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Biophysical effects of an old tundra fire in the Brooks Range Foothills of Northern Alaska, U.S.A

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ABSTRACT

Our understanding of tundra fire effects in Northern Alaska is limited because fires have been relatively rare. We sampled a 70+ year-old burn visible in a 1948 aerial photograph for vegetation composition and structure, soil attributes, terrain rugosity, and thermokarst pit density. Between 1948 and 2017 the burn initially became wetter as ice wedges melted but then drained and dried as the troughs became hydrologically connected. The reference tundra has become wetter over the last few decades and appears to be lagging through a similar sequence. The burn averaged 2.5 °C warmer than the reference tundra at 30 cm depth. Thinning of organic soil following fire appears to dramatically accelerate the background degradation of ground-ice features in response to climate change and promotes a plant community that is distinct in terms of taxa and structure, dominated by tall willows and other competitive, rather than cold-tolerant, species. The cover of sedges and mosses is low while that of willows and grass is high relative to the reference tundra. The changes in plant community composition and structure, increasing ground temperature, and thermokarst lead us to expect the observed biophysical changes to the tundra will persist centuries into the future.

1. Introduction

Wildfire is a relatively rare event on the tundra north of the Brooks Range in Alaska, U.S.A. Jones et al. (2009), Hu et al. (2010), French et al. (2015), Hu et al. (2015), Chipman et al. (2015), Jones et al. (2013), Masrur et al. (2018), Nitze et al. (2018), Chen et al. (2021a) and Masrur et al. (2022). There are only 138 known fires between 1969 and 2022 (Miller et al., 2023) spread over broad gradients in soil genesis, acidity, ground-ice richness, vegetation, and climate (Zhang et al., 1996; Gough et al., 2000; Walker, 2000; Heijmans et al., 2022), limiting our understanding of the factors that determine the response of tundra to fire. Responses of tundra also depend on the seasonal timing of fire. Early-season fires seldom burn for longer than an afternoon while late-season drought can result in days or weeks of fire spread with significant consumption of organic soil (duff), a keystone attribute of tundra that controls ground freeze-thaw processes and vegetative structure and composition (Racine et al., 1987; Heijmans et al., 2022). In addition to disturbance by fire, the tundra landscape is simultaneously responding to climate change, for example by expansion of willows and alder (Tape et al., 2006; Myers-Smith et al., 2011; Chen et al., 2021a; Mekonnen et al., 2021), and broad-scale degradation of ground-ice features (Jorgenson et al., 2006; Frost et al., 2018a; Jorgenson et al., 2015b; Liljedahl et al., 2016; Jorgenson et al., 2022a). The relatively small number of fires as well as a temporally limited historical record (Barney and Comiskey, 1973; Miller et al., 2023) do not allow confident isolation of the influence of any one of these gradients or factors on the short- or long-term response of tundra to fire but examination of key burns can provide some insight.

Jones et al. (2013) discerned a 280 ha burn of uncertain age that appears in a 1948 aerial image near the confluence of the Colville and Chandler Rivers which we call the Shivugak Bluffs Burn. This burn offers an opportunity for comparison of fire effects at the time scale of more than a half-century. We became interested in the Shivugak Bluffs Burn as a complement to our monitoring of vegetation and soils of the nearby 2007 Anaktuvuk River Burn, a large tundra fire that extended nearly 70 km between the Itkillik and Nanushek Rivers in the central Brooks Range Foothills (Jones et al., 2009; Mack et al., 2011; Jandt et al., 2012; Bret-Harte et al., 2013; Jandt et al., 2021). In contrast to most of the Anaktuvuk River Burn which occurred in moist

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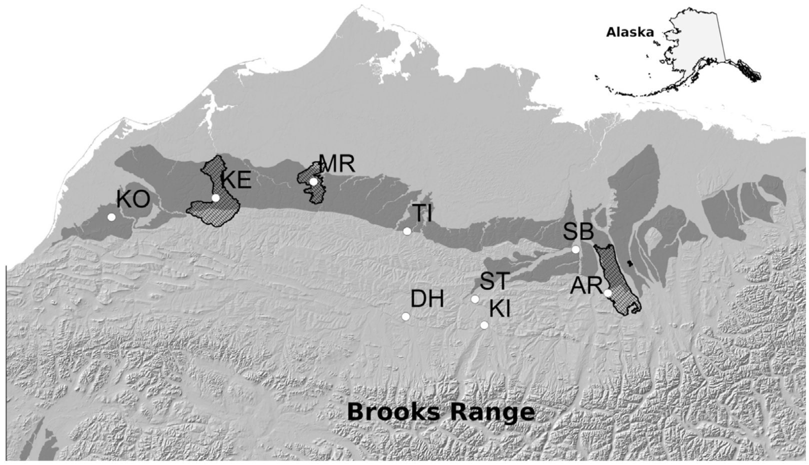

Fig. 1. Location of the Shivugak Bluffs Burn and other burns mentioned in the text. The band of yedoma is shown in dark gray (Strauss et al., 2022). Burns are KO=1977 Kokolik River, KE = c. 1880–1920 Ketik River, MR = c. 1880–1920 Meade River, DH = 1976 Deadhorse, TI = 1985 Titaluk, ST = < 1948 Starfish Bluff, KI = 1969 Killik River, SB = < 1948 Shivugak Bluffs Burn, AR = 2007 Anaktuvuk River. Large burn areas are shown hashed. Outline of the state of Alaska, USA is inset.

acidic tundra, the Shivugak Bluffs Burn is located in moist nonacidic tundra (Fig. 1) (Walker et al., 1994, 2014). Nonacidic tundra is often associated with yedoma, a type of soil that is rich in ground-ice and vulnerable to thermokarst (Kanevskiy et al., 2011). In 2017, we resampled a set of fire effects monitoring transects at the Anaktuvuk River Burn and took the opportunity to add an additional pair of comparative transects at the Shivugak Bluffs Burn. Our objective was to compare the burn to adjacent unburned tundra in a "control-treatment" approach. Since the unburned tundra is also showing responses to changing climate we refer to it as "reference" tundra. The broad question we address is, how does wildfire compound the ongoing response of tundra to climate change?

Climate change is borne out in numerous records of air and ground temperature, river runoff, tundra "greenness", shoulder-season snow cover, end-of-season sea ice extent, thermokarst development, glacier mass balance, and other climate records (e.g., Ballinger et al., 2023; Chapin et al., 2005; Hu et al., 2010; Kittel et al., 2011; Ahmed et al., 2013; Overland et al., 2017; Wang et al., 2017b; Box et al., 2019; Overland et al., 2019; Biskaborn et al., 2019; Vaks et al., 2020; Heijmans et al., 2022; Jorgenson et al., 2022b; Ballinger et al., 2023). Paleoclimatic records indicate that the Arctic has been most recently warming since c. 1840 and is warmer now than it has been in the last 400 or more years (Overpeck et al., 1997; Ahmed et al., 2013). Annual air temperature on the Arctic Slope has been warming 0.50 °C/decade since 1957 (Ballinger et al., 2023). Warming is amplified north of the Brooks Range relative to lower latitudes because it borders sea-ice-covered waters that are undergoing stark changes in albedo that affect regional land-surface energy budgets (Chapin et al., 2005; Serreze and Barry, 2011; Rantanen et al., 2022; Ballinger et al., 2023). Work by Hu et al. (2015) and Descals et al. (2022) suggest that warming will reduce the fire rotation time as thresholds in summer air temperature and/or precipitation are crossed.

Old burns on the order of 50–100 years such as the Shivugak Bluffs Burn may provide insight into the future of the tundra landscape of the Northern Brooks Range Foothills. The tundra is of particular concern for its vulnerability to a changing fire regime that potentially features increasing fire size and severity, both of which determine the potential to release atmospheric greenhouse gases from deep organic soils in a biome that may hold 50% of the world's soil carbon (Schuur et al., 2013; Hugelius et al., 2014), including ancient carbon (Hu et al., 2015; Billings and de Souza, 2020). In this study, we specifically examined several fire effects: ground-layer vegetation cover, shrub abundance and canopy architecture, soil attributes, and degradation of ground-ice relative to reference tundra.

2. Methods

2.1. Study site

The Shivugak Bluffs Burn is 25 km east of Umiat at the confluence of the Colville and Chandler Rivers. It occurs on yedoma (Kanevskiy et al., 2011; Strauss et al., 2017, 2022) or silt with syngenetic permafrost of late-Pleistocene origin characterized by high ice content that may reach 50%–90% by volume (Jorgenson and Osterkamp, 2005; Jorgenson et al., 2015a; Farquharson et al., 2016). The near-surface ground-ice features are of Holocene age and include epigenetic ice wedges and quasi-syngenetic permafrost (Kanevskiy et al., 2011; Jorgenson et al., 2015b, Personal communication, M.T. Jorgenson). The vegetation of the reference area is moist nonacidic tundra on continuous permafrost, featuring frost boils, high-centered polygons, pH> 6.5, low-statured shrubs, shallow organic soils, and deeper active layers relative to moist acidic tundra (Muller et al., 1999; Walker et al., 1994; Walker, 2000; Walker et al., 2014).

The site occurs in circumpolar arctic bioclimatic subzone D characterized by a mean July temperature of 7-9 °C (Walker and Raynolds, 2018). Snow covers the tundra about two-thirds of the year. On average the snow is melted by 28 May at Umiat and begins to accumulate on 2 October for a snow-free season of 127 days (Zhang et al., 1997; Cherry et al., 2014). Snow contributes about 120 mm to the annual water budget of 313 mm and reaches a maximum thickness of 430 mm (Zhang et al., 1996). Mean annual air temperature is −12.4 °C (Zhang et al., 1996). The aspect at the transects is southeast and the slope is about 3%.

2.2. Field and analytical methods

Several visits were made to the Shivugak Bluffs Burn prior to sampling a pair of transects in 2017. Jones et al. (2013) first visited the site in 2012 after identifying it in remote sensing imagery. They collected some soil samples in an attempt to locate charcoal or an ash layer to confirm the occurrence of fire. A second brief visit occurred in June 2013 and some initial soil pH and organic soil layer (duff) thickness measurements were made.

Transects were established in 2017 in the reference tundra at 69.41348° × −151.50417° and within the burn at 69.41286° × −151.50264°, during visits on 10 and 16 July. The transects were georeferenced but were not permanently marked. We collected nine soil monoliths from the burn in which to look for ash and charcoal. These were dried and destructively sectioned in the laboratory. Charcoal was confirmed by streaking across white paper (Jones et al., 2013).

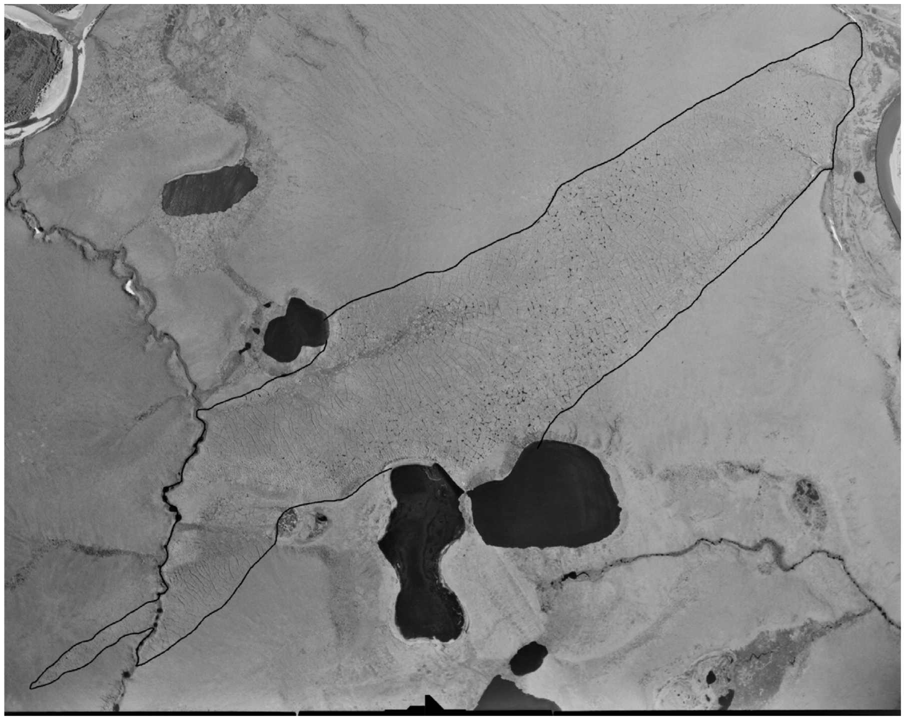

Fig. 2. Aerial photograph of the Shivugak Bluffs Burn in 1948 with interpreted perimeter. Note the thaw pits inside the burn. United States Geological Survey Entity ID: ARCBAR000540063. Acquisition Date: 1948-Jul-18. The longest axis of the burn is 4.8 km. The Chandler River is to the northeast. The Colville River is to the northwest.

Transect sampling methods matched those of Jandt et al. (2012, 2021) for comparability. One transect was run roughly northwest in the reference tundra and the other was run southeast into the burn. The transects were imaged with a camera from each end and also obliquely from a hovering helicopter. Ground-layer vegetation was characterized at 100 points along each 50-m transect using a mounted laser pointed at the ground. Each species or substrate hit by the laser beam was recorded down to ground level. Only one hit per species per point was recorded. Nomenclature follows the Natural Resources Conservation Service PLANTS database (USDA, NRCS, 2020).

Tall willows and tussock cottongrass (*Eriophorum vaginatum*) were characterized in five quadrats of 1 m^2 evenly spaced along the transect. We consider *Salix glauca*, *Salix richardsonii*, and *Salix arbusculoides* to be “tall willows”. These species grow taller than *Salix pulchra* which is a low-growing willow associated with tussock tundra. For our purposes, dwarf willow (*Salix reticulata*) was considered an herb and not included in the shrub sampling. The basal area of willows was used as an easily-measured proxy for willow biomass. Basal diameter was measured with calipers and converted to basal area defined as the sum of the cross-sectional area at the base of the shrub stems per square meter of ground area ($mm^2\ m^{-2}$). Alder was not encountered. Cottongrass tussocks were counted in the shrub quadrats for density (m^{-2}). Each quadrat was imaged with a camera from chin height.

We used a remote-sensing dataset of above-ground shrub biomass by Berner et al. (2018b,a) to confirm and extend our ground-based measurements. Biomass values ($kg\ m^{-2}$) in 1 425 pixels inside the burn were compared with 1 600 pixels adjacent to the burn using a t-test at α=0.05 assuming unequal variances.

Three soil pits were dug at the 5-, 25-, and 45-m marks of the transect offset to the left 2 m. Organic soil thickness was measured, supplemented with measurements from the previous visit in 2013. The soil was frozen above the mineral layer in the reference area in 2013 and thus those three samples are minimum thicknesses. Acidity was measured in the organic and mineral layers with a handheld meter.

We compared visible features in the 1948 aerial photograph with subsequent remote sensing images, looking for trends in gross, landscape-scale differences in vegetation and soils both inside and outside the burn. Changes outside the burn reflect background stressors such as climate change. Changes inside the burn reflect the compounding effects of disturbance by fire. We focused on the most visible response which was the density of thermokarst “thaw pits” or impounded water, generally occurring at the intersections of ice wedge troughs in the network of polygons. These were quantified by eye in a Geographic Information System inside randomly located 50-m radius plots (0.79 ha), 13 each inside and outside the burn. Pit density was counted in four image years (1948, 1980, 2006, and 2017). The distribution of thaw pit density was highly skewed. Using the median as a measure of central tendency resulted in many zeros for each image year which was misleading. Geometric means, which approximate the median, are plotted and given in Fig. 8.

Hobo U23-003 Pro V2 temperature-sensing data loggers (Onset Computer Corporation, Bourne, MA, USA) were installed in polygon centers inside and outside the Shivugak Bluffs Burn and the Anaktuvuk River Burn. An organic soil monolith was extracted and a 5-cm diameter auger was used to drill through the mineral soil. Ground temperature thermistors were placed at a depth of 100 cm. Thermistors were also placed at depths of 30 cm and 15 cm, at the Shivugak Bluffs Burn and the Anaktuvuk River Burn, respectively. The borehole was infilled and the monolith placed back on the hole. Hourly measurements were averaged into daily temperature. Degree-days were calculated for days outside the zero curtain, the period of time when the ground is freezing or thawing and the temperature remains near 0 °C. Freezing and thawing degree-days were calculated as the sum of mean daily temperatures below −0.25 °C and above 0.25 °C, respectively, over the measurement period between 12 July 2017 and 15 July 2018, nominally one year.

3. Results

Evidence of fire. An ash layer and charcoal were found in two of the nine collected soil profiles, confirming that fire disturbed the patch. The shape of the burn suggests the fire ignited on the southwest flank

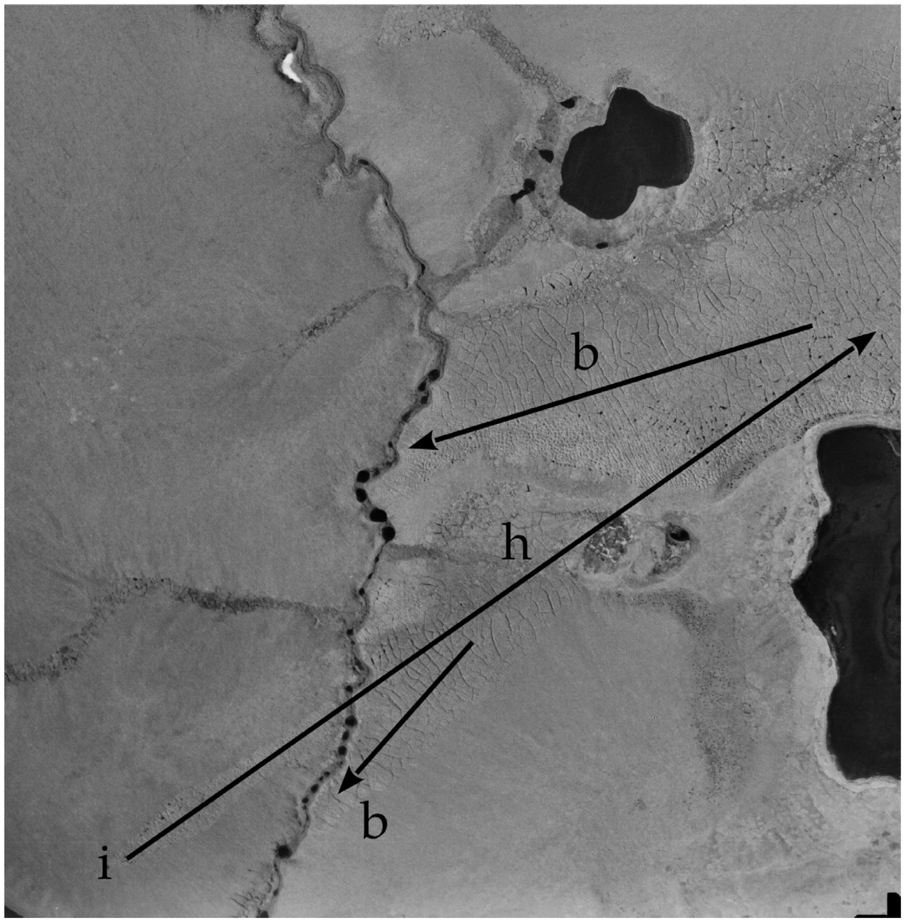

Fig. 3. Close-up of the southwest corner of Fig. 2. Our interpretation of fire spread progression is: "i"=ignition point, "h"=head fire run that crossed the stream, "b"=backing runs stopped by the stream.

(Figs. 2 and 3). The winds were from the southwest and strong, resulting in a length-to-width ratio of about 5.4:1. This direction matches the prevailing winds at Umiat during mid-June when arctic tundra fires are most likely to ignite and spread (WRCC, 2021). Wind appears to have pushed head fire across the intervening stream in Fig. 3 and prevented backing fire from re-crossing. The fire ran over four kilometers to the northeast and dropped into the Chandler River floodplain. The features at Shivugak are consistent with other known historical and prehistorical tundra burns. The elongated outline is very similar to the wind-driven Dead Horse Fire which was fought by smokejumpers in 1976 (Alaska Interagency Coordination Center records) and is strikingly similar to another putative burn at the confluence of the Killik and Colville Rivers, Starfish Bluff, that was also found in 1948 aerial imagery (Miller et al., 2023).

Physiognomy. Gross physiognomic differences between the reference tundra and the burn are apparent in modern remote sensing imagery (Fig. 4) and on the ground (Fig. 5). The reference tundra consists of low-growing herbs and shrubs interspersed with frost boils. In contrast the burn features a vegetative layer that is dominated by tall willows and a ground surface that is more deeply rugose. These gross differences in shrub biomass seen on the ground are also apparent in the remotely sensed shrub biomass dataset of Berner et al. (2018a): 571 ± 139 s.d. $g\,m^{-2}$ in the burn versus 311 ± 73 $g\,m^{-2}$ in surrounding reference tundra (t = 63.7, df=2 058, *p*-value ≪0.0001).

Soils. The thickness of organic soil was greater in the reference tundra, although the magnitude of the difference is uncertain due to frozen soils in the June 2013 measurements (Table 1). The 1-m deep holes bored for the temperature thermistors brought up copious ice shavings, confirming a high ice content in the soil. The pH of the organic layer in the burn was more acidic (6.4) than in the reference tundra (7.7) but both values were circumneutral and less acidic than the transects at the Anaktuvuk River Burn (median 5.4 for burned transects and 5.0 for unburned transects (Jandt et al., 2021)).

Table 1
Mean soil organic layer thickness (±s.e.).

Transect	Organic layer thickness (cm)	n
Reference (2013)	> 16.3 ± 0.7[a]	3
Reference (2017)	21.0 ± 2.6	3
Burn (2013, 2017)	11.2 ± 3.5	6

[a] Minimum thickness; The soil was frozen above the mineral soil layer.

Ground temperature. Ground temperatures in the burn were clearly warmer than the reference tundra both shallowly (30 cm) and deeply (100 cm) at all times of the year except during the early winter zero curtain when temperatures at each transect were near the freezing point (Fig. 6 and Table 2). Annually, mean ground temperature at 30 cm depth was 2.5 °C warmer than the reference tundra. The maximum difference of +11 °C occurred in the winter. The difference in thawing degree-days (31 °C d) was small relative to that of freezing degree-days (887 °C d) (Table 3). The burn was in the process of freezing or thawing for 113 days in the burn, 39 days longer than the reference tundra. The burn reached a minimum temperature of −6.4 °C compared to −12.1°C in the reference tundra.

At 100 cm depth the ground was frozen the entire year in both the burn and reference tundra. Averaged over a year, the burn was 2.0

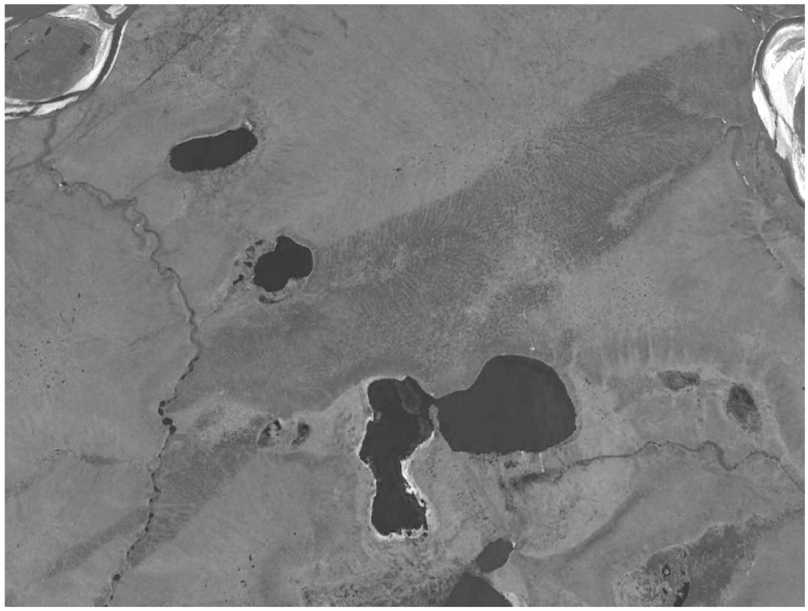

Fig. 4. Remote sensing satellite image of the Shivugak Bluffs Burn in 2010. Note the “greening” of tall shrubs and prominence of ice wedge troughs in the burn and the emergence of thaw pits in the reference tundra. GeoEye-1 image (DigitalGlobe, Inc., Longmont CO USA) Entity ID: GE120100621213904M00. Acquisition Date: 2010-06-21.

Table 2
Ground temperatures (annual basis) at the Shivugak Bluffs Burn and Anaktuvuk River Burn.

Site, Depth	Tundra	Min. (°C)	Mean (°C)	Max. (°C)
Shivugak, 30 cm	Reference	−12.1	−3.7	+2.3
	Burn	−6.4	−1.2	+3.1
Shivugak, 100 cm	Reference	−9.8	−3.7	−0.5
	Burn	−5.3	−1.8	−0.5
Anaktuvuk, 100 cm	Reference	−10.3	−4.0	−0.6
	Burn	−7.5	−2.4	−0.2

Table 3
Number of thawing and freezing days and degree-days outside the zero curtain.

Site, Depth	Tundra	Days	°C d
Thawing			
Shivugak, 30 cm	Reference	62	71
	Burn	69	102
Shivugak, 100 cm	Reference	0	0
	Burn	0	0
Anaktuvuk, 100 cm	Reference	0	0
	Burn	0	0
Freezing			
Shivugak, 30 cm	Reference	229	−1 423
	Burn	183	−536
Shivugak, 100 cm	Reference	365	−1 366
	Burn	365	−643
Anaktuvuk, 100	Reference	365	−1 475
	Burn	313	−851

°C warmer than the reference tundra. The burn reached a minimum temperature of −5.3 °C, much warmer than the reference tundra, −9.8 °C. The reference tundra experienced 723 more freezing degree-days, a factor of 2.1.

A comparison of ground temperatures at 100 cm depth against the Anaktuvuk River Burn suggests that post-fire warming in tundra burns continues for many decades following fire. The pattern in the reference tundra at the 10-year-old Anaktuvuk River Burn was remarkably well-matched and synchronous with the reference tundra at the 70+ year-old Shivugak Bluffs Burn, suggesting similar physical responses to weather (Fig. 6b). Freezing degree-days were within 8% of each other (Table 2). However, inside the burns, freezing degree days differed by 28%. Mean annual temperature was +0.6 °C warmer inside the older Shivugak Bluffs Burn and there were 208 fewer freezing degree-days, suggesting that fire does not result in a short pulse of warming but sustained warming that persists for many decades.

Table 4
Cover of ground-layer species with ≥ 2% of total point-intercept hits, ordered by difference.

Species	Common name	Cover (%)		Diff.
		Burn	Ref.	
Eriophorum vaginatum	Tussock cottongrass	7	31	−24
Dryas integrifolia	Entireleaf mountain-avens	4	21	−17
Pleurozium schreberi	Schreber’s big red stem moss	4	16	−12
Tomentypnum nitens	Tomentypnum moss	12	23	−11
Carex bigelowii	Bigelow’s sedge	5	15	−10
Salix reticulata	Netleaf willow	0	3	−3
Cassiope tetragona	White arctic mountain heather	2	3	−1
Aulacomnium sp.	Aulacomnium moss	7	8	−1
Saussurea angustifolia	Narrowleaf saw-wort	2	2	0
Peltigera sp.	Felt lichen	5	5	0
Vaccinium vitis-idaea	Lingonberry	8	4	+4
Vaccinium uliginosum	Bog blueberry	6	1	+5
Ledum palustre	Marsh Labrador tea	11	4	+7
Salix pulchra	Tealeaf willow	7	0	+7
Betula nana	Dwarf birch	9	0	+9
Salix richardsonii	Richardson’s willow	10	0	+10
Arctagrostis latifolia	Wideleaf polargrass	16	2	+14
Salix glauca	Grayleaf willow	19	2	+17

Ground layer cover. The cover of several plant species was lower at the burned transect relative to the reference transect: tussock cottongrass, mountain-avens, feathermosses, *Tomentypnum* moss, and Bigelow’s sedge (scientific names are given in Table 4). The cover of other species increased: the tall willows, the grass, dwarf birch, Labrador tea, and blueberry. A general pattern is seen in Table 4: sedges, forbs, and mosses are found at the top of the table and are associated with reference tundra. Tall willows, deciduous shrubs, and grass are found toward the bottom, associated with burned tundra.

Shrub layer. Total willow cover in the burn was 36% versus 2% in the reference tundra. *Salix glauca* was the dominant willow in both the burn and reference tundra in terms of cover, basal area, and stem density (Table 5 and Fig. 7). *Salix pulchra* also occurred in both the

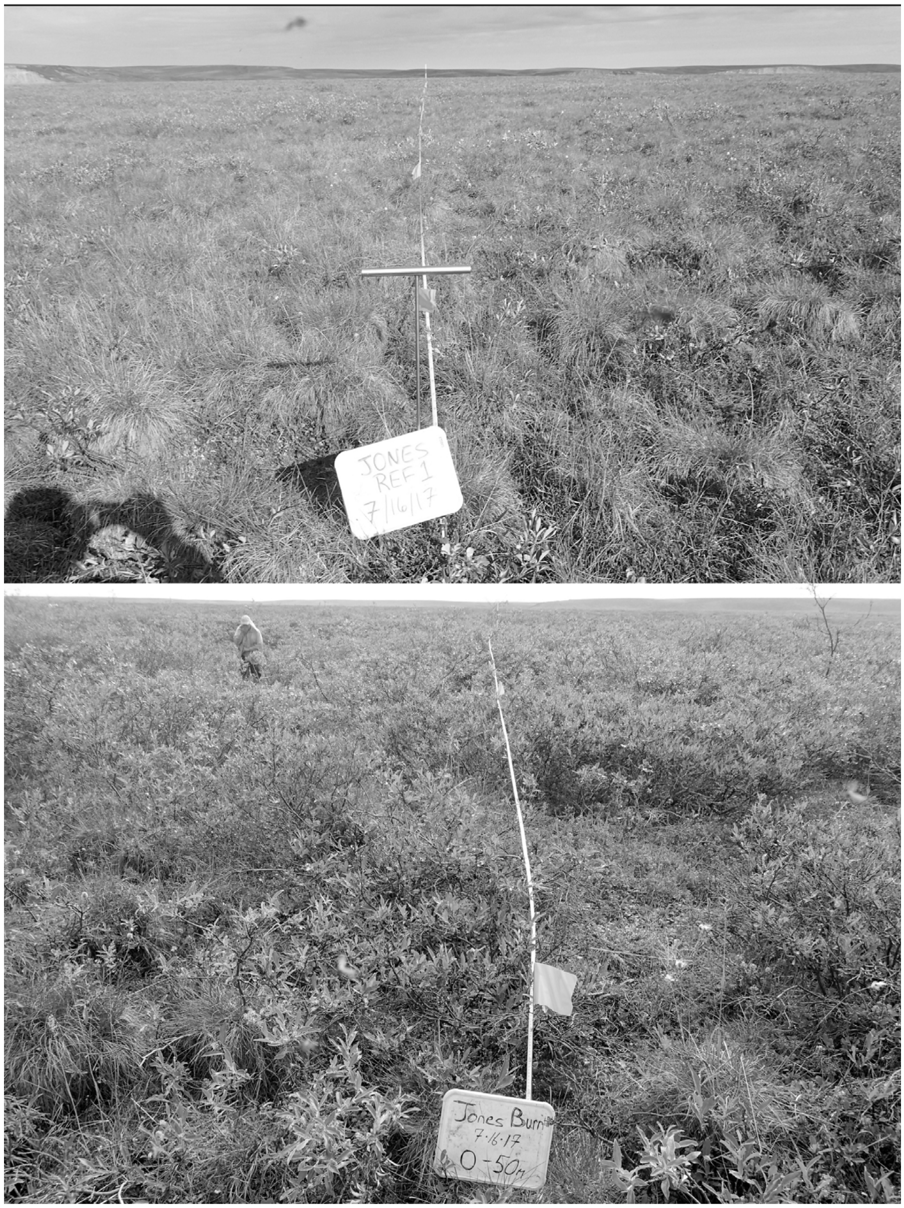

Fig. 5. The reference (top) and burned (bottom) transects. The range pole at 50-m is 6 feet/1.8 m tall incremented at 1 foot/30 cm. The pin flags are spaced 5 m apart. The burn was not named at the time of sampling so the photoboard is labeled "Jones" after author B.M. Jones who discovered it.

burned and reference tundra but at lower basal area and density. *Salix arbusculoides* and *Salix richardsonii* occurred only in the burn. Alder was not encountered. The density of willow stems was three and a half times greater in the burn than in the reference area but basal area was nearly seven times greater.

Tussock density. Tussock density was 3.5 m^{-2} in the reference tundra and 0.9 m^{-2} in the burn. Dead tussocks were also found in the burned tundra at 0.8 m^{-2}.

Thaw pit density. Thaw pit density in the reference tundra increased from 0.0 in 1948 to 1.4 ha^{-1} in 2017 (Fig. 8). Thaw pit density inside the burn showed the opposite pattern and declined from 2.8 ha^{-1} in 1948 to 0.33 ha^{-1} in 2017. The burn is drying while the reference tundra is wetting.

Table 5
Willow mean diameter, basal area, and stem density by species and treatment.

Transect	Species	Diameter (mm)	Basal area (mm^2 m^{-2})	Density (m^{-2})
Reference	*Salix glauca*	6.3	63	1.6
Reference	*Salix pulchra*	5.7	13	0.48
Reference	All spp.	**6.0**	**76**	**2.1**
Burn	*Salix* sp.	13.5	100	0.60
Burn	*Salix glauca*	7.0	261	5.1
Burn	*Salix pulchra*	5.3	16	0.60
Burn	*Salix richardsonii*	11.0	140	1.20
Burn	All spp.	**8.0**	**518**	**7.5**

4. Discussion

The tundra of the Northern Brooks Range Foothills does not feature a mosaic of old burn patches as does, for example, tundra of the Noatak drainage on the south side of the mountains, because fire has been so rare here (Racine et al., 1985; Higuera et al., 2011; Gaglioti et al., 2021; Miller et al., 2023). The rarity of fire has led to a relatively homogeneous expanse of undisturbed tundra whose

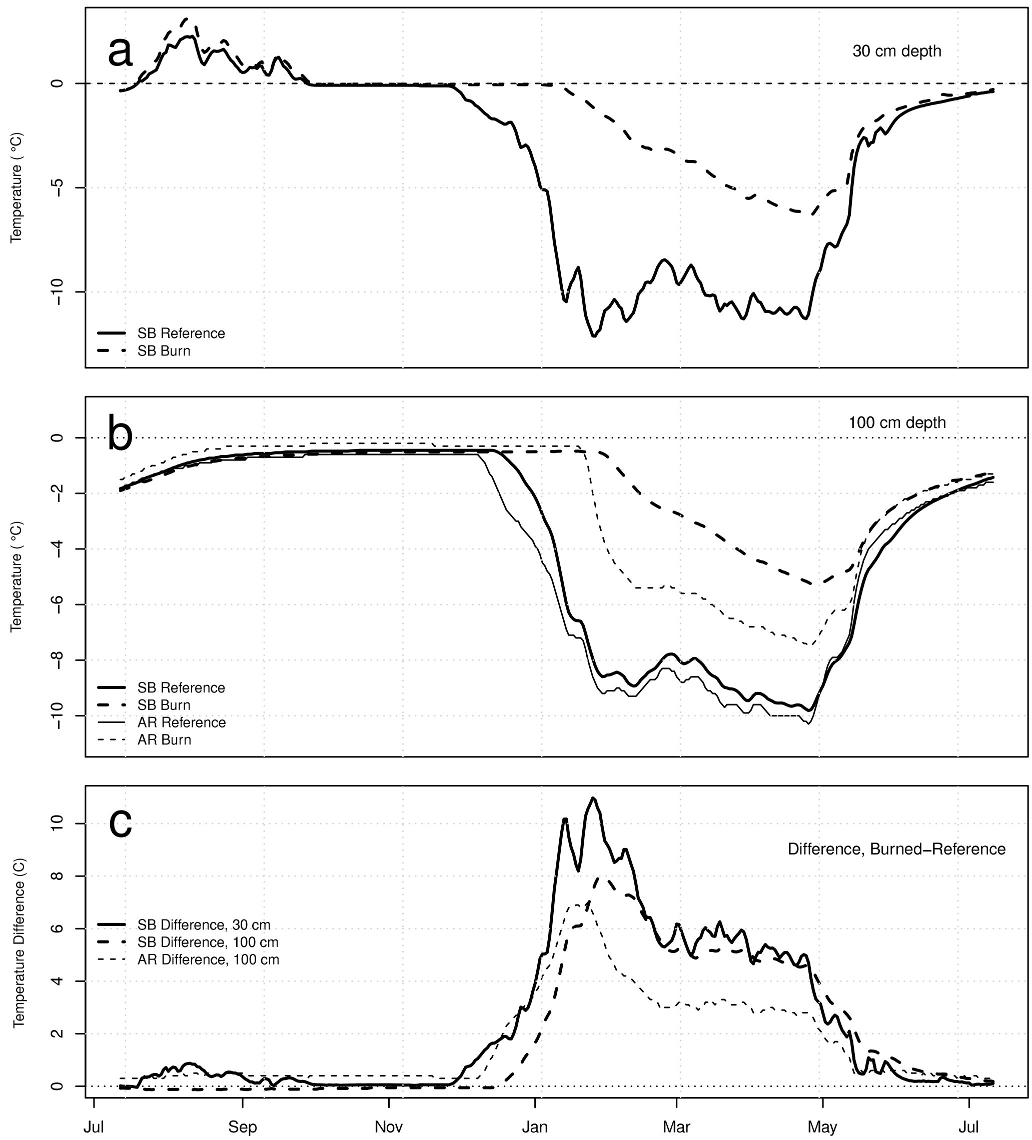

Fig. 6. Ground temperature at (a) 30 cm and (b) 100 cm depth and (c) their difference (Burn-Reference) for one year beginning 12 July 2017. SB is the Shivugak Bluffs Burn. AR is the Anaktuvuk River Burn.

species composition has been shaped for thousands of years by tolerance of the cold environment rather than resilience to disturbance by fire and competition for post-burn resources (Grime, 1977; Billings, 1987; Svoboda and Henry, 1987; Mann et al., 2002; Dormann et al., 2004; Hu et al., 2010, 2015; Chipman et al., 2015; He et al., 2013). The moist nonacidic tundra in the lower foothills on the yedoma silt belt (Jorgenson et al., 2015a; Farquharson et al., 2016) is somewhat unique relative to other tundra regions in that many old burns have been found long after the fire event by their distinct features which are in such stark contrast to the surrounding tundra that they are readily apparent from the air or space, even many decades after fire (Jones et al., 2015; Miller et al., 2023). Burned areas often stand out from the landscape, distinguished by persistent increases in terrain rugosity and conspicuous vegetation (e.g., Hall et al., 1978a,b; Racine et al., 1987; Jones et al., 2013, 2015). The terrain rugosity of the Shivugak Bluffs Burn matches that of the northern parts of the 2007 Anaktuvuk River Burn (Jones et al., 2015, Fig. 3d) (Jandt et al., 2021), the 1977 Kokolik River Burn (Official name “AIN SSE 38”) (Hall et al., 1978a,b), the 1985 Titaluk Burn (Miller et al., 2023), and the c. 100-year-old Ketik Burn described by Jones et al. (2013) all of which occur within the belt of yedoma (Fig. 9).

The proximity (≈ 5 km) of the burn to the Gubik 1 and 2 natural gas test wells drilled in 1951 in the Chandler River floodplain suggests the possibility of a human-caused ignition during the era of oil exploration. A U.S. Geological Survey (USGS) Professional Paper by Spetzman (1959) states: “Owing to the activities [related to oil exploration] and earth-moving machines, scattered areas near Umiat have been stripped of their natural vegetative cover or burned”. The field phase of the PET-4 exploration project in the Umiat area began in 1944 (Robinson, 1958; Reed, 1958; Gryc, 1985, 1988). The degree of thermokarst and mix of drained troughs and thaw pits in the 1948 image suggests that the Shivugak Fire burned some decades prior. The development of thermokarst can take 5–10 years to manifest. Jones et al. (2015) observed that it took about five years following the Anaktuvuk River Fire for the initial signs of ice wedge degradation to show. Yoshikawa et al. (2002) found that thawing, drainage, and drying of polygon networks at a chronosequence of boreal forest burns in Interior Alaska was complete after about ten years. It is possible that the burn resulted from an escaped campfire during exploratory trips down the Colville or Chandler river corridors in the early part of the last century. A prospecting party led by J.L. Reed and W. Lucas went down the Killik River to the Colville River in 1903, passing by the Shivugak Bluffs (Schrader, 1904). A USGS survey party led by P. S. Smith and

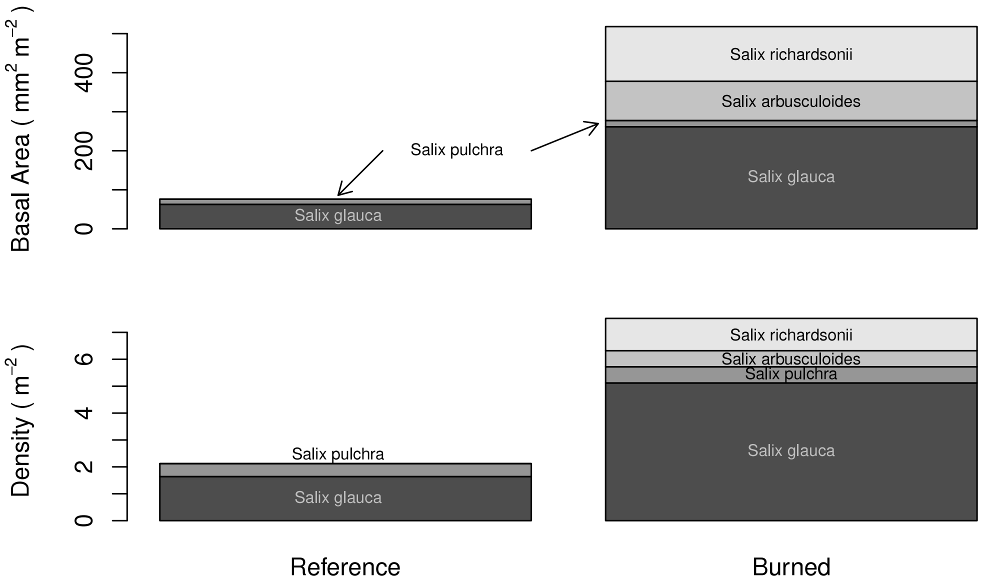

Fig. 7. Basal area and density of tall willows.

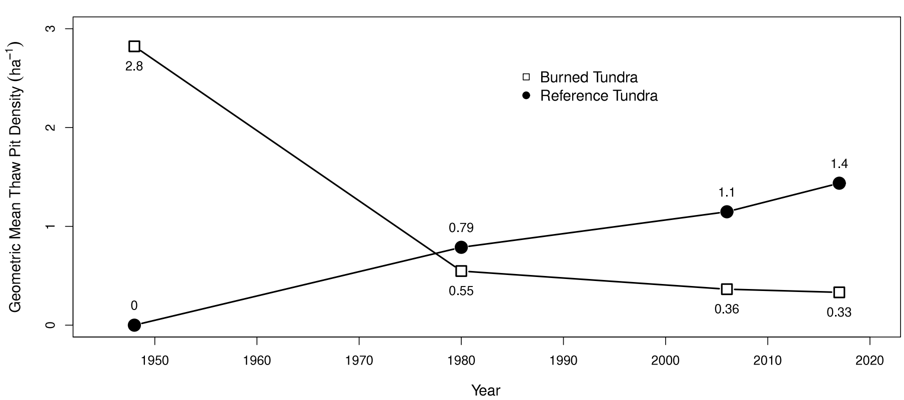

Fig. 8. Geometric mean density of thaw pits in the Shivugak Bluffs Burn and adjacent reference tundra.

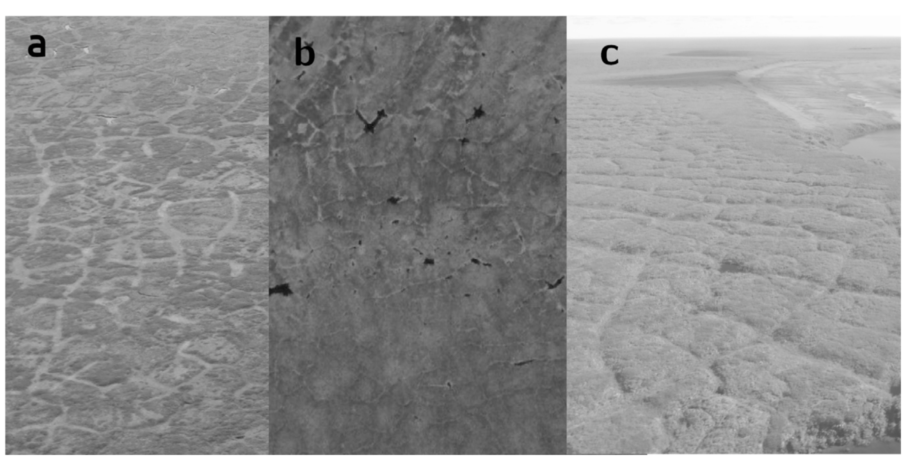

Fig. 9. Surface rugosity at (a.) the 1977 Kokolik Burn, approximately 69.5264° × −161.9630° imaged on 2009-08-01 by David Yokel, (b.) 1985 Titaluk Burn, GeoEye-1 Entity ID: 105001001E061500 and 105001001E061600, Acquisition Date: 2020-06-19, and (c.) 1880–1920 Ketik Burn, imaged on 2016-07-24 at 69.9834° × −159.03937° by B.M. Jones.

J.B. Mertie explored the region near the confluence of the Colville and Chandler Rivers in the mid-1920s (Smith and Mertie, 1930). They devote several pages to the presence and quality of various willows as campfire fuel during their survey. They also note that 1926 was an exceptionally dry summer. Most tundra fires, however, are not human-caused but ignited by lightning (Barney and Comiskey, 1973; Miller et al., 2023). Reports and records of thunderstorms in Utqiaġvik on the Beaufort seacoast date back as far as 1903 (Schrader, 1904; Summers, 1921) and Detterman et al. (1963) recorded many thunderstorms over five years of oil exploration activities 1948–1953 in the foothills.

The fire at the Shivugak Bluffs Burn led to two parallel tundra histories, one inside the burn and the other in the surrounding landscape. The two histories diverged following ignition more than seventy years ago, leading to dramatically different outward appearances. We will discuss our observations in the reference tundra before the burned tundra and then discuss the role of fire in shaping the future of tundra of the Northern Brooks Range Foothills.

4.1. Reference tundra

The permafrost at the Shivugak Bluffs Burn is "climate-driven, ecosystem-modified" in the framework of Shur and Jorgenson (Shur and Jorgenson, 2007). The agent of modification is the duff that protects and shapes the near-surface ground-ice features (Jorgenson et al., 2010b; Jin et al., 2021). The permafrost is buffered from equilibrating with the air temperature by the insulating organic soil and is a legacy of previous climate, perhaps centuries ago, depending on depth (Overpeck et al., 1997; Baughman et al., 2015; Smith et al., 2022). Duff has high thermal resistivity due to its low bulk density and high porosity and serves to protect permafrost through its capacity to insulate the ground from heat during the warm season (Chapin et al., 2000; O'Donnell et al., 2009a; Blok et al., 2011; Rocha and Shaver, 2011; Jorgenson et al., 2022b).

Within the yedoma silt belt, there is "excess ice" or ice content beyond the porosity of the silt itself and the magnitude of thaw subsidence is directly related to its abundance (Jorgenson et al., 2010b; Heijmans et al., 2022). Melting of ice wedges in the reference tundra at the Shivugak Bluffs Burn occurs at the intersections of the polygons and appears in aerial photographs as pockets of standing water (Frost et al., 2018a). Farquharson et al. (2016) refer to this thermokarst landform as "thermokarst troughs and pits". Jorgenson et al. (2006) more simply describe the phenomenon as "pitting". Jorgenson et al. (2022b) documented a rapid increase in thaw pit density between 1955 and 1978 at a foothills tussock tundra site in the Jago River drainage in the eastern foothills while Frost et al. (2018a) observed increased thaw pit development beginning about 1982 at five disparate foothills sites on yedoma soils. Our data indicate the onset of thermokarsting occurred at Shivugak Bluffs Burn between 1948 and 1980 (Fig. 8). We found that pit density in the reference tundra was an order of magnitude lower than for the Jago River site, however, 1.4 ha^{-1} versus 15 ha^{-1} for the most comparable years, 2017 versus 2018, respectively. Pit density there is thought to be stabilizing due to drainage of impounded water but drainage does not appear to be happening yet at the Shivugak Bluffs Burn.

Jorgenson et al. (2006) recognize six stages of permafrost degradation. The reference tundra at the Shivugak Bluffs Burn currently corresponds to stage three in which degradation and settlement are obvious, standing water is present, and tussocks are robust and green near the trough edges, but there are also dead tussocks under the impounded water (Fig. 10). Stabilization occurs in stages five and six in which organic matter reaccumulates and a permafrost layer reestablishes above the ice wedges but terrain subsidence persists indefinitely (Jorgenson et al., 2022b).

Permafrost features within the yedoma silt belt in the Northern Brooks Range Foothills are thought to be stable over secular time frames due to the cold mean annual temperature, the thermal resistance of the organic soil layers, and the sheer amount of latent energy required to melt massive ground-ice (Shur et al., 2005; Hinzman et al., 2013; Saito et al., 2013; Clayton et al., 2021). Kanevskiy et al. (2017). Deep ground-ice was syngenetically built in the late Pleistocene and has persisted through previous warm periods (Kanevskiy et al., 2011; Jorgenson et al., 2010b) but globally permafrost has been trending toward thaw in the last c. 2000 years (Treat and Jones, 2018). Presently, near-surface warming and melting is most clearly seen on older, unglaciated surficial deposits (Jorgenson et al., 2022b). Mean annual ground temperature at 1.2 m depth at Umiat Urban and Clow (2018) has warmed 1.7 °C between 1999 and 2018, a rate of +0.9 °C per decade (Fig. 11), a trend also reflected at six other Arctic Slope sites (Farquharson et al., 2016). The temporal and spatially widespread pattern of thermokarst suggests that climate warming is responsible for increasingly observable thermokarst (Racine et al., 2006; Liljedahl et al., 2016; Gaglioti et al., 2021; Chen et al., 2021a).

The plant species in the top half of Table 4 are typical of moist nonacidic tundra and represent a community that is tolerant of the cold, near-surface environment. Tundra plant traits have been shown to primarily reflect two orthogonal ordinates representing size-structure and resource-use strategy (Díaz et al., 2016; Bruelheide et al., 2018; Thomas et al., 2019, 2020; Kemppinen et al., 2021; von Oppen et al., 2021; Happonen et al., 2022). Tundra plants are typically short-statured and feature resource-conservative, rather than resource-acquisitive traits, e.g., the ability to tolerate the shallow permafrost table through an annual or adventitious root system (*Eriophorum vaginatum*) or no root system at all (e.g., mosses, lichens, and nonvascular species) and the ability to metabolize and grow at temperatures only slightly above freezing (Billings, 1987; Mekonnen et al., 2021). Ecological interactions between organisms are thought to become more positive as environmental stress increases (Bertness and Callaway, 1994; Maestre et al., 2009; He et al., 2013; Adams et al., 2022), suggesting that facilitation has allowed moist nonacidic tundra species to persist as a relatively undisturbed and homogeneous community over the vast area of the foothills for thousands of years (Mann et al., 2002). Warming associated with climate change, however, appears to be relaxing the stress on the tundra community, allowing competition to increasingly shape its composition. Shrubbification, or the expansion of area occupied by tall willows and shrubs is one manifestation (Mekonnen et al., 2021). The species of willow that have colonized the burn are not typical of upland tundra; they are tall and more characteristic of water tracks and floodplains. Liljedahl et al. (2020) found an association with riparian shrub canopy density and soil warming and stream water loss, suggesting a linkage between permafrost thaw, drainage, and shrub expansion in unburned tundra. We predict that the reference tundra will eventually dry as the polygon network interconnects and water is able to drain away (Liljedahl et al., 2016; Frost et al., 2018a; Rettelbach et al., 2021) but the willows will likely remain.

4.2. Burned tundra

The second parallel tundra history occurs within the burn. The most apparent effect of fire has been dramatic thermokarst. Abrupt near-surface ground warming and thermokarst has also been observed at other tundra burns (Rocha and Shaver, 2011). Jones et al. (2015) found that microtopography increased by 340% between the second and seventh year after the Anaktuvuk River Burn on severely burned, ice-rich upland terrain, suggesting thermokarst occurs rapidly following fire. Consumption of the duff by fire typically results in increased heat propagation through the diminished organic soil layer and a deepening of the active layer (Johnson and Viereck, 1983; Mackay, 1995; Shur et al., 2005; Shur and Jorgenson, 2007; Jorgenson et al., 2010b; Michaelides et al., 2019). Thaw pit density inside the Shivugak Bluffs Burn was greatest in 1948 at 2.8 ha^{-1}, indicating wetter conditions following the fire than the reference tundra which featured no pits (Fig. 8). Thaw pit density thereafter declined nonlinearly; in 1980 pit density was 0.55 ha^{-1} and by 2017 it was 0.33 ha^{-1}. Degradation eventually became so severe that the ice wedge troughs hydrologically connected and the pits drained.

It is difficult to assign a stage in the model of Jorgenson et al. (2006) because their model was not intended to represent burned tundra but

Fig. 10. Thermokarst area in the reference tundra where the soil is cracking and slumping into a thawing ice wedge trough. The tussocks become green and robust before slumping into the trough and drowning.

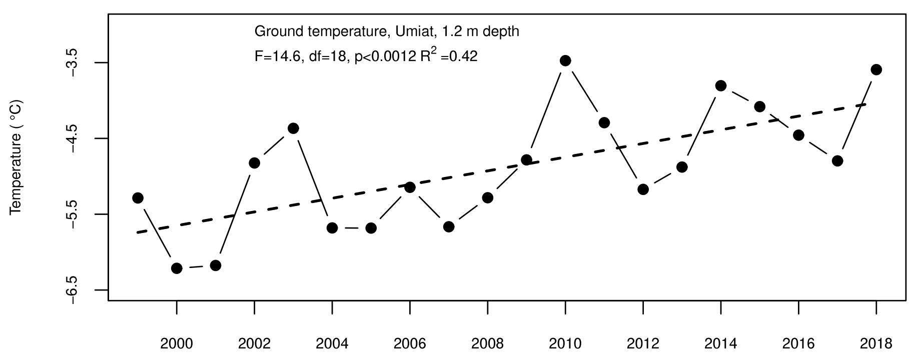

Fig. 11. Mean annual ground temperature at 1.2 m depth, 1999–2018 at Umiat with linear regression trend line (Urban and Clow, 2018).

also because the Shivugak Bluffs Burn occurs on sloped rather than flat terrain and water has drained away rather than pooled (Jorgenson et al., 2010b). This stage better corresponds to advanced degradation characterized by interconnected and drained troughs described by Liljedahl et al. (2016). Troughs are over a meter deep in places and few of them contain standing water. The initial wet stage following fire is currently underway at the Anaktuvuk River Burn (Rocha and Shaver, 2011; Jiang et al., 2015; Jones et al., 2015; Jandt et al., 2021) and has been documented following tundra fires at the 1977 Kokolik Burn (Johnson and Viereck, 1983), in the Noatak drainage (Chen et al., 2021a) and on the Seward Peninsula (Liljedahl et al., 2007). It is also common following disturbance by seismic trails on ice-rich permafrost (Jorgenson et al., 2010a) and following fires in lowland taiga forests (Yoshikawa et al., 2002; O'Donnell et al., 2009b; Brown et al., 2015; Potter and Hugny, 2020; Foster et al., 2022). The wet stage is characterized by an increase in the rate of heat flux into the ground through pooled water compared to porous duff, a feedback that leads to relatively rapid thaw as long as liquid water persists (Jorgenson et al., 2010b, 2015b; Iwahana et al., 2016; Loranty et al., 2018; Clayton et al., 2021). Subsequent draining and drying decreases thermal conductance and the rate of ground heat flux declines (Haag and Bliss, 1974; O'Donnell et al., 2009a; Jorgenson et al., 2010b; Clayton et al., 2021; Jorgenson et al., 2022b).

The response of tundra vegetation to fire varies individually by taxon, but we infer some similarities by group: sedges, grasses, and willows.

Sedges. The cover of tussock cottongrass and Bigelow's sedge was lower inside the burn than outside the burn (Table 4), suggesting a decline in response to fire. This result is in contrast to other studies which report that tussock cottongrass is resilient to fire or even fire dependent, typically increasing in abundance and vigor following fire (Fetcher et al., 1984; Racine et al., 2006; Liljedahl et al., 2007; Loranty et al., 2014). After the 2007 Anaktuvuk River Fire, tussock cottongrass was released from constrained growing space and appeared healthier and more robust (Jandt et al., 2021). Prolific blooming continued at least ten years after the fire. Observations of competitive release led Racine et al. (1987), working primarily on the Seward Peninsula and the Noatak Drainage, to conclude that fire maintains the long-term growth and survival of *Eriophorum vaginatum*. While we have observed that tussocks become overgrown with accumulated debris, mosses, lichens, and cast foliage in unburned tundra on the Northern Brooks Range Foothills they nevertheless remain a persistent and ubiquitous component of the plant community. *E. vaginatum* has an annual root system and is able to maintain meristems near the surface of the soil as detritus accumulates upward (Chapin et al., 1979). While *E. vaginatum* is resistant (Rowe, 1983) and resilient to fire, it is not fire dependent as evidenced by its persistence over vast areas of the foothills in the absence of fire for millenia (Hu et al., 2010; Chipman et al., 2015; Mann et al., 2002; Hu et al., 2015).

A decline in tussock cottongrass abundance following fire has seldom been described in the literature because few studies have looked at changes induced by fire at a time scale of 70 years or more. At the Shivugak Bluffs Burn tussocks may have thrived in the burn for some decades, consistent with previous observations of initial growth release (Wein and Bliss, 1973; Racine, 1981; Racine et al., 1987, 2006; Jandt et al., 2021). The environment near melting ice wedge troughs, both in the burn and out, is temporarily warmed by increased heat flux into the ground associated with liquid water (Jorgenson et al., 2006, 2010b; Gaglioti et al., 2021; Jorgenson et al., 2022b). The tussocks respond with robust growth and flowering. But eventually these tussocks succumbed to drowning at the Shivugak Bluffs Burn due to differential thaw settlement and water impoundment as seen in Fig. 10 (Jorgenson et al., 2015b; Frost et al., 2018a). Dead tussock remnants, now covered in moss, are still visible in the bottoms of dry, thermokarsted troughs (Fig. 12). Drowning of tussocks would require soils with high ice volume which does not occur under all tundras. Tussocks that avoided drowning eventually became over-topped by competing willows. Bigelow's sedge may have suffered a similar fate as it was also less abundant inside the burn than out. Measurements of vegetative cover across a chronosequence of burns in the Northern Brooks Range Foothills by Jones et al. (2013, supplementary material) show a gradual decline in *Eriophorum vaginatum* with burn age from an average of 36% in reference tundra to 2% after approximately 100 years. This trend is supported at the Shivugak Bluffs Burn; cover was 31% in the reference tundra and 7% in the burn after 70 or more years.

Grasses. In contrast with sedge decline, cover of the grass, *Arctagrostis latifolia*, was higher in the burn. Rowe (1983) regards this species as a post-fire "invader". Grasses become more competitive at greater burn severities and seem to replace sedges proportional to the depth of burn (Wein and Bliss, 1973; Racine et al., 1987; Jandt et al., 2012; Jones et al., 2013; Jandt et al., 2021). Within the Anaktuvuk River Burn grasses favored south sloping bluffs where duff consumption, ground-ice degradation, and soil movement was greatest and soil cracks and slumps exposed a mineral seed bed. Jones et al. (2013) found that grass cover was greatest in a 19-year old burn but remained persistently high relative to unburned tundra even a hundred or more years after fire. Hollingsworth et al. (2021) found that the abundance of grasses in tundra on the Seward Peninsula was related to burn severity but also to repeat burning which has been negligibly rare so far north of the Brooks Range (Masrur et al., 2022). Wang et al. (2017a) found that *Arctagrostis latifolia* gains a competitive advantage in soil nutrient acquisition as soils thaw deeper through root growth plasticity. Their vegetative manipulations suggest that grasses compete better for nutrients in the upper soil layers. The association of grass abundance with burn severity or repeated burning indicates that its presence is determined by factors related to a threshold thickness of duff.

Willows. The prominence of willows in the burn is striking when seen from the ground or from aircraft. Unlike the surrounding tundra, the burn features a tall, robust overstory canopy layer. Willows in the reference tundra were ankle to lower calf in height (Fig. 5). Inside the burn, heights were about waist high with occasional stems reaching head high or greater. The remotely sensed dataset by Berner et al. (2018a,b) suggests the biomass density of shrubs in the burn is 1.8 times greater than that of the reference tundra. Our measurements of basal area (as a proxy for biomass density) suggests a factor of 6.8.

There are many observations of increases in willow abundance following tundra fire. Racine et al. (2006) found expansion of tall willows by seeding and resprouting 24 years following fire at Nimrod Hill on the Seward Peninsula. They observed post-fire seeding of willows even after 32 years. Chen et al. (2021a) found that fire increased shrub (genera *Salix*, *Betula*, and *Alnus*) expansion on tundra uplands in the Noatak Drainage by a factor of about seven relative to unburned tundra. Jones et al. (2013) found a persistent increase in shrub cover relative to reference tundra in a chronosequence of five tundra burns on the Northern Brooks Range Foothills spanning ages up to *c.* 140 years since fire. They found the cover of *Salix glauca* was greatest in a 19-year-old burn suggesting that it could occupy a temporal optimum several decades following fire. Repaludification of the soil may then favor a return to dominance by the more cold-tolerant *Salix pulchra* whose cover was greatest in burns a hundred or more years old (Jones et al., 2013, supplementary material). We found *Salix pulchra* to be ubiquitous at the Anaktuvuk River Burn across upland tundra at burned as well as reference transects (Jandt et al., 2012, 2021). It is more tolerant of a shallow active layer, soil acidity, and poor drainage than *Salix glauca* and *Salix richardsonii* (Swanson, 2015). It is fairly short-statured and comparable in height to other shrubs typical of tussock tundra. In contrast, *Salix glauca* and *Salix richardsonii* are less tolerant of shallow permafrost, poor drainage, soil acidity, and late snow-lie (Swanson, 2015), and are typically taller. They tend to occupy warmer soils associated with water tracks with subsurface water flow (Curasi et al., 2016) and flood plains. *Salix glauca* is a resource-acquisitive or competitive species that is characteristic of tundra locations with relatively low resource stress (von Oppen et al., 2021) At the Anaktuvuk River Burn *Salix glauca* was not common but it occurred in both burned and unburned upland tussock tundra (Jandt et al., 2021). *Salix richardsonii* was found at a single unburned transect on nonacidic soil. Willows typically require exposed mineral soil in order to colonize by seed (Swanson, 2015; Liljedahl et al., 2020). We found mineral soil was most exposed at the Anaktuvuk River Burn on severely burned sites, particularly at the slumping and cracking soil edges near melting ice wedges, suggesting that colonization rate could be proportional to subsidence rate.

Several studies link willow occurrence and growth to summer air temperature (Forbes et al., 2010; Ackerman et al., 2017, 2018; Andreu-Hayles et al., 2020; Chen et al., 2021a). Swanson (2015) found July air temperature thresholds were associated with nonlinear increases in willow canopy volume. *Salix pulchra* had the lowest threshold of (10.5 °C) while the tall willows *S. richardsonii, S. alaxensis*, and *S. glauca* exhibited thresholds of 11.7, 11.8, and 12.0 °C, respectively. The presence of relatively warm soils and thermokarst features at the Shivugak Bluffs Burn suggests that ground temperature may be at least as important as air temperature in determining tall willow abundance. Given the warming and wetting pattern observed in the early decades at Shivugak Bluffs, the burn perhaps resembled a temporary water track in the sense of deeper seasonal thaw and subsurface flow of heat, water and nutrients as the landscape slowly subsided and drained, attracting colonization by taller and more competitive willow species (Curasi et al., 2016). Size is a plant trait positively associated with climate warming (Bjorkman et al., 2018).

There are also places where willows and shrubs do not appear to respond to wildfire. We can find no shrub response in aerial imagery or the geospatial shrub biomass dataset of Berner et al. (2018a) at the 1 600 ha 1969 Killik tundra burn on rocky, morainal terrain in the upper foothills or the 1976 Dead Horse Burn on upper slope colluvium. The lack of response on these thaw-stable soils (Farquharson et al., 2016) suggests that shrub expansion is linked to the presence of excess ground-ice.

4.3. Ground temperature and thermokarst

The vegetative differences between the burned and reference tundras are associated with increased ground temperature. Comparison of ground temperatures at the Shivugak Bluffs Burn with the Anaktuvuk River Burn suggests that warming continues even after seven or more decades. Temperature trends at 100 cm depth in the undisturbed reference tundras at the Shivugak Bluffs Burn and Anaktuvuk River Burn were well synchronized (Fig. 6b) and freezing degree-days were within 8% of each other (Table 3). Yet there were 208 fewer freezing degree-days inside the Shivugak Bluffs Burn relative to the Anaktuvuk River Burn, a difference of 28%. Mean annual temperature in the Shivugak Bluffs Burn was 0.6 °C warmer than at the younger Anaktuvuk River

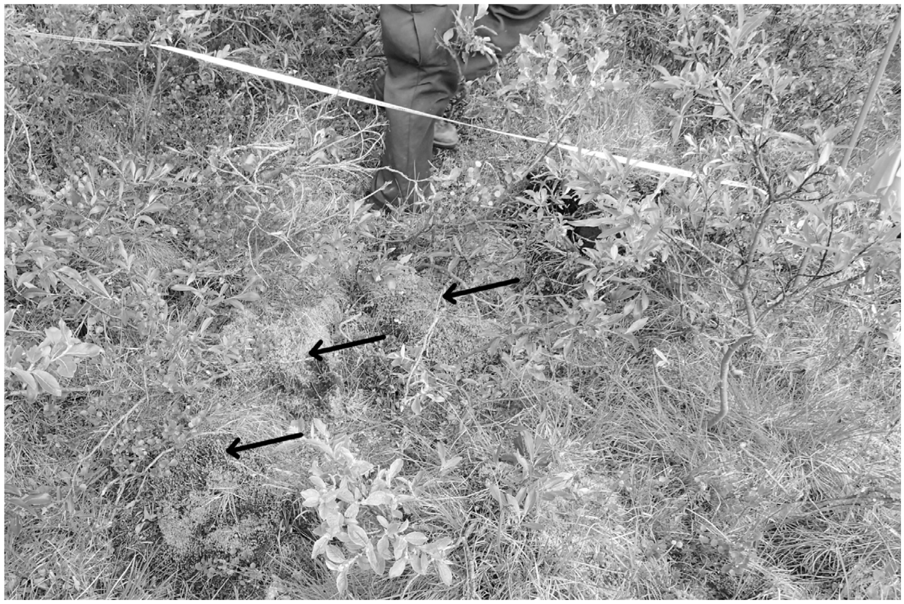

Fig. 12. Moss-covered knobs (indicated by arrows) are old dead cottongrass tussocks inside the burn that appear to have drowned in melting ice wedge troughs decades ago.

Burn. Minimum annual temperature was 2.2 °C warmer. These values and patterns suggest considerable ground warming occurs in the first decade following tundra fire, as at the Anaktuvuk River Burn, but that warming continues for many decades.

We speculate that the mechanism for continued warming involves the tall willow canopy layer. Differences in temperature between the reference and burned tundras are greater in the winter than in the summer (Fig. 6c), a pattern that suggests warming has less to do with increases in heat gain in the summer than reductions in heat loss in the winter (Zhang et al., 1997; Kropp et al., 2020). This pattern implicates the tall, robust willow canopy layer at the Shivugak Bluffs Burn which has not yet developed at the Anaktuvuk River Burn (Frost et al., 2018b). While some observational and manipulative studies indicate that shrub canopies insulate and cool tundra soils in summer (Frost et al., 2018b; Loranty et al., 2018; Mekonnen et al., 2021) others demonstrate increases in the annual ground temperature (Frost et al., 2018b). Kropp et al. (2020) found evidence that ecosystems on permafrost characterized by tall-statured vegetation have warmer shallow soils than short-statured vegetation. Measurements by Frost et al. (2018b) indicate that an alder canopy in Siberian arctic tundra both cools the soil in summer and warms it in winter relative to tundra without a canopy. Ground heat flux as a proportion of net available energy is smaller under a tall canopy relative to a short one; More of the energy is shunted to above-ground sensible and latent heat fluxes (Heijmans et al., 2022).

Canopies capture snow and retain deep drifts which inhibits wintertime heat loss (Sturm et al., 2001, 2005; Jorgenson et al., 2010b; Myers-Smith and Hik, 2013; Paradis et al., 2016; Frost et al., 2018b; Loranty et al., 2018; Kropp et al., 2020; Heijmans et al., 2022). A deep snowpack in the Shivugak Bluffs Burn relative to the reference tundra was confirmed by author B.M. Jones during a late winter traverse in April 2015 (Fig. 13). Springtime snow depth very nearly matches the willow canopy height and suggests the ground is strongly insulated from cold air temperatures in the winter. This pattern may be self-reinforcing in that warming allows competition by tall willows that further warm the soil. Gaglioti et al. (2021) describe the process as “fire-shrub-greening positive feedback”. If ground warming inside the burn is due to tall willows then the permafrost remains climate-driven, ecosystem-modified but the agent of modification is shifting from the organic soil layer to the canopy layer. The interacting effects of duff and canopy effects on permafrost remain poorly understood, however (Myers-Smith and Hik, 2013).

Jorgenson et al. (2010b) and Jorgenson et al. (2015b) suggest that stabilization of permafrost can take 30–100 years following disturbance but development of ice wedges is a process that can take hundreds to thousands of years. Globally, permafrost has been trending toward thaw since 250 BCE (Treat and Jones, 2018) and colder permafrost regions are warming at the depth of zero annual amplitude faster than warmer regions (Smith et al., 2022). Permafrost at 20 m depth has warmed between 1.4 and 1.9 °C over the 37 year period between 1983 and 2020 at Happy Valley and Franklin Bluffs on the Arctic Slope (Anonymous, 2022). Persistent rugose terrain at the > 100-year-old Meade and Ketik tundra burns (Jones et al., 2013) (Fig. 9) suggest that reaggradation of ice wedges and ground-ice features will require a time frame of centuries to millenia.

4.4. Synthesis and outlook

Tundra plant communities of the Northern Brooks Range Foothills reflect a suite of cold-tolerant species adapted to a previous climate which has been most recently warming since c. 1840 following the Little Ice Age (Overpeck et al., 1997). Several interrelated trends suggest that tussock tundra on ice-rich yedoma may be a legacy vegetation whose persistence under future climate scenarios is uncertain. Summer air temperature exerts control over fire season extent in both boreal forests (Duffy et al., 2005) and tundra regions of Alaska (Hu et al., 2010, 2015; Descals et al., 2022). As summer (June-August) air temperature exceeds ≈11 °C we can expect nonlinear increases in the area of tundra burns (Hu et al., 2015; Masrur et al., 2018), a pattern already seen in the increasing sizes of the largest recorded fires: the 3 400 ha Kokolik Burn in 1977, the 33 300 ha DCKN190 Burn in 1993, and the 104 000 ha Anaktuvuk River Burn in 2007 (Rocha et al., 2012). Simultaneous with increasing fire size, ongoing “shrubbification” suggests that tall willows and alders are increasingly competitive under current above- and below-ground climates. Thus, the same warming of air temperature that increases the likelihood of extensive burns favors deciduous shrubs in a positive feedback that will be particularly acute within the yedoma silt belt. Grasses and other competitive species are also expected to increase in abundance.

Size traits in tundra vegetation, such as plant height, specific leaf area, and leaf dry matter content, are positively correlated with warming (Bjorkman et al., 2018; Kemppinen et al., 2021) and larger plants are typically more competitive. Plants in the tundra biome have already

Fig. 13. The tall willow canopy at the Shivugak Bluffs Burn captures and retains a deep snowpack. The left image was taken on 23 June 2012. The right image was taken on 26 April 2015 during a snowmachine traverse. Note the height of the shrubs in the summertime photo relative to the portion of the shrubs that are protruding through the deep winter snow cover. Images by B.M. Jones at approximately 69.406° × −151.509°.

shown an increase in plant height in response to warming temperatures over three decades of monitoring (Elmendorf et al., 2012; Bjorkman et al., 2018). Lichens recover from fire slowly in tundra and are expected to compete poorly with shrubs (Jandt et al., 2008; Bret-Harte et al., 2013). Fruticose lichens (e.g., *Cladonia* spp.) did not recover to pre-fire cover 44 years following fire in dry Siberian tundra (Heim et al., 2021). Cornelissen et al. (2001) found that the abundance of nonvascular macrolichens in global subarctic and mid-arctic ecosystems is inversely related to that of vascular plants. Pajunen et al. (2011) similarly found that lichen (as well as bryophyte, dwarf shrub, and graminoid) cover was inversely related to deciduous shrub volume in Western Eurasian tundra. Forbs were positively related. These patterns suggest that we can expect that as the tundra warms and/or burns it may increasingly feature taller, more robust, competitive, and resource-acquisitive species such as tall willows at the expense of smaller, nonvascular lichens and other cold-tolerant taxa.

Duff may take many centuries to reaccumulate to pre-fire thickness. Soil organic layers on a floodplain point bar on the Ikpikpuk River in the Northern Brooks Range Foothills are thought to have taken 500–700 years to reach steady-state thickness following deposition (Baughman et al., 2015). Although it is possible that duff will reaccumulate in the burn over the next few centuries with a shallowing of the active layer, repaludification of organic soils, and a return to tussock-dominated tundra (Gaglioti et al., 2021), several lines of evidence suggest this is unlikely. First, the soil in the burn is persistently warmer than the reference tundra even many decades after fire and shows no sign of cooling. Second, the terrain rugosity and the structure and composition of the plant communities at the Shivugak Bluffs Burn are more similar to the century-old Meade and Ketik Burns (Jones et al., 2013) than to its own surrounding reference tundra. Third, the state of thermokarst pitting and the outward appearance of the reference tundra are beginning to resemble the burn, rather than the other way around. The evidence suggest that the burn is not returning to its pre-fire state of moist nonacidic tundra but has been catalyzed by fire toward a new physiognomic state. It also suggests that the reference tundra is vulnerable to climate change and, although presently protected by intact duff, it may be lagging toward a similar successional endpoint as the burn. At the scale of the landscape, episodic consumption of duff by more frequent fires in the tundra will accelerate the change (Gaglioti et al., 2021; Miller et al., 2023).

This conjectured post-fire successional trajectory does not apply to all tundras in the Northern Brooks Range Foothills. Lasting traces of degraded ice wedges following fire are most prominent in the band of yedoma soils (Jones et al., 2015; Iwahana et al., 2016; Frost et al., 2018a). Traces are less apparent for fires at higher elevations, on colluvial and alluvial soils, and glacial drift, which are relatively thaw-stable (Jorgenson et al., 2010b; Chen et al., 2021b). Farquharson et al. (2016) project that yedoma is the most vulnerable to climate-induced thermokarst and therefore has the greatest potential impact from fire. If true, our observations from the Shivugak Bluffs Burn lead us to expect that the extensive areas of the northern part of the Anaktuvuk River Burn within the yedoma silt belt may experience relatively severe ground-ice degradation and increasing dominance by tall willows, grasses, and competitive species. Portions at higher elevations on thaw-stable soils may be less affected.

CRediT authorship contribution statement

Eric A. Miller: Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data Curation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision, Project administration, Funding acquisition.. **Carson A. Baughman:** Investigation, Writing - Review & Editing.. **Benjamin M. Jones:** Investigation, Resources, Writing - Review & Editing, Funding acquisition.. **Randi R. Jandt:** Conceptualization, Methodology, Investigation, Resources, Writing - Review & Editing..

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data used in this paper is available from the authors.

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