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Technical Report #64

Fire Effects 10 Years After the Anaktuvuk River Tundra Fires

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Cover Photos

Background photo: *Aerial photo of burn patterns from the 2007 North Slope Anaktuvuk River Fire (7/6/2008)*
Bottom inset photos: *Plot photos of the same severely burned transect from 2008 and 2017, respectively. R.R. Jandt / E.A. Miller (BLM)*

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List of Acronyms

AFS BLM Alaska Fire Service

AICC Alaska Interagency Coordination Center

ARF Anaktuvuk River Fire

ARLIS Alaska Resources Library and Information Services

BLM Bureau of Land Management

DTM Digital terrain models

LTER Long-Term Ecological Research

NRCS Natural Resources Conservation Service (USDA)

TR Technical Report

UAF University of Alaska-Fairbanks

USDA U.S. Department of Agriculture

USGS U.S. Geological Survey

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Abstract

Data on fire effects and vegetation recovery are important for assessing the impacts of increasing temperatures and lightning on tundra fire regimes and the implications of increased fire in the Arctic for wildlife and ecosystem processes. This report summarizes information collected by the Bureau of Land Management (BLM), U.S. Geological Survey, and University of Alaska Fairbanks, as well as other cooperators between 2008 and 2017 on the effects of 2007 tundra fires on Alaska's North Slope.

We monitored vegetation, soil properties, thaw depths, and collected repeat photos on a set of 23 burned transects and 11 unburned reference transects periodically (N=5 visits) between 2008 and 2017 on the Anaktuvuk River and adjacent Kuparuk River fires. Post-fire regrowth of vegetation was rapid for some species such as cottongrass (*Eriophorum vaginatum*) and expansive carpets of fire mosses and liverworts that developed after the first year on severely burned areas. Relative to unburned tussocks, tussocks that experienced burning inside the fire perimeter continue to grow and flower more vigorously after ten years, suggesting a continued increase of soil nutrients, competitional release, or a response to warming at root-level. Other species were declining (*Sphagnum* mosses) or virtually absent (lichens) in the burned areas. Post-fire accumulation of organic material over the first decade was about 5 cm of moss and plant litter. This layer of recently cast fine fuel along with sedge leaf litter carried two small lightning-ignited reburns in early-2017. Shrubs re-established more slowly than herbaceous species: by the tenth year post-fire, cover of deciduous shrubs on burned transects equaled reference transects but that of ericaceous subshrubs still lagged. Species of tall willow appeared to be responding by increases in stature and colonization of thermokarst-affected terrain. Other studies suggest that tundra north of the Brooks Range is responding to climate change with widespread expansion of and dominance by tall shrubs in the absence of fire. Our observations from this burn, as well as at several other older burns, suggest that fire greatly accelerates this succession. Shifts in community species composition seem likely for many years to come in the burn area.

We documented burn severity and effects on permafrost, thaw depth, and surface topography. Field-validated burn severity indices from satellite remote sensing showed that 80% of the fire burned with moderate-to-high severity (Kolden and Rogan, 2013). Thaw depth, pH, temperature, residual organic duff depth, and other soil characteristics were recorded. Burned transects, especially those underlain by yedoma soils (ice-rich Pleistocene permafrost deposits), exhibited substantial subsidence as a result of thermokarst. At some transects, ground-ice melt created ice wedge troughs deeper than 1 m in the first ten years following the burn. Even low severity burn areas experienced notable ground subsidence as evidenced by degrading ice wedges. Mean annual ground temperature at 1 m depth has warmed 1.5°C relative to unburned tundra over the ten years post-burn.

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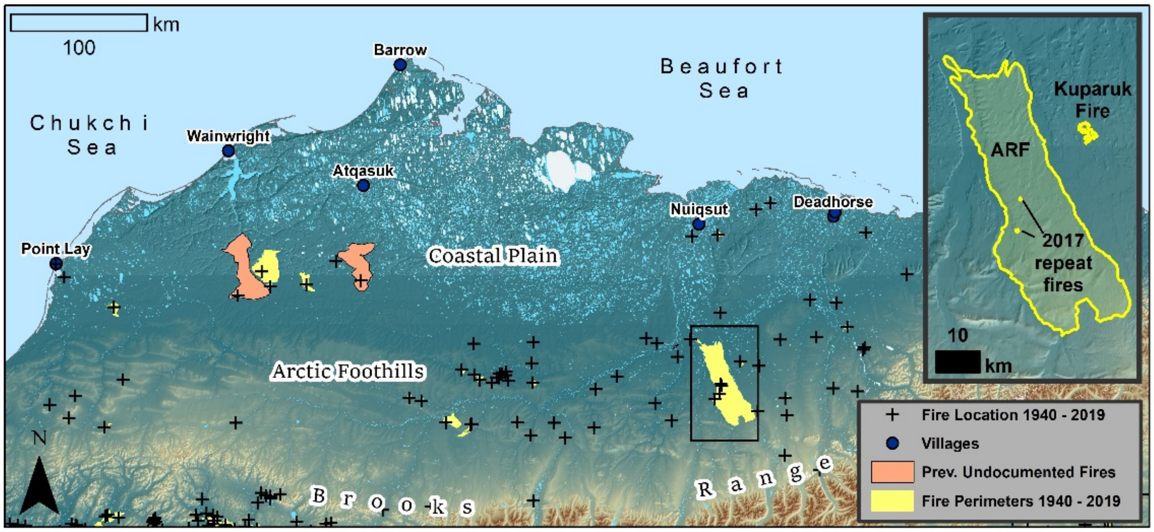
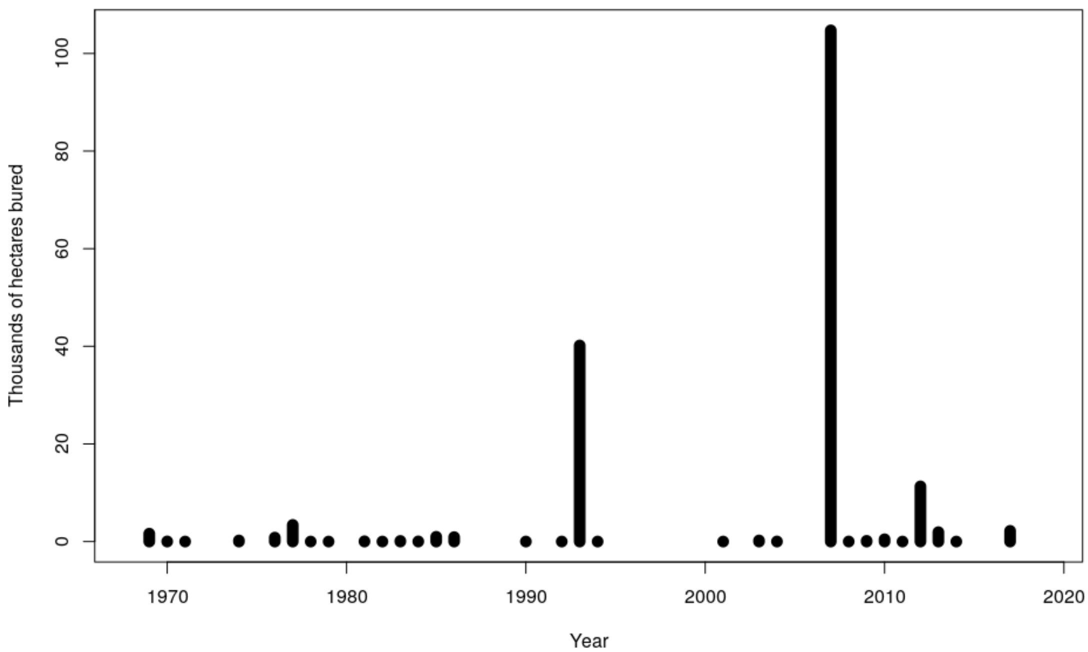
Introduction

Temperatures all over Alaska have been rising, especially in the Arctic (Serreze and Barry 2011, Box *et al*. 2019). At Utqiaġvik (formerly known as Barrow), annual temperature increased by 3.8 ºC (6.8 ºF) from 1949-2018, and autumn temperature by over 4 ºC. The rate of climate warming is predicted to increase and warmer and drier summers are strongly correlated with greater area burned in Alaska's interior (Veraverbeke *et al.* 2017). Historically, tundra fires on Alaska's North Slope are rare events (Barney and Comiskey, 1973). Only 71 fires north of the Brooks Range are recorded in the fire history records kept by the Alaska Fire Service from 1968-2019 (Fig. 1.a). Detection of small and short-duration fires is difficult in this remote area: there are few mapped perimeters. The total known area burned is 169,919 ha, with the Anaktuvuk River Fire (ARF) accounting for 61% (Fig. 1. a, b) although disturbance footprints discovered via remote sensing images have been discovered that pre-date fire agency records.

Detection of small and short-duration fires is difficult in this remote area: perimeters are available for just 131 of these fires, resulting in 845,000 acres (3,420 km²) burned over that 70 years, with the ARF accounting for almost a third of that area. In the tundra ecosystem, which covers nearly one-third of Alaska, wildfires are also predicted to increase (French *et al*. 2015). With the advent of warmer summers and more open water along the Arctic coast during autumn, large fires on the North Slope could become more frequent (Hu *et al*. 2010). Vegetation, wildlife, and communities are adapting to a new regime. Over 60 communities and about 350 native allotments are located within this ecoregion, and as in any region, fire and land managers working with tundra face decisions on fuels management, suppression tactics and pre-suppression staffing. Empirical knowledge on the relationships between fire, climate and vegetation from field studies like this one is important for assessing the impacts of increasing temperatures on tundra fire regimes and the cascading effects this could have on wildlife and ecosystem processes.

In the late summer and autumn of 2007, the ARF burned 256,000 acres (104,000 ha) of arctic tundra north of the Brooks Range, doubling the recorded area burned in this region over the past 50 years (Fig. 1.a and 1.b) (Jones *et al*. 2009). Although this fire was four orders of magnitude larger than the median fire size in the historic record for northern Alaska (24 ha; Miller *et al*. in preparation) another fire that ignited nearby in the same mid-July lightning storm (Kuparuk Fire) attained only 1,800 acres (725 ha). Indices of burn severity on ARF were substantially higher than for other recorded tundra burns (Chen *et al*. 2020), while the Kuparuk Fire demonstrated typically low burn severity, with minimal consumption of organic layers (Fig. 3).





Figures 1.a. and b. a. Map shows location of Anaktuvuk River Fire on Alaska's North Slope with other known fires (dots for all recorded fires, only larger fires show perimeters); right inset shows ARF, Kuparuk 2007 fires (previously undocumented fires in map are from Jones *et al*. 2013.) and **b.** Line graph shows annual areas burned since 1968 north of the Brooks Range, Alaska, from records maintained at the Alaska Interagency Coordination Center (https://fire.ak.blm.gov/incinfo/aklgfire.php, accessed April 2020).

An interdisciplinary team assessed fire effects including burn severity, potential plant community shifts, and effects on permafrost and active layers between 2008 and 2017. Observers monumented, photographed, and measured 24 burned and 17 unburned reference transects for four years, starting the year after the fire. The initial years' observations are summarized in an unpublished but public report (Jandt *et al*. 2012). The Arctic Long-Term Ecological Research (LTER) group established 16 transects in an intensive watershed study area on the fire (Fig. 2). Studies by other investigators examined gas exchange over the burn area, thermokarst features, and watershed effects. Peer-reviewed journals have published a number of studies by cooperators (Jones *et al*., 2009; Jones *et al*. 2013; Jones *et al*. 2015; Liu *et al*. 2014; Iwahana *et al*. 2016; Bret-Harte *et al*. 2013, Rocha and Shaver, 2011, Mack *et al*. 2011, Boelman *et al*. 2011).

In 2017, we re-surveyed the two burns, examining mid-term vegetation recovery and other fire effects on a subset of 14 burned and 11 unburned reference transects spanning the range of vegetation types and burn severities. Since the 2017 field work was only able to monitor the BLM's transects, this report details the results from those 25 transects (Fig 2). We also collected survey-grade GPS locations for each of the benchmarks visited. In 2017, we found new opportunities to expand our understanding of fire's ecological effects on this arctic ecosystem by establishing a permanent transect opportunistically on one of two 2017 re-burns discovered within the 2007 fire perimeter and a pair of transects on the pre-1948 Shivugak Bluffs fire to the northwest of ARF (Miller *et al*. in preparation).

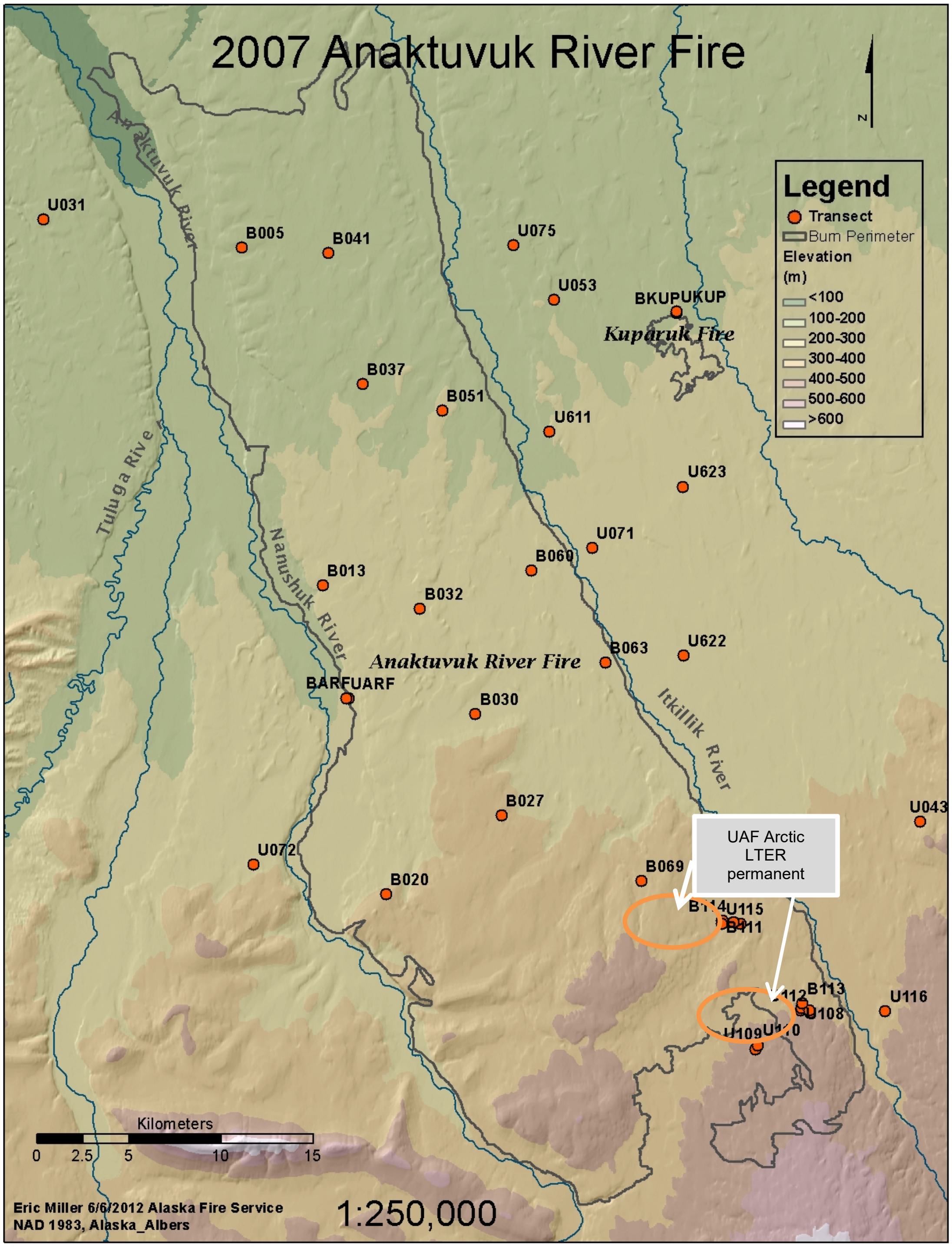


Figure 2. Map of study area fires and permanent transects (Arctic LTER plots were not included in the 2017 re-survey).

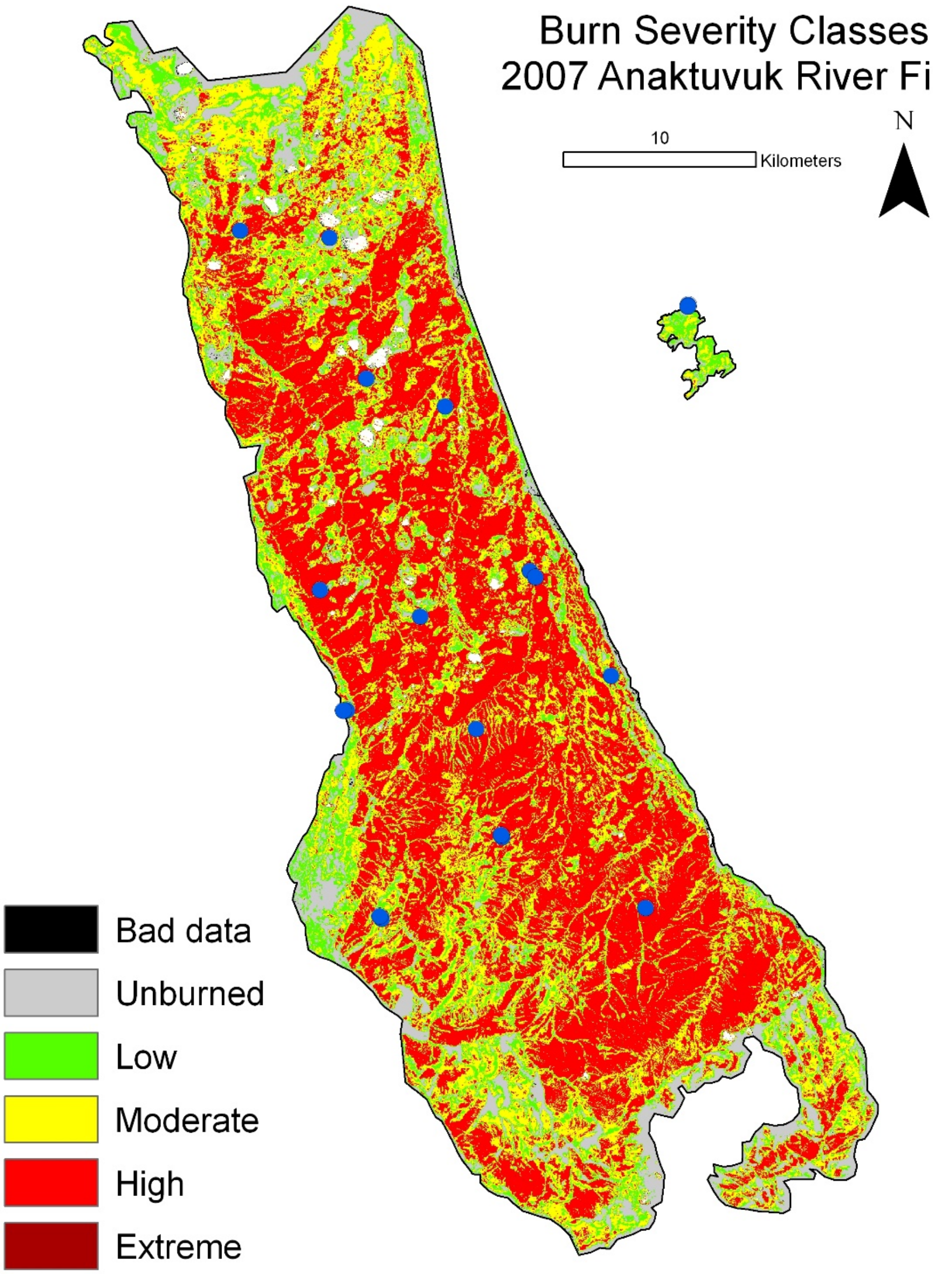


Figure 3. Burn severity map of Anaktuvuk River Fire with blue dots indicating the location of the BLM's permanent plots. (Figure by Crystal Kolden, USGS)

Description of the Study Area

Physical Setting

The ARF burn area extends from the glaciated portion of the Brooks Range Foothills 67 km (40 miles) north, ultimately transiting through the loess belt, or the eolian silt belt that was deposited during the last glacial period and consists of extremely ice-rich permafrost deposits known as Yedoma. Coordinates of the fire start location are 69.047° N and 150.837° W. Elevations range from 500 m in the south to 100 m in the north (Fig. 2). The burned area was confined by gravelly meandering floodplains of the Itkilik River to the east and the Anaktuvuk and Nanushuk rivers to the west. This area lies within the Brooks Foothills ecoregion of the North Slope (Muller, *et al*. 2018), where the ecosystem is described as upland, shrubby tussock tundra, with gently sloping uplands and ridges in loess and colluvium (Jorgenson and Heiner, 2008). Prior to the fire, 54% of the burn area was classified as upland moist acidic tundra (soil pH <5.5), 15% as moist non-acidic tundra (soil pH>5.5), and 30% as shrubland (Auerbach 1997).

We used Viereck *et al*.'s (1992) vegetation classification to describe reconstructed pre-burn plant communities, based on remnants, unburned islands and observations from reference transects. The most prevalent plant community–represented by 80% of burned transects–was open low mixed shrub-sedge tussock tundra, having > 25% shrub cover by definition, and shrubs mainly dwarf or subshrub species. Remaining burned transects were wet sedge meadows or sedge tussock tundra. Appendix Table A-1 lists location data and Viereck classifications for each transect.

Vegetation is dominated by the tussock-forming sedges cottongrass (*Eriophorum vaginatum*) and Bigelow's sedge (*Carex bigelowii*). Wet depressions and meadows have water sedge (*C. aquatilis*) and the rhizomatous aquatic grass (*Dupontia fisheri*). The dominant shrub types included willow (*Salix pulchra, S. fuscescens, S. glauca, S. phlebophylla*), dwarf birch (*Betula nana*), Labrador tea (*Ledum palustre*), blueberry (*Vaccinium uliginosum*), and prostrate shrubs lowbush cranberry (*V. vitis-idaea*), bearberry (*Arctostaphylos alpina*), and crowberry (*Empetrum nigrum*). Grasses other than tussock-formers and forbs are typically scarce, except for the deciduous cloudberry (*Rubus chaemamorus*), which we treat as a forb in this study after Viereck *et al*. (1992). Other herbs include grasses (*Arctagrostis latifolia*) and (*Poa arctica*) and forbs (*Petasites frigida, Pedicularis sp., Polygonum bistorta, Arnica lessingii* and *Saussurea angustifolium*). Willow (*Salix pulchra* or *S. glauca*) was generally the tallest shrub present, but alders (*Alnus spp.*) also burned along the rivers. Acidophilous mosses (*Sphagnum sp., Aulacomnium sp., Polytrichum spp*. and *Dicranum sp.*), and the moss-like liverwort (*Lepidozia reptans*) carpeted the surface between the tussocks. On undisturbed reference areas, fruticose lichens also were found in relatively protected hollows between tussocks, growing in clumps, and on some rises and ridges between depressions. Plant nomenclature follows the USDA Natural Resources Conservation Service Plants Database (http://plants.usda.gov).

Climate

The climate of the central North Slope is characterized by cold winters (-25°C/-13°F mean high in January), relatively cool summers (20°C/68°F mean high in July), and about 15 cm (5.9 in.) average annual precipitation near the coast and slightly more in the foothills, although the local climate is undergoing rapid flux. Only three months, June to August, typically have average temperatures above freezing and historically the area had almost nine months of snow cover (Wendler *et al*. 2010). Average precipitation in the summer months (June-September) averages just 11 cm. In the central North Slope, the summer of 2007 was the driest of the 29-year record (1979–2007), with a four-month precipitation total of just over 2 cm (Jones *et al*. 2009). Temperatures are rising all across Alaska, but changes are largest over northern and western Alaska, where snow and especially sea ice losses are impacting the regional climate. Annual air temperature on the North Slope increased 3.2 ºC (5.8 ºF) between 1969 and 2018 (Thoman and Walsh, 2019).

Ice-rich permafrost is common in northern Alaska and is particularly prevalent in the broad coastal plain region as well as the loess deposits and buried glacial deposits in the foothills (Kanevskiy *et al*. 2016). The latter deposits typify the region burned by the fire. Permafrost in the region is continuous, and the active layer (the layer of the soil which thaws in summer and freezes in the winter), has a thickness of about 30 to 40 cm in undisturbed locations (Wendler *et al*. 2010). Yedoma permafrost soils which primarily formed during the Pleistocene and have generally been frozen >50,000 years are very ice rich—often containing >80% ice content by volume with large syngenetic ice wedges (Kanevskiy *et al*. 2016). Yedoma permafrost underlies the northern two-thirds of the Anaktuvuk River fire. Recently, permafrost in northern Alaska and elsewhere in the Arctic has been warming – even at depths of 9-20 m (30-65 ft). Monitoring sites along the northern Dalton highway have warmed by 1.1-2.8 °C (2-5 °F) from the 1980s to 2018 (Romanovsky *et al*. 2017).

Description of Previous Burn Severity Assessments

In 2008, three independent ocular estimates of burn severity at varying scales were made, two ground-based indices and one aerial index (Jandt *et al.* 2012). Remotely sensed data and indices were compared to field ocular estimates as previously documented (Jandt *et al.* 2012) and summarized in the Appendix (Table A-2). Consumption of plant biomass and organic soils was estimated using direct measurements of plants and soils in burned plots and allometric scaling developed from unburned comparison plots (Mack *et al.* 2011). Pre- and post-fire Landsat imagery and field data were used to prepare a burn severity map, which showed that 80% of the fire burned with moderate-to-high severity (Fig. 3) (Jones *et al.* 2009). Initially, for areal burn severity mapping, a post-fire image was acquired from Landsat 5 TM on June 14, 2008, and a pre-fire image from Landsat 7 ETM+ on June 30, 1999. While the differenced image dates are optimally closer in time, the North Slope is often cloudy and there were no other clear dates during the growing season between 1999 and 2008. Burn severity for the ARF was then mapped using the differenced Normalized Burn Ratio (dNBR) method described in Key and Benson (2006) and validated with 19 modified Composite

Burn Index (CBI) plots, modified for Alaska ecotypes (Jandt *et al.* 2012), surveyed in the field during the summer of 2008 (Table A-2). CBI plots—a 30 m radius circular plot–are the standard approach for developing thresholds of burn severity for remote sensing data (Key and Benson 2006). An overall burn severity rating is derived from an average of ratings for assessments in three fuel layers: substrate, low vegetation, and tall shrubs based on pre-defined observational criteria. Complete methods and other tests completed are described by Kolden (2010). One-year post-fire and extended assessments and have been described elsewhere (Kolden and Rogan, 2013). In the initial 2008 survey, burn severity in the 1 x 1 m quadrats (N=10/transect) was also assessed for soil and vegetation along each burned transect using a scale of 1 (heavily burned)-to-5 (unburned) according to the Alaska Interagency Fire Effects Task Group protocol (2007).

Methods

Study Design

In 2008 (July 2-9), we established 16 permanent transects marked by aluminum stakes with retaining wires to resist frost-jacking and evaluated burn severity, vegetation, fire effects on soils and active layers. We re-surveyed these transects in 2009 (July 16-21), 2010 (July 15-25), 2011 (July 9-12) and 2017 (July). Site selection for the BLM transects was based on a random grid of points generated onto a map, stratified by an unpublished vegetation classification (Jorgensen and Heiner, 2003) and preliminary burn severity classes from unsupervised remotely sensed mapping (D. Verbyla). In 2010, we established nine additional unburned reference transects in representative plant communities outside the burn area, using physiographic parameters to select sites similar to transects inside the burn. Our expectation was not to pair each burned transect with an unburned transect, but rather to represent the same broad gradients in physiography and geomorphology encountered on the burn transects. Partners with Arctic LTER concurrently established and assessed ten burned and six unburned comparison transects in an intensive study watershed in the south end of the burn (in 2008-2010) for a total of 24 burned and 17 unburned reference transects after the 2010 field season (Jandt *et al.* 2012). Team members were integrated between the BLM and LTER field teams to standardize methods between partners on vegetative recovery transects.

Locations were established using a hand-held GPS unit. All BLM transects run true east (90°) for 50.1 m. Aluminum survey stakes with caps were pounded into the ground at each end and a fiberglass measuring tape was stretched between them. The location and elevation of each survey was updated in July 2017 using a survey-grade differential GPS unit. Transects consist of two sub-transects running parallel to each other separated by 2.5 m. The north sub-transect (2.5 m North of the survey stakes) was used for destructive samplings (soil sampling etc.) and for measurement of the active layer. Active layer depths were measured using a frost probe on the north sub-transect starting at 2.5 m and subsequently 2.5-m intervals thereafter (N=20). The probe was inserted into the soil down to ice or rock and the depth recorded. Insertions that hit rock instead of ice were noted. The south sub-transect was used for estimation of vegetation. No foot traffic occurred in a 1 m band south of the south sub-transect to prevent trampling damage to the vegetation. The south sub-transect was imaged from each end. The transect area was also photographed obliquely from a helicopter hovering at approximately 20 m in the air. Slope, aspect, and elevation were recorded.

In 2017, we re-surveyed the two burns, examining mid-term vegetation recovery and other fire effects on a subset of 14 burned and 11 unburned reference transects spanning the range of vegetation types and burn severities. Since the 2017 field work was only able to monitor the BLM's transects, this report details the results from those 25 transects (Fig 3). In 2017, we also established a permanent transect opportunistically on one of two 2017 re-burns discovered within the 2007 fire perimeter and a pair of transects on the pre-1948 Shivugak Bluffs fire to the northwest of ARF. The latter is a previously unrecorded presumed burn discovered by Jones *et al.* (2013) on a 1948 photograph and still visible in satellite imagery. As in previous years, we visited the most active areas exhibiting thermokarst mass wasting along the Nanushek River on the fire's southwest flank including two photopoints established in 2009.

Vegetation and Soils Measurements

For vegetation cover estimates, observers measured cover of substrate or vegetation at 100 points along each transect using a point-sighting device. Percent cover was calculated as the sum of all hits of a species along the 50-m transect, disregarding multiple hits on the same species at one point. Transects were photographed from each end in a landscape configuration. Additionally, in all years, ten 1 x 1 m photoplot quadrats were framed along each transect, at 5-m intervals, and photographed from a height of approximately 2 m. These were the same quadrats used for evaluation of substrate and burn severity in 2008 (Jandt *et al.* 2012). Shrub species (willow and alder), but not those classified as "subshrub" by the NRCS, were counted in ten 1 x 1 m quadrats by three height classes: <20 cm, 20-150 cm, and >1.5 m (although no shrubs over 1.5 m were recorded).

The quadrats were placed south of the southern sub-transect with the lower right corner placed at the meter mark at which a pin flag was placed. Although the plastic flags themselves eventually disintegrated, it was generally possible to locate the wire so that repeated placement of the quadrat was accurate. The first quadrat was placed at 1 m and subsequent quadrats were placed at 5 m and every 5 m thereafter. The last quadrat was placed at 45 m. We counted the shrubs as genets rather than ramets, that is, clumps of stems originating at a single point were counted as one individual. Seedlings were distinguished from established plants. In 2008, we distinguished resprouts from mature stems. After 2008 this distinction became meaningless and all were classified as mature.

These methods are admittedly subject to observer interpretation but are sufficient to document gross changes in shrub density over time. Individual tussocks of *Eriophorum vaginatum* and *Carex bigelowii* were also counted in the quadrats. Where more than one tussock grew together, tussocks were distinguished based on their "cow licks", or whorl of leaves above the tussock core. If they were only partially within the quadrat, they were counted only if ≥ ½ of their area lay within the quadrat. Newly dead tussocks and seedlings were noted. Shannon's diversity index (Shannon and Weaver, 1949) was used to estimate plant species diversity. Off-transect, additional species not intercepted on the cover transect were noted.

Active layer, pH, temperature, residual organic duff depth and other soil characteristics were recorded and in 2010, organic layers were destructively sampled for laboratory analysis of fire fuel biomass and density of fuel layers. In early post-fire visits, soil cores for pH and microbe analysis were taken and analyzed in the lab (Mack *et al.* 2011, Hewitt *et al.* 2013). 2008 pH values were averaged using [H+] determined as 10^(-pH) then converted back to pH as (LOG10[H+])*-1 (Mack *et al.* 2011). Values in 2017 were determined in the field using a handheld pH meter, converted to acidity for averaging. In 2017, pH of organic and mineral (if available) horizons was estimated in the field with a handheld pH meter, along with soil organic layer depth at 3 locations along the offset transect.

Surface Subsidence

The opportunity to quantitatively assess the areal extent of fire-induced ground subsidence in the burn came fortuitously in 2009, with a survey by the Alaska Department of Transportation using an airplane-mounted lidar system evaluating the ARF area for a proposed road. The 2009 lidar covered 650 km^2 (62%) of the burn area. A second lidar dataset was acquired in July 2014 to take advantage of the opportunity provided by the 2009 lidar (Jones *et al.* 2015). These data overlapped 350 km^2 of the 2009 dataset, with 310 km^2 located within the burn perimeter and 40 km^2 located outside of the burn perimeter. Ground subsidence was opportunistically quantified where independent and consecutive lidar datasets overlapped five transects (T41, T37, T51, and T60A). Digital terrain models (DTMs) at 1 m spatial resolution were developed for each acquisition and their difference found to produce differential digital terrain models (dDTMs; Jones *et al.* 2015). In a GIS environment, we laid the survey-grade GPS endpoint coordinates over the dDTM. We manually inferred the coordinate location of the 100 vegetation sampling points spaced 50 cm apart along each transect. Values from the dDTM were then extracted to each point and summarized for each transect. Ground subsidence along the transect could then be graphically displayed and summarized as an average for the entire transect. In time, this pairing of remotely sensed elevation data within situ vegetation surveys may allow for the tracking of vegetation responses to different ground subsidence patterns.

Table 1. Summary of Site Visits

Dates	2007 Burn Transects	Reference Transects	Other Burn Transects	**Survey team** *(Italics indicate observers for UAF LTER transects)*
July 2-9, 2008	**14 BLM** *10 LTER*	**2 BLM** *6 LTER*	--	Jandt, Yokel, Hollingsworth, Mack, Miller, Ahgook, *Bret-Harte, Jorgenson*
July 16-21, 2009	**14 BLM** *10 LTER*	**2 BLM** *6 LTER*	--	Jandt, Yokel, Miller, C. Racine, M. Racine
July 15- 25, 2010	**14 BLM** *10 LTER*	**11 BLM** *6 LTER*	--	Jandt, Yokel, Miller, McNulty
July 9-12, 2011	**14 BLM** *10 LTER*	**2 BLM** *6 LTER*	--	Miller, Jandt, Yokel, McNulty
July 8-16, 2017	**14 BLM**	**11 BLM** Shivugak fire: **1**	2017 Reburn: **1** Shivugak fire: **1**	Miller, Jandt, Jones, Baughman, Raevsky

Results

Plant communities

In the summer after the fire, we noted the consumption of feathermosses and ericaceous shrubs was high throughout the ARF burned area (cover photos). Frequently, almost all evidence of mosses (other than sphagnums) and dwarf shrubs was obliterated, leaving just charred remnants of the roots and rhizomes in a few centimeters of deeply charred lower duff. We encountered small resprouts of blueberry, Labrador tea, cloudberry, and lowbush cranberry sometimes sprouting from a tussock base where a piece of rhizome was protected. The burn continuity was also unusually high, consuming riparian stringers and wet polygonated depressions (fens), which are usually maintained as unburned inclusions.

Even so,11% of the area within the fire perimeter (excluding water features) did not burn. These unburned islands and 'fingers' of unburned extending from the perimeter into the interior of the fire tended to be in areas which burned earlier in the fire progression (Jandt *et al.* 2012). Reconstructed pre-fire organic depth averaged 20.3 cm (range 10.4-43.3 cm, N=20) whereas post-fire the mean residual organic depth was 15.7 cm (Mack *et al.* 2011). Residual organic layers on BLM plots ranged from 8.5 cm to 28 cm and were not always correlated with burn severity indices (Jandt *et al*. 2012; Table 1). Much of this residual organic horizon was likely frozen and unavailable for combustion during the fire.

On the ARF, more than 40% of transects demonstrated high severity corresponding to >20% mineral soil exposure and/or >60% tussock basal area consumption (Jandt *et al.* 2012). Tussock bases, similar to the boles of live trees in forested areas, are virtually never completely consumed in fires, so these observations, along with the 10% tussock mortality estimates in the first three years post-fire are notable. The drought conditions during September 2007 were coincident with record low Arctic Ocean pack ice adjacent to the coast (Jones *et al.* 2009; Hu *et al.* 2010). The summers of 2008, 2009, 2010 and 2017 were also unusually warm from mid-June through July during our sampling trips. We found that wet depressions inside and outside the burned area often dried out, leaving mats of dying algae and exposed emergent vegetation (like *Dupontia fischeri* grasses). Warmer summers spawn thunderstorms as well as dry out the grass and sedge litter, mosses, and deciduous leaf litter, which produces better conditions for tundra fire propagation and spread. Thunderstorms were observed regularly during our brief stints of field work.

Regrowth of vegetation was rapid for some species (e.g., tussock cottongrass *E. vaginatum* and colonizers like ruderal mosses also responded rapidly). Extensive mats of fire mosses (e.g., *Ceratodon purpureus, Pohlia nutans*) and liverworts (*Marchantia polymorpha*) developed after the first year on severely burned areas. The response of tussock sedges was remarkable given the estimate of roughly 10% mortality on study transects after the 2009 survey (range 0-40%). Tussock bases are almost never completely consumed in fires, but in this case, many were deeply burned into a "pillar" conformation. Graminoid cover, primarily *E. vaginatum*, increased from 6% to 60%

between 2008 and 2011 (Table 2). In 2017, graminoid cover was increased just 6% since 2011 on burned transects (66%, N=14; Table 2), but tussocks had clearly increased in height and diameter and were flowering more prolifically in burned transects. New tussock seedlings were documented in burned inter-tussock hollows, especially where mineral soil was exposed, in 2012 and 2017.

Table 2. Absolute cover of major vegetation components over time on 2007 burned plots (excluding substrate hits, of moss for example).

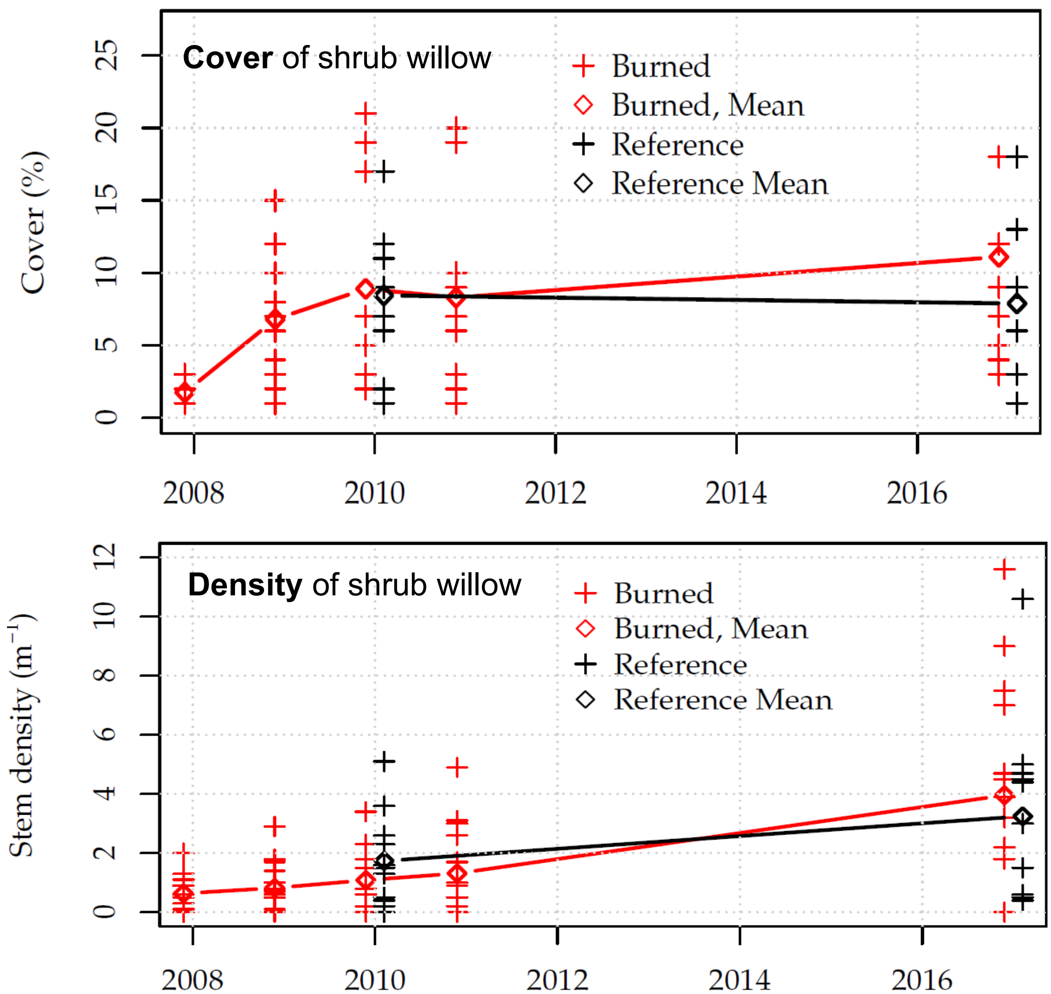
Cover %	**Burned** N=14					**Ref.**			
						N=2	N=2	N=11	N=11
	2008	2009	2010	2011	2017	2008	2009	2010	2017
FORB	0.71	6.29	7.29	10.07	12.43	2.00	6.50	4.82	5.64
Artemisia tilesii	0.00	0.00	0.07	0.21	0.50	0	0	0	0
Equisetum spp.	0.00	0.93	0.93	1.29	2.29	0	0	0.45	0.09
Chamerion angustifolium	0.00	0.07	0.07	0.43	1.43	0	0	0	0
Pedicularis spp.	0.00	0.07	0.14	0	0.29	0	0	0.18	1.09
Petasites frigidum	0.07	0.43	0.57	0.86	1.57	0	2.00	0.27	0.55
Rubus chamaemorus	0.57	3.86	4.00	4.71	4.71	2.00	3.50	2.91	2.09
Saussurea angustifolia	0.00	0.29	0.07	0.14	0.36	0	0	0.18	0.27
OTHER FORB	0.07	0.64	1.43	2.43	1.29	0	1.00	0.82	1.55
GRAMINOID	6.43	39.36	45.07	59.57	66.36	47.50	57.50	50.00	48.27
Arctagrostis latifolia	0.07	0.86	1.29	1.86	5.93	0	2.50	0	0.09
Carex aquatilis	1.00	4.29	3.79	5.07	3.64	0	0	1.45	2.27
Carex bigelowii	1.50	4.00	4.07	7.71	7.86	10.00	10.00	10.27	8.91
Calamagrostis spp.	0.00	4.29	6.21	9.14	4.07	0	1.00	0	0
Eriophorum vaginatum	3.64	20.14	22.21	27.71	32.79	37.50	43.50	30.18	30.00
OTHER GRASS	0.00	1.64	2.21	2.00	4.57	0	0	1.18	0.27
OTHER SEDGE	0.21	4.14	5.29	15.21	7.50	0.00	0.50	6.91	6.73
SHD & SSD	6.00	13.21	14.93	17.07	22.29	14.00	24.00	31.18	28.18
Arctostaphylos spp.	0.00	0.07	0.14	0.29	0.14	0	0	0.55	0.55
Betula nana	2.71	5.64	5.86	7.93	10.50	8.00	16	17.73	15.18
Comarum palustre	0.00	0.21	0.21	0.21	0.21	0	0	0.09	0.18
Dwarf *Salix spp.*	0.00	0.00	0.00	0.00	0.00	0	0.5	0.64	0.55
Salix fuscescens	0.07	0.57	0.5	0.93	1.21	0	0	0.55	0.18
Salix pulcra	2.43	5.86	6.64	5.57	6.93	5.50	5.50	5.18	4.82
"Tall" *Salix spp.**	0.07	0	0.14	0.36	1.43	0	0	1.73	1.64
Spirea stevenii	0.00	0.00	0.07	0.07	0.07	0	0	0	0
Vaccinium uliginosum	0.64	0.86	1.36	1.71	1.79	0.50	2.00	4.73	5.09
OTHER DEC. SHRUB	0.07	0.00	0.00	0	0	0	0.00	0.00	0
SSE	2.21	7.29	7.64	9.57	17.93	33.50	69.00	40.18	42.45
Andromeda polifolia	0.36	0.50	0.57	0.93	2.00	0	2.50	2.82	2.73
Cassiope tetragona	0.29	0	0.07	0	0	0.50	1	4.82	4.09
Dryas integrifolia	0.00	0.00	0.00	0.00	0.00	0	0	0.91	1.27

Cover %	Burned N=14					Ref.			
						N=2	N=2	N=11	N=11
	2008	2009	2010	2011	2017	2008	2009	2010	2017
Empetrum nigrum	0.00	0.00	0.00	0.00	0.00	3.00	6	1.36	1.45
Ledum palustre	1.00	4.36	4.07	5.43	10.64	16.00	20.50	14.09	14.45
Vaccinium vitis-idaea	0.50	2.43	2.93	3.07	5.21	14.00	38.50	15.91	18.18
OTHER ERIC. SHRUB	0.07	0.00	0	0.14	0.07	0	0.5	0.27	0.27
LICHEN	0.21	0.29	0.43	0.14	0.57	4.00	8.00	8.82	8.64
FOLIOSE	0.14	0.07	0.29	0	0	3.00	4.50	6.09	5.73
NON-FOLIOSE	0.07	0.14	0.07	0.14	0.57	1.00	3.50	2.55	2.91
LIVERWORT	0.21	10.36	9.57	6.57	0.50	0	1.50	1.09	1.64
MOSS	15.00	34.21	25.50	26.93	19.36	16.50	46.50	34.18	43.64
Ceratodon purpureus	0.29	1.57	5.50	5.36	2.14	0	0.5	0	0
Polytrichum spp.	0.07	1.57	3.14	2.86	5.29	0	1.50	0.73	1.00
OTHER MOSS	11.86	10.93	11.14	12.64	8.29	15.50	12.50	22.27	27.00
SPHAGNUM	2.79	20.14	5.71	6.07	3.64	1.00	32.00	11.18	15.64

*"Tall" Salix here refers to forms generally > 1m tall when mature such as *S. glauca, S. alaxsensis*, etc.

Figure 4. Alder resprouting ten years post-fire, ARF T63, July 8, 2017 (R. Jandt).

Ericaceous shrub cover increased from 2 to 8% on burned transects in the first four years, compared to 40% cover on reference transects (N=11; 2010). After ten years, cover of ericaceous shrub, especially Labrador tea (*L. palustre*), on the BLM subset of 14 burned plots, had nearly doubled (18% in 2017), but had not reached reference transect levels (42%, N=11; Fig. 6). Deciduous shrubs (including *Salix spp., Betula nana, Arctostaphylos, Vaccinium uliginosum,* etc.) and subshrubs averaged about 22% cover after ten years, close to the reference transect value of 28% (Table 2; Fig. 6). Subshrub species of prostrate willow and purple marshlocks (*Comarum palustre*) generally comprised less than 1% of the deciduous shrub cover. *S. fuscescens* and *S. pulchra* accounted for most of the shrub-statured (here defined as generally between 0.1-1 m at maturity) willow we tallied on quadrats along the transects and at least the stem density of these species, if not cover, still appeared to be increasing after ten years (Fig. 5.a. and b.). Expansion of shrub-statured willow recruitment was quite obvious on repeat photopoints and photoplots (Cover photo). Cover of “tall” shrub species (generally > 1 m) which was negligible on initial post-fire surveys seemed to be still increasing—from 0% in 2008 to just 0.4% in four years and then 1.4% in 2017 (reference transects 1.6%). Species tallied included *Salix richardsonii, S. glauca, S. alaxensis, S. interior* and also *Spirea stevenii*. Surprisingly, some of the burned alder previously thought dead were just beginning to resprout after ten years (Fig 4). Still, alder was rare in our survey areas. Subshrubs, *Cassiope tetragona* and *Dryas sp.*, were found on half of unburned reference transects (UKUP, U031, U043, U053, U071 U623) but just a single burned plot in the ten years after fire (B005). It is uncertain whether these species, which prefer a less acidic soil substrate, were underrepresented in our burned transects due to more acidic soil types or slow regeneration post-fire.



Figures 5.a and 5 b. a. Cover (top) and **b.** density (bottom) of shrub willows from 2008 to 2017 on individual burned and reference transects (+) with trend line. Primary species tallied on quadrats were *S. pulchra* and *S. fuscescens*; prostrate willows were excluded.

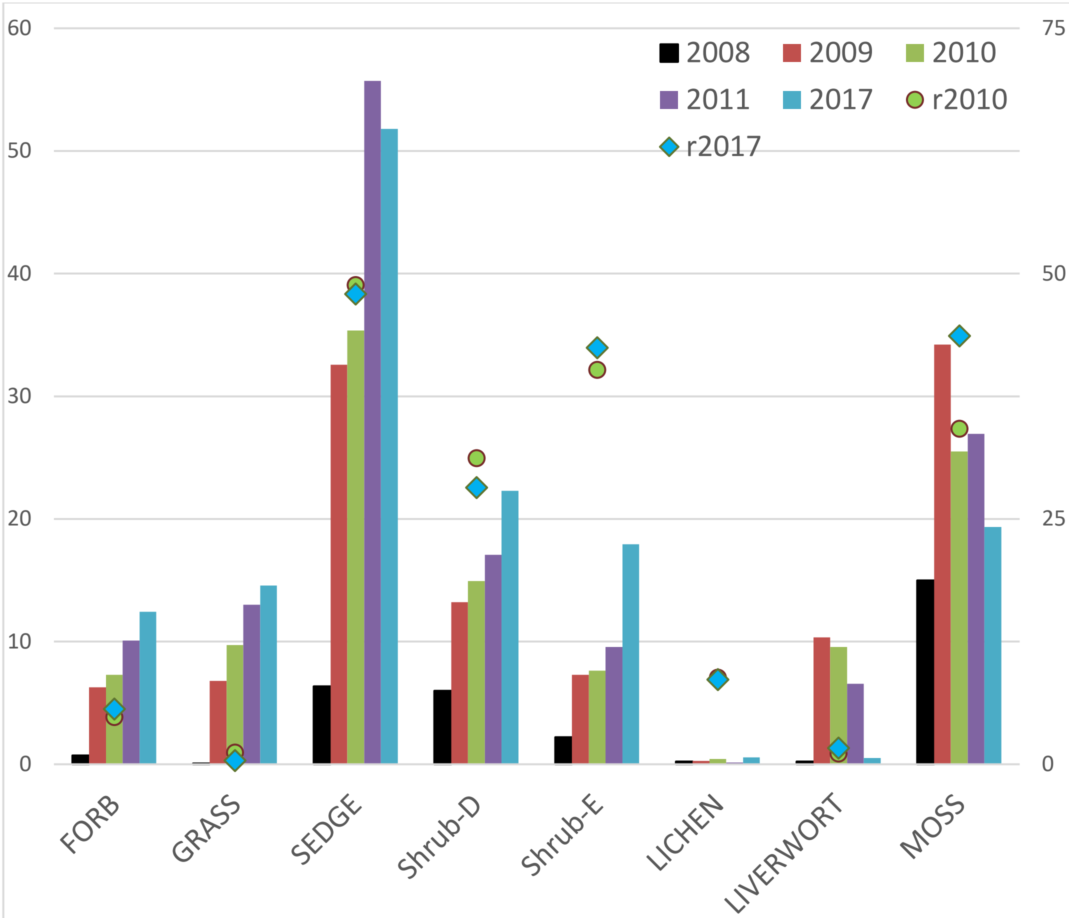


Figure 6. Mean annual vegetation cover (%) by lifeform on burned (bars) and unburned reference ("r" points) transects over the years of study. Graminoid vegetation is divided into grasses and sedges. Shrubs are grouped into deciduous (D) or ericaceous (E). Reference plot data for 2008-2009 omitted due to small sample size (see Table 2).

The abundance of perennial grasses, and forbs like cloudberry (*R. chaemomorus*) and horsetail (*Equisetum sp.*) increased notably over the first four years. True grasses—largely *Calamagrostis* and *Arctagrostis sp*.—increased from 0.1% to 13%, forbs from 0.7% to 10.1% (Fig. 6). Ten years post-fire cover of true grasses was 14.6% on burned, 0.3% on reference transects, and appeared to still be spreading. Forbs had also increased in number and diversity by 2017 and comprised 12.4% of cover on burned transects, or twice the forb cover seen on reference transects (6%, N=11). Fireweed (*Chamerion angustifolium*) was rare in 2008, and we recorded no hits on reference transects but increased patch-wise in burned transects through 2011, apparently spreading rhizomatously. It appeared to still be increasing after ten years and comprised 1.4% cover by 2017.

Bryophyte communities exhibited some of the most striking and dynamic changes over the study period. Two years post-fire large mats of "copper wire moss" *Pohlia nutans*, "fire moss" *Ceratadon purpureus*, and the liverwort *Marchantia polymorpha* had established. Combined, cover of these three averaged about 1% in 2008, while the burn area was still very dry (before summer rains). They increased to 11% in 2009 and 16% in 2010 (Table 2). Some of these bryophytes seemed to be trending downward by 2011 (*M. polymorpha* in particular) and being replaced by other successional mosses like *Polytrichum* sp. and *Aulacomnium* (Jandt *et al*. 2012). Moss mats appeared to hold the ashed fine soils, which would help mitigate wind and water erosion. Mosses also appeared to be keeping at least some moisture in burned areas, which overall seemed to be drier than normal. After ten years, "fire mosses" comprised <3% of cover on burned transects but had not completely disappeared (Table 2). In early post-fire surveys, hydrophilous *Sphagnum* peat mosses were much less abundant on burned than unburned transects (1.8% live cover in 2010 *vs.* 14.5%; Jandt *et al*. 2012) and appeared to be dying in some of the burned areas, even where they had not been scorched (10.3% dead *Sphagnum* moss cover in 2009 on burned transects). This trend was still observed in 2017, as burned transects had just a quarter of the live sphagnum cover (4%, N=14) seen on reference transects (16%, N=11).

Lichen cover on the unburned reference transects was around 8% in 2009-2011), about 2/3 of which consisted of caribou forage species such as Cladina rangiferina and Cetraria or Flavocetraria sp. and the rest of foliose species like Peltigera sp. After ten years there is virtually no forage lichen cover in the burn area: <0.2%. Drier ridges which would have supported most of the forage lichens and areas with low or tall shrub cover were the most completely burned habitats within the burn perimeter, whereas boggy Sphagnum and sedge meadows or fens had the least organic mat consumption. We did not record caribou utilization signs within the burn area in 2017 but still found areas of use and recent pellet groups in some unburned reference transects, particularly on the southeast perimeter of the fire.

Overall diversity of the vegetation community based on number of species recorded appeared to have returned to reference levels (Fig. 7).

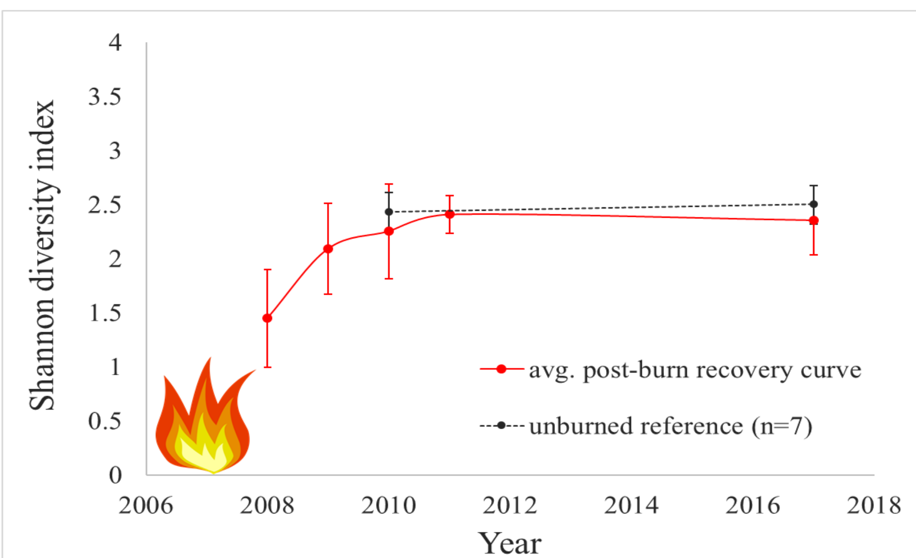


Figure 7. Diversity of all plant species over time using Shannon's diversity index (Shannon and Weaver, 1949).

Soil Characteristics, pH, Thaw Depth and Thermokarst

Residual organic soil depth following the burn averaged 16.6 cm. By 2017, mean depth was 20.8, indicating 4.2 cm of litter and duff have reaccumulated in nine years or about 0.47 cm/year. Mineral soil core pH values in 2008 ranged from 3.9 to 5.2 overall (N=23) while organic duff pH samples (5-10 cm depth) from the 35 transects sampled in 2010 ranged from 4.2 to 6.4—slightly more alkaline, although depth in the soil core is likely to influence pH due to higher mineral content of the parent material. Table 3 compares the set of transects sampled in both 2008-2010 and 2017. Median pH on the BLM's 14 burned transects was 4.6 for mineral soil pH in 2008 and 5.4 for both burned/unburned transects in 2017 (N=12, 8). Median organic soil pH was 5.3 for burned (N=11) and 4.9 for unburned (N=9) transects in 2010. In 2017, organic soils measured median pH 5.4 (N=14) for burned transects and 5.0 (N=8) for unburned transects. Previously reported pH from unburned mesic tussock tundra in the Arctic Foothills averaged 4.6 ± 0.1 (Walker *et al.* 1994). It is possible that burning made soils less acidic, but variability between sampling sites was too high for statistical significance. On individual transects, we noted that near surface layers on individual transects with much consumption (and ash residues) had a relatively high near-surface organic mat—such as at T063—where the 2017 near-surface pH was 7.1, but decreased to 5.5 as one reached deeper, uncombusted layers.

Table 3. pH data from tundra fire and reference transects sampled in 2008 (mineral)/2010 (organic) and 2017. 2008 values were measured in lab using soil cores (Mack, et al. 2011). pH values in 2010 and 2017 were determined in the field using a handheld pH meter.

Transect Name	Plot Type	2010 Organic pH (mean)	2017 Organic pH (mean)	2008 Mineral pH (mean)	2017 Mineral pH (mean)	Site Class
B005	Burned	5.53	5.33	4.70	5.62	--
B013	Burned	5.34	5.21	4.49	5.33	--
B020	Burned	5.07	5.20	4.18	5.17	--
B027	Burned	--	5.42	4.43	frozen	--
B030	Burned	4.40	4.53	4.49	5.05	--
B032	Burned	--	5.58	5.23	frozen	--
B037	Burned	5.17	5.40	4.97	5.46	--
B041	Burned	4.42	4.45	4.66	6.16	--
B051	Burned	5.54	5.83	4.69	6.05	--
B060	Burned	5.70	5.77	4.93	5.50	--
B063	Burned	5.55	6.47	4.47	5.20	--
B069	Burned	4.58	4.36	3.86	4.78	--
B101	Burned	4.51	--	4.58	--	--
B102	Burned	5.07	--	4.89	--	--
B103	Burned	4.69	--	--	--	--
B104	Burned	4.85	--	4.74	--	--
B105	Burned	4.90	--	5.15	--	--
B106	Burned	4.59	--	4.62	--	--
B107	Burned	4.51	--	4.03	--	--
B111	Burned	4.36	--	--	--	--
B113	Burned	4.31	--	--	--	--
B114	Burned	4.46	--	--	--	--
BKUP	Burned	5.48	5.67	4.67	5.59	--
BNAN	Burned	--	5.26	4.62	4.90	--
BREB	Burned, 2X	--	4.55	--	4.62	--
U031	Unburned	4.66	5.06	--	5.57	--
U043	Unburned	4.70	4.48	--	5.36	--
U053	Unburned	5.07	5.22	--	frozen	--
U071	Unburned	6.45	6.78	--	7.04	--
U072	Unburned	--	--	--	5.22	--
U075	Unburned	5.17	6.03	--	--	--
U108	Unburned	4.37	--	4.92	--	--
U109	Unburned	4.41	--	--	--	--
U110	Unburned	4.21	--	--	--	--
U112	Unburned	5.25	--	--	--	--

Transect Name	Plot Type	2010 Organic pH (mean)	2017 Organic pH (mean)	2008 Mineral pH (mean)	2017 Mineral pH (mean)	Site Class
U115	Unburned	5.65	--	--	--	--
U116	Unburned	4.42	--	--	--	--
U611	Unburned	5.26	--	--	--	--
U622	Unburned	4.89	4.60	--	frozen	--
U623	Unburned		4.50	--	4.52	--
UKUP	Unburned	4.85	4.95	4.44	5.76	--
UNAN	Unburned		4.07	4.78	5.50	--

Differences in active layer thaw were much reduced from early post-fire surveys. Mean thaw depths of burned transects exceeded that of the unburned transects by almost ten cm in 2011 and by 2017 the difference of 5 cm narrowly missed statistical significance (Table 4). Thaw depth was somewhat correlated with increased severity in early years post-fire but not significantly (Jandt *et al.* 2012). Thaw depth is strongly influenced by sample date range between 2008 and 2017.

Table 4. Differenced active layer thaw depths (cm) on 2007 burned and reference transects (2008-2011).

YEAR	Sample Date	THAW DEPTH BURN (cm)	BURN N	BURN Std E	THAW DEPTH REF (cm)	REF N	REF Std E	Difference BURN-REF
2008	7/2-7/9	-39.5	24	7.8	-29.7	2	--	9.8
2009	7/16-7/21	-47.4	24	5.6	-34.0	2	--	13.4
2010	7/15-7/25	-44.0	24	7.1	-26.5	11	7.7	17.5
2011	7/9-7/12	-42.3	24	10.8	-23.1	11	5.8	19.2
2017	7/8-7/16	-27.1	14	5.7	-22.0	11	5.5	5.1

The bulk density of organic layers in the ARF from 2008 samples ranged from 0.07 g/cm3 (±0.01, N=20) in the 0-5 cm layer, which would be mostly moss, litter, and surface vegetation, to 0.15 g/cm3 (±0.02, N=4) in the 15-20 cm layer, which would be compacted duff (Mack *et al*. 2011). Bulk densities are regionally specific because they are strongly influenced by mineral content in the layers, which can be influenced by factors like wind, glacial dust, flooding, and cryoturbation.

Figure 8. Well-developed thermokarst pond 10 years after fire (BNAN).

On a larger scale, the degradation of permafrost was widespread in 2017, even in areas where burn severity was light, such as the Kuparuk Fire. Degradation is especially prominent in yedoma soils, less so on glaciated uplands and fluvial soils. We observed ground subsidence >1 m in cases, often in troughs between polygons, primarily associated with the melting of ice wedges, which in some cases led to ponding of water (Fig. 8). In contrast, ice wedge polygonal centers appeared to be become drier in several burned transect neighborhoods, with less standing surface water and relay succession from hydrophilous and emergent species to more mesic plant species. For example, *Carex aquatilis* at B041 lacked vitality and appeared to be senescent, being overtaken by *Salix fuscescens*. Drying peat and *Sphagnum* mounds resembled char. Shrubs had invaded previously wet areas in many places. For example, Transect B032 was a wet sedgy marsh, but by 2017 shrubs (*L. palustre* and *B. nana*) were filling in spaces between tussocks, with little evidence of marshy ground. Observations here and at older burns suggests the tundra initially becomes wetter, then drier, as water drains through degrading ice wedge troughs (Liljedahl *et al*. 2016, Chen *et al*. 2020).

We saw evidence of substantial overland flow of water at some transects and speculated that this may be a factor of a higher snowpack due to taller vegetation trapping windblown snow in the winter, as well as more snow accumulation occurring in degrading ice wedge troughs because of wind redistribution. However, a shallower duff layer—diminished by consumption—might also reduce the overall water storage capacity of the organic layer. Collectively, these factors might lead to significant spring flooding.

Soil temperatures, measured by two datalogger probes located in representative locations inside and outside the burn perimeter, showed that organic soil temperatures (at 15 cm depth) in the burn continue to average 1.5º C warmer than reference site, even after the recovery of vegetation. Maximum temperatures in the soil organic layer were consistently warmer in the burn (as much as 6°C in summer; 1.7°C annually) from 2010-2017 compared to a reference station (Fig. 9). The growing season (above 0°C) was about 13 days longer in the 10-year-old burn scar. Thawing degree days were 2.7 times greater at the burn datalogger station compared to the reference (Fig. 10).

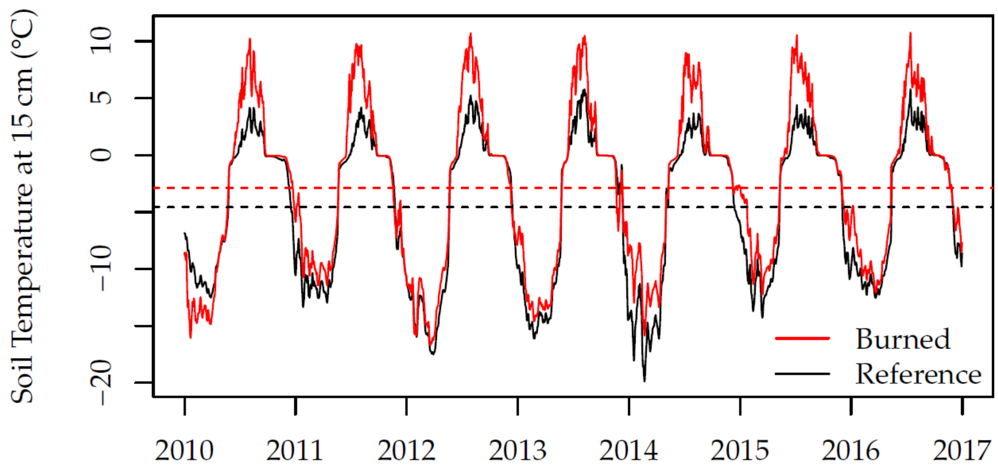


Figure 9. Interannual and seasonal variation in 15 cm deep soil temperatures (^{0}C) from 2010-2017 at representative stations in burned and reference areas. Dotted lines represent overall mean soil temperature between 2010 and 2017

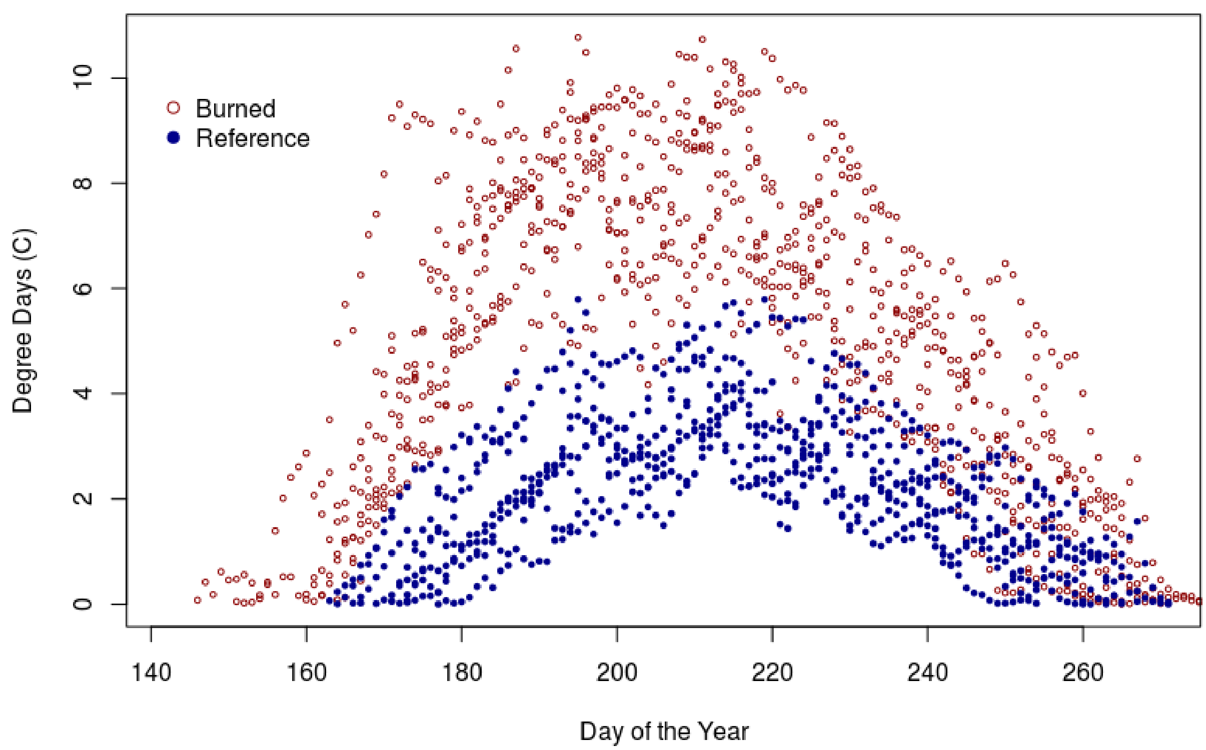


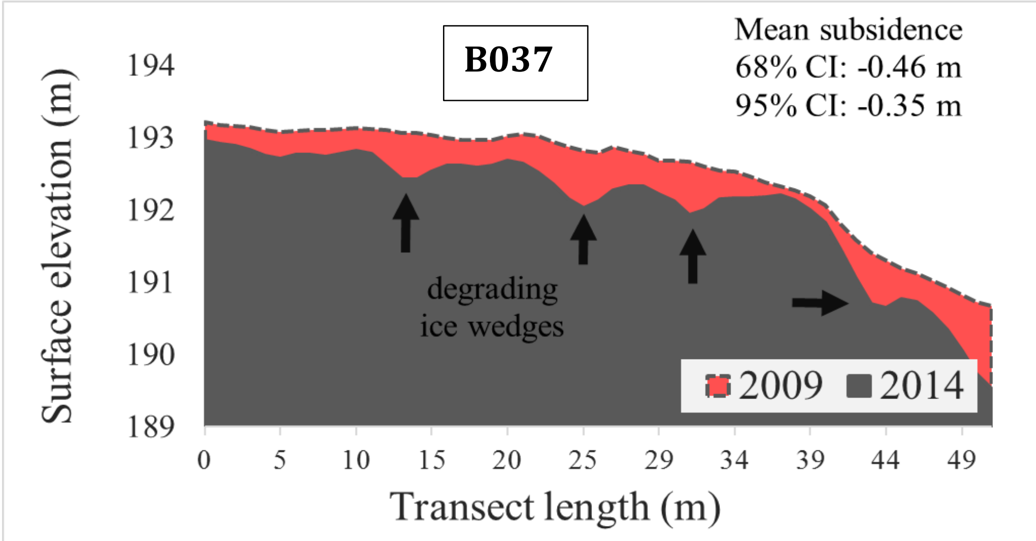
Figure 10. Scattergram of degree days above freezing by Julian date based on soil temperature data (15 cm depth) from burned and reference datalogger sites from 2010-2017.

Figure 11.a. and b. a. Thaw slump headwall (NAN2) in 2011 and b. same area in 2017.

Along the Nanushek River (southwest perimeter of the fire) the retrogressive thaw slumps documented from 2009-2011 appeared to be stabilizing. Photopoint site NAN2 contained an exposed 3-m tall ice wedge and an erosional gully/silt flow about 30 m wide and 100 m long in 2009, which widened to more than 70 m the next year. By 2011, a large silt pile (2 m tall) had accumulated at the toe of the slump. The crater had almost joined the neighboring slump to the south, with just a narrow ribbon of undisturbed ground separating them. Prior year silt flows were starting to revegetate with mosses, *Equisetum sp.* and grasses. By 2017 these slumps had revegetated, and the old headwalls had eroded to sloped hills (Fig. 11) but there were still numerous large cracks and rivulets of water draining from the thaw slump, indicating that permafrost degradation might still be occurring but at a much slower rate. Photopoint locations had been covered or obscured by mass wasting flows. Large willows were abundant in the thaw slumps and we saw evidence of moose and bear activity.

Jones *et al.* (2015) provided compelling evidence of widespread surface subsidence and increased surface roughness over much of the eastern and northern half of the ARF burn area. These changes could also be easily appreciated on the ground and from aerial platforms (Fig. 12). Using lidar data from 2009 and 2014 along with survey-grade GPS coordinates and a digital terrain model, we were able to construct 2-D subsidence profiles for several study transects (Fig. 13). The profiles show variable surface subsidence exceeding 1 m in depth in places, particularly in severely burned transects that were underlain by yedoma soils (Fig. 13: B037). Transects underlain by river cobble showed negligible subsidence (Fig. 13: B063). The digital terrain model was not available for all glaciated soil areas in the southern part of the burn but thermokarst was observed to be less developed there.

Figure 12. 2017 aerial photo contrasts thermokarst on 2007 burned surface of ARF (left of the pond) compared with unburned surface (right; WP186). Increased cottongrass bloom is also observable in the burn.



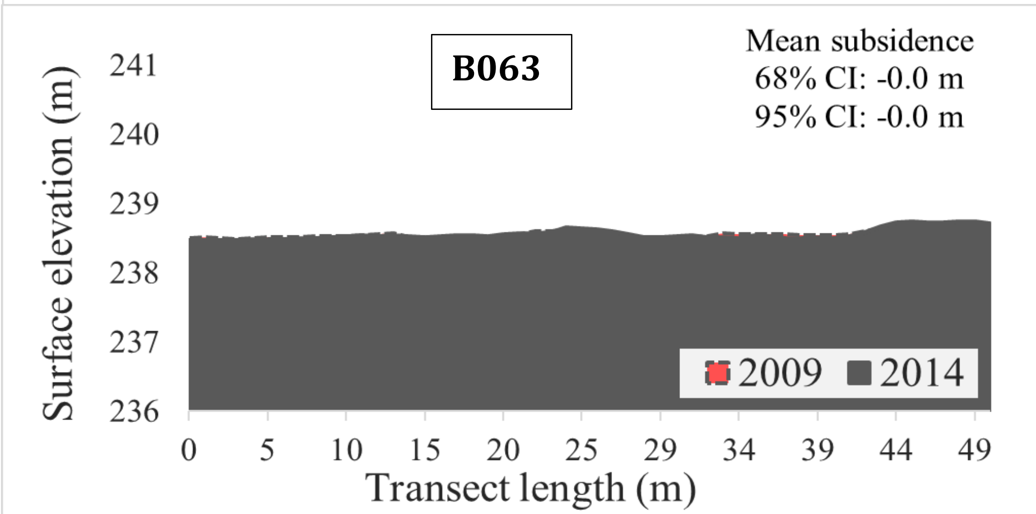


Figure 13.a. and b. a. Subsidence and surface deformation due to permafrost thaw and ground ice melt over a five-year period along two transects using differenced DTM data from repeat airborne lidar surveys over the ARF. Subsidence was pronounced on transects in yedoma uplands (B037) but **b.** negligible on a cobble/gravel-filled floodplain (B063)

Observations on 2017 re-burn

Figure 14.a. The entire area in this photo burned in the 2007 Anaktuvuk River Fire and a 2017 repeat burn is visible. The reddish color is due to scorched (rather than consumed) dwarf birch leaves as the overall burn severity was light. Note the ice wedge.

Burn severity within a 2017 re-burn, 14 ha (35 acres) in size, was very light (4 on a scale of 1 = severely burned to 5 = unburned; Appendix Table A2). Based on lightning occurrence records, we believe the fire started June 28, 2017, so that the burn would be 12 days old on the first day we landed there (July 9, 2017). Tussocks had already generated new leaves. Leaves of ericaceous and deciduous shrubs, which had likely just emerged and had high fuel moisture at the time of the fire, were merely scorched but not consumed (Fig. 14 a and b). Leaf litter and dried mosses in between tussocks was 90% consumed by the fire. We recorded mineral soil on 4% of the transect, “char” as the substrate on 25% and litter on 44%, with live vegetation or tussock composing the remainder. Vegetation cover on the transect averaged 28% *E. vaginatum*, 17% *Aulacomnium* and other mosses, 12% *Ledum palustre,* 9% *Betula nana,* 8% *V. vitis-idaea*, 5% *Carex bigelowii*, 3% grasses, and 2% *Rubus chamaemorus*. Due to its location completely within the 2007 burn perimeter (Fig. 14a), we were unable to create a nearby reference transect.

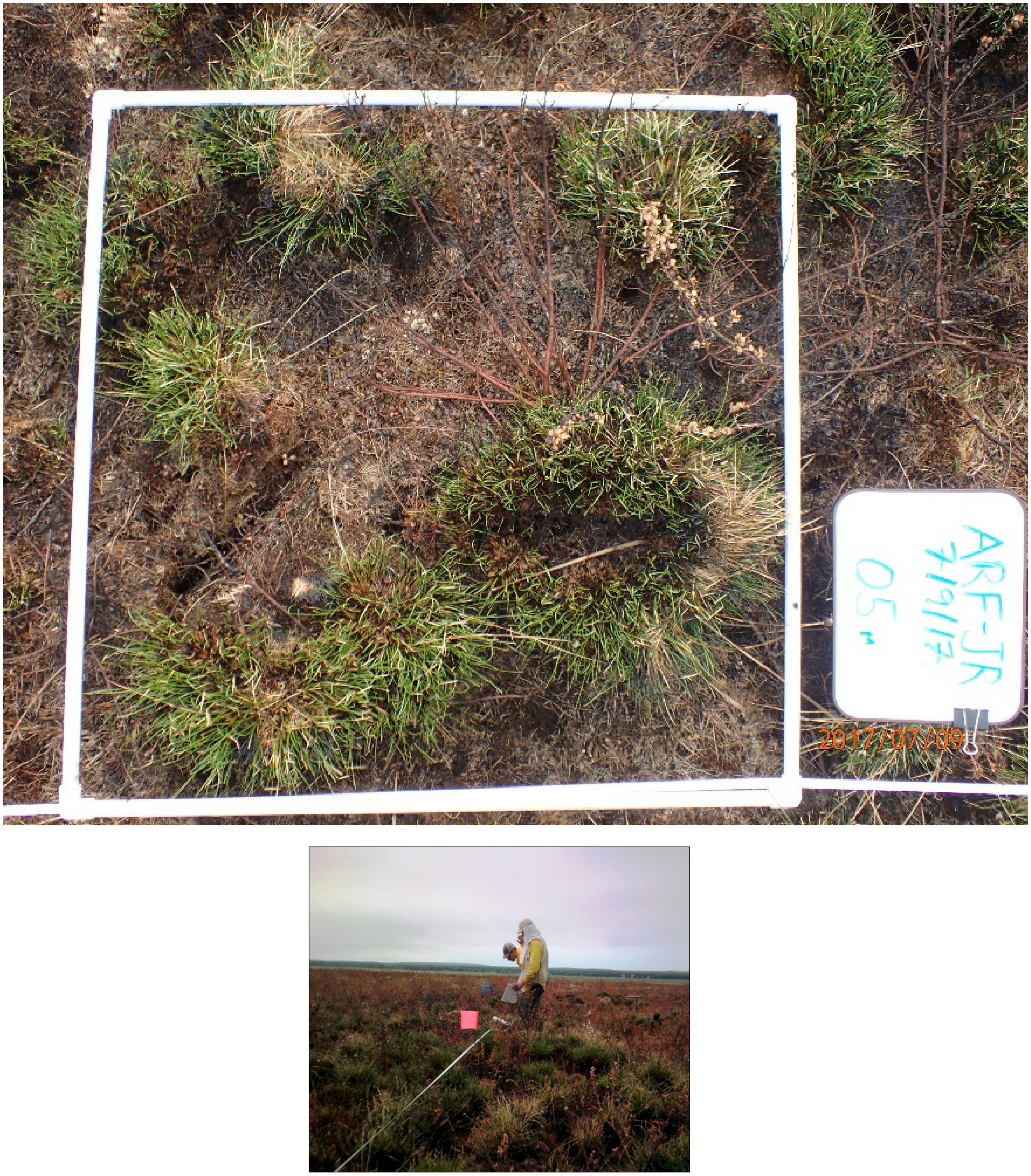


Figure 14.b. A new transect placed in the 2017 re-burn (12 days post-fire) shows resilience of tussock sedges, and light burn severity.

Discussion

Ten years following a large and severe wildfire in the arctic foothills north of the Brooks Range, Alaska, tundra is experiencing rapid biophysical changes. Plant communities are responding to primary disturbance by fire, but also to permafrost degradation, terrain subsidence, and apparent increase in soil drainage and/or evapotranspiration.

Although overall plant diversity returned to levels similar to reference tundra within four years (Fig. 7), plant communities continue to show different patterns within lifeform groups compared to reference transects. For example, new disturbance-loving bryophyte communities established quickly post-burn and were very important to soil/moisture retention on severely burned transects. By year 10, early colonizing non-vascular species, like *Marchantia, Pohlia* and *Ceratodon*, have given way to slightly more developed *Polytrichums*, herbs, and shrubs. Feathermosses like *Pleurozium* and *Hylocomium* are beginning to reappear on transects and some live Sphagnum was observed.

There is still a notable lack of forage lichens in the 10-year-old burn, <0.2% on burned plots vs ~6% in both years of reference plots. Drier ridges which supported higher densities of lichens (and where we found concentrated caribou utilization in 2008) tended to show higher burn severity. Lichens and bryophytes have few perennating structures and are often completely removed by burning or even scorching, unlike woody and vascular plants. Their short stature also puts them at a competitive disadvantage in areas where regenerating vascular vegetation can quickly overtop and shade them. Willow and tussock vitality is much greater inside the burn. Ten years after the fire, tussocks still exhibited increased productivity (based on vertical and radial growth in plot photos) and continued prolific flowering, which was estimated about 3x higher than undisturbed areas in over a third of burned transects. Cover of taller shrubs was comparable to reference areas by year four, and both cover and density of stems was still increasing in year ten(Fig. 5.a. and b.). Indeed, our observations, data and photos show willows, true grasses (like *Arctagrostis latifolia, Calamagrostis canadensis, Poa arctica, Festuca sp*, and *Trisetum sp*), fireweed, and horsetail are still colonizing severely burned sites and exposed mineral soil. Shifts in community species composition seem likely for many years to come in the burn area.

Drier ridges and shrubby edges of low-center polygons and any areas with dense low or tall shrub cover such as riparian areas were the most completely burned habitats within the burn perimeter (cover photo). Accumulations of shrub leaf litter adding fuel, or the efficiency of shrubs at “drying” the organic soil via transpiration could explain this observation. New shrub seedlings were not detected on burned transects until 2011, when a few were documented in hollows where only a small amount of organic soil remained after burning. New shrub seedlings and new resprouting growth were being observed a decade after burning. Alder, though, seemed to be a sluggish re-sprouter. Upon closer examination of one of the severe burn sites with ice wedge polygons, there was apparent oxidation, or at least discoloration, of soils present (WP197). A red mineral layer at this site was 2-10 cm thick with compacted, highly decomposed,

Figure 15. Red mineral layer above char observed at severely burned site WP197 in 2017.

organic soil below (which apparently escaped combustion by being frozen; Fig 15). Very acidic pH values from the site (4.4) likely indicate this surface was once deep and had a higher mineral content than surface moss layers. Over much of this area, lush grasses and many shrubs had colonized the area (Fig. 16).

Boggy *Sphagnum* and sedge meadows or fens had the least organic mat consumption. Although marshy transects appeared to us to be drying, as evidenced by shifts in plant communities, including shrubbification and shifts from marsh sedges toward *Carex bigelowii*. However, it is hard to separate hydrologic changes from the fire independent from the extreme warming that is occurring all over northern Alaska. Measurements of duff bulk density at ARF transects show a linear increase with depth (Mack *et al.* 2011: unpublished data). Although not explicitly tested, O'Donnell *et al.* (2009) found that thermal conductivity varied by organic horizon and data from Yoshikawa *et al.* (2003) indicate a strong, positive relationship between duff bulk density and thermal conductivity. Given that fire consumes the duff layers from the top down, it makes sense that increasing burn depth would leave behind duff layers of higher bulk density and, by extension, higher thermal conductivity. That is, deeper burns leave behind soil layers of diminished insulative value resulting in deeper active layers. It should be re-emphasized that arctic Alaska climate is in flux and warming of near-surface permafrost along with localized degradation has been documented in the absence of disturbance (Romanovsky *et al.* 2017, Liljedhal, *et al.* 2016).

Species of tall willow are responding by increases in stature and colonization of thermokarst-affected terrain in our study area, but this trend is occurring, albeit more gradually, across the North Slope (Tape *et al*. 2016). Other studies suggest that tundra north of the Brooks Range is responding to climate change with widespread expansion of and dominance by tall shrubs and that this is likely to profoundly alter the tundra biome because of its influence on biogeochemical cycling and feedbacks to climate (Beck *et al*. 2011). Our observations from ARF and the pre-1948 Shivugak Bluffs sampled in 2017, as well as at several other older burns (Jones *et al*. 2013), suggest that fire greatly accelerates this succession, leading to willow expansion that can persist for many decades and degradation of permafrost features already stressed by global warming. At Shivugak Bluffs, the willow basal area determined in a burn transect was 6.8x greater than in a random reference transect outside the disturbance footprint (Fig. 17; Miller *et al*. in prep.).

Post-fire accumulation of organic material is around 4.2 cm of mostly moss and plant litter. This layer of recently cast fine fuel along with dead cottongrass litter carried two small lightning-ignited reburns in 2017—the first documented repeat burns on Alaska's North Slope. This is an extraordinarily short fire return interval for arctic Alaska: within the extent of the ARF, no large fires were detected in lake sediment cores in the previous 6,500 years (Chipman *et al*. 2015). Short-interval repeat fire should favor fire resistant (e.g., tussock grasses), resilient (e.g., resprouting shrubs), and colonizing (e.g., true grasses) species with each disturbance clearing accumulated insulating litter/duff and thus continuing the soil warming.

Thermokarst was much more evident inside the burn than outside. Even low severity burn areas experienced noticeable ground subsidence. In some cases, ice wedge troughs have deepened by more than 1 m in areas underlain by yedoma soils. Interestingly, we found evidence of thermokarst and subsidence on the low-burn-severity Kuparuk Fire as well as on higher severity ARF transects. Troughs were characterized by slumping tussocks, often into ponded water and increases in Equisetum, tall shrubs, and true grasses. Jones *et al*. (2015) documented a 340% increase in microtopography from 2009-2014 where the burn is underlain by yedoma (less effect on glaciated soils). Mean annual ground temperature at 1 m depth has warmed 1.5 °C relative to unburned tundra (Fig. 9). Tussock sedges inside the burn continue to grow and flower vigorously, suggesting a continued flush of soil nutrients, competitional release, or a response to warming at root-level. The similarities between the pattern of vegetation shift on burned areas were strikingly similar to patterns on experimental fertilization enhancement plots maintained at the nearby University of Alaska Toolik Research Station.

Evidence of fire-induced thermokarst and subsidence were documented at multiple scales by our study (Jones *et al*. 2015). Iwahana also studied the surface displacement using satellite and airborne synthetic aperture radar (SAR) remote sensing (2006-2018) as well as collecting in-situ field measurements (2014-2019) at a separate set of marked plots (Iwahana *et al*. 2019, Iwahana *et al*. 2016). Both inter-annual (thermokarst) and seasonal subsidence were measured and validated by field measurements. Significantly large amounts of annual subsidence (up to 6.2 cm/year as spatial average) were measured by differential SAR interferometry using satellite (ALOS-PALSAR) in burned areas relative to nearby unburned areas in the first three years after the fire (2008-2010) decreasing to about 2 cm/year overall from 2015-2018. Iwahana's team proposed that these changes were initiated by the disturbance as well as recent enhancement of natural thermokarst development by climate warming. Rapid climate warming at high latitudes, even in the absence of fire, is causing accelerated decomposition of stored permafrost carbon, releasing greenhouse gases into the atmosphere (Schuur *et al*. 2008). Initial studies indicate permafrost carbon emissions from abrupt thaw of permafrost in susceptible soils types could be large enough to create substantial impacts on the climate system—perhaps as much as doubling the C release currently included in models from gradual thawing (Turetsky *et al.* 2020). Our observations indicate that increasing fire disturbance in the arctic ecosystem can be an additional process contributing to abrupt thaw of permafrost.

Fire is also a widely recognized mechanism for release of carbon stored in vegetation and soils and contributes to greenhouse gases into the atmosphere. Mack *et al.* (2011) used data gathered in this study to show the ARF released approximately 2.1 Tg C to the atmosphere, as much as the annual net C sink for the entire arctic tundra biome over the last 25 years of the 20th century. They speculate that a climate-driven increase in tundra fire disturbance may represent a positive feedback, potentially offsetting arctic greening (another effect of warming climate) and shifting the tundra biome from a net sink for atmospheric C to a net source. However, the rate of C deposition on burned areas may be increased with elevated productivity due to increased nutrient availability and warmer soils. In western Alaska tundra, increased nutrient (N, P) levels have been observed for over 40 years post-fire (Baillargeon *et al.* 2019). Mack *et al.* (2011) estimated the average age of C consumed on in the ARF to be < 50 years old (based on detection of bomb-enriched radiocarbon in all surface soils from the burned sites) and estimated it took 37 years on average to develop the 6.1 cm (range 3-23 cm) of surface organic soil thought to have been consumed by the fire. We believe that the bottom layers of the organic horizon were frozen at the time of burn and now these layers are thawed and active, contributing to plant growth and microbial respiration.

Figure 16. Ice wedge degradation created troughs > 1 m deep in some areas. Vigorous response of taller shrubs and true grasses are also notable ten years post-fire.

Slight but consistent differences in pH at burned and reference transects observed in early post-fire surveys (Jandt *et al.* 2012; Mack *et al.* 2011) suggested that biogeochemical properties of the organic soil may be altered by disturbance, but in 2017 differences were not statistically different on simple t-tests. Nor did our prior studies show correlations between acidity and surface or vegetative burn severity (CBI). The underlying geological substrate of transects seemed to be the most important indicator of acidity, with well-drained riparian transects and some at the north end of the burn region having lower acidity. This is consistent with Auerbach's (1997) mapping of tundra types in the region.

Figure 17. Shiguvak Bluffs firescar (>69 years) had extensive tall willow cover in 2017. Five willow species were found inside the burn area vs. three outside.

Wildlife habitat implications vary with species and time since burn. A dietary analysis on pre-burn caribou scat collected from ARF in 2008 (Jandt *et al.* 2012) showed approximately 50% lichen composition in the fall/winter diet, uncorrected for digestibility. Since preferred lichens are absent for many years post-fire (Zouaoui *et al.* 2014), the fire has reduced winter forage availability for caribou. Although caribou are less likely to use the ARF for winter range for decades due to low availability of preferred lichens, they may find the burn area attractive in the spring with a flush of greening sedges, herbs, and deciduous shrubs. Recovery time is unknown, although in the Yukon-Kuskokwim region, tundra burns had recovered a little over a third of lichen cover compared to undisturbed reference plots after 45 years (Frost, *et al.* 2020). Microtine and raptor activity increased dramatically in years 3 and 4 post burn. We saw considerable *Microtus sp.* activity in the form of middens, tunnels and harvesting beginning in 2010 followed by an irruption of short-eared owls (*Asio flammeus*) (10 owls observed the first two days of 2011 survey; Jandt *et al.* 2012). By 2017 microtine activity was much less notable. Some of the riparian shrub cover favored by moose for winter forage was consumed by the burn, but aquatic forage used in summer would be unaffected. The regenerating shrub cover should be high in nutrients and digestibility, which may benefit moose and possibly bears. We observed evidence of both species in the burn area during 2017. A study on post-fire bird abundance and diversity at the ARF suggested avifauna may be relatively resilient to effects of fire after seven years, with moderately burned areas scoring slightly better than reference or severely burned patches (Perez *et al*. 2018).

Recommendations

While this study summarizes the early successional changes on the ARF, long-term follow-up will be essential to determine the magnitude and duration of ecological change. Changes in relative species abundance over time, microtopography changes, hydrological changes and snow-holding capacity of the landscape are important characteristics for determining future ecosystem function. Future surveys on the ARF should include documenting shrub cover changes and competition between species—especially vascular vs. bryophyte recovery. *Betula* may have competitive advantage over other shrubs on warmed, fertilized sites due to its growth plasticity (Bret-Harte *et al*. 2001), but we saw larger gains in willow shrubs after the first decade at our study sites. Breen *et al*. (2019) assessed vegetation on North Slope fires up to 100 years old and demonstrated that tundra fires can facilitate the invasion of tundra by shrubs there as well as in western Alaska tundra (Breen *et al*. 2018). Tape *et al*. (2016) associated the 17% increase in thaw degree days along the Chandler and Colville rivers from 1901 to 2009 with a 63% increase in shrub height, whereas we observed a 270% increase in thaw days in the burned area in our limited sample (Fig. 10). Additionally, soil temperature may be more limiting for trees than air temperature, at least for deciduous species (Sveinbjörnsson 2012) and we observed elevated soil temperatures lasting at least ten years in the burn scar.

Increased shrubbiness could have other consequences, such as snow retention and shading of understory species, including lichen. It has also been suggested that vegetation change including taller willows in northern Alaska is facilitating expansion of moose into these area (Tape *et al*. 2016). Higuera *et al*. (2011) demonstrated, however, that the species makeup of tundra vegetation shows remarkable resilience over long time periods, with similar species composition across fire return intervals from as low as 150 years in the Noatak National Preserve in western Alaska to more than 5,000 years in the ARF. Yet, on Alaska's North Slope, it is apparent that fire can induce surface landform and vegetation changes which persist for > 100 years (Jones *et al*. 2013) and these transitions could, in fact, represent threshold shifts in arctic vegetation communities under modern climatic conditions. We believe these burned area studies may provide a preview of future north slope tundra ecosystems.

The deepening of the active layer that we documented could have important implications for water retention, decomposition, and other soil changes that could affect successional trajectory, plant phenology changes, surface roughness and changes in energy balance. However, after ten years, seasonal thaw depth (measured at a single point in time in early summer) was not statistically different from undisturbed areas. Remote sensing studies at a landscape scale could more accurately ascertain the duration of fire impacts on seasonal thaw. Nevertheless, the implications of increased surface roughness due to the subterranean thawing and reorganization that has already occurred assures changes in snow retention, surface drainage, and vegetation are likely to persist. Recent studies from western Alaska tundra have revealed dramatic changes in subsurface drainage including wholesale disappearance of water bodies (Chen *et al*. 2020). On the ARF, although more ponded thermokarst depressions were visible, we also anecdotally observed an overall drying of marshier transects a decade post-fire, with species considered emergent being replaced by more upland types of vegetation. Further study to quantify the overall changes of surface water and soil moisture trends are needed.

Data on fire effects and vegetation recovery are important for assessing the impacts of increasing temperatures on tundra fire regimes and the implications of increased fire in the Arctic for wildlife and ecosystem processes. Our monitoring of this burn over the last ten years reveals a story much larger than our team can tell, inviting involvement of other disciplines, particularly hydrology, soil and landform science, and wildlife and subsistence resource management. What is the fate of forage lichens which take decades to recover and how will caribou respond? How will increasing willow abundance affect snow dynamics, ground-layer plant communities, and moose and other animal habitat? Can we quantitatively confirm our anecdotal observations of hydrologic changes? Remote sensing studies may be very helpful to follow future landform changes, drainage and snow depth and to scale up from transects to landscape. It is our hope that the permanent transects will be monitored periodically for several decades using the same methods to document long-term recovery from the fire during a period of significant climate change.

GPS locations of transects reported here are listed in Appendix Table A.1. Archived data from this study is available at the Alaska Fire Science Consortium website (https://www.frames.gov/afsc/tundra-fire-effects-studies) and (for UAF transects) in the Arctic Long Term Ecological Research data archive (http://ecosystems.mbl.edu/arc/datacatalog.html). Jandt *et al*. 2012 provides details of the field data collection methods, allowing for methodical interpretation and reproducibility of the study.

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Appendix A

Table A-1. Permanent BLM transect locations and descriptions for Anaktuvuk River Fire study (Lat/Long in NAD83). Vegetation class interpreted from Alaska Vegetation Classification (Viereck *et al*. 1992).

Unit	Plot Type	Transect Name	Latitude Origin	Longitude Origin	Viereck Class	Elevation (m)	Aspect Deg.	Slope %	Transect Azimuth	Site Moisture
ARF	Burned	B005	69.34	150.91	2C2H	161	90	0	90	MOIST
ARF	Burned	B013	69.17	150.82	2C2A	210	180	2	90	MOIST
ARF	Burned	B020	69.02	150.76	2C2A	322	360	3	90	MOIST
ARF	Burned	B027	69.05	150.59	3A2I	306	135	1	90	WET
ARF	Burned	B030	69.11	150.62	2C2A	255	FLAT	0	90	MOIST
ARF	Burned	B032	69.16	150.69	3A3	228	FLAT	0	90	WET
ARF	Burned	B037	69.27	150.75	3A2D	191	90	2	90	MOIST
ARF	Burned	B041	69.34	150.79	3A2D	166	FLAT	0	90	MOIST
ARF	Burned	B051	69.26	150.65	2C2A	205	FLAT	0	90	MOIST
ARF	Burned	B060	69.17	150.54	3A2H	217	90	3	90	MOIST
ARF	Burned	B063	69.13	150.44	2C2C	239	FLAT	0	90	DRY
ARF	Burned	B069	69.02	150.41	2C2A	342	218	6	90	MOIST
ARF	Burned	BKUP	69.30	150.32	2C2A	198	FLAT	0	90	MOIST
ARF	Burned	BNAN	69.12	150.79	2C2A	206	FLAT	0	90	MOIST
ARFR	Unburned	U031	69.36	151.18	2C2H	162	245	2	90	DRY
ARFR	Unburned	U043	69.04	150.04	3A2D	356	344	6	90	MOIST
ARFR	Unburned	U053	69.31	150.49	2C2A	198	62	3	90	MOIST
ARFR	Unburned	U071	69.18	150.45	2C2F	218	FLAT	0	90	MOIST
ARFR	Unburned	U072	69.04	150.93	2C2A	284	270	2	90	MOIST
ARFR	Unburned	U075	69.34	150.54	3A3	171	270	2	90	WET
ARFR	Unburned	U611	69.24	150.50	2C2H	206	242	2	90	MOIST
ARFR	Unburned	U622	69.13	150.34	2C2C	253	FLAT	0	90	MOIST
ARFR	Unburned	U623	69.21	150.33	3A2D	217	30	2	90	MOIST
KUPR	Unburned	UKUP	69.30	150.32	2C2A	198	FLAT	0	90	MOIST
ARFR	Unburned	UNAN	69.12	150.80	2C2A	206	FLAT	0	90	MOIST
ARF2	Burned	BREB	69.08065	150.7516	2C2A	253	315	0	90 (decl. 18º E)	DRY

Unit	Plot Type	Transect Name	Latitude Origin	Longitude Origin	Viereck Class	Elevation (m)	Aspect Deg.	Slope %	Transect Azimuth	Site Moisture
JON	Burned	BSHI	69.41286	151.5026	2C2G	96	--	--	148 (decl. 24 º E)	DRY
JONR	Unburned	USHI	69.41348	151.5042	2C2A	100	--	--	328 (decl. 24º E)	DRY

Table A-2. Previously documented and new (BREB) burn severity measurements on Anaktuvuk River Fire study transects (Jandt *et al*. 2012). Burn severity was estimated along each burned transect in the 1x1 m quadrats (N=10/transect) for soil and vegetation using a scale of 1-heavily burned to 5-unburned, according to the Alaska Interagency Fire Effects Task Group protocol (2007).

Unit	Plot Type	Transect	Substrate Mean	Vegetation Mean	Overall Mean Transect Severity	N	CBI	Residual Organic
ARF	Burned	B005	2.3	2.3	2.3	10	1.8	16.35
ARF	Burned	B013	1.4	1.0	1.2	10	2.9	12.05
ARF	Burned	B020	2.0	1.0	1.5	10	2.5	12.27
ARF	Burned	B027	3.3	2.8	3.05	10	2.3	27.45
ARF	Burned	B030	2.3	1.3	1.8	10	2.2	11.45
ARF	Burned	B032	3.0	1.1	2.05	10	2.2	25.6
ARF	Burned	B037	1.6	1.2	1.4	10	2.7	8.55
ARF	Burned	B041	2.6	1.8	2.2	10	2.3	21.5
ARF	Burned	B051	2.7	2.5	2.6	10	1.4	19.15
ARF	Burned	B060	1.3	1.3	1.3	10	2.5*	8.5
ARF	Burned	B063	1.9	1.8	1.85	10	3.0	17.9
ARF	Burned	B069	1.9	1.0	1.45	10	2.2	12.25
ARF	Burned	BKUP	2.9	2.6	2.75	10	1.9	27.95
ARF	Burned	BNAN	1.6	1.7	1.65	10	2.6	13.1
ARF2	Burned	BREB	4.0	4.0	4.0	10	--	--

**Taken at nearby location B060A*