same points (Bowser 2010). In 2021, pre-fire organic layer thickness – litter, lichen, live and dead moss, and duff – was estimated at several representative sites in and adjacent to the plot as a component of the CBI method. The presence of exposed adventitious spruce roots or other clues were used to determine pre-fire thickness (Kasischke et al 2008, Barnes et al 2020).

Analysis

We housed our field data in the FFI-Lite v.1.05.13.78, a purpose-built database used by federal agencies for monitoring fire effects on public lands (Lutes et al. 2009). Taxonomy and life form assignment are in accordance with the USDA Plants Database (USDA 2022). Where multiple life forms are listed for woody species, we deferred to the Alaska-specific life form designations presented in Viereck and Little (2007). The plant species and categories of substrate recorded are listed in Appendix C.

We calculated summary statistics and performed multivariate ordinations and indicator analysis using the software program PC-ORD version 7.08 (McCune and Mefford 2011). The Sørenson's distance measure was selected as the basis for ordination as it emphasizes the presence rather than the absence of species and is thus less sensitive to zero-rich datasets. We ordinated the data using Nonmetric Multidimensional Scaling (NMS), retained significant solutions ($\alpha = 0.05$) with stress less than or equal to 20, and selected the two most significant axes for final interpretation. We limited the display of site variables to those with an R^2 greater than 0.2 (indicating a greater than 20% correlation to a given axis). We quantified the strengths of association between species and significant axes by calculating Pearson's correlations coefficients (Pearson 1901). For 20 plots (18 degrees of freedom), a coefficient value (i.e., r value) of 0.561was identified as the critical value for a directional test at $\alpha = 0.01$; for 21 plots (19 degrees of freedom), a coefficient value (i.e., r value) of 0.549 was identified as the critical value for a directional test at $\alpha = 0.01$ (Sokal and Rolf 1995).

Average fire return interval is calculated as the average number of years between wildfires or prescribed burning. Because plot FMHMC-03 was incompletely burned in the 2019 Swan Lake Fire, we did not include the 2019 fire in its total number of fires or the calculation of average fire return interval. Similarly, because plot FMHMC-08 was incompletely burned during the 2002 prescribe burn of Unit V, we did not include the 2002 fire in the total number of fires or average fire return interval.

Because the 2004 resurvey of the Mystery Creek plots following the 2002 prescribed burn did not characterize overstory burn severity, we were only able to compare substrate and understory burn severity between survey periods. We equate substrate with duff, litter, non-vascular species, soil, rock, and downed fuel (i.e., the A strata of Barnes and Hrobak 2020) whereas understory vegetation includes herbs, shrubs and tree trees less than 2 m tall (i.e. the B and C strata of Barnes and Hrobak 2020). Because different methods were used in 2004 and 2021 to assess burn severity, we also needed to translate the severity scores collected in 2004 to the equivalent composite burn index calculated for the same ten sites in 2021. In 2004, burn severity ratings were made for a 0.04 m^2 area every 1.52 m along the 15.2 m fuel transects and the extent to which the organic substrate and understory vegetation had been burned was ranked from unburned (5) to heavily burned (1) following the coding matrix presented in the Fire Monitoring Handbook (USDOI 1992). We averaged the scores recorded in 2004 for substrate and understory and we limited the use of the CBI scores collected in 2021 to strata A (substrate) and B (herbs and low shrubs). We then translated the burn severity scale used in 2004 to the CBI used in 2021 in accordance with Whitman et al. (2018) as shown in Table 6. Because FMH burn severity is scored on a scale from 5 (unburned) to 1 (heavily burned), we reversed the scale of these categories to translate to CBI such that a severity of less than 5 to 3 was considered a low severity burn, less than 3 to 2 was considered a moderate burn, and less than 2 to 1 was considered a high severity burn.

Table 6. Translation of fire severity metrics from value to category (adopted from Whitman et al. 2018).

Burn Severity Metric	Unchanged	Low	Moderate	High
Composite Burn Index (0-3)	≤0.1	>0.1-1.5	>1.5-2.25	>2.25
Burn Severity (5-1)	5.0	<5-3	<3-2	<2-1

Data Structure

Although our dataset is small (21 plots), plant species composition is relatively consistent among the plots, and for this reason sample effort is deemed sufficient for statistical analysis. The species area curve in Figure 5 shows that the average number of species detected plateaus as each plot is added to the sample, suggesting a low probability of detecting novel species with additional plot sampling. The distance measure, included as the lower, dotted line, relates to the separation between centroids of the subsample and the entire dataset. Thus, as plots are added to the subsample, the distance between the two centroids approaches zero.

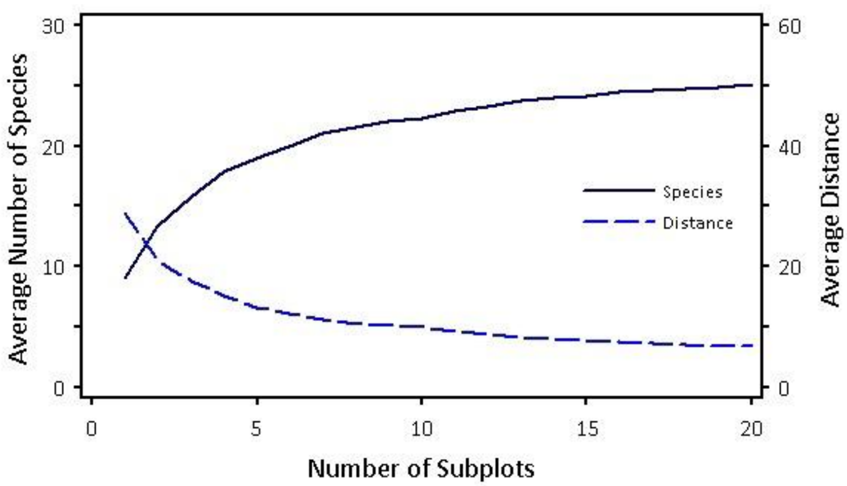

Figure 5. Species-area curve regressing the average number of species detected against number of plots sampled; the distance curve shows decreasing separation between plot centroids.

For the purposes of data summary, we group plots by categories of CBI and fire history. Categories of CBI are low, medium, or high and analyses summarized by CBI category include all 21 permanent plots unless specified otherwise. Data summarized by burn history includes 18 of the permanent plots. Owing to their unique burn histories and the insufficient representation of plots, the two Hidden Creek plots that were burned by wildfire in 1996 and 2019 and plot FMHMC-03 that was incompletely burned in 2019 are not included in analyses summarized by burn history. Categories of burn history are ‘Wildfire Only’ and ‘Wild and Prescribed Fire.’ Plots categorized as Wildfire Only were burned by both the 1947 Kenai Fire and the 2019 Swan Lake Fire, whereas the plots categorized as ‘Wild and Prescribed Fire’ were burned an additional time by prescribed fire in 2002, 1999, or 1998.

To select an appropriate tool for data analysis, we assessed the normality of our variable responses, for example the distribution of our species cover and tree and shrub density values. As extreme values can disproportionally affect the shape of a distribution, we assessed our datasets for outlying plots (i.e., those with average responses greater than two standard deviations from the grand mean):

- Based on plant species type and abundance, FMHMC-03 is the only outlying plot. This plot was incompletely burned in the 2019 fire and as such, supports an abundance of live spruce and carpeting moss and lichens. The plot was retained for summary statistics yet omitted from multivariate and cluster analysis.
- Based on a plant species presence and absence dataset that accounts for all species recorded along the line point intercept as well as the vascular plant species recorded from our diversity search, Hidden Creek plot FMHHC-01 registers as the only outlier. FMHHC-01 has a high fire severity (CBI 2.6) and is characterized by low species diversity (*Betula neoalaskana*, *Chamerion angustifolium, Marchantia polymorpha*, *Ceratodon purpureus*). Because this low diversity relates to ecological pattern rather than an effect of sampling design, the plot was retained for analysis.
- No outlying measures of plant species cover or tree or shrub species density were found.

We further assessed the normality of species covers and densities through the coefficient of variation among plots and the skewness (asymmetry) and kurtosis (peakedness) of their distributions. In accordance with these measures, a perfectly normal distribution is characterized by a low coefficient of variation, and a skewness and kurtosis of zero.

For species covers, the coefficient of variation among plots is 35%, skewness is 3.1, and kurtosis is 11.0, indicating a non-normal distribution. Removal of outlying plot FMHMC-03 reduced the coefficient of variation among plots to 29.6%, and slightly lowered skewness and kurtosis of species distributions to 3.0 and 10.1, respectively. This revised dataset produced the closest approximation of a normal distribution and was therefore used for ordination.

For tree and shrub species densities, the coefficient of variation among plots is 93.7%, skewness is 3.3, and kurtosis is 11.6, also indicating a non-normal distribution. A general relativization of tree and shrub species densities provided the greatest improvement for the coefficient variation among plots but because the response is already normalized to density, did not change the shape of the distribution. We selected to use the raw, unmodified data in ordination.

Results

Vegetation Cover

Relative cover of substrate and plant functional type indicates that all plots except FMHMC-03 were dominated by non-living substrate and early nonvascular species two years after the Swan Lake Fire (Figure 6). Plot FMHMC-03, burned by prescribed fire in 2002 but only partially burned by Swan Lake Fire, had almost 50% cover of trees. Given the absence of data between 2004 and 2019, this plot can provide some insight into what the prescribed burned plots might look like had they not reburned. Tree cover in plots burned only by Swan Lake was comprised entirely of quaking aspen, presumably suckers. Wild and Prescribed Fire plots had more diversity, with aspen, Alaska birch, and black and white spruce detected on plots.

Species Diversity

We documented a total of 35 plant taxa among 21 plots; 28 taxa were recorded along the vegetation transects with an additional seven taxa recorded within the vascular species search area. When summarized by CBI at the plot level, plant species diversity measures decrease with increasing fire severity (Table 7). The inverse relationship between species diversity and fire severity is supported for several measures of diversity including: species richness, derived from the presence of species along the vegetation transects (i.e., LPI) and within the diversity search area, as well as species richness and diversity derived from cover of species along the vegetation transects.

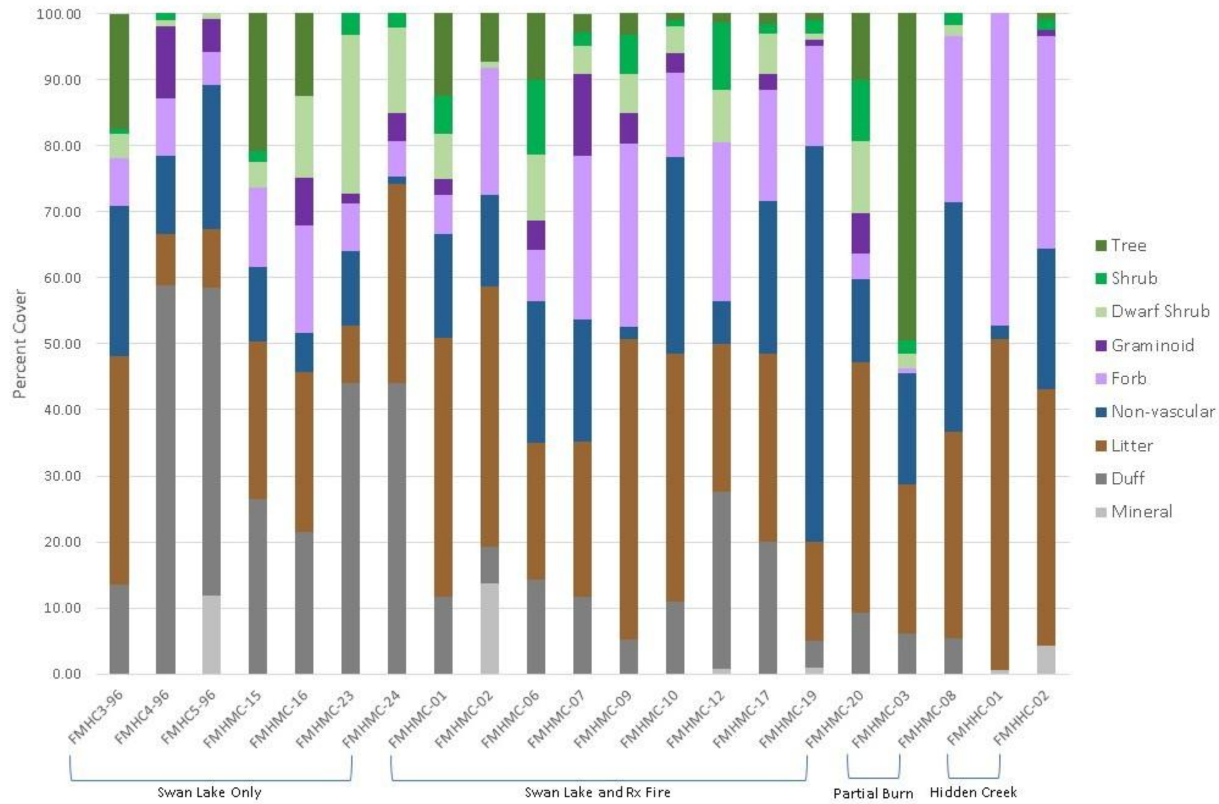

Figure 6. Line Point Intercept cover of substrate and plant functional types, standardized to 100% cover for comparison.

Table 7. Comparison of plot-level Composite Burn Index to plant species diversity metrics.

Diversity Metric	Low	Moderate	High
Number of Plots	3	7	11
Species Richness (based on presence absence of all species)	14.7	13.4	10.6
Species Richness (based on percent cover of LPI species)	13.7	10.3	7.5
Shannon's Species Diversity (based on percent cover of LPI species)	2.2	1.9	1.4

Species diversity metrics are also related to burn history, which rather than capturing the severity of the most recent fire, speaks to the frequency of fire. A comparison of Wildfire Only plots to Wild and Prescribed Fire plots shows that species richness and diversity were higher for the plots that burned more frequently. For the plots presented in Table 8, those categorized as Wildfire Only were burned by both the 1947 Kenai Fire and the 2019 Swan Lake Fire, whereas the plots categorized as Wild and Prescribed Fire were burned an additional time by prescribed fire in 2002, or for two plots, in 1998-1999. The two Hidden Creek plots that burned by wildfire in 1996 and 2019 and plot FMHMC-03 that was incompletely burned in 2019 are not included in this summary because of their unique burn histories and the insufficient representation of plots for these histories.

Table 8. Comparison of plot burn history to plant species diversity metrics.

Diversity Metric	Wildfire Only	Wild and Prescribed Fire
Number of Plots	8	10
Species Richness (based on presence absence of all species)	11.1	14.1
Species Richness (based on percent cover of LPI species)	7.6	11.3
Shannon's Species Diversity (based on percent cover of LPI species)	1.6	1.9

Burn Severity

To explore how burn history may have influenced the severity of the Swan Lake Fire, we compared average CBI of plots burned by wildfire only (two fire events with a longer interfire period) to plots that were burned by wild and prescribed fire (three fire events with a shorter interfire period). Average CBI for Wildfire Only plots is higher than that of Prescribed and Wildfire plots burned by both wild and prescribed fire (Table 9). Based on comparisons between the substrate, understory and overstory specific CBIs for the two categories of burn history, the higher overall CBI for the Wildfire Only plots appears to be driven by more severe burning in the overstory.

Table 9. Comparison of plot burn history to composite burn indices assessed two years after the Swan Lake Fire.

	Wildfire Only		Wild and Prescribed Fire	
Composite Burn Index	average	*standard deviation*	average	*standard deviation*
Plot CBI	2.43	*0.20*	1.88	*0.32*
Substrate CBI	2.14	*0.40*	1.86	*0.49*
Understory CBI	2.28	*0.32*	1.85	*0.36*
Overstory CBI	2.69	*0.34*	1.97	*0.42*

Burn severity was significantly lower in prescribed fire plots (Wilcoxon rank sum test, W = 8, *p* value = 0.006787), but these plots also had more variability in CBI scores (Figure 7). Plots FMHMC-08 and FMHMC-03 were excluded from the analysis due to incomplete burning in 2002 or 2019, respectively.

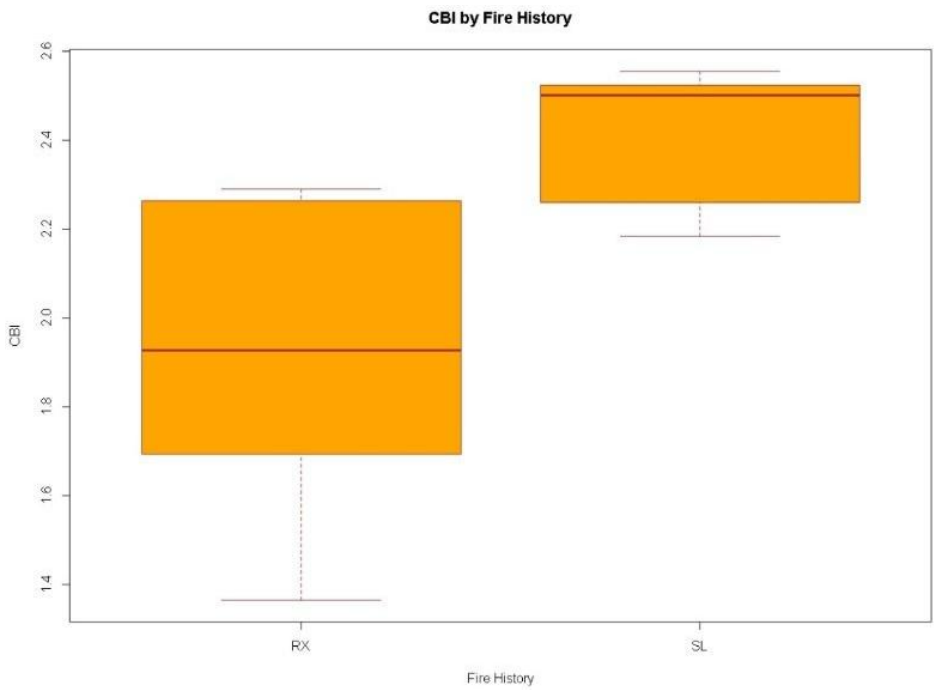

Figure 7. Boxplots of Mystery Creek CBI scores. RX indicates plots that were prescribed burned and burned by Swan Lake Fire. SL indicates plots were burned by Swan Lake Fire alone. Plots that were partially burned in either event were excluded.

Comparison of Severity following Prescribed Burn and Wildland Fire

The ten plots in the Mystery Creek burn units for which burn severity was assessed for the substrate and understory vegetation following both prescribed burning in 2002 and the Swan Lake Fire in 2019 were evaluated to see if past severity could predict future severity. When converted to CBI, burn severity assessed after the 2002 prescribed burn ranged from 1.0 (low) to 2.3 (moderate). The burn severity of plots assessed after the Swan Lake Fire was comparatively higher, ranging from 1.3 (low) to 2.8 (high). No significant relationships were found between burn severity of 2002 prescribed burns and the 2019 Swan Lake Fire; linear regression shows that only 26 percent of the variation in CBI scores assessed in 2021 is explained by burn severity data collected in 2004 (Figure 8). Absence of a relationship between past and present burn severity may relate to differences in methodology (line point versus whole plot assessment of fire severity), the translation of burn severity to CBI, or insufficient statistical power of few plots and absence of overstory severity data. More broadly, the weak association between the severity of successive fire events illustrates the complexity of predicting fire effects.

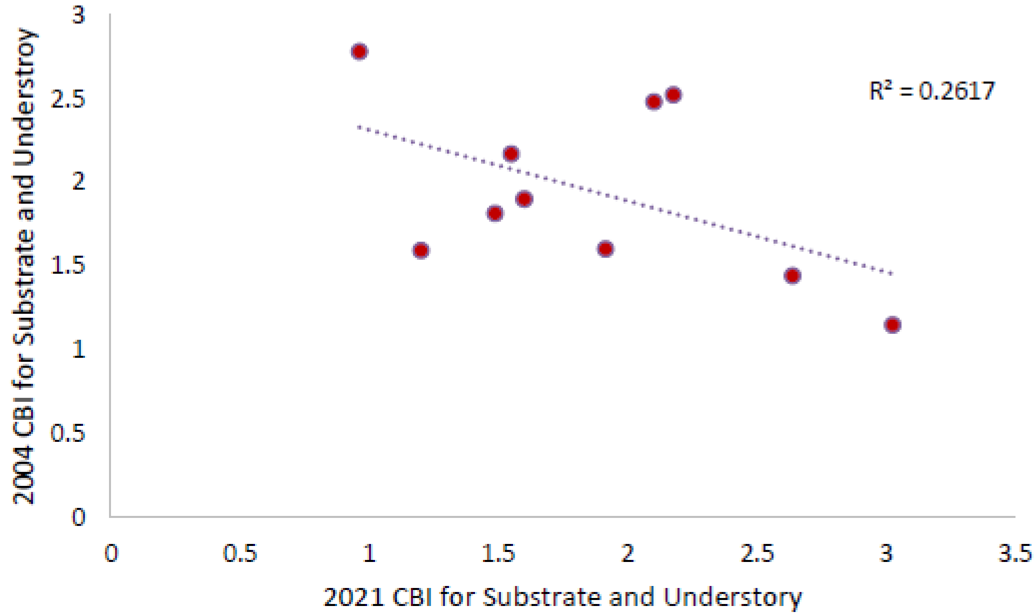

Figure 8. Linear regression of composite burn indices assessed in 2004 following the 2002 prescribed burn to those assessed in 2021 following the 2019 Swan Lake Fire.

Duff Consumption

Estimated 2019 organic layer thickness prior to the Swan Lake Fire (including litter and moss layers) averaged 8.7 cm in Wild and Prescribed Fire plots and 10.1 cm in Wildfire Only Mystery Creek plots (Table 10). Plots FMHMC-03 and FMHMC-08 were excluded due to incomplete burning in one fire event. Estimated organic layer depth following the Swan Lake fire was 5.2 cm (40.2% consumption) in Wild and Prescribed Fire plots and 6.2 cm (38.6% consumption) in Wildfire Only plots. It was sometimes difficult to find adventitious roots in severely burned sites or areas without standing spruce, contributing to uncertainty about the estimates at these sites.

Organic layer thickness was not available for the two Hidden Creek plots prior to the 1996 fire, but when established in 1997 they had relatively high means of 8.5 cm (SE=0.69) and 18.9 cm (SE=3.0) for FMHHC-01 and FMHHC-02, respectively. The Swan Lake Fire had almost completely removed the organic layer in these plots, illustrating the extreme dryness and high availability of fuels for burning when the fire reached this area in September.

Table 10. Estimated organic layer thickness in Mystery Creek Plots, 2021.

	2019 Pre-fire Organic Layer Thickness (cm)		**2021 Post-fire Organic Layer Thickness (cm)**		**Organic Matte Consumption**	
Plot Type	average	*standard deviation*	average	*standard deviation*	(cm)	%
Wild and Prescribed Fire	8.7	*1.6*	5.2	*1.2*	3.5	40.2
Wildfire Only	10.1	*1.2*	6.2	*1.3*	3.9	38.6

Tree, Seedling, and Tall Shrub Density

The number of live spruce trees was negligible, except for Plot FMHMC-03, prescribed burned in 2002 but only partially burned by Swan Lake. It contained 90 live trees (48 white spruce, 15 black spruce, and 27 aspen) within the smaller 5-m radius tree subplot. Aspen, predominantly originating as suckers, were found in 8 of the Mystery Creek Plots, including FMHMC-03. Numbers varied, from single individuals to 184 tree-sized aspens counted in the 10-m radius plot of FMHMC-15. Despite numerous Alaska birch sprouts, none were tall enough to be considered trees thus all were counted as seedlings.

No trees were found in the two Hidden Creek plots and the only seedlings were birch, likely seeded in from neighboring portions of the Hidden Creek fire that did not reburn in 2019 (Figure 9). One Hidden Creek plot contained aspen trees pre-fire but no seedlings/suckers were detected as most of the plot burned to mineral soil, killing roots.

Black spruce and/or Alaska birch seedlings were found to varying degrees in all Mystery Creek plots except for FMHMC-24 where no seedlings were detected in subplots. Plots fully burned by both prescribed fire and the Swan Lake Fire contained fewer black spruce seedlings than Wildfire Only plots (Figure 9). No spruce seedlings were found in 6 of these plots, possibly because few spruces survived the prescribed burn and resulting seedlings were not sexually mature by 2019. FMHMC-03 had a high density of mature (>10 cm but <1. 37 m) spruce seedlings in addition to trees. Of the 286 aspen seedlings counted, 13% were immature (<10 cm tall), 48% were mature, and 39% were suckers of any size <1.37 m. One plot, FMHC5-96, did not contain any aspen trees but had immature and mature aspen seedlings, suggesting that regeneration from seed can occur without an aspen tree being immediately present.

A total of 98 living tall shrubs, all willows, were found in 13 of the full 10-m radius plots. The number of shrubs per plot ranged from 1 – 30 and was highly variable (mean=14, SD=25.5). Ninety-five percent were classified as resprouts and the remainder were mature.

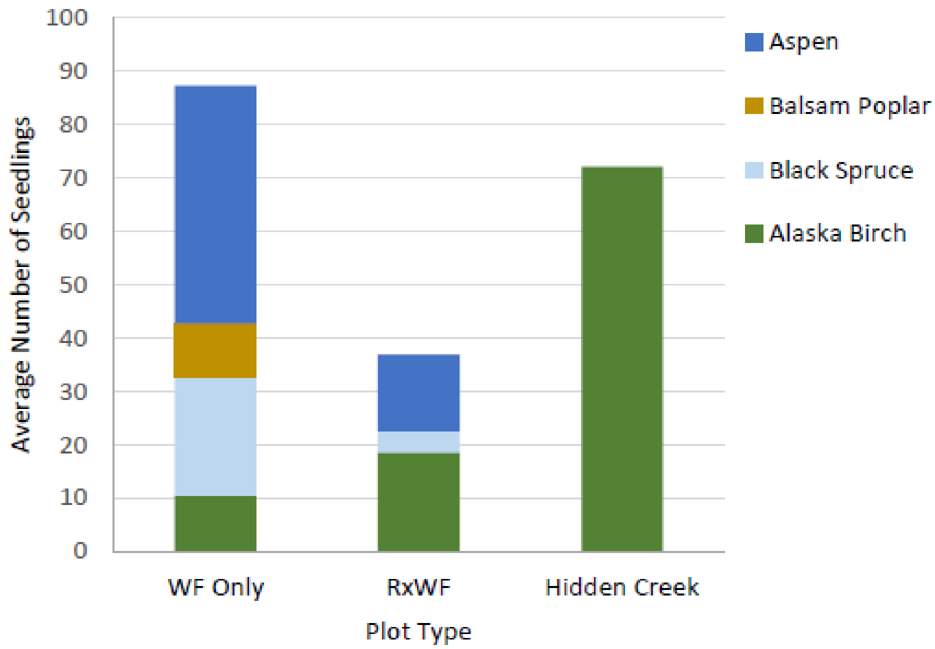

Figure 9. Average number of seedlings by plot type and species.WF Only = wildfire only, RxWF = prescribed plus wildfire. Plots with partial burns are not included.

Surface Fuels

A comparison of dead and down fuel volumes between burn categories two years after the Swan Lake Fire shows that Wildfire Only plots had more woody debris (2.28 kg/m^2) than Wild and Prescribed Fire plots (0.79 kg/m^2), excluding plots known to have partially burned in one event (FMHMC-03 and FMHMC-08). Hidden Creek plots had the highest total volume of woody debris, 4.81 kg/m^2 averaged across the two plots, mostly occurring as 1000-hour fuels.

Mystery Creek plots that burned only during the Swan Lake Fire contained almost twice the average fuel volume relative to plots that had experienced both wild and prescribed burns (Table 11). Most of the volume in Wildfire Only plots was in coarse woody debris (1000-hour fuels), possibly due to a greater number of spruce trees pre-fire that fell during the fire or in the subsequent two years. Coarse woody debris resulting from prescribed fire was likely consumed during the Swan Lake Fire. Most (70%) of the 1000-hr fuels in the Wildfire Only plots were rotten, perhaps suggesting the presence of decaying wood from the 1947 fire. Biomass of 1000-hour fuels in the Wild and Prescribed Fire plots was similar between the two categories (0.06 kg/m^2 sound vs 0.07 kg/m^2 rotten), suggesting that older downed wood was consumed during the prescribed fire.

Table 11. Comparison of Mystery Creek plot burn history to surface fuel volumes estimated two years after the Swan Lake Fire. Plots partially burned by prescribed fire or wildfire are not included.

	Wildfire Only		Wild and Prescribed Fire	
Timelag Category (kg/m^2)	average	*standard deviation*	average	*standard deviation*
all fuels	0.55	*0.23*	0.67	*0.61*
1-hr fuels	0.05	*0.04*	0.02	*0.02*
10-hr fuels	0.12	*0.11*	0.08	*0.05*
100-hr fuels	0.39	*0.20*	0.56	*0.59*

Indicator Analysis

We performed indicator analysis to identify the substrate types, plant life forms, and plant taxa characteristics of plots categorized by either fire severity or burn history. Indicator analysis evaluates the abundance and frequency of a response variable to calculate a percent of perfect indication. For example, a value of 100 would be assigned to specialist species that occurs exclusively in a given category at high abundance whereas a low indication value would be assigned to a generalist species that occurs at low abundance among all categories. Because indicator values will vary according to the number of categories (e.g., fire severity, burn history) defined, units (i.e., plots) sampled, and response variables (e.g., species cover, tree and shrub densities) measured, there is no threshold value for interpretation. In this analysis we list all response variables (Tables 12, 13), but focus our discussion on those with indicator values greater than 40.

When grouped by categories of fire severity (Table 12), plots that were severely burned in the 2019 Swan Lake Fire were in 2021 characterized by high percent covers of woody litter, ruderal species such as fireweed (*Chamerion angustifolium*), the liverwort *Marchantia polymorpha,* and fire moss (*Ceratodon purpureus*). High densities of Alaska birch seedlings also indicate these severely burned plots. Plots that were moderately burned in the Swan Lake Fire are characterized by high cover of dwarf shrubs such as lingonberry (*Vaccinium vitis-idaea*) and bog blueberry (*Vaccinium uliginosum*) and forbs, specifically nitrogen-fixing Nootka lupine (*Lupinus nootkatensis*). The mid-successional bluejoint reedgrass and high densities of dead Alaska birch trees and live willow (*Salix* spp.) shrubs also indicate the moderate CBI category. Less severely burned plots are indicated by high cover of tree, shrub, and herbaceous litter – from vegetation killed during the fire as well as litter from surviving plants – as well as typical boreal forest species such as black spruce, feathermoss, lichen, Alaska birch, quaking aspen, and willow species. With respect to tree and shrub densities, live quaking aspen trees and seedlings, dead quaking aspen trees, and live white spruce trees have potential to indicate these low severity plots.

Collectively, these indicators suggest that the most severely burned plots are reset to an earlier successional stage characterized by fast growing forbs and non-vascular and shrub species whose propagules are dispersed by wind and able to establish on mineral soils or in unprotected microsites. Comparatively, less severely plots are more likely to retain characteristics of the pre-fire plant community through the survival of larger, woody species or the regrowth of these species from live root systems.

We also performed indicator analysis on plots grouped by categories of burn history (Table 13). Plots burned by the 1947 Kenai and 2019 Swan Lake fires have a longer interfire period and are characterized by high covers of duff, woody litter, dwarf shrub, and total non-vegetated area. With respect to species, the dwarf shrub, dogwood bunchberry (*Cornus canadensis*), fireweed, and Altai grass (*Festuca altaica*) also have indication potential. High density of live black spruce seedlings, yet dead black spruce trees, further indicate the Wildfire Only plots in Mystery Creek. Wild and Prescribed Fire plots have a shorter interfire period and are characterized by a greater diversity of life forms, substrates, and species including: shrubs, litter, forbs, total non-vascular cover, and graminoids. With respect to species, high covers of Alaska birch, Nootka lupine, willow species, bluejoint reedgrass, fire moss, other, unspecified moss species, and lingonberry have potential to indicate the plots that have experienced both wild and prescribed fire.

Collectively these indicators suggest Mystery Creek Wildfire Only plots appear to be recovering towards spruce-aspen mixed stands whereas Wild and Prescribed Fire plots appear to be recovering towards birch-dominated stands with a willow understory.

Ecological Gradients

Nonmetric multidimensional scaling (NMS) was used to visually demonstrate the separation of plots based on plant species composition and their relation to the most influential site variables. In ordination space, plots located closer together are more similar with respect to the type and abundance of species they support. Site variable vectors are not involved in the analysis but are overlain to indicate the direction of increasing abundance or magnitude of the association with the ordination axes.

We ordinated species covers among plots against site variables to explore the relationships between post-fire plant communities and measures of burn history, fire severity, and fuel volume. We selected a three-dimensional solution with stress of 10.8 and axes explaining 50.4, 11.3, and 22.8 percent of the variation within the dataset for interpretation (Figure 10). We interpret the primary axis (Axis 1) as a fire severity gradient where percent duff consumed, CBI, and total fuel volumes increase to the right. We interpret the secondary axis (Axis 3) as a fire frequency gradient where the time between the 2019 Swan Lake and the next most recent fire increases upwards along the axis.

Three species are significantly correlated to the fire severity gradient; the abundance of fireweed ($r = 0.69$) increases with increasing severity whereas the abundances of Nootka lupine ($r = -0.68$) and field horsetail (*Equisetum arvense*, $r = 0.57$) increase with decreasing severity. Owing to its prolific seed production, adaptation to mineral soils, and capacity to resprout from rhizomes, fireweed often forms a monoculture following severe burns. As a member of the pea family, lupine is able to fix atmospheric nitrogen and in this way is well-adapted to impoverished soils but,

Table 12. Substrate types and life forms organized by decreasing potential to indicate plots grouped by composite burn index; the high, moderate, and low CBI categories are represented by 9, 9, and 3 plots, respectively.

High CBI	**Moderate CBI**	**Low CBI**
Woody Litter (57.5)	Dwarf Shrub (50)	Tree (77.9)
Non-vascular (37.5)	Forb (47.5)	Shrub (51.1)
Rock (20.6)	Duff (40.2)	Herbaceous Litter (44.5)
Ash (11.1)	Graminoid (37)	

Table 13. Plant species, and tree and shrub densities organized by decreasing potential to indicate plots grouped by composite burn index; the high, moderate, and low CBI categories are represented by 9, 9, and 3 plots, respectively.

High CBI	**Moderate CBI**	**Low CBI**
Chamerion angustifolium (59.0)	*Lupinus nootkatensis* (59.8)	*Picea mariana* (66.7)
Marchantia polymorpha (53.0)	*Vaccinium vitis-idaea* (55.0)	Feathermoss (65.1)
Ceratodon purpureus (45.9)	*Calamagrostis canadensis* (40.6)	Lichen (65.1)
Equisetum sylvaticum (27.5)	*Vaccinium uliginosum* (25.0)	*Betula neoalaskana* (60.9)
Rosa acicularis (22.2)	*Equisetum arvense* (22.2)	*Populus tremuloides* (57.1)
Cornus canadensis (11.1)		*Salix* spp. (56.6)
Linnaea borealis (11.1)		Moss (42.5)
		Ledum groenlandicum (38.3)
		Empetrum nigrum (33.3)
		Picea glauca (30.8)
		Polytrichum commune (22.7)
		Arctostaphylos uva-ursi (22.2)
		Festuca altaica (20.7)
		Geocaulon lividum (16.7)
		Salix barclayi (16.7)

Table 14. Tree and shrub densities organized by decreasing potential to indicate plots grouped by composite burn index; the high, moderate, and low CBI categories are represented by 9, 9, and 3 plots, respectively.

High CBI	Moderate CBI	Low CBI
Live *Betula neoalaskana* seedling (44.8)	Dead *Betula neoalaskana* sapling (44.5)	Live *Populus tremuloides* tree (74.1)
Dead *Picea mariana* sapling (40.5)	Live *Salix* shrub (43)	Dead *Populus tremuloides* sapling (68)
Dead *Picea mariana* tree (25.0)		Live *Picea glauca* sapling (66.7)
Live *Populus balsamifera* seedling (11.1)		Live *Picea glauca* tree (66.7)
Live *Alnus* shrub (11.1)		Dead *Picea glauca* sapling (65.3)
Live *Populus trichocarpa* seedling (10.6)		Live *Populus tremuloides* sapling (46.2)
		Live *Populus tremuloides* seedling (42.7)
		Live *Picea mariana* sapling (32.6)
		Live *Picea mariana* tree (30.8)
		Live *Picea mariana* seedling (29.5)

Table 15. Substrate types and life forms organized by decreasing potential to indicate plots grouped by categories of burn history; the ‘Wildfire Only’ and ‘Wild and ‘Prescribed Fire’ categories are represented by 8 and 10 plots, respectively.

Wildfire Only	Wild and Prescribed Fire
duff (70.0)	shrub (71.8)
woody litter (61.5)	litter (67.0)
dwarf shrub (54.9)	forb (61.0)
total non-vegetated (52.5)	total non-vascular (58.4)
rock (11.0)	graminoid (43.4)
	tree (42.9)

Table 16. Plant species organized by decreasing potential to indicate plots grouped by categories of burn history; the 'Wildfire Only' and 'Wild and 'Prescribed Fire' categories are represented by 8 and 10 plots, respectively.

Wildfire Only	**Wild and Prescribed Fire**
Cornus canadensis (73.5)	*Betula neoalaskana* (70.0)
Chamerion angustifolium (58.6)	*Lupinus nootkatensis* (67.7)
Festuca altaica (40.0)	*Salix* spp. (63.4)
Marchantia polymorpha (39.7)	*Calamagrostis canadensis* (57.9)
Populus tremuloides (29.7)	*Ceratodon purpureus* (57.6)
Rosa acicularis (13.9)	moss (47.3)
Carex canescens (12.5)	*Vaccinium vitis-idaea* (47)
Linnaea borealis (12.5)	*Ledum groenlandicum* (38.6)
Equisetum sylvaticum (8.2)	lichen (30.0)
	Arctostaphylos uva-ursi (30.0)
	Geocaulon lividum (30.0)
	Polytrichum commune (26.6)
	Vaccinium uliginosum (26.3)
	feathermoss (20.0)
	Equisetum arvense (20.0)
	Salix barclayi (20.0)
	Picea mariana (10.0)
	Picea glauca (10.0)

Table 17. Tree and shrub densities organized by decreasing potential to indicate plots grouped by categories of burn history; the 'Wildfire Only' and 'Wild and 'Prescribed Fire' categories are represented by 8 and 10 plots, respectively.

Wildfire Only	**Wild and Prescribed Fire**
Live *Picea mariana* seedling (79.9)	Live *Salix* shrub (93.6)
Dead *Picea mariana* sapling (77.2)	Dead *Betula neoalaskana* sapling (77.5)
Dead *Picea mariana* tree (50.0)	Live *Betula neoalaskana* seedling (64.9)
Live *Populus tremuloides* seedling (43.3)	Live *Populus tremuloides* tree (23.3)
Dead *Populus tremuloides* sapling (33.1)	Live *Picea mariana* sapling (20.0)
Live *Populus tremuloides* sapling (32.9)	Live *Picea mariana* tree (20.0)
Live *Populus trichocarpa* seedling (25.0)	Live *Picea glauca* sapling (10.0)
Live *Populus balsamifera* seedling (12.5)	Live *Picea glauca* tree (10.0)
	Dead *Picea glauca* sapling (7.6)

different from fireweed, requires more organic material and moist to mesic soil conditions to thrive. Both lupine and field horsetail readily resprout from the caudex or rhizomes, respectively, following fire. Bunchberry dogwood (r = -0.68), a mid to late successional species that readily regenerates from rhizome, is the only species significantly correlated to the fire frequency gradient where its abundance increases with longer period between recent fires. Although not significantly correlated, fire moss (r = 0.57) shows the strongest relationship to the opposite end of the fire frequency gradient with its abundance increasing with shorter period between recent fires. As the wind-dispersed spores of fire moss readily germinate on exposed mineral soil, it is often the dominant ground cover for several years following high-severity fire (Tesky 1992).

When categorized by burn history, plots characterized by species cover segregate well in multivariate space. Plots burned by the Kenai and Swan Lake fires only are characterized by a longer interval between fires, and/or greater fuel volume, percent duff consumption, and plot-level CBI. Presumably, the accumulation of organic material over a longer period between fires and more severe burning in 2019 contributes to the high percent of duff consumption. The greater total fuel volume characterizing these wildfire-only plots may relate to trees, limbs, and branches falling in the two years since fire, and thus being captured in the quantification of downed woody debris. Comparatively, plots that were burned by prescribed fire between the Kenai and Swan Lake fires are characterized by a shorter interfire period, and/or lesser total fuels, lower plot-level CBI, and lower duff consumption. The lesser duff consumption seen in these wild and prescribed fire plots might be due to less severe burning in 2019 but might be additionally explained by the lesser time for organic material to accumulate between fires, which could make these plots more susceptible to burning to mineral soil.

Images in Figure 11 show extremes of fire severity and frequency, and are positioned to approximate the plot locations in multivariate space. Along the horizontal fire severity gradient, plot FMHMC-12 shows low severity and high Nootka lupine (upright forb bearing seed pods) abundance, while to the right, plot FMHHC-01 provides an example of high severity and fireweed (pink flowers) abundance. Along the vertical, fire frequency gradient, plot FMHMC-24 provides an example of a plot with longer period between the two most recent fires and high bunchberry dogwood (shiny green leaves and low growing in foreground) abundance, whereas plot FMHMC-19 shows a plot with shorter period between most recent fires and abundance of fire moss (orange tinged turf moss).

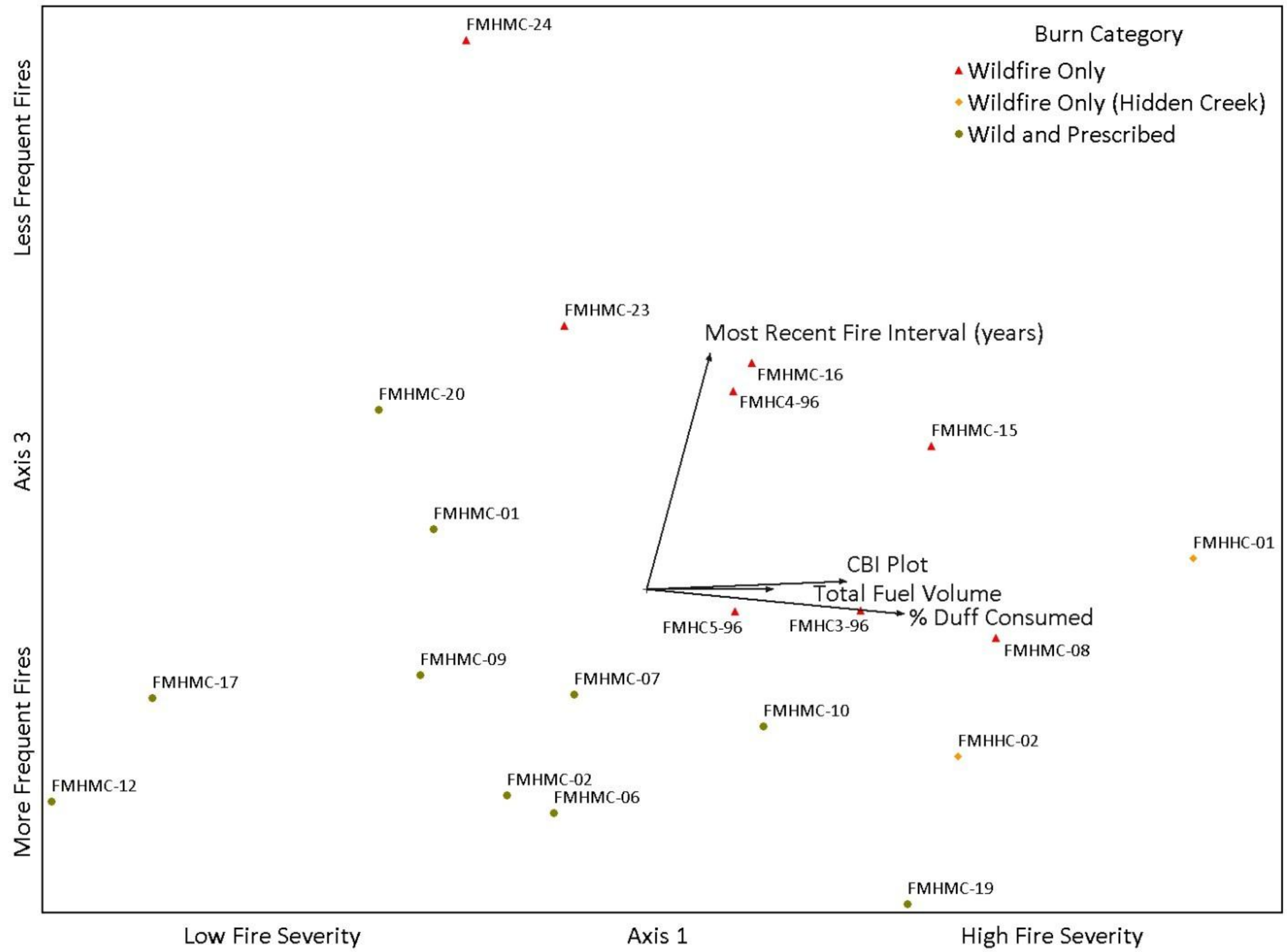

Figure 10. Nonmetric Multidimensional Scaling (NMS) ordination of species composition by plot with plots symbolized by category of burn history and significant site variables overlain in a joint biplot. Axis 1 is interpreted as a gradient of plot CBI, Axis 3 is interpreted as a gradient of fire frequency.

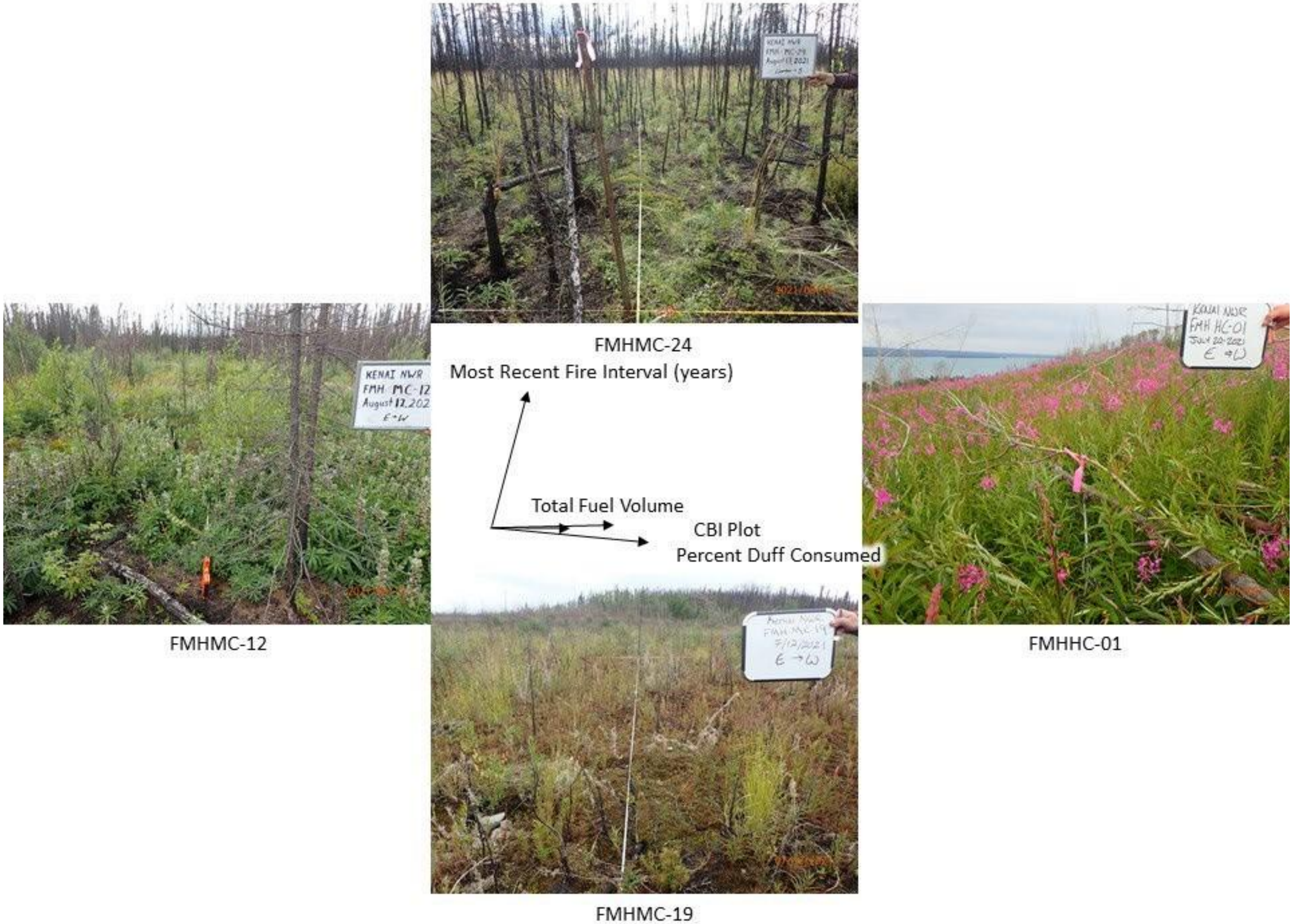

Figure 11. Plot photographs representing gradient extremes identified in the ordination of plots by species composition.

Successional Trajectory

We examined the type and density of trees (live and dead by species), tree seedlings, and tall shrubs to explore the post-fire regeneration of woody species and potential successional trajectory of plots. We selected a three-dimensional NMS solution with stress of 8.9 and axes explaining 34.1, 32.7 and 18.3 percent of the variation in the dataset for interpretation (Figure 12). Unsurprisingly, the site variables that are significantly related to woody species survival and establishment are largely related to substrate condition and pre-fire canopy composition. The primary axis (Axis 1) is difficult to interpret using a single variable. It tends to have a gradient of substrate burn severity where the left side includes plots with severely burned duff and non-vasculars that, two-years post fire, supported a high cover of forbs. Some plots with moderate substrate burn severity are located on the left side of Axis 1, however, and the right side includes plots with moderate-high substrate severity. Plots experiencing a longer period between the two most recent fires support high cover of duff and trees and are located to the right. We interpret the secondary axis (Axis 2), which is correlated to overstory fire severity, as a gradient of canopy composition with plots dominated by more flammable needleleaf species located towards the top and plots dominated by less flammable broadleaf species located towards the bottom of the axis.

With respect to vegetation recovery, density of tall willows ($r = -0.57$) is significantly correlated to Axis 1 where it is highest in plots associated with higher substrate burn severity. As 95% of the tall willows were sprouts from existing rootstock, plots with a higher density contained mature individuals pre-fire and a burn severity high enough to top-kill existing willows but not high enough to kill the roots. Density of live black spruce seedlings ($r = 0.743$) and quaking aspen trees ($r = 0.60$) are significantly correlated to the right side of Axis 1. These plots tended to be Mystery Creek Wildfire Only plots, which supported mature black spruce trees capable of producing viable seeds. Torching was common in these plots, but spruce seed held in the canopy was not killed. Substrate burn depth was not sufficient to kill aspen root stock such that regrowth could occur from suckering or by seed. Reduced aspen regeneration has been associated with competition from post-fire forbs and shrubs (Jean et al. 2020), which may also explain increased abundance in sites with lower substrate severity.

Live quaking aspen sucker density ($r = -0.56$) is significantly correlated to the broadleaf canopy end of Axis 2 and is associated with a less severely burned overstory. While not significant, dead and live quaking aspen tree densities are also strongly associated with the lower end of Axis 2 suggesting that established stands of aspen which are able to survive fire, or at least have surviving root systems, may provide the source of seed or suckers for aspen regrowth. Dead black spruce tree densities are significantly correlated to the needleleaf canopy end of Axis 2 where Wildfire Only plots are correlated to a severely burned overstory. Prescribed burn plots tended to have more deciduous trees that did not torch, resulting in lower overstory severity, and young black spruce with immature seed. Self-replacement of black spruce forest is therefore most likely to occur in plots that were not prescribed burned as they had an opportunity to produce mature seed in the interval between the 1947 Kenai and 2019 Swan Lake fires.

When categorized by burn history, plots characterized by tree and shrub densities segregate reasonably well in multivariate space. Most Wildfire Only plots are associated with a more severely burned overstory and greater post-fire cover of duff and trees; whereas most Wild and Prescribed

Fire plots are associated with higher CBI for duff and non-vasculars and greater post-fire cover of forbs.

Different from the clustering of plots based on species covers (Figure 10) where the Hidden Creek plots grouped with Wildfire Only plots, clustering based on tree and shrub densities associates the Hidden Creek plots with the Wild and Prescribed Fire plots (Figure 12). We interpret this different placement as the general response of forb growth to severely burned substrate compared to the species-specific response of fireweed and lupine to plot-level CBI.

The somewhat diffuse location of plots categorized by wildfire only versus those experiencing wild and prescribed fire (or variations thereof) suggests that the type of tree and shrub species that establish and survive on plots is influenced by a variable not captured in our study. Proximity to seed/rootstock source is a major driver of tree and shrub establishment and growth, and is a likely candidate for the explanation of seedling, tree, and shrub density. The original FMH methodology involved larger plot size and mapping of trees within the plot, which would have provided more information about potential sources of tree regeneration. If this type of information is desired, we recommend reverting to these methods.

Images in Figure 13 show extremes of substrate burn severity and canopy composition, and are positioned to approximate the plot locations in multivariate space. Along the horizontal axis, plot FMHMC-09, shows high cover of forbs (note blue-flowered lupine) supports the highest density of tall willows. To the right, plot FMHMC-03, which burned incompletely in the 2019 Swan Lake Fire, provides an example of a less frequently burned plot that supports the highest density of spruce seedlings (note the abundance of live spruce). Along the vertical axis, plot FMHMC-23 shows a severely burned, spruce dominated overstory, as indicated by torching (blackened) and trees killed by heat. This plot supports the second highest density of dead spruce trees (surpassed only by plot 24 shown in Figure 11) and one of the highest densities of dead black spruce trees, but the understory was only partially burned and has low to moderate burn severity for the substrate and herbs, and low shrubs and trees strata (i.e., Stratum B). This suggests a crown fire that did not burn deeply into the duff, allowing survival of roots and regrowth of shrubs. Plot FMHC3-96 shown at the bottom, provides an example of a less severely burned, quaking aspen dominated overstory which supports the greatest density of quaking aspen seedlings/suckers (note live quaking aspen tree in picture).

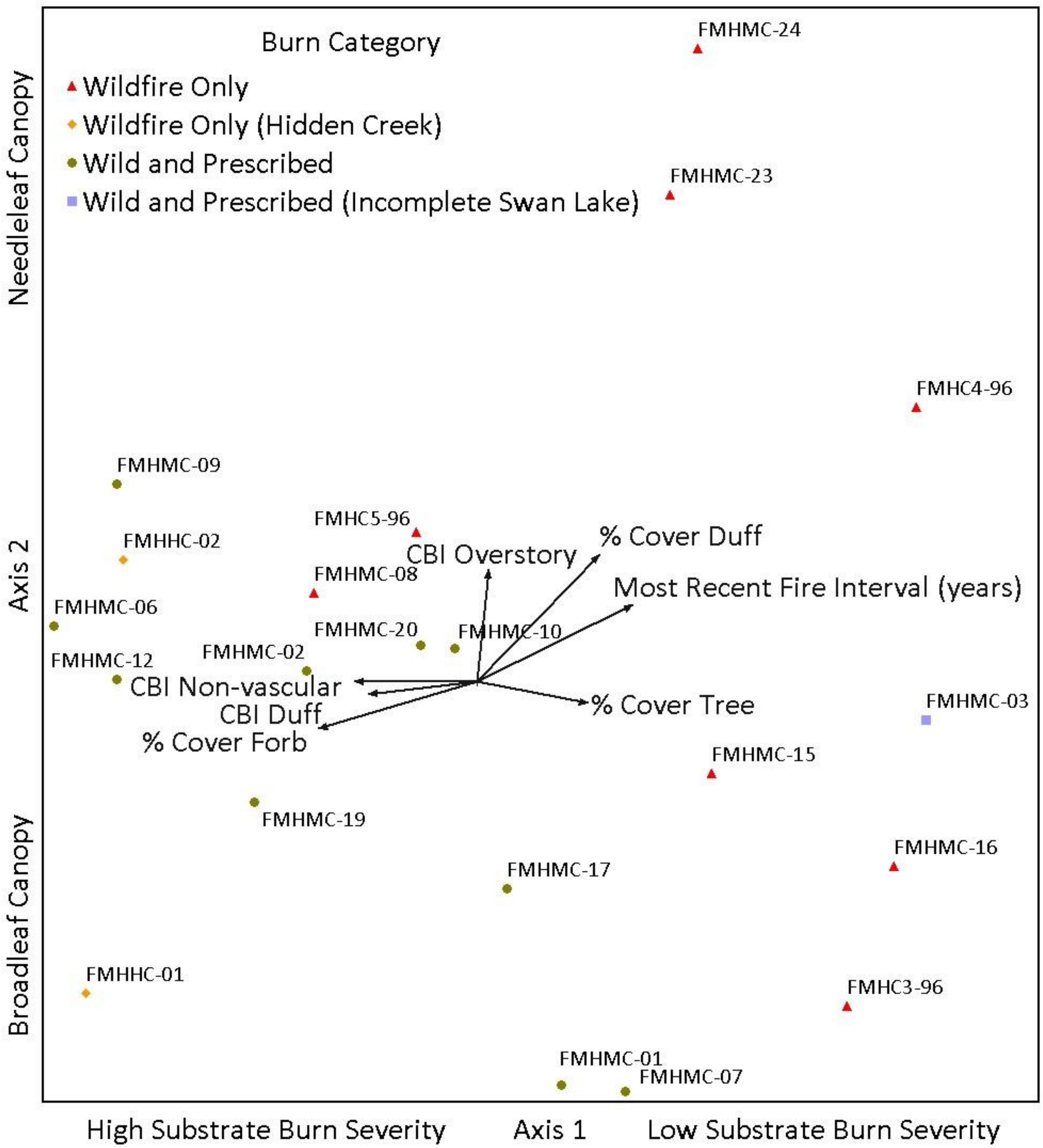

Figure 12. Nonmetric Multidimensional Scaling (NMS) ordination of tree and shrub species density by plot with plots symbolized by category of burn history and significant site variables overlain in a joint biplot. Axis 1 is interpreted as a gradient of substrate burn severity, Axis 2 is interpreted as transition in overstory canopy composition.

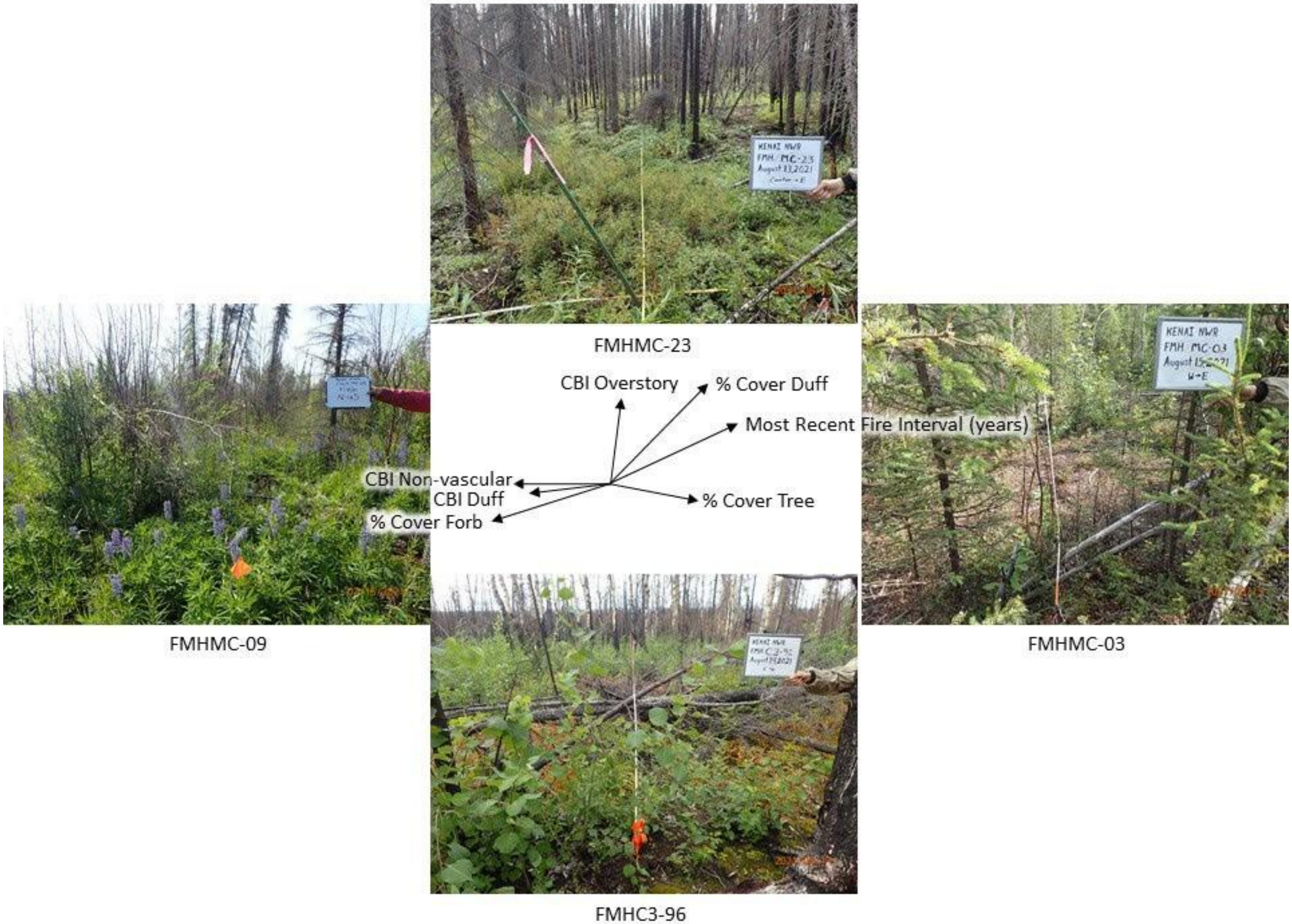

Figure 13. Plot photographs representing gradient extremes identified in the ordination of plots by tree and shrub species density.

Discussion

Assessment of permanent vegetation and fuels plots two years following the 2019 Swan Lake Fire illustrate the importance of fire frequency, fire weather, pre-fire canopy, and burn severity in driving current site condition and influencing successional trajectory. Plots burned by prescribed fire 1998-2002 tended to have a strong deciduous tree and shrub component, had lower overall burn severity, and supported a greater diversity of plant species and life forms in 2021 than plots burned only by Swan Lake. Species found in these plots are typical of mid-successional boreal shrublands and include Alaska birch, willows, Nootka lupine, bluejoint reedgrass, and fire moss. Alternatively, Mystery Creek plots that were not prescribed burned and plots burned by the 1996 Hidden Creek Fire were more severely burned by the Swan Lake Fire and were characterized by a lower diversity of species which were largely restricted to understory strata by 2021. Species indicating these less frequently burned plots are fire-adapted and colonizing species such as bunchberry dogwood, fireweed, Altai grass and *Marchantia* liverwort. Only two substrates, woody litter and duff, are characteristic of the less frequent, more severe burns.

The influence of fire frequency and severity on plot condition was supported by multivariate analysis. Plots that have been burned less frequently (1947 or 1996 and 2019) cluster in the ordination space characterized by higher fire severity and abundance of fireweed, whereas plots that have burned more frequently (1947, prescribed fire, and 2019) are located in the ordination space characterized by lower fire severity and abundance of Nootka lupine and bunchberry. With respect to successional trajectory, substrate burn severity and pre-fire canopy composition have the greatest influence on the type and success of woody species establishment and/or regrowth.

Assessment of fire effects from this study is limited by a small sample sizes and variability within the plots in terms of fire history and burn severity. Results, however, provide insight that can inform fire management approaches and expectations of future conditions. The successional analysis of post-fire vegetation presented here supports the maintenance of mid-successional habitats by more frequent, less severe fires. In the KNWR, mid-successional habitats are characterized by a diversity of species, multiple vegetation strata and patchy distribution of types. In addition to the provision of valuable structural habitat, the plant species that dominate these habitats (e.g., willow, birch, aspen, cottonwood) provide browse for moose and hare. As climate change is both extending the fire season and increasing fire activity (Walker et al. 2021), the likelihood of these broadleaf-dominated plots experiencing a fire event prior to transition to a coniferous phase becomes greater. Such increased stochaism leads to dominance of plants with broad ecological amplitude that can survive and reproduce under highly variable spatial and temporal conditions. The potential for fire-mediated diversion of successional trajectory from coniferous to broadleaf forests excludes the eventual establishment of long-lived perennials that provide crucial stability to ecosystems, thereby threatening the long-term resilience of the broader ecosystem (Baltzer et al. 2021, Hughes et al. 2019). In this study, few black spruce seedlings in plots reburned within 23 years versus high densities in plots that had not burned in 72 years supports research indicating that fire return intervals shorter than 30 years can limit the availability of sufficient mature seed required for black spruce self-replacement in stands following fire (Baltzer et al 2021, Johnstone et al. 2020). Additionally, Successive fires at intervals too short to allow recovery of the surface organic layer to pre-fire thickness can result in increasingly thinner layers that are more susceptible to deeper burning and alternate post-fire seral trajectories.

Patterns observed in the FMH plots in 2021 will likely persist for an extended period. Johnstone et al (2020) noted a strong relationship between seedling establishment two years post fire in interior Alaska and tree density 13 years post-fire. They also found that deciduous dominance was associated with >30% exposure of mineral soil, an organic layer <3 cm thick, or abundant deciduous trees in the pre-fire stand. None of the Mystery Creek plots had high enough mineral soil exposure expected to instigate a shift in dominance, but some were estimated to have an organic layer less than 3 cm thick and others supported deciduous trees prior to 2019, both characteristics favoring establishment of deciduous species. Exposed mineral soil in severely burned Hidden Creek plots was obscured by dense cover of litter, non-vascular plants, and forbs, but proximity to unburned mixed forest and a high density of Alaska birch seedlings indicate that these plots will regenerate as deciduous forest.

Analysis of post-fire vegetation and severity metrics from the most recent fire are insufficient to fully explain fire effects. Kasischke and Johnstone (2005) noted the complexity of factors influencing the consumption of the surface organic layer including climatic conditions at the time of the fire, previous fire history, and soil moisture, among others. The Hidden Creek Fire and Mystery Creek prescribed burn plots both experienced short-interval repeat burns but their burn severity and subsequent plant communities following the Swan Lake Fire were dramatically different. Portions of the Hidden Creek Fire adjacent to the two plots did not reburn in 2019 and supported a dense hardwood stand with some spruce in 2021 (see photo in Appendix D). The post-fire organic layer when plots were established in 1997 was relatively thick compared to measurements after the Mystery Creek prescribed burns, and there were large numbers of birch and aspen seedlings, suckers, and basal sprouts but few living trees. By 2019, vegetation regrowth and organic layer thickness were unknown, but the organic layer was mostly consumed by the Swan Lake Fire. Extreme values (>110) of the BUI were recorded at the Kenai NWR RAWS for 10 days before the Hidden Creek plots burned, drying the duff to the extent that much was available for burning. Mature white spruce, birch, and aspen in nearby areas fell with little charring of their trunks because the organic soil supporting their roots was consumed. Differences between the response of Hidden Creek versus Mystery Creek plots, despite both experiencing relatively short-interval reburns, illustrate how reporting of fire weather information in addition to vegetation and burn severity characteristics can provide a more complete picture of fire effects and successional trajectory.

The FMH plots on Kenai NWR are a valuable resource for understanding changes in fuels over time and, when they inevitably reburn, response to fire. Suggestions for future study, depending on Refuge objectives, funding, and personnel, include:

- Routine monitoring of these plots is recommended, particularly in the Mystery Creek area, to document changes in vegetation, fuel load, and organic layer development. Bowser (2010) indicated no future plans for resampling Mystery Creek plots beyond the initial visit after prescribed burning. While one visit can determine if burn objectives were met, it is insufficient for assessing vegetation change and fuel buildup over time or response to subsequent fire. Monitoring data will be especially valuable if the Refuge is considering future use of prescribed burns in mature black spruce stands. Sampling frequency will depend on objectives and capacity and could include selection of additional FMH plots not sampled in 2021 if needed. Work with the regional Fire Management Program for assistance in monitoring the plots. Assess whether the more time-consuming FMH methodology is necessary or if the methods used in this report are sufficient to meet long-term objectives. Investigate the use of terrestrial laser scanners and other remote sensing methods to assess plot characteristics and fuels over time.

- As the proximity to seed source is a major driver of ecological change, future work should quantify the influence of adjacent vegetation types so that the influence of fire can be separated from that of propagule pressure.
- Compare plant community data collected in 2021 to that collected at plot establishment to assess fire-directed successional change over a longer time period.

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Appendices

Appendix A. Relocation and sampling status of FMH plots at the end of the 2021 field season.

Plot Name	Latitude	Longitude	Status
FMH95-01	60.59761	-150.402	Not accessible by road
FMH95-02	60.60528	-150.351	Not able to relocate (KNWR)
FMH95-03	60.6049	-150.394	Not accessible by road
FMH95-04	60.60002	-150.353	Not able to relocate (KNWR)
FMH95-05	60.59774	-150.445	Not accessible by road
FMH95-06	60.60775	-150.404	Not accessible by road
FMH95-07	60.5981	-150.423	Not accessible by road
FMH95-08	60.57637	-150.489	Found (KNWR) not surveyed due to distance from roads
FMH95-09	60.59067	-150.48	Not accessible by road
FMH95-10	60.58676	-150.5	Not accessible by road
FMH95-11	60.58654	-150.521	Not accessible by road, on burn perimeter
FMHC1-96	60.62194	-150.27	Not able to relocate (ACCS)
FMHC2-96	60.65301	-150.276	Not able to relocate (KNWR)
FMHC3-96	60.62454	-150.253	Surveyed in 2021 (ACCS)
FMHC4-96	60.61946	-150.253	Surveyed in 2021 (ACCS)
FMHC5-96	60.61499	-150.265	Surveyed in 2021 (ACCS)
FMHHC-01	60.44202	-150.316	Surveyed in 2021 (USFWS)
FMHHC-02	60.44268	-150.315	Surveyed in 2021 (USFWS)
FMHMC-01	60.62863	-150.279	Surveyed in 2021 (ACCS)
FMHMC-02	60.63672	-150.289	Surveyed in 2021 (USFWS)
FMHMC-03	60.62992	-150.267	Surveyed in 2021 (ACCS)
FMHMC-04	60.64647	-150.255	Not able to relocate (KNWR)
FMHMC-05	60.6466	-150.277	Not able to relocate (KNWR)
FMHMC-06	60.64092	-150.268	Surveyed in 2021 (USFWS)
FMHMC-07	60.65044	-150.268	Surveyed in 2021 (USFWS)
FMHMC-08	60.63754	-150.274	Surveyed in 2021 (USFWS)
FMHMC-09	60.635	-150.288	Surveyed in 2021 (USFWS)
FMHMC-10	60.64158	-150.281	Surveyed in 2021 (USFWS)
FMHMC-11	60.63197	-150.293	Not able to relocate (KNWR, ACCS)
FMHMC-12	60.62771	-150.285	Surveyed in 2021 (ACCS)
FMHMC-13	60.62478	-150.293	Not able to relocate (KNWR, ACCS)
FMHMC-14	60.6249	-150.299	Not able to relocate (KNWR, ACCS)
FMHMC-15	60.6044	-150.299	Surveyed in 2021 (ACCS)
FMHMC-16	60.60412	-150.308	Surveyed in 2021 (ACCS)
FMHMC-17	60.62893	-150.308	Surveyed in 2021 (ACCS)
FMHMC-18	60.61826	-150.326	Not able to relocate (KNWR)
FMHMC-19	60.65217	-150.267	Surveyed in 2021 (USFWS)

Plot Name	Latitude	Longitude	Status
FMHMC-20	60.64184	-150.255	Surveyed in 2021 (USFWS)
FMHMC-21	60.63475	-150.297	Not able to reconstruct (ACCS)
FMHMC-22	60.62224	-150.311	Not able to relocate (KNWR)
FMHMC-23	60.6139	-150.339	Surveyed in 2021 (ACCS)
FMHMC-24	60.60688	-150.334	Surveyed in 2021 (ACCS)
FMHPHLF-01	60.46262	-150.169	Not able to relocate (KNWR)
FMHPHLF-02	60.46617	-150.161	Not able to relocate (KNWR)

ACCS - Alaska Center for Conservation Science, University of Alaska Anchorage; Lindsey Flagstad, Brian Heitz, Sabrina Kessakorn

USFWS - US Fish and Wildlife Service, Regional Office: Lisa Saperstein, Kenya Gates; KNWR - Kenai National Wildlife Refuge; various staff

Appendix B. Locations, centerlines, and fuel transect azimuths in degrees from true north for the plots visited in the 2021 sampling event.

Plot ID	Latitude (dd)	Longitude (dd)	Centerline Azimuth	Transect 1 Azimuth	Transect 2 Azimuth	Transect 3 Azimuth	Transect 4 Azimuth
FMHC3-96	60.62454	-150.253	287	60	276	21	159
FMHC4-96	60.61946	-150.253	240	264	228	18	184
FMHC5-96	60.61499	-150.265	320	90	217	60	348
FMHHC-01	60.44202	-150.316	220	253	344	261	187
FMHHC-02	60.44268	-150.315	138	93	73	310	173
FMHMC-01	60.62863	-150.279	66	355	190	107	144
FMHMC-02	60.63672	-150.289	100	301	351	118	274
FMHMC-03	60.62992	-150.267	274	117	359	186	196
FMHMC-06	60.64092	-150.268	250	160	75	78	190
FMHMC-07	60.65044	-150.268	20	226	88	160	24
FMHMC-08	60.63754	-150.274	140	78	273	34	305
FMHMC-09	60.635	-150.288	52	127	197	331	23
FMHMC-10	60.64158	-150.281	31	287	129	342	76
FMHMC-12	60.62771	-150.285	359	222	194	314	121
FMHMC-15	60.6044	-150.299	29	91	25	21	54
FMHMC-16	60.60412	-150.308	200	96	114	4	126
FMHMC-17	60.62893	-150.308	291	176	318	46	52
FMHMC-19	60.65217	-150.267	295	209	17	82	334
FMHMC-20	60.64184	-150.255	80	283	351	1	82
FMHMC-23	60.6139	-150.339	305	134	192	70	270
FMHMC-24	60.60688	-150.334	296	58	80	342	286

Appendix C. List of plant taxa and substrate types observed during the 2021 sampling event.

Life Form	Species Symbol	Scientific Name	Common Name
Tree	2TreeBase	NA	Base of Tree
Tree	BENE4	*Betula neoalaskana*	resin birch
Tree	PIGL	*Picea glauca*	white spruce
Tree	PIMA	*Picea mariana*	black spruce
Tree	POBA2	*Populus balsamifera*	balsam poplar
Tree	POTR15	*Populus trichocarpa*	cottonwood
Tree	POTR5	*Populus tremuloides*	quaking aspen
Shrub	ALNUS	*Alnus* spp.	alder
Shrub	LEGR	*Ledum groenlandicum*	bog Labrador tea
Shrub	ROAC	*Rosa acicularis*	prickly rose
Shrub	SAAL	*Salix alaxensis*	feltleaf willow
Shrub	SABA3	*Salix barclayi*	Barclay's willow
Shrub	SABE2	*Salix bebbiana*	Bebb willow
Shrub	SAGL	*Salix glauca*	grayleaf willow
Shrub	SALIX	*Salix*	willow
Shrub	SAPU15	*Salix pulchra*	tealeaf willow
Shrub	SOSI2	*Sorbus sitchensis*	western mountain ash
Shrub	SPST3	*Spiraea stevenii*	beauverd spirea
Dwarf Shrub	ARUV	*Arctostaphylos uva-ursi*	kinnikinnick
Dwarf Shrub	COCA13	*Cornus canadensis*	bunchberry dogwood
Dwarf Shrub	EMNI	*Empetrum nigrum*	black crowberry
Dwarf Shrub	PYROL	*Pyrola* spp.	wintergreen
Dwarf Shrub	VAUL	*Vaccinium uliginosum*	bog blueberry
Dwarf Shrub	VAVI	*Vaccinium vitis-idaea*	lingonberry
Forb	CHAN9	*Chamerion angustifolium*	fireweed
Forb	COSE5	*Corydalis sempervirens*	rock harlequin
Forb	EQAR	*Equisetum arvense*	field horsetail
Forb	EQSY	*Equisetum sylvaticum*	woodland horsetail
Forb	GELI2	*Geocaulon lividum*	false toadflax
Forb	LIBO3	*Linnaea borealis*	twinflower
Forb	LUNO	*Lupinus nootkatensis*	Nootka lupine
Forb	LYCO3	*Lycopodium complanatum*	groundcedar
Forb	PELA	*Pedicularis labradorica*	Labrador lousewort
Forb	POAC	*Polemonium acutiflorum*	tall Jacob's ladder
Graminoid	AGSC5	*Agrostis scabra*	rough bentgrass
Graminoid	CACA11	*Carex canescens*	silvery sedge
Graminoid	CACA4	*Calamagrostis canadensis*	bluejoint
Graminoid	DECE	*Deschampsia cespitosa*	tufted hairgrass
Graminoid	FEAL	*Festuca altaica*	Altai fescue
Nonvascular	2LICHN	NA	lichen
Nonvascular	2MOSS	NA	moss
Nonvascular	2MOSSF	NA	feathermoss
Nonvascular	CEPU12	*Ceratodon purpureus*	ceratodon moss
Nonvascular	MAPO16	*Marchantia polymorpha*	NA
Nonvascular	POCO38	*Polytrichum commune*	polytrichum moss
Nonvascular	SPHAG2	*Sphagnum*	sphagnum moss

Life Form	Species Symbol	Scientific Name	Common Name
Other	2ASH	NA	Ash
Other	2BARE	NA	Mineral Soil
Other	2DUFF	NA	Duff
Other	2LTR	NA	Litter
Other	2LTRWL	NA	Litter, woody, >2.5 cm
Other	2RF	NA	Rock, fragments
Other	NoPlants	NA	No vascular plants

NA – Not Applicable

Appendix D. Representative plot photos selected to show different burn histories.

Photo of plot FMHC3-96, which was burned in 1849, by the 1947 Kenai Fire, and by the 2019 Swan Lake Fire; unlike other plots in the Mystery Creek Burn Unit, FMHC3-96 was not prescribe burned in 2002.

Photo of plot FMHC4-96, which was burned in 1849, by the 1947 Kenai Fire, and by the 2019 Swan Lake Fire; unlike other plots in the Mystery Creek Burn Unit, FMHC3-96 was not prescribe burned in 2002.

Photo of plot FMHMC-09, which was burned by the 1947 Kenai Fire, prescribed fire in 2002, and the 2019 Swan Lake Fire; note some black spruce appear to have survived the prescribed burn.

Photo of plot FMHMC-20, which was burned by the 1947 Kenai Fire, prescribed fire in 2002, and the 2019 Swan Lake Fire.

Photo of plot FMHMC-03, which was burned in the 1947 Kenai Fire, in 2002 by prescribed fire, yet incompletely in the 2019 Swan Lake Fire.

Photo of plot FMHMC-03, which was burned in the 1947 Kenai Fire, in 2002 prescribed fire, yet incompletely in the 2019 Swan Lake Fire.

Photo of plot FMHMC-08, showing difference between the fireweed-rich foreground, which was burned in 1947 and 2019 only, and the shrub and tree-rich background, which was burned by the 1947 Kenai Fire, prescribed fire in 2002, and the Swan Lake Fire in 2019.

Photo of plot FMHMC-08, showing the fireweed-rich portion of the plot, which was burned in the 1947 Kenai Fire and the 2019 Swan Lake Fire.

Photo of area near plot FMHMC-08 showing shrub and tree abundance for habitat burned in the 1947 Kenai Fire, by prescribed fire in 2002, and the Swan Lake Fire in 2019.

Photo of plot FMHHC-02, which was burned by the 1996 Hidden Creek Fire and the 2019 Swan Lake Fire.

Photo of plot FMHHC-01, which was burned by the 1996 Hidden Creek Fire and the 2019 Swan Lake Fire.