FINDINGS OF ANAKTUVUK RIVER FIRE RECOVERY STUDY

2007-2011

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Last Date of Revision: 21 June 2012

KEYWORDS

- Tundra fire, fire recovery, North Slope, Anaktuvuk River Fire, lichens, burn severity, caribou, dietary analysis, active layer, thermokarst, normalized burn ratio, climate change, *Eriophorum vaginatum*, *Salix pulchra*.

ABSTRACT

The 2007 Anaktuvuk River Fire was an order of magnitude larger than the average fire size in the historic record for northern Alaska and indices of severity were substantially higher than for other recorded tundra burns. An interdisciplinary team assessed fire effects including burn severity, potential plant community shifts, and effects on permafrost and active layers. Observers monumented, photographed, and measured 24 burned and 17 unburned reference transects, starting the year after the fire, and spanning the range of vegetation types and burn severities. Three independent ocular estimates of burn severity at varying scales were made, two ground-based indices and one aerial index. Remotely sensed data and indices were compared to ocular estimates. 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. 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. Active layer, pH, temperature, residual organic duff depth and other soil characteristics were recorded and vegetation and organic layers were destructively sampled for laboratory analysis of fire fuel biomass and density of fuel layers. Regrowth of vegetation was rapid for some species (*Eriophorum vaginatum* [cottongrass]) and lush stands of fire mosses and liverworts developed after the first year on severely burned areas. Graminoid cover, primarily *E. vaginatum*, increased from 11% to 63% between 2008 and 2011. Shrubs were recovering more slowly by the 4th year after burning and other species were declining (*Sphagnum* mosses) or virtually absent (lichens: 0.1%). Shifts in community species composition seem likely for many years to come in the burn area. A dietary analysis on caribou scat collected from the area showed approximately 50% lichen composition in the fall/winter diet, uncorrected for digestibility. Since lichens are absent for some years post-fire, the fire has reduced forage availability for caribou. Foraging conditions for some microtines and their predators may have improved. 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.

INTRODUCTION

Tundra fires on Alaska's North Slope are historically rare events (Barney and Comiskey, 1973). Only 122 fires north of 68º N latitude are recorded in the fire history records kept by the Alaska Fire Service since 1950 (Fig. 1). The 2007 Anaktuvuk River Fire (ARF) was unprecedented for fire size at that latitude (103,600 ha or 256,000 acres) and also for a long burn duration from July through the end of September. Lightning ignited the ARF July 16 and it burned rather slowly initially (about 62 ha/day or 153 ac/day) until the beginning of August (Jones et al. 2009). In early September it accelerated to a burn rate of roughly 7,000 ha/day (17,000 ac/day)—expanding rapidly to the north—and continued to smolder until covered by snow in early October (Figs. 2, 3).

Conditions contributing to fire size and severity included record heat and record low summer precipitation, associated with a late-season high-pressure system located over the Beaufort Sea (Jones et al. 2009). Drought in the organic mat and sustained southerly winds during late summer when vegetation had started to senesce appeared to be factors in the burn size and dramatic consumption, which resulted in heavy smoke production. Thick smoke from the fire triggered a shutdown of one of the turbines at a pipeline pump station, impacted residents of the village of Anaktuvuk Pass village, and caused concern from residents all over the North Slope. The drought conditions during September 2007 were coincident with record low Arctic Ocean pack ice adjacent to the coast (Hu et al. 2010), possibly bringing warmer, drier conditions and an unusual number of thunderstorms—a phenomenon that has continued in more recent years. Due to the drought and late phenology, burn severity, as measured by depth of consumption of the organic moss and duff layers, was higher than typical for tundra fires (Fig. 3). The burn continuity was also unusually high, consuming riparian stringers and wet polygonated depressions (fens), which are usually maintained as unburned inclusions (Fig. 4).

The Bureau of Land Management (BLM) engaged partners from the USFS Boreal Ecology Cooperative Research Unit at the University of Alaska, Fairbanks (UAF), the Arctic Long Term Ecological Research program (LTER) and the U.S. Geological Survey to assess the 2007 fire. An interdisciplinary team assessed fire effects including burn severity, potential plant community shifts, and effects on permafrost and active layers. The objectives were:

1. Establish permanent transects for long-term monitoring of revegetation and fire effects on the burn area, including all major vegetation types. Vegetation changes will be extrapolated to hypothesize effects on wildlife, especially caribou, which is an important subsistence species locally.

2. Assess burn severity at the transect level and map severity on the entire burn area using remotely sensed data.

3. Measure post-burn active layer depths in the burn and on paired unburned transects. Collect soil samples for UAF and LTER to analyze burn effects on soil composition, pH and microbes. Qualitatively monitor thermokarsting and erosion.

4. Measure depth of remaining organic matter quantitatively with other allometric markers to determine the total amount of material consumed by the fire that contributed to regional smoke.

5. Collect caribou fecal pellets to analyze for dietary preference in the fire region.

6. Establish new reference transects outside the burn for long-term assessment of the effects of fire and the effects of climate on Arctic vegetation.

7. Involve local stakeholders in post-fire studies and ensure they remain engaged and involved with research efforts and results. The North Slope Borough, Department of Wildlife, assisted with this by hiring a field assistant from Anaktuvuk Pass Village who became part of the first year field team.

Portions of the results from the study have already been published by cooperators in peer-reviewed journals, and citations are provided for those results.

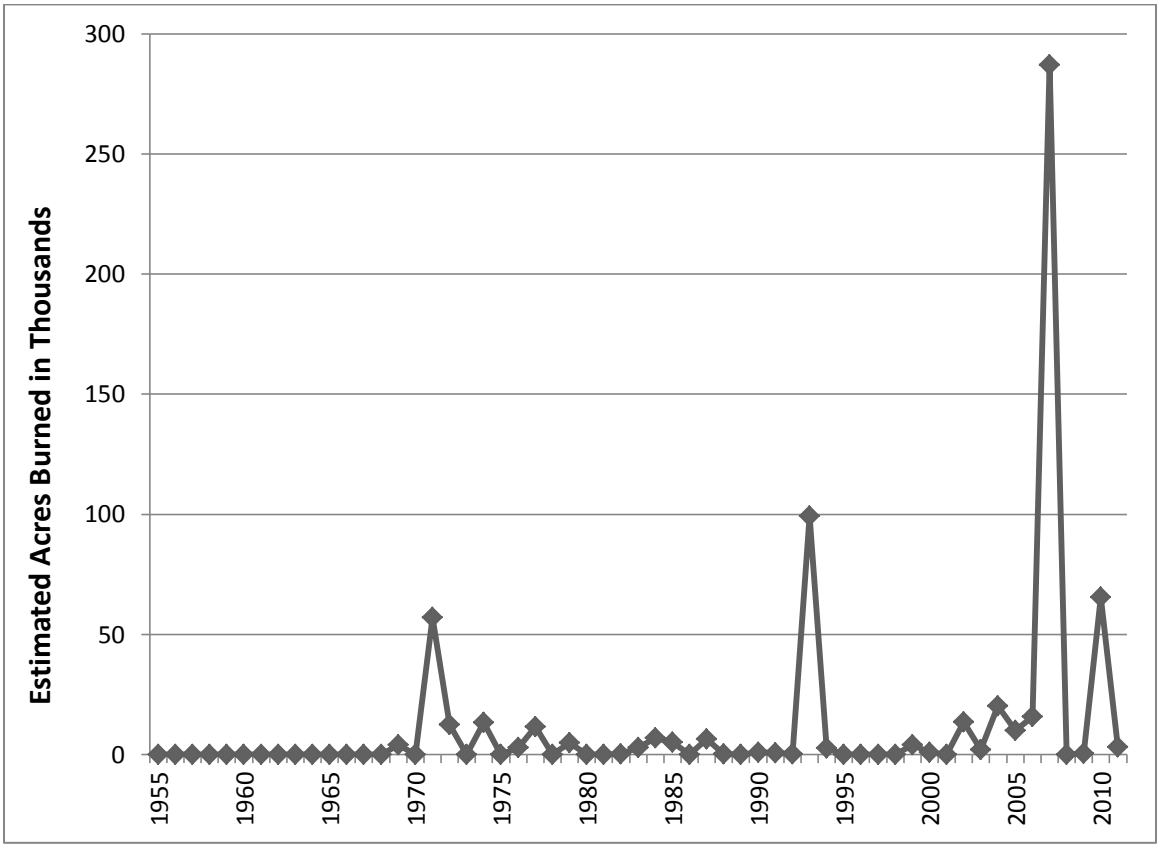


Figure 1. Acres burned north of 68º N latitude as reported in the Alaska Fire Service database from 1950-2011.

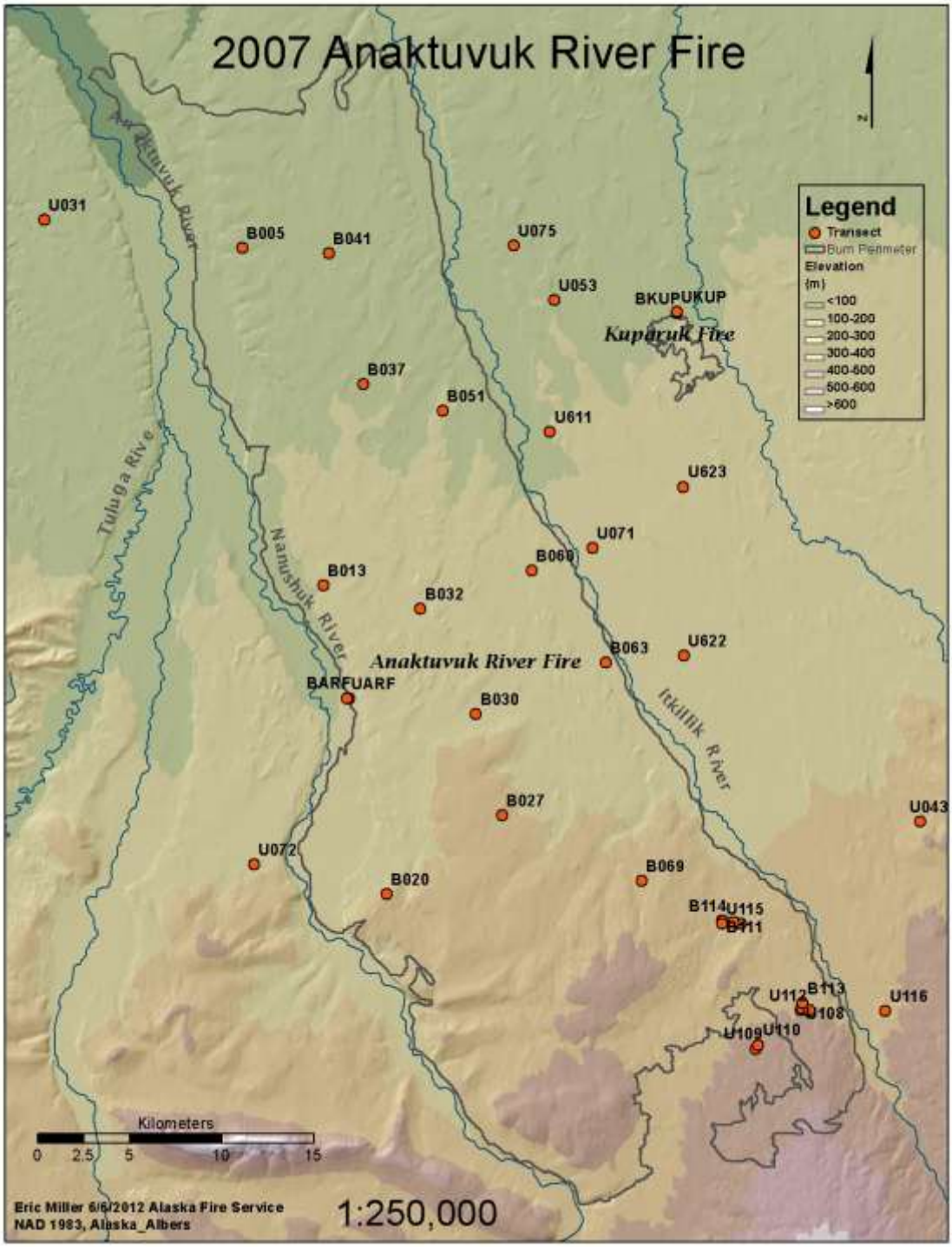


Figure 2. Location of permanent burned and unburned reference transects established to monitor the Anaktuvuk River Fire.

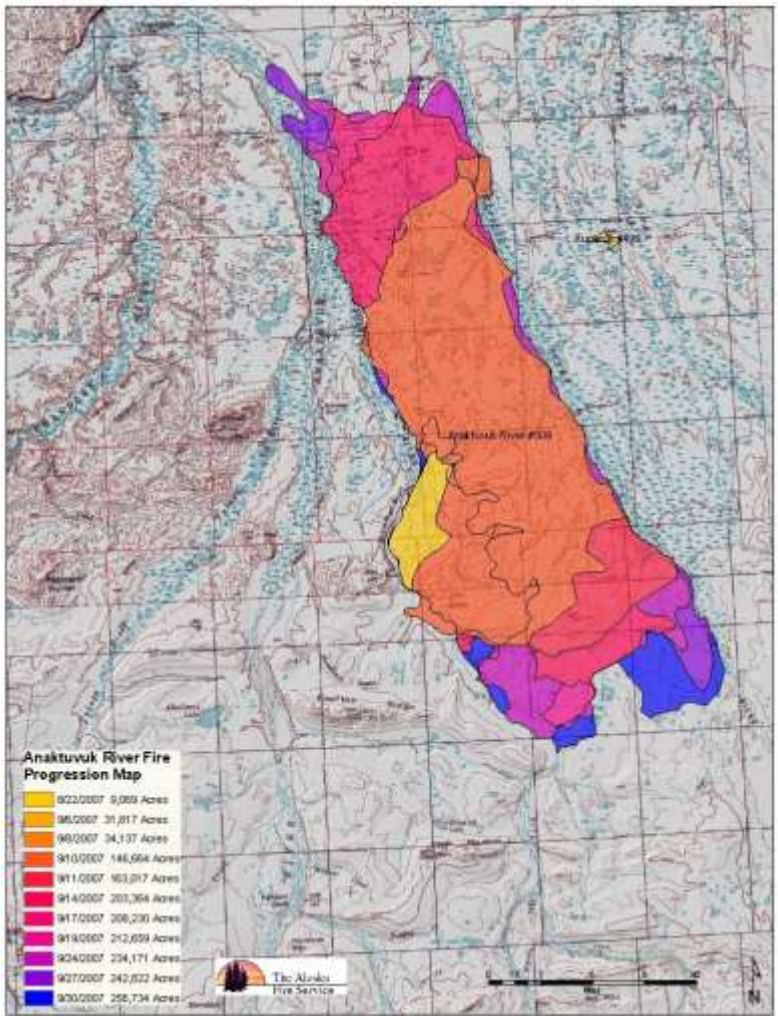


Figure 3. Fire progression map (left) of 2007 Anaktuvuk River Fire shows the bulk of the area burned in September. The resulting burn severity map with BLM transects (blue dots) at permanent plots is below. (*Figure by Crystal Kolden, USGS*)

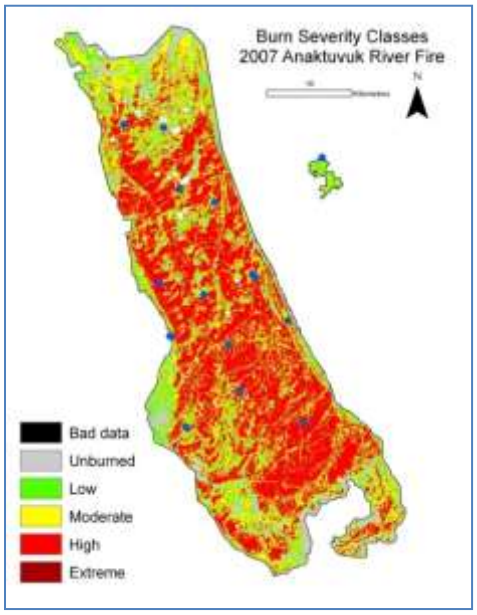


Figure 4. The Anaktuvuk River fire burned across riparian stringers and wet channels around high-centered polygons that are typically left as unburned inclusions. *(2008 photo by D. Yokel).*

The Arctic LTER (Long-Term Ecological Research) group received a grant from the National Science Foundation for additional studies in several watershed study areas on the fire to gather data on gas exchange over the burn area, watershed effects, and deploy additional permanent vegetation recovery transects (including several unburned comparison transects and calibration transects for consumption estimates). Team members were integrated between BLM and LTER field teams to standardize methods between partners.

Gaps in Previous Knowledge

Tundra fires have been studied in western Alaska, where they are more common than on the North Slope (Fig. 5; Racine et al. 1985). Most tundra fires are ignited by lightning and often burn with very light severity—consuming little more than dry cottongrass (*Eriophorum vaginatum*) leaf litter and lichens (Wein 1976). Moist sphagnum hummocks and low boggy areas are usually spared. Recovery of graminoid cover on burns is rapid, often greening in the same season as they were burned, and dwarf shrubs recover by 5-7 years post-burn (Racine et al. 2004, Jandt and Meyers 2000). Terricolous lichens take much longer to recover: studies in western Alaska suggest it takes >25 years (Holt et al. 2008), and possibly as long as 50-100 years to recover lichen cover and biomass usable by caribou in northwestern Alaska (Jandt et al. 2008, Joly et al. 2009). In severe burns, Racine et al. (2004) found that new colonization by willows (*Salix sp.*) substantially changed the plant community and function after 25 years. Graminoid cover was still increasing due to increased growth and vigor of tussocks 29 years after a deep-burning tundra fire on the Seward Peninsula (Jandt et al. 2008). Little is known about recovery after the second- and third-largest tundra fires on the North Slope, although early recovery on the 1977 Kokolik River Fire was monitored (Johnson and Viereck, 1983; Hall et al. 1978). The Kokolik River fire at 69.5° latitude (AIN SSE 38 on Fig. 5) burned 4,400 ha or 11,000 acres between July 26 and August 7, 1977, during a year when much larger tundra areas burned on the Seward Peninsula and in the Noatak River area. After 24 years, observers noted that a thick grass turf was established on severely burned high-centered polygons, which were occupied by dwarf birch or willow before the fire (C. Racine, pers. comm.) Anecdotal information indicates vegetation communities are still distinct from surrounding unburned vegetation, both on this fire and on the 1993 DCKN 190 fire by Wainwright (Fig. 5), the second-largest historical fire event on the North Slope.

North Slope residents and wildlife managers are interested in the possible impacts of large tundra fires on caribou and other subsistence resources. Groups of caribou from the Central Arctic Herd and Teshekpuk Herd have migrated through or wintered in the ARF area prior to the burn. Hunters from Anaktuvuk Pass Village rely on caribou movements inland from the Beaufort Sea coast toward the village in early September. Villagers who are long-time observers of caribou behaviour opined that smoke from the ARF disrupted migration in 2007 and expressed concern about the burn scar effect on future movements.

In addition to collecting data on recovering vegetation, we collected data for a tundra fire fuels model. Although >50 standardized fuel models exist to predict fire behaviour in ecosystems of North America, none adequately represent tundra. We measured above- and below-ground fuel loadings (oven-dry mass per unit area) of graminoid, shrub, moss, lichen, and duff. Results will provide basic inputs to current fire behavior and fire effects models. We would like to better understand the impacts of increasing fire in tundra ecosystems on fire cycle, vegetation regrowth, soil microbial activity, and carbon emissions. Land managers need sound, science-based information for critical "carbon banking" and fire management policy changes that are currently being considered. We measured above- and below-ground fuel loadings (mass per unit area) of graminoid, shrub, moss, lichen, and duff by collecting, oven-drying, and weighing samples. Results will provide basic inputs to current fire behaviour and fire effects models.

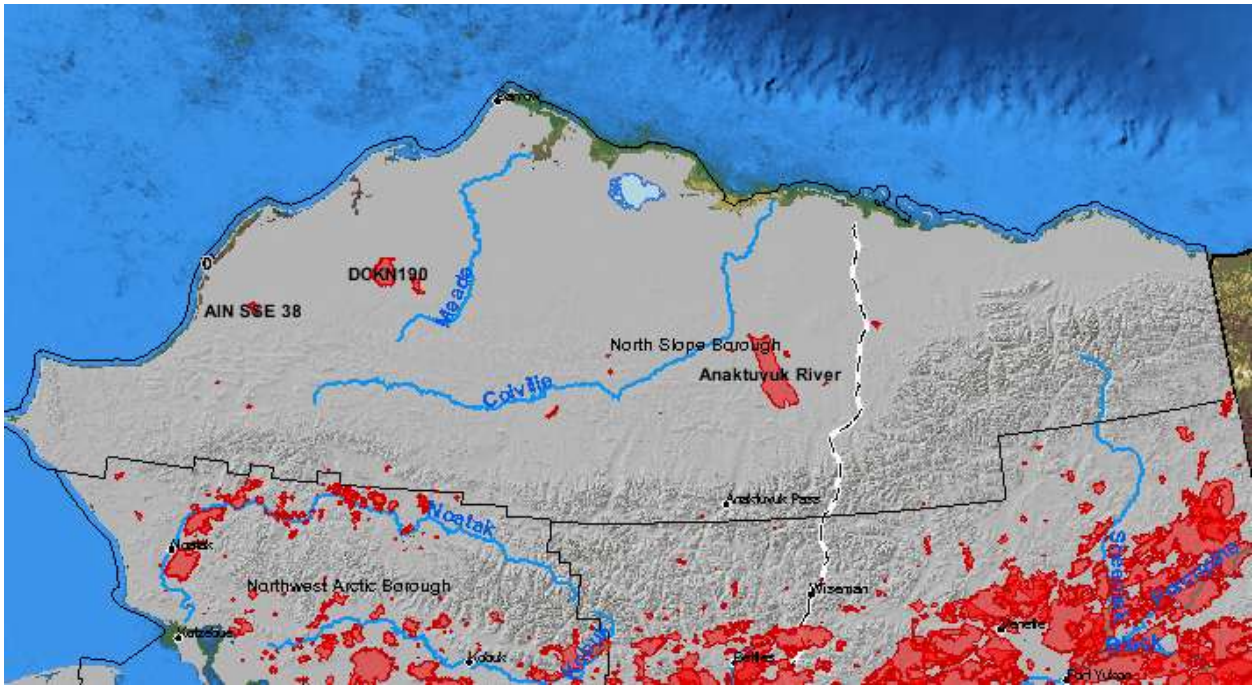


Figure 5. Map of Alaska's North Slope showing fire perimeters 1940-2011 from the Alaska Fire Service database (http://fire.ak.blm.gov/ predsvcs/maps.php). Prior to 1956 only sporadic data is available as fires were not always mapped and some records are missing. The 3 largest fires are labeled: Anaktuvuk River fire (2007), Wainwright fires (DCKN190, 1993), and the Kokolik River fire (AINSSE38, 1977).

Overview of project accomplishments

Initial field work and establishment of permanent transects began early in July, 2008, at the start of the North Slope growing season, so that photos and plots from 2008 describe the immediate post-burn conditions except for areas which burned in July/August (Fig. 3). Ultimately a total of 24 burned and 17 unburned comparison transects were monumented, photographed, and measured. In order to represent a "light" burn severity, the crew placed one of the paired burned/unburned transects in the nearby Kuparak fire which started at the same time as the ARF but burned for just two weeks in July. Three independent estimates of burn severity were made: burn transect severity was indexed directly while macroplot burn severity was assessed from both ground and air for satellite map classification. Consumption of plant biomass and organic soils was estimated using allometric equations developed from unburned comparison plots specifically for this study. Active layer, pH, temperature, residual organic duff depth and other soil characteristics were recorded beside the permanent transects. In 2011 vegetation and organic layers were destructively sampled for laboratory analysis of fire fuel biomass and density of fuel layers.

Wildlife observations were noted within the burned area during the work, and we collected pellet groups from caribou for analysis of diet composition. We visited the most active areas of thermokarsting along the Nanushek River on the fire's southwest flank each year and established two photopoints for continuing observations.

MATERIALS AND METHODS

See full Methods Description in Appendix A for details of the field data collection methods, allowing for methodical interpretation and reproducibility of the study. It is our hope that these 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.

STUDY AREA

The ARF burn area stretches from gentle northern slopes of the Brooks Range Foothills 67 km (40 miles) north, ultimately transitioning to flat coastal plain with large shallow lakes and polygonated fens. Coordinates of the 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 climate of the central North Slope is characterized by cold winters (-25°C mean high in January), relatively cool summers (20°C mean high in July), and 30 cm average annual precipitation. 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 (Fig. 5). Relict glacial ice wedges and lenses are common across the fire area and the entire North Slope, as is high ice volume in near-surface permafrost (Fig. D-11, Appendix). Vegetation is dominated by the tussock-forming sedges *Eriophorum vaginatum* (cottongrass) and *Carex bigelowii*. Wet depressions and meadows have *C. aquatilis* and the rhizomatous aquatic grass *Dupontia fisheri*. The dominant shrub types included willow (*Salix pulchra, S. fuscescens, S. glauca*), 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*). Herbs other than tussock-formers are typically scarce, except for the deciduous cloudberry (*Rubus chaemamorus*), which we treat as a forb in this study after Viereck (1992). Other herbs include grasses *Arctagrostis latifolia* and *Poa arctica* and forbs *Petasites frigida*, *Pedicularis* sp., *Polygonum bistorta, Arnica lessingii* and *Saussurea angustifolium*.

We used Viereck's (1992) vegetation classification to describe pre-burn plant communities (Appendix A). The most prevalent plant community, represented by 14 burned and 6 unburned transects was open low mixed shrub-sedge tussock tundra, having > 25% shrub cover by definition. At least 75% of transects were classified as shrub-dominated tundra or shrublands with >25% shrub cover and the remainder were wet sedge meadows or sedge tussock tundra. Acidophilous mosses (*Sphagnum* sp., *Aulacomnium* sp., *Polytrichum* spp. and *Dicranum* sp.), and the moss-like liverwort (*Lepidozia reptans*) carpeted the surface between the tussocks. Fruticose lichens also were usually found in relatively protected hollows between tussocks, growing in clumps. Plant nomenclature follows the USDA Natural Resources Conservation Service Plants Database (http://plants.usda.gov). Prior to the fire, 54% of the burn area was classified as upland moist acidic tundra (MAT; soil pH <5.5), 15% as moist non-acidic tundra (soil pH>5.5), and 30% as shrubland (Auerbach 1997; map http://data.arcticatlas.org/geodata/maps/ku/ku_veg_u6.pdf).

FIELD DATA COLLECTION & ANALYSIS

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) and 2011 (July 9-12). Sampling methods were developed in cooperation with Arctic LTER so that data sets could be later combined for analysis (Appendix A). 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 BARC mapping (D. Verbyla). In 2010 we established 9 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 10 burned and 6 unburned comparison transects 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 (Fig. 2). Observers measured cover of substrate or vegetation at 100 points along each transect using a point-sighting device and evaluated shrub and tussock density in ten 1-m^2 frames (also photographed) along the transect (see Methods, Appendix A). 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. Active layer depths were measured and soil cores for pH and microbe analysis were taken along a parallel transect offset 2.5 m to the north of the vegetation transect.

Transects were photographed from each end in a landscape configuration. Additionally, ten 1 x 1m quadrats were framed along each transect, at 5-m intervals, and photographed from a height of approximately 2 m. Burn severity in the 1 x 1m quadrats (n=10/transect) was 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). Numbers of woody shrubs, tussocks, and seedlings were also counted in the 1 x 1-m quadrats and additional species not intercepted on the cover transect were noted.

For areal burn severity mapping, a post-fire image was acquired from Landsat 5 TM on June 14, 2008 (path 75, row 11), 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 (Appendix B), surveyed in the field during the summer of 2008. For the CBI, burn severity was estimated in a 30 m radius plot centered on the transect origin. 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. For each set of burn severity mapping ground validation data, the Pearson correlation coefficient and a corresponding p-value were calculated for the relationship between the validation set (i.e. CBI, severity class) and the dNBR at that location. Complete methods and other tests completed are described by Kolden (2010).

The Normalized Burn Ratio (NBR) is calculated from a single, atmospherically corrected, post-fire image as: NBR = (B4 – B7) / (B4 + B7) * 1000, where B represents different bandwidths detected. CBI plots are the standard approach for developing thresholds of burn severity for remote sensing data (Key and Benson 2006) but are difficult to collect in remote landscapes like the North Slope of Alaska, where field work requires transport by helicopter or float plane, and it is difficult to randomly sample the fire based on budget and landing site constraints. Thus, we also tested an aerial assessment approach that collected an additional 87 ground truth points from a hovering helicopter. Observers used aircraft GPS to navigate to points and held hover at 50' or less to categorize a site about 30m in diameter at point center according to Unburned, Low, Moderate, or High burn severity. Characteristics learned in ground visits like remaining vegetation, soil color, moss type, profile of burned tussocks and shrub remnants were criteria in making the calls. There are several advantages to this approach, in that it can be done entirely from the air and can be used to better sample across the entire burned area. The disadvantages, however, are that an expert familiar with levels of severity in the ecotype is required to make quick decisions about subjectively

defined categories of severity as the plane flies over an area, and it is essential to record the severity for the exact geographic location that is recorded simultaneously on a Global Positioning System.

Soils properties, and pH and consumption measures

Active layer depth was measured using a tile probe at 20 points along a parallel transect offset 2.5 m from the vegetation cover transect.

Dr. Michelle Mack, from the University of Florida, developed a method for estimating the amount of organic matter which had been consumed during the fire using meristems of the dominant plant species, *Eriophorum vaginatum*, which persisted through fire and provided a benchmark of pre-fire soil organic matter depth and plant biomass. Her results have been published separately (Mack et al. 2011). She developed regional biometric relationships between *E. vaginatum* meristem height above the mineral soil *versus* pre-fire soil organic layer depth, and depth *versus* bulk density. Radiocarbon dating of the post-fire soil surface was used to determine the age of the carbon pools released by the fire. Mineral soil cores--5 for each of 23 transects--were taken from active layer sampling lines in 2008 for pH analysis. Mineral soil pH was measured on a 1:1 paste of field moist soil and distilled water. In 2010, organic soil cores were taken along 35 transects and analysed by Bret-Harte for pH, again using 5 samples per transect. Statistical analyses of organic and mineral soil pH data, including means, used the untransformed variable, i.e., hydrogen ion concentration [H+] since pH = - log [H^+].

Dietary analysis from caribou fecal pellets

We collected 16 pellet groups from the burned area in 2008 and in 2009, some of which were scorched and thus deposited in a winter preceding the fire. In 2010 we collected 29 caribou pellet groups from burned and reference unburned transects and sent all samples for diet composition analysis at the Washington State University Wildlife Habitat Nutrition Laboratory. The samples were emulsified and examined on slides with an intensity of 100 views per slides to identify dietary components. Composition differences from burned and unburned sites were compared using a Student's t-test.

RESULTS

Burn severity

Median burn severity assessed on 24 burned transects was 1.9 or "moderate" (Table 1). Consumption of feathermosses and ericaceous shrubs was high throughout the burned area (Fig. 6, 7). Frequently, almost all evidence of mosses (other than sphagnums) and dwarf shrubs was obliterated, or only charred remnants of the roots and rhizomes remained 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 (Figs. D-7, a-c, Appendix). Reconstructed pre-fire organic depth averaged 20.3 cm (range 10.4-43.3 cm, n=20) whereas post-fire the residual organic depth was 15.7 cm. With respect to remotely sensed burn severity, dNBR values derived from the Landsat imagery had a high Pearson product moment correlation coefficient ($R^2 = 0.814$) to the CBI values, showing high significance ($p = 0.001$), and were thus deemed to be an appropriate metric for mapping burn severity over the ARF and Kuparak fires (Jones et al. 2009).

Table 1. Burn severity summary from transects, arranged in decreasing average burn severity. Transect burn severity index (average of indices from 10 quadrats/transect) ranges from 5=unburned, 4=just scorched, 3=lightly burned, 2=moderate burn to 1=severely burned. dNBR is the Normalized Burn Ratio. The Composite Burn Index (CBI) ranges from unburned=0 to a maximum of 3 for the most severe burn in a 30m circle at transect origin.

Unit	Transect Name	Substrate Burn Avg.	Vegetation Burn Avg.	Burn Severity Avg.	n	dNBR	Residual Organic (cm)	CBI
UAF	B111	1.2	1.1	1.1	10	785		2.83
BLM	B013	1.4	1.0	1.2	10	872	12.0	2.89
BLM	B060	1.3	1.3	1.3	10	637	8.5	2.50
BLM	B037	1.6	1.2	1.4	10	805	8.6	2.69
BLM	B069	1.9	1.0	1.5	10	823	12.2	2.38
BLM	B020	2.0	1.0	1.5	10	827	12.3	2.50
UAF	B114	1.5	1.5	1.5	10	785		
BLM	BARF	1.6	1.7	1.7	10	798	13.1	2.63
UAF	B107	1.8	1.6	1.7	10	867		2.92
UAF	B101	1.7	1.9	1.8	10	814		2.96
BLM	B030	2.3	1.3	1.8	10	751	11.4	2.19
BLM	B063	1.9	1.8	1.9	10	837	17.9	2.96
UAF	B106	2.0	1.8	1.9	10	847		2.21
UAF	B102	1.9	2.2	2.0	10	861		2.60
BLM	B032	3.0	1.1	2.1	10	689	25.6	2.19
BLM	B041	2.6	1.8	2.2	10	789	21.5	2.31
BLM	B005	2.3	2.3	2.3	10	578	16.4	1.81
UAF	B104	2.6	2.5	2.5	10	812		2.33
BLM	B051	2.7	2.5	2.6	10	548	19.2	1.44
UAF	B113	3.0	2.4	2.7	10	295		0.92
UAF	B105	2.7	2.7	2.7	10	684		2.38
BLM	BKUP	2.9	2.6	2.8	10	525	28.0	1.94
BLM	B027	3.3	2.8	3.1	10	648	27.5	
UAF	B103	3.1	3.2	3.1	10	521		1.65

The CBI was correlated with dNBR at 30m, 90m, and 150m spatial scales (Kolden 2010). To set final severity class thresholds for burn severity mapping of the ARF, an objective assessment based on standard deviations was employed. The median reflectance value for the entire region (both burned and unburned areas) was determined to be near zero (-14). The standard deviation of just the pixels within the fire perimeter was calculated and the burn severity class thresholds were calculated as standard deviations from the median of the entire region (which is essentially the mean value of the unburned area) using the 90-meter dNBR (Kolden 2010). Using these classes, nearly half of the ARF burned at high severity (47 percent), with over one-third of the fire burning at moderate severity (35 percent), and 18 percent low severity. Excluding water features, 11 percent of the area within the fire perimeter did not burn, including both unburned islands, and 'fingers' of unburned extending from the perimeter into the interior of the fire.

In contrast, categorical burn severity plots from aerial sampling (n=87) showed only weak correlation with remotely sensed burn severity metrics. The highest correlation between the aerial observations and the burn severity metrics was with a "Relativized" dNBR at 90m resolution (derived by passing a 3x3 mean

aggregate filter over the native 30 m dNBR). The Relativized dNBR (RdNBR) accounts for the level of greenness before the fire to describe the relative change due to fire effects (Miller and Thode 2007) and has proven useful in low biomass ecosystems in the west. For the Spearman Rank Correlation coefficients, the RdNBR showed the strongest correlation to burn severity observations at the 150m scale, with all coefficients demonstrating significance. RdNBR was most strongly correlated to observations of surface vegetation (R^2 = 0.86), and less strongly correlated to substrate observations (R^2 = 0.77), suggesting that surface vegetation was the greater contributor to the strong overall correlations to CBI (R^2 = 0.84).

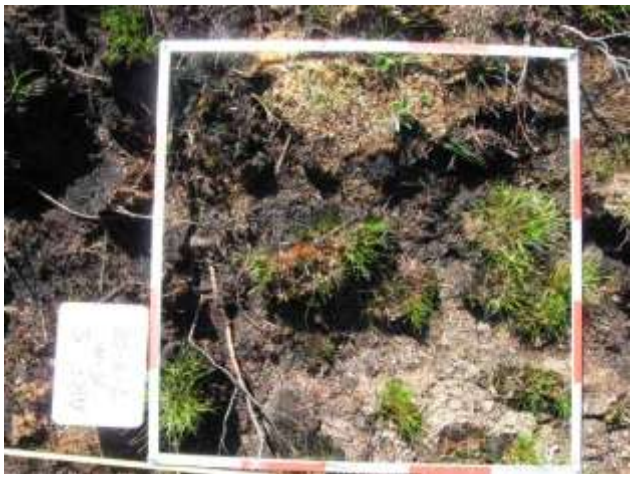


Figure 6. Typical light-to-moderate burn severity in a sample frame (B005 -15m), 2008**.**

Figure 6. High severity with consumption of almost all vegetation and duff layers (B037 - 5m), 2008.

Soil Characteristics, pH, Active Layer and Thermokarst Formation

Mean mineral soil core pH values ranged from 3.9 to 5.2 (2008, 23 transects) while organic duff samples (5-10 cm depth) from the 35 transects sampled in 2010 ranged from 4.2 to 6.4. Mineral soil was almost always more acidic than the organic layer (15/19 paired samples) sometimes markedly so (Appendix C, Table II; Fig. 8). Burned transects averaged 4.48 for mineral soil pH and 4.72 for organic soil pH. The average pH for unburned transects was (4.70). Previously reported pH from unburned mesic tussock tundra in the Arctic Foothills was reported to average 4.6 ± 0.1 (Walker et al. 1994). The physiogeographic location 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 (*i.e.* higher pH; Appendix C, Table II). This is consistent with Auerbach's (1997) mapping of tundra types in the region.

The bulk density of organic layers in the ARF from 2008 ranged from 0.07 g/cm^3 (±0.01, n=20) in the 0-5cm layer, which would be mostly moss, litter, and surface vegetation, to 0.15 g/cm^3 (±0.02, n=4) in the 15-20cm 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.

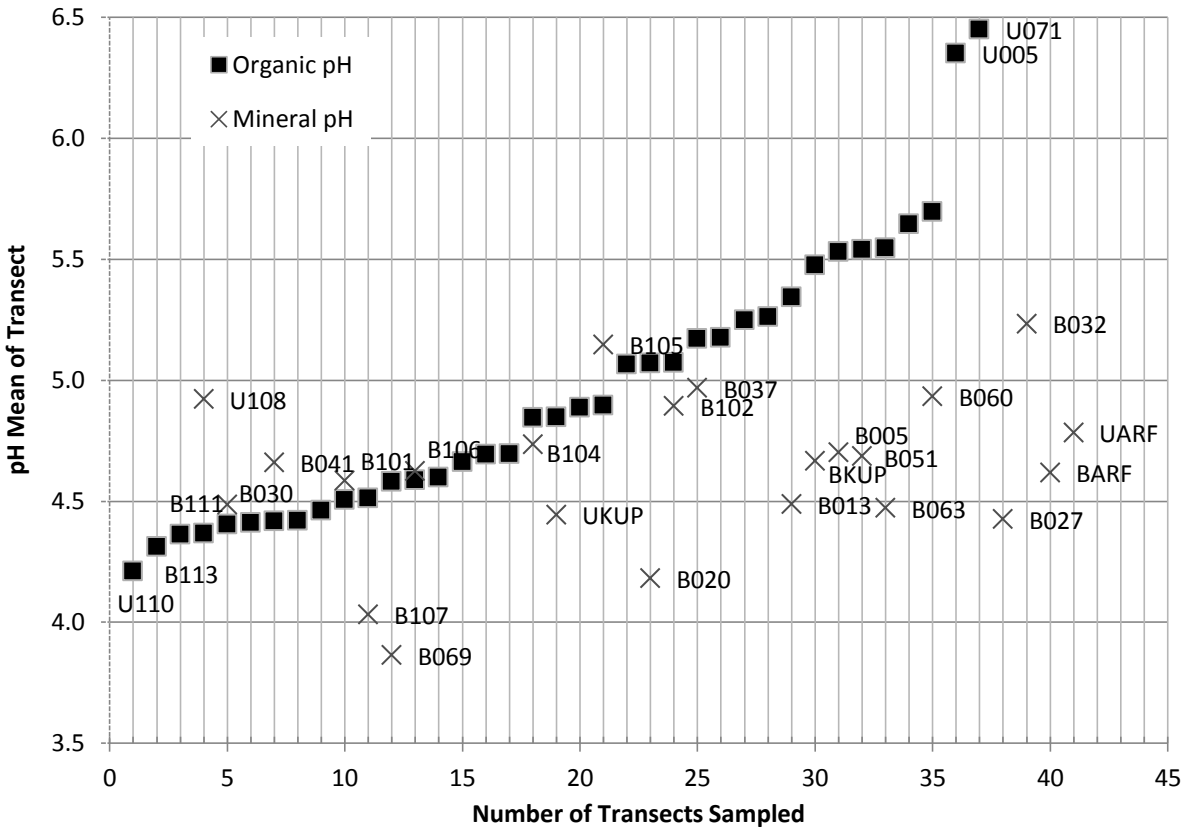


Figure 8. Comparison of 2008 mineral (N= 23) and 2010 organic soil (N=37) mean pH values on ARF transects. 19 transects had pH calculated both from mineral soil cores in 2008 and organic soil cores in 2010.

Depth of active layer thaw ranged from 40 to 47 cm on the burned transects from 2008-2011 and from 23 to 34 cm on unburned reference transects (Table 2; Fig. D-1&2, Appendix). Although active layer depths in Table 2 appear to have reached a minimum in 2009, this is the effect of sample date, as thaw depth increases throughout the summer. Differencing the burned from the unburned transects reveals that depths have actually increased from 134% in 2008 to 180% in 2011 (Table 2). Thaw depth seemed to increase with burn severity in the substrate layer (Fig. D-3, Appendix) but the trend was not significant. Similarly, regression analysis failed to show a consistent or significant relationship between dNBR or CBI and active layer depth (Fig. 9). Some of the error may be related to different observer's wildland fire experience which affected subjective evaluation of burn severity (CBI).

Table 2. Summary of differenced active layer thaw depths on burned and reference transects 2008-2011.

YEAR	BURN	BURN N	BURN SE	REF	REF N	REF SE	Difference BURN-REF	Difference % OF REF
2008	-39.94	23	7.81	-29.73	2	-	-10.22	134%
2009	-47.36	23	5.62	-33.98	2	-	-13.39	139%
2010	-43.52	23	7.06	-26.51	11	7.70	-17.01	164%
2011	-41.57	23	10.84	-23.05	11	5.76	-18.52	180%

Thaw depth at the severely burned BARF transect continued to increase through 2011. Residual duff depth here was 13.1 cm. A similar deepening of the active layer failed to appear at the lightly burned BKUP transect where residual duff depth was 28.2 cm. This pattern suggests that thaw depth is negatively related to the thickness of the residual duff.

Regression analysis revealed that sample date accounted for most of the variance in thaw depth (R^2=0.55). This was not surprising because sampling later in the season yields deeper thaw depths. Our data indicate that thaw occurs at 0.79 cm/day for burned transects and 1.15 cm/day for unburned transects. Burn effect (burned or unburned) was also highly significant. Adding burn effect to the model greatly improved the fit (Adj. R^2=079) and seasonally averaged, burned transects were about 12 cm deeper (Fig. 9).

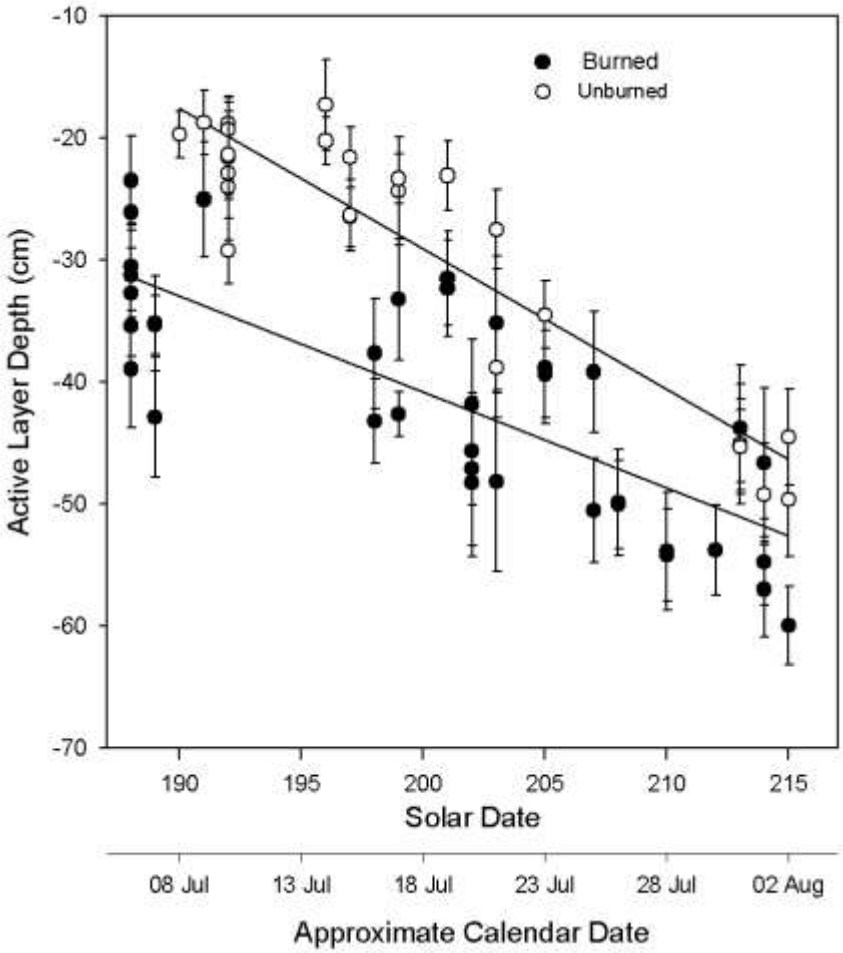


Figure 9. Active layer depth was consistently greater in the set of burned transects than the unburned transects (2010-2011 data).

Melting and subsidence were noted in some transects (Fig. D-9, Appendix), often where there was previous evidence of frost scarring. Melting may continue for several years due to the loss of protective organic mat. South and west-facing steep slopes demonstrated the most noticeable subsidence and erosional effects (Fig. D-10 a & b, Appendix). Along the Nanushek River (west perimeter of the fire) the most active thermokarst and erosional features increased in number and extent between 2009 and 2011. We established two ground-based photopoints in this area (N68.90486 x W150.62341 and N68.87824 x

W150.55766, NAD 83) with views in all 4 cardinal directions, as well as aerial oblique photos. The latter 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 had widened to more than 70 m wide and deposited a 1.5-m high berm of outflow silt near the original photopoint in 2010. By 2011, a large silt pile (2 m tall) had accumulated at the toe of the slump, almost obscuring the view of the karst from the photopoint origin (Fig. D-12, Appendix). 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.

Vegetation

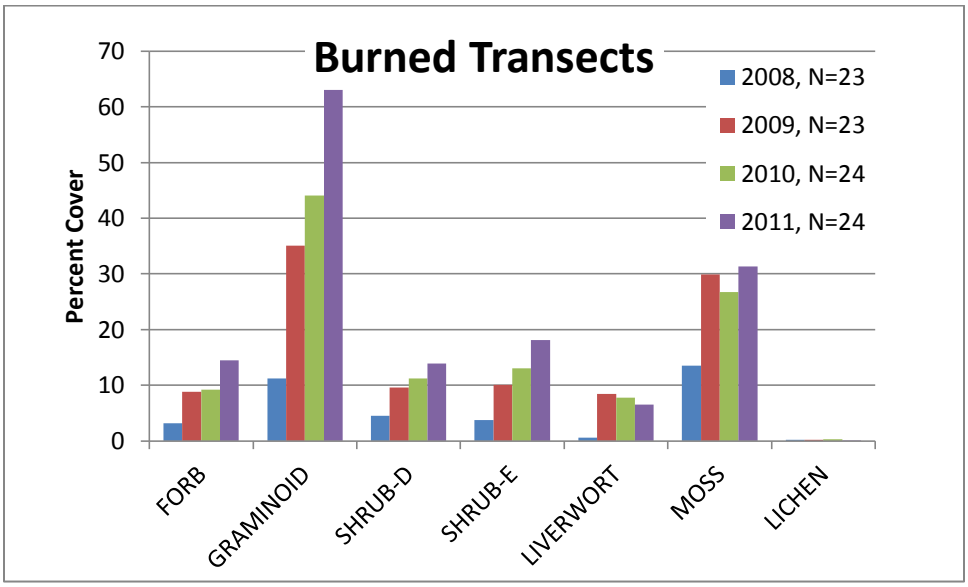
The most dramatic change in plant cover over four years on the burned transects was graminoid, which increased from 11% to 63% compared to unburned transects which varied between 35-50% (Fig. 10). Cottongrass cover increased 28%, *Calamagrostis* sp. 10% and *Carex* sedges 9% over that period for all burned transects. Some transects showed almost complete dominance of graminoid cover (Fig. D-7c, Appendix). Shrub cover also increased, although less dramatically. Deciduous shrubs increased from 4% in 2008 to 14% in 2011, while ericaceous shrub cover increased from 4 to 18% on burned transects. Meanwhile, unburned transects averaged 33% deciduous and 42% ericaceous shrub cover with the full complement of reference transects in 2011 (N=17). Forb cover on the burned transects increased from 3% in the first year post-burn to 14% by year four, equalling the average forb cover on unburned transects for that year. The abundance of perennial grasses, forbs and horsetail increased through time (*Calamagrostis* : 0.3-10.3%, *Arctagrostis*: 0.1-2%, *Equisetum arvense:* 0-1%). Fireweed (*Chamerion angustifolium*) was rare in 2008 but increased patch-wise through 2011, apparently spreading rhizomatously, but still <1% cover on our burned transects.

Tussock mortality on study transects was documented at 10% 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 (Fig. D-5, Appendix). Some tussocks survived to sprout a live leaf or two in 2009 and subsequently suffered delayed mortality when surveyed in 2010-2011. Sedge seedlings (especially *C. bigelowii*) and the grasses *Calamagrostis* spp. and *Arctagrostis latifolia* had colonized some of the dead tussocks by the third season following the fire. We also documented new tussock seedlings in burned inter-tussock hollows, especially where mineral soil was exposed. In 2010-2011, large vigorous tussocks of cottongrass, resprouting willow and dwarf birch were starting to dominate more moderately burned areas. From the air, parts of the fire area appeared light-colored from all the cottongrass in bloom. Shrub mortality was much higher—estimated at >50%, but this may be an underestimate as mortality was difficult to determine where entire plants and roots were consumed. Areas which had higher densities of dwarf birch, willows and alders appear to have burned even more severely, as illustrated in the riparian willow/alder shrub Transect BO60 (Fig. D-4, Appendix). Shrubby edges of low-center polygons also burned very deeply (Fig. 4).

Lichen cover on the unburned reference transects measured 8%, about 2/3 of which consisted of caribou forage species such as *Cladina rangiferina* and *Cladonia* sp. and the rest by foliose species like *Peltigera* sp. (Fig. 10). It is likely that some microhabitats within the burn probably had higher lichen concentrations that would have been attractive to winter foraging caribou. After four years there is virtually no forage lichen cover in the burn area: about 0.1%. 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.

The most notable cover on severely burned sites in 2009-2010, were mats of "copper wire moss" *Pohlia nutans*, "fire moss" *Ceratadon purpureus*, and the liverwort *Marchantia polymorpha* (Fig. D-5, Appendix).

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. Some of these bryophytes seemed to be trending downward by 2011 (*M. polymorpha*) and being replaced by other successional mosses like *Polytrichum* sp. and *Aulacomnium* (Table 3). Moss mats were holding the ashed fine soils, which would otherwise likely disappear with the winds that frequent this area (Fig. D-4, Appendix). Mosses also appeared to be keeping at least some moisture in burned areas, which overall seemed to be drier than normal. Live *Sphagnum* peat mosses were much less abundant on burned transects (Table 3). Hydrophilous *Sphagnum* mosses appeared to be dying in some of the burned areas, even where they had not apparently been scorched. We recorded 3.4% dead *Sphagnum* moss cover in 2008, 10.3% in 2009, 2.0% in 2010 and 3.0% in 2011, while no dead *Sphagnum* was recorded on unburned transects.



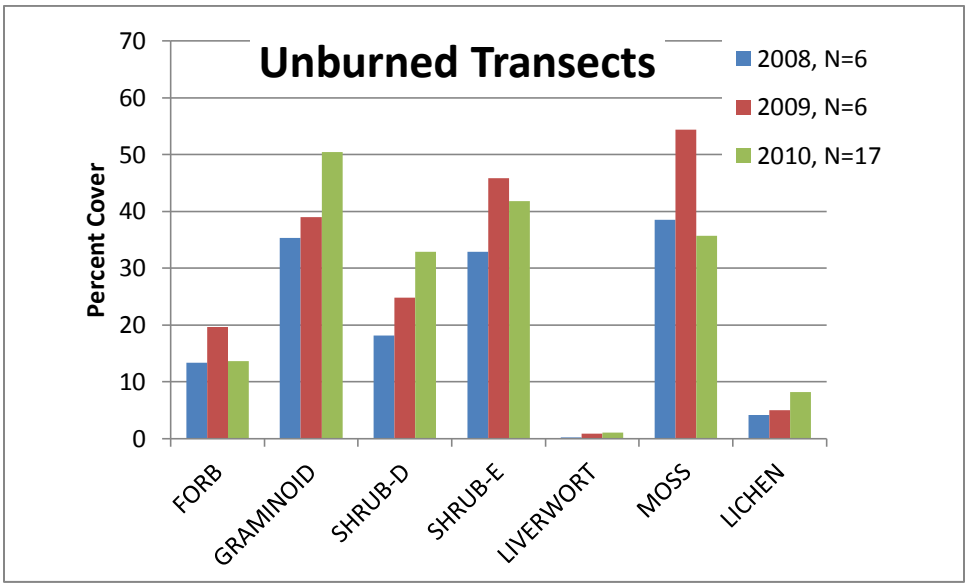


Figure 10. Percent cover by growth form and year, burned and unburned transects. Shrubs are divided into deciduous (SHRUB-D) and ericaceous (SHRUB-E).

Table 3. Percent cover of most common species (live vegetation), by year, on burned and unburned transects. Arrow indicates an apparent cover trend.

% Cover	Burned Transects					Unburned Transects			
Year	2008	2009	2010	2011		2008	2009	2010	
E. vaginatum	8.2	21.5	27.8	36.7	↑	24.8	26.0	27.8	
L. palustre	1.3	5.8	7.6	11.2	↑	16.8	18.5	16.0	
R. chaemaemorus	2.9	7.0	6.6	10.1	↑	8.7	13.0	7.0	
V. vitis-idaea	1.5	3.5	4.8	6.0	↑	12.3	19.7	16.1	
Salix sp.	0.8	3.8	5.0	5.0	↑	7.5	9.5	12.2	↑
Betula nana	0.5	2.2	4.5	6.6	↑	10.2	14.5	15.8	
Marchantia sp.	0.6	8.4	7.8	6.5		0.0	0.2	0.1	
Calamagrostis sp.	0.3	4.0	5.2	10.3	↑	0.8	3.2	3.5	
Carex sp.	1.8	7.3	6.9	11.0	↑	6.2	6.2	13.4	↑
Sphagnum sp.	0.7	2.7	1.8	1.0		21.3	36.5	14.5	
Polytrichum sp.	0.1	1.8	3.9	7.6	↑	2.7	2.3	2.1	

Caribou dietary analysis

A total of 45 pellet groups, 22 from burned areas and 23 from unburned areas, over 3 field-collection years were examined. The results of dietary components (uncorrected for digestibility) are summarized in Table 4. Lichens were the largest dietary component identified, comprising 48.9 ± 13.1% of all samples. Samples on average contained 30% moss, 9% ericaceous or deciduous shrub, 8% graminoid, and 2% forb. The percent lichen composition differed between the 22 samples gathered from burned sites (43.9 ± 9.7%) and 23 samples from non-burned areas (53.7 ± 14.3, p=0.01). Lesser dietary components were not statistically different between the treatments.

Table 4. Percent composition of caribou fecal pellets from 2008-2010 by lifeform.

Component	**Burn**		**Non-burned**		**All Samples**	
	% N = 22	**Std Dev**	**% N = 23**	**Std Dev**	**% N = 45**	**Std Dev**
Lichen	**43.9**	9.7	**53.7**	13.1	48.9	13.1
Moss	31.7	10.3	28.4	9.2	30.0	9.7
Shrub	9.9	5.2	10.5	5.1	9.3	5.3
Sedge/Rush	9.2	10.4	6.1	4.2	7.6	7.9
Grasses	1.1	1.7	0.3	0.8	0.7	1.4
Forb/Equisetem	3.6	4.1	2.3	2.6	2.9	3.4

See Appendix 2 for more data tables of raw data obtained from this study.
Datasets for the Anaktuvuk River Fire study are archived and available at www.frames.gov, and in the Arctic Long Term Ecological Research data archive (http://ecosystems.mbl.edu/arc/datacatalog.html).

DISCUSSION

Fire Characteristics and Burn Severity

Over half of 23 burned transects assessed by ground had burn severity greater than "moderate" and we estimated 80% of the fire area burned with moderate or high severity using remotely sensed data. More than 40% of transects demonstrated high severity corresponding to >20% mineral soil exposure and/or >60% tussock basal area consumption. Tussock bases, similar to the boles of live trees in forested areas, are virtually never completely consumed in fires. Only 20% of the points had low severity and 5% represented unburned inclusions. This level of severity is atypical of tundra fires, which are generally light severity with little or no mineral soil exposure. The level of consumption combined with the scale of the burn is unprecedented for the North Slope within human history. Sediment cores of lakes on the central North Slope so far have been negative for charcoal layers indicating large fires in at least the last 5,000 years (Hu et al. 2010).

Consumption of the organic matter in tussock tundra areas was uncharacteristically high over most of the burn area. Organic soil depths measured in 2008, where burned transects averaged 15.7 cm and the unburned transects averaged 23.4 cm of remaining organic soils (Mack et al. 2011). The depth of the soil organic layer—a factor likely to influence permafrost melting--was thus reduced by 30 ± 3%. Mack et al. (2011) found that all surface soils from the burned sites contained bomb-enriched radiocarbon, setting the maximum age of lost soil C at 50 years and estimated it took 37 years on average to develop the 6.1 cm of surface organic soil thought to have been consumed by the fire. The biggest predictor of residual organic layer depth was not burn severity but pre-fire organic layer depth (R^2=0.82, P<0.001, n=20; Mack et al. 2011). This is consistent with observations of organic soil burning in Alaskan boreal forest (Ottmar and Sandberg 2003) and suggests that in the structured organic layer, deep burning is limited by a mechanism independent of potential fuel, such as increased bulk density and less oxygen in deeper strata, particle size, fuel moisture and mineral content. In addition to influencing smoldering combustion, there is also some evidence that active layer depth is not simplistically related to residual duff depth alone but also to the bulk density and thermal conductivity of the remaining individual organic soil horizons. Regression analysis shows that active layer depth is related to duff depth but addition of burn effect (burned or unburned) greatly improves the model, suggesting that burned duff is much different than unburned duff. Duff is often composed of many individual layers with different properties. 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. Measurements of duff bulk density at our transects show a linear increase with depth (Mack , unpublished data). 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 decreasing insulative value resulting in deeper active layers.

Consumption of feathermosses and ericaceous shrubs was so high throughout the burned area it was challenging to reconstruct the pre-burn environment in 2008 to assess the level of disturbance. It is always preferable to have pre-fire data on specific transects but often this is not possible, particularly in locations as remote and difficult to access as Alaska's North Slope. Although most evidence of mosses (other than sphagnums) and dwarf shrubs was obliterated in severely burned transects, charred remnants of the roots and rhizomes remained in a few centimeters of deeply charred lower duff.

The drought conditions during September 2007 were coincident with record low Arctic Ocean pack ice adjacent to the coast—likely bringing warmer, drier conditions (Hu et al. 2010). The summers of 2009 and

2010 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. Warmer summers spawn thunderstorms as well as drying out the grass and sedge litter, mosses, and deciduous leaf litter, which produces better conditions for tundra fire propagation and spread. Climate scientists have found that periods of sea ice loss are coupled with western Arctic land warming trends up to three degrees C° warmer and penetrating over 500 miles inland (Lawrence et al. 2008). The effect peaks in late summer/autumn, when vegetation and soils are in prime condition to set the stage for large wildfires (although lighting ignitions peak earlier, in June-July). Modeling shortened fire return intervals in tundra indicated decline in availability of caribou winter habitat (Rupp et al. 2006). Thermokarsting caused fairly dramatic changes in hydrology, soils and vegetation, similar to changes documented on a severe burn in western Alaska (Liljedahl et al. 2007) but was limited in scope.

Burn severity mapping lessons learned

The CBI plots showed a strong correlation with spectral indices and demonstrated that dNBR is the best metric for mapping burn severity for this fire. We feel the resulting burn severity map (Fig. 3, Jones et al. 2009) is representative of ecological burn severity. The contrast between areal burn severity on the Kuparak fire and that on the ARF is striking. The Kuparuk Fire was detected two days before the Anaktuvuk River Fire on July 14, but burned just 3 weeks before being called out. The resulting 725-ha burn was representative of most high latitude tundra fires, burning with primarily low severity and minimal consumption of organic layers. Burn mapping using the 90-m dNBR metric confirmed that only 20% of the Kuparak fire burned with moderate severity, and 80% burned with low severity, while over 80% of the ARF was high (47%) or moderate (35%) severity and only 18% with low severity (Fig. 3).

The determination of where to set thresholds in the reflectance values for burn severity is important to yield the best, most discerning map product and it is tempting to default to set thresholds used in previous tundra mapping efforts. However, if we had used the lower thresholds set by previous dNBR assessments in Alaskan tundra fires (MTBS 2009), nearly 90% of the ARF would have been mapped as high severity, with almost no moderate severity and approximately 10% at low severity. The use of standard deviations to determine thresholds better characterizes the range of ARF burn severity and complements classifications made in the field on CBI plots.

The aerial burn assessment work required approximately 3.5 flight hours to cover points distributed throughout the 256,000-acre burn area. However, aerial plots were poorly correlated with remotely-sensed burn severity metrics. The aerial assessment approach has several advantages, in that it can be done entirely from the air and provides the opportunity to quickly collect training points over the entire burned area. The method does require an expert familiar with levels of severity in the ecotype to make quick decisions about subjectively defined categories of severity as the aircraft flies over an area. The poor correlation with remotely sensed data was disappointing for our objective of developing a more economical ground-truthing method. Sample and image point location agreement was difficult to achieve in practice, in that it proved difficult to record the severity for the exact geographic location that is recorded simultaneously on the GPS from a moving (even hovering) aircraft and match that with a point in the spatial data. Datum and image rectification processing error may also have been factors. Additionally, the observer's definition of burn severity and the spectral composition of burn severity calculated by the sensor are quite different. The CBI index was designed to specifically measure components of ecosystem change from fire that contribute to change in a spectral metric such as dNBR. An observer who is an experienced ecologist may pick up on landscape indicators of burn severity that are not amplified by the ratioed indices used as burn severity metrics. Spectral indices have been shown to be strongly correlated to ground data that quantifies aboveground vegetation but poorly correlated to measures of organic soil

horizon consumption (Kolden 2010) even though consumption is probably the most important factor affecting succession, moisture regime, and active layer changes.

Vegetation Cover

Shrub-tussock communities have been considered the "climax" vegetation for large areas of arctic Alaska (Viereck et al. 1992), although that definition may change as the climate warms. As these communities age they accumulate more organic matter due to the slow decomposition rates dictated by cold climate and permafrost substrate. Older surfaces favor mosses and lichens (which don't require unfrozen soils), and possibly shrubs, which can colonize and overtop the tussocks leading to tussock senescence and death. This appears to be the mechanism by which tussock tundra progresses to wet shrub birch-ericaceous shrub communities. Fire disturbance returns dominance to the tussocks and resets succession of the bryophyte and shrub communities, but can favor shrubs by removing insulating and competing cover and decreased surface albedo warming the soil.

Despite the unusually high severity of the fire, vegetation recovered substantially over the first four years post-burn. By 2011, cover of live vascular plant cover in the ARF transects was approximately 80% of that found in the reference transects (Fig. 9). The sum of non-vascular plant cover in the burned transects was nearly equal to that in the reference transects but had a different composition, with pioneering mosses and liverworts replacing the *Sphagnum*/feathermoss and lichen cover. Most of the vascular plant cover was comprised of resprouting biomass from individuals present before the fire, which were damaged but not completely killed, rather than seeding of new plants. Tussocks of Eriophorum vaginatum resprouted vigorously in the first year following the fire, and tussock mortality was estimated at only 10% the first year, but with some delayed mortality. Heavy flowering (Fig. D-6, Appendix) is a response to soil warming and nutrient enrichment on burns which is a common characteristic of tundra fires (Racine et al. 1985). In fact, soil inorganic nitrogen and phosphorus availability, as measured with resin bags, was approximately three times higher in the burned transects than in reference transects one year after burning (Bret-Harte, unpublished data).

Shrub mortality was higher, >50%, although, again, it was difficult to estimate due to consumption of stems and roots. In 2011, graminoid cover was still substantially greater than shrub cover, with both continuing to increase (Fig. 9). Areas dominated by low shrub cover, such as the edges of low-center polygons (Fig. 4) and drainageways burned more severely than tussock-dominated areas, which is interesting because shrubby riparian areas are often spared in typical tundra fires. Accumulations of shrub leaf litter adding fuel, or the efficiency of shrubs "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. Revegetation primarily occurred by re-sprouting of roots and rhizomes. Lichens and bryophytes have few perennating structures and are often destroyed by burning, but many arctic vascular plants are woody or suffrutescent, and burned stumps and buried rhizomes are usually capable of resprouting (Holt et al. 2008). On very favorable habitats, such as riparian slopes watered by melting permafrost, willow seedlings that were located off-transect were over a foot tall in 2009. Alder, on the other hand, showed minimal re-sprouting but a few very early seedlings were detected in 2011.

Non-native plant species have not been documented in the ARF transects to date, although certain grass species found at low abundance in the reference transects are much more abundant in severely burned transects. In contrast, much of the cover of non-vascular vegetation is comprised of species that were not abundant in tundra before the fire, but are common following fire in boreal forest. These include the

liverwort *Marchantia polymorpha*, and the mosses *Ceratodon purpureus* and *Pohlia nutans*. Other bryophytes, including *Sphagnum* mosses, feathermosses, and lichens are much less common on burned transects. The recovery period of these species is likely to be decades (Racine et al. 1985, Jandt et al. 2008). High rates of consumption combined with slow regeneration of mosses ensures there will be suitable seedbeds for pioneering species for many years, so establishment of new stands and communities cannot be ruled out.

Dietary Analysis

Fecal pellet analysis indicated that a high percentage of caribou winter diet in the ARF area is lichens. Lichens comprised 24-60% of fecal pellets from burned areas and 25-82% of those from non-burned sites. Since lichens are highly digestible by caribou, lichen content is typically under-represented without correction factors (Russell et al. 1993). Our results are similar to 2005 results from the Western Arctic Herd in northwestern Alaska, where uncorrected diet was 51% lichen, 22% graminoid, 14% moss, 9% shrub, and 4% forb (Joly et al. 2007b). In the latter study, the authors showed that diet mirrored range condition, in that lower lichen availability on winter range was correlated with less lichen in scat. The percent lichen composition differed between the 22 samples gathered from burned sites (43.9 ± 9.7%) and 23 samples from non-burned areas (53.7 ± 14.3, p=0.01), even though some of the "burned" samples were likely deposited before the fire. Lesser dietary components were similar between the samples. Pellet groups from ARF region had twice the moss composition of WAH samples. Moss has low digestibility and is thought to be incidentally ingested during browsing. Klein (1987) correlated increasing moss with degraded range conditions and low lichen availability on reindeer range. The dietary analysis results suggest that lichens are highly targeted by North Slope caribou in spite of relatively low abundance in this region, and that lichen cover is probably an important factor influencing range selection and movements here, as has been documented for other parts of the state (Joly et al. 2007a).

Implications & Further Directions for Study

While this study summarizes the early successional changes on the ARF, long-term follow-up will be essential to determine how the ecosystem will respond. The most important impacts of tundra burning on vegetation will likely be through changes in relative species abundance that emerge over time. Future survey on the ARF should include documenting shrub cover changes and competition between species. *Betula* may have competitive advantage over other shrubs on warmed, fertilized sites due to its growth plasticity (Bret-Harte et al. 2001), and increased shrubbiness could have other consequences, such as snow retention and shading of understory species. 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, phenologic changes, surface roughness and changes in energy balance. Higuera et al. (2011) suggest, 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 5000 years in the ARF.

Wildlife habitat implications vary with species and time since burn. Caribou are unlikely to use the ARF for winter range for decades due to low availability of preferred lichens, but could find the burn area attractive in the spring with a flush of greening sedges, herbs, and deciduous shrubs. 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 observed the first 2 days of 2011 survey). 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.

Fire is also a widely recognized mechanism for release of 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.

Temperatures all over Alaska have been rising, including in the Arctic, while Barrow has seen declines in annual precipitation (ACIA 2005). 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 (Duffy et al. 2005). In the tundra ecosystem, wildfires are also predicted to increase (Hu et al. 2010). If warmer summers and more open water along the Arctic coast during autumn continue, large fires on the North Slope could become more frequent, and vegetation, wildlife, and communities will have to adapt to a new regime. Tundra ecosystems cover nearly one-third of Alaska. Over 60 communities and about 350 native allotments are located within this ecotype, 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.

ACKNOWLEDGEMENTS

Primary funding for this work was provided by the Bureau of Land Management--Alaska Fire Service and Arctic Field Office--the Arctic Long-term Ecological Research Unit (by a grant from the National Science Foundation), and the U.S. Arctic Landscape Conservation Cooperative administered by the U.S. Fish and Wildlife Service.

Other cooperators during field collection of data came from the U.S. Forest Service Boreal Ecology Cooperative Research Unit at UAF, the North Slope Borough Department of Wildlife Management, Village of Anaktuvuk Pass and the U.S. Fish and Wildlife Service, Arctic Refuge. Most of burn area is on State of Alaska lands, and the Alaska Department of Natural Resources supported and permitted the field work. Dr. Dave Verbyla, UAF, assisted Alaska Fire Service in preparing a preliminary differenced Normalized Burn Ratio map from Landsat 5 imagery to ground truth. C. Racine, M. Racine, T. Hollingsworth, J. Jorgenson, C. Wachs, K. McNulty, and J. Ahgook, Jr. assisted with field data collection along with other fine field assistants from the University of Alaska-Fairbanks. D. Mann and M. Kunz provided expertise for thermokarst and paleogeologic interpretation.

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APPENDICES

APPENDIX A. FIELD SAMPLING METHODS FOR PERMANENT TRANSECTS

- Transect azimuths were defined as 90˚ T east from the pre-selected points of origin (BLM transects). LTER transects were oriented randomly or along drainageways. *Surv-cap*® aluminum survey stakes, 2.5' long with magnetized caps and retaining wires were set at **0** and **50.1 m**. GPS coordinates were recorded at both ends of transects. Slope, aspect, and elevation were recorded.

- Oblique photos of the permanent transect were taken with the tape laid out from 0-50m and 50-0m ends, standing about 1.5 m behind the respective stake to capture the whole transect in the photos, in a landscape orientation.

- Points were sampled at each 0.5 m along each transect, beginning at 0.5 m and ending at 50.0 m (n=100). In 2008 and 2009 we used a sight tube attached to a pointed rod. Note: *Looking from the zero point toward the 50 m point, walk on the **left** (north) and sample on the **right** (south) side of the tape.* In 2010 and 2011 we used a laser pointer attached to the rod. The base of the laser or sight tube rod was pushed into the ground at the transect meter mark and the vegetation read approximately 5-15 cm south of the tape. At each point, vascular and non-vascular vegetation hits were recorded. Substrates were recorded only if hit, that is, visible without digging. Plants or substrates hit underneath overhanging foliage were also recorded. Hits on a dead part of a live leaf or branch were counted as live hits on that species. A hit on a stump of a resprouting shrub was recorded as a live hit of that species. Dead detached pieces of vegetation were recorded as litter. Any woody material >6 mm (1/4 inch) was recorded as "wood". Substrates included mineral soil, frost-boil, litter, duff, char, rock, and water. Char included any organic material that was charred. At the UAF transects, the total number of hits for each species was recorded. For the BLM transects only the first hit on each species per sample point was recorded.

    - In 2011 we recorded the height of birch, willow, and alder in height classes intercepted on the cover transect as a metric of shrub growth. The height was measured at the point on the shrub where the hit occurred. Height classes were < 1cm, 1-2 cm, 2-5 cm, 5-10cm, 10-25 cm, 25-50 cm, 50-100 cm, 1-2m, and 2-3m.

Quadrats

- 1 x 1-m quadrats were placed south of the main transect line 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 re-locate the wire so that repeated placement of the quadrat in subsequent years 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.

- Passing back down the transect from 50-m, a photograph was taken at each of the ten, 1 x 1 m photo frames (placed on the same side as the point sampling, at 45, 40, 35, 30 …5, and 1-m) and the identity of any living vascular species that occured in the photo-frame, but was not intercepted at a sample point, was recorded. Each quadrat was imaged while standing on a stool at a height of approximately 2 m.

- Individual tussocks of *Eriophorum vaginatum* and *Carex bigelowii* were counted in the quadrats. Tussocks with >50% of their basal area inside the frame were counted as "in". Where more than one

tussock grew together, tussocks were distinguished based on their "cow licks". Newly dead tussocks and seedlings were noted.

- Species of willow and alder were counted in each of the ten 1×1 m quadrats by height classes. We tallied the number of individual shrubs (*i.e.* 1 SALPUL resprout with 6 stems) and height class within the quadrat frame. We used three height classes: <20 cm, 20-150 cm, and >1.5 m. In practice, however, we found no shrubs >1.5m tall. We counted the shrubs as genets rather than ramets, that is, clumps of stems originating at a single point were counted. 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.

- In 2008, we recorded burn severity for the vegetation and substrate in each quadrat. Severity was rated using five classes ranging from "Unburned" to "Heavily Burned" (Alaska Interagency Fire Effects Task Group 2007). Severity class descriptions were somewhat modified to capture structural components of tundra fuelbeds.

ACTIVE LAYER

- On a parallel transect, 2.5m to the LEFT (north) of the 50-m vegetation transect, depth of the active layer (organic and soil depth to ice or, infrequently, rock) was measured using a tile probe every 2.5 m beginning at 2.5-m mark, for 20 total points. If a tussock was encountered, the probe was inserted between tussocks, not through a tussock.

- In 2008 and 2009 temperature was recorded at 5 and 10 cm depth at each point.

- In 2008 soils were intensively examined. The depth of the remaining organic soil was measured from the organic-mineral interface at each active layer probe insertion point (n=20). Five soil monoliths were extracted from each transect for soils analysis including pH (Mack et al. 2011).

- In 2011 organic soil samples were collected from 5-10 cm deep in the organic layer at 35 burned and reference transects for pH analysis.

AERIAL IMAGE FROM HELICOPTER

The transect area was also imaged obliquely from a helicopter hovering at approximately 20 m the air. Colored flagging was placed on the Origin and End stakes for visibility in aerial photo.

VIERECK CLASSES DESCRIBING PLANT COMMUNITIES/FREQUENCY

CLASS	NUMBER TRANSECTS	DESCRIPTION	KEY SP.
2C2A	20 (14 burned)	Open Low mixed shrub-sedge tussock tundra	>25% shrub cover, tussock forming sedges (EriVag, CarBig); shrubs Betula, Ledum, Vaccinium
2C2H	5 (3 burned)	Open Low willow-sedge shrub tundra	Same, but shrubs are willows
2C2C	2 (1 burned)	Open Low mesic shrub birch-ericaceous shrub	Lack the tussock forming sedges
2C2F	1 Unburned	Open Low birch-willow shrub	> 25% shrub cover, similar to 2C2C but willows co-dominant with birch; poorly drained lowland and moist slopes
2C1B	4 (1 burned)	Closed low willow shrub	>75% willow shrub >20 cm but < 1.5 m high; drainageways
3A2D	5 (2 burned)	Tussock Tundra	<25% shrub cover, acidic, poorly drained soils; EriVag or CarBig, tussocks spaced 1-2 feet
3A2I	1 burned	Sedge-Birch tundra	CarAqu or CarBig, with Betula cover<25%.
3A2H	1 burned	Sedge-willow Tundra	Same, but with Salix spp. Wet to mesic sites on floodplains, low-center polygons, hummocks, solifluction lobes.
3A3	2 (1 burned)	Wet graminoid Herbaceous	<25% shrub cover, Soils saturated or underwater for all most of growing season; CarAqu, EriAng. Successional w/tussock tundra depending on water table?

APPENDIX B. CBI INDEX DATA SHEET FOR ALASKA TUNDRA

BURN SEVERITY -- COMPOSITE BURN INDEX (BI) – Modified for AK TUNDRA 5/1/08

Plot Description	Examiners:			Fire Name:	
Registration Code		Project Code		Plot Number	
Field Date mmddyyyy	/ /	Fire Date mmyyyy	/		
Plot Aspect		Plot % Slope		Elevation	
Plot Radius Overstory	10 meters	Latitude plot center		GPS Datum	
Plot Radius Understory	10 meters	Longitute plot center		GPS Error (m)	
Number of Plot Photos		Plot Photo IDs and Time			

BI – Long Form	***% BURNED 20 M PLOT =***	***% BURNED 30 M PLOT =***	***FUEL PHOTO SERIES =***

STRATA	BURN SEVERITY SCALE							FACTOR
	No Effect	**Low**		**Moderate**		**High**		
RATING FACTORS	**0.0**	**0.5**	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	SCORES
A. SUBSTRATES								
% Pre-Fire Cover: Litter = Duff = Soil/Rock = Tussocks =								
Pre-Fire Depth (inches): Litter = Duff = Fuel Bed =								
Litter/Dead Grass/1 hr Fuel Consumed	Nochange	--	50% litter	--	100% litter	>80% light fuel	98% Light Fuel	
Duff	Nochange	--	Light char	--	50% loss deep char	--	Consumed	
Medium Woody Fuel, 3-8 in. **or** Tussocks basal area	Nochange	--	20% consumed	--	40% consumed	--	>60% loss, deep ch	
Heavy Fuel, > 8 in.	Nochange	--	10% loss	--	25% loss, deep char	--	>40% loss, deep ch	
Exposed Mineral Soil Cover	Nochange	--	<1%	--	10%	--	>25%	
PRE-FIRE COVER: HERBACEOUS/GRAMINOIDS = MOSS/LICHEN= SHRUBS < 1M =								
Moss/lichens	Unchanged	--	30%	--	80%	95%	100%	
% Foliage Altered (blk-brn)	Unchanged	--	30%	--	80%	95%	100% + branch loss	
Frequency % Living	100%	--	90%	--	50%	< 20%	None	
Colonizers	Unchanged	--	Low	--	Moderate	High-Low	Low to None	
Sp. Comp. - Rel. Abund.	Unchanged	--	Little change	--	Moderate change	--	High change	

Σ =

$\bar{N}$

Σ =

$\bar{N}$ =

PRE-FIRE COVER =									Σ = N̄ =
% Foliage Altered (blk-brn)	0%	--	20%	--	60-90%	> 95%	Signifcnt branch loss		
Frequency % Living	100%	--	90%	--	30%	< 15%	< 1%		
% Change in Cover	Unchanged	--	15%	--	70%	90%	100%		
Sp. Comp. - Rel. Abund.	Unchanged	--	Little change	--	Moderate change	--	High Change		

D. INTERMEDIATE TREES (SUBCANOPY, POLE-SIZED TREES) 2-8 METERS

PRE-FIRE % COVER =			PRE-FIRE NUMBER LIVING =		PRE-FIRE NUMBER DEAD =				Σ = N̄ =
% Green (Unaltered)	100%	--	80%	--	40%	< 10%	None		
% Black (Torch)	None	--	5-20%	--	60%	> 85%	100% + branch loss		
% Brown (Scorch)	None	--	5-20%	--	40-80%	< 40 or > 80%	None due to torch		
% Canopy Mortality	None	--	15%	--	60%	80%	%100		
Char Height	None	--	1.5 m	--	2.8 m	--	> 5 m		
POST FIRE: %FELLED =		%TREE MORTALITY =							

E. BIG TREES (UPPER CANOPY, DOMINANT, CODOMINANT TREES) >8 METERS

PRE-FIRE % COVER =			PRE-FIRE NUMBER LIVING =		PRE-FIRE NUMBER DEAD =				Σ = N̄ =
% Green (Unaltered)	100%	--	95%	--	50%	< 10%	None		
% Black (Torch)	None	--	5-10%	--	50%	> 80%	100% + branch loss		
% Brown (Scorch)	None	--	5-10%	--	30-70%	< 30 or > 70%	None due to torch		
% Canopy Mortality	None	--	10%	--	50%	70%	%100		
Char Height	None	--	1.8 m	--	4 m	--	> 7 m		
POST FIRE: %FELLED =		%TREE MORTALITY =							

COMMUNITY NOTES/COMMENTS:	CBI = SUM OF SCORES / N RATED:	SUM OF SCORES	N RATED	CBI
	UNDERSTORY (A+B+C)			
	OVERSTORY (D+E)			
	TOTAL PLOT (A+B+C+D+E)			

% Estimators: **20 m Plot:** 314 m² 1% = 1x3 m 5% = 3x5 m 10% = 5x6 m
30 m Plot: 707 m² 1% = 1x7 m (<2x4 m) 5% = 5x7 m 10% = 7x10 m

After, Key and Benson 1999, USGS NRMSC, Glacier Field Station.
Version 4.0 June 4, 2005

Strata and Factors are defined in FIREMON Landscape Assessment, Chapter 2, and on accompanying BI "cheat sheet". www.fire.org/firemon/lc.htm

APPENDIX C. DATA TABLES FROM ANAKTUVUK RIVER FIRE STUDY 2008-2011

Table I. Permanent transect locations and descriptions for Anaktuvuk River Fire study. 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
BLM	Burned	B005	69.34	150.91	2C2H	161	90	0	90	MOIST
BLM	Burned	B013	69.17	150.82	2C2A	210	180	2	90	MOIST
BLM	Burned	B020	69.02	150.76	2C2A	322	360	3	90	MOIST
BLM	Burned	B027	69.05	150.59	3A2I	306	135	1	90	WET
BLM	Burned	B030	69.11	150.62	2C2A	255	FLAT	0	90	MOIST
BLM	Burned	B032	69.16	150.69	3A3	228	FLAT	0	90	WET
BLM	Burned	B037	69.27	150.75	3A2D	191	90	2	90	MOIST
BLM	Burned	B041	69.34	150.79	3A2D	166	FLAT	0	90	MOIST
BLM	Burned	B051	69.26	150.65	2C2A	205	FLAT	0	90	MOIST
BLM	Burned	B060	69.17	150.54	3A2H	217	90	3	90	MOIST
BLM	Burned	B063	69.13	150.44	2C2C	239	FLAT	0	90	DRY
BLM	Burned	B069	69.02	150.41	2C2A	342	218	6	90	MOIST
BLM	Burned	BKUP	69.30	150.32	2C2A	198	FLAT	0	90	MOIST
BLM	Burned	BARF	69.12	150.79	2C2A	206	FLAT	0	90	MOIST
UAF	Burned	B101	69.00	150.28	2C2A	359	252	1	344	DRY
UAF	Burned	B102	69.00	150.29	2C2H	335	356	6	344	DRY
UAF	Burned	B103	68.95	150.21	2C2A	403	12	4	202	DRY
UAF	Burned	B104	68.95	150.21	2C2A	412	8	4	104	DRY
UAF	Burned	B105	68.95	150.20	2C1B	399	274	11	5	RIPARIAN
UAF	Burned	B106	68.95	150.20	2C2A	402	280	11	4	MOIST
UAF	Burned	B107	68.95	150.20	2C2H	412	103	4	12	DRY
UAF	Burned	B111	69.00	150.31	2C2A	318	35	1	310	WET
UAF	Burned	B113	68.95	150.21	2C2A	400	198	2	96	DRY
UAF	Burned	B114	69.00	150.31	2C2A	325	40	1	320	MOIST
BLM	Unburned	U031	69.36	151.18	2C2H	162	245	2	90	DRY
BLM	Unburned	U043	69.04	150.04	3A2D	356	344	6	90	MOIST
BLM	Unburned	U053	69.31	150.49	2C2A	198	62	3	90	MOIST
BLM	Unburned	U071	69.18	150.45	2C2F	218	FLAT	0	90	MOIST
BLM	Unburned	U072	69.04	150.93	2C2A	284	270	2	90	MOIST
BLM	Unburned	U075	69.34	150.54	3A3	171	270	2	90	WET
BLM	Unburned	U611	69.24	150.50	2C2H	206	242	2	90	MOIST
BLM	Unburned	U622	69.13	150.34	2C2C	253	FLAT	0	90	MOIST
BLM	Unburned	U623	69.21	150.33	3A2D	217	30	2	90	MOIST
BLM	Unburned	UKUP	69.30	150.32	2C2A	198	FLAT	0	90	MOIST
BLM	Unburned	UARF	69.12	150.80	2C2A	206	FLAT	0	90	MOIST
UAF	Unburned	U108	68.95	150.21	2C2A	414	2	3	2	DRY
UAF	Unburned	U109	68.93	150.27	3A2D	435	264	2	23	DRY
UAF	Unburned	U110	68.94	150.27	2C1B	429	215	4	130	RIPARIAN
UAF	Unburned	U112	68.95	150.20	2C1B	394	104	10	6	RIPARIAN
UAF	Unburned	U115	69.00	150.31	2C1B	325	74	0	150	RIPARIAN
UAF	Unburned	U116	68.95	150.10	2C2A	401	11	4	132	DRY

Table II. pH data from ARF transects sampled in 2008 (n=23) or 2010 (n=35). All values were averaged using [H+] determined as 10^(-pH) then converted back to pH as (LOG10[H+])*-1.

Transect Name	Plot Type	Organic pH (mean)	Organic Mean [H+]	Mineral pH (mean)*	Mineral Mean [H+]*	Latitude (dd.dd)	Longitude (ddd.ddd)
B005	Burned	5.532	2.94E-06	4.702	1.99E-05	69.34	-150.908
B013	Burned	5.343	4.54E-06	4.488	3.25E-05	69.17	-150.820
B020	Burned	5.070	8.51E-06	4.181	6.6E-05	69.02	-150.755
B027	Burned			4.426	3.75E-05	69.05	-150.595
B030	Burned	4.405	3.94E-05	4.485	3.27E-05	69.11	-150.623
B032	Burned			5.233	5.85E-06	69.16	-150.689
B037	Burned	5.172	6.74E-06	4.968	1.08E-05	69.27	-150.753
B041	Burned	4.418	3.82E-05	4.660	2.19E-05	69.34	-150.791
B051	Burned	5.540	2.88E-06	4.687	2.05E-05	69.26	-150.648
B060	Burned	5.696	2.01E-06	4.934	1.16E-05	69.17	-150.538
B063	Burned	5.545	2.85E-06	4.472	3.37E-05	69.13	-150.445
B069	Burned	4.580	2.63E-05	3.864	0.000137	69.02	-150.412
B101	Burned	4.505	3.12E-05	4.585	2.6E-05	69.00	-150.283
B102	Burned	5.072	8.47E-06	4.893	1.28E-05	69.00	-150.292
B103	Burned	4.694	2.02E-05			68.95	-150.207
B104	Burned	4.845	1.43E-05	4.736	1.84E-05	68.95	-150.210
B105	Burned	4.896	1.27E-05	5.148	7.11E-06	68.95	-150.197
B106	Burned	4.587	2.59E-05	4.625	2.37E-05	68.95	-150.197
B107	Burned	4.513	3.07E-05	4.032	9.29E-05	68.95	-150.197
B111	Burned	4.362	4.35E-05			69.00	-150.307
B113	Burned	4.312	4.88E-05			68.95	-150.206
B114	Burned	4.462	3.45E-05			69.00	-150.307
BKUP	Burned	5.475	3.35E-06	4.666	2.16E-05	69.30	-150.323
BARF	Burned			4.619	2.41E-05	69.12	-150.792
U005	Unburned	6.350	4.47E-07	pH sample adjacent to B005 in unburned (n=1)			
U020	Unburned	4.599	2.52E-05	Sample at unburned CBI plot 20A by B020 (n=5)			
U031	Unburned	4.663	2.17E-05			69.36	-151.176
U043	Unburned	4.695	2.02E-05			69.04	-150.035
U053	Unburned	5.066	8.6E-06			69.31	-150.489
U071	Unburned	6.449	3.55E-07			69.18	-150.455
U075	Unburned	5.175	6.68E-06			69.34	-150.539
U108	Unburned	4.367	4.29E-05	4.923	1.19E-05	68.95	-150.208
U109	Unburned	4.410	3.89E-05			68.93	-150.273
U110	Unburned	4.211	6.16E-05			68.94	-150.269
U112	Unburned	5.249	5.64E-06			68.95	-150.198
U115	Unburned	5.646	2.26E-06			69.00	-150.308
U116	Unburned	4.420	3.81E-05			68.95	-150.096
U611	Unburned	5.261	5.48E-06			69.24	-150.504
U622	Unburned	4.886	1.3E-05			69.13	-150.340
UKUP	Unburned	4.846	1.42E-05	4.444	3.6E-05	69.30	-150.323
UARF	Unburned			4.784	1.64E-05	69.12	-150.796

*Data courtesy of Michelle Mack, University of Florida.

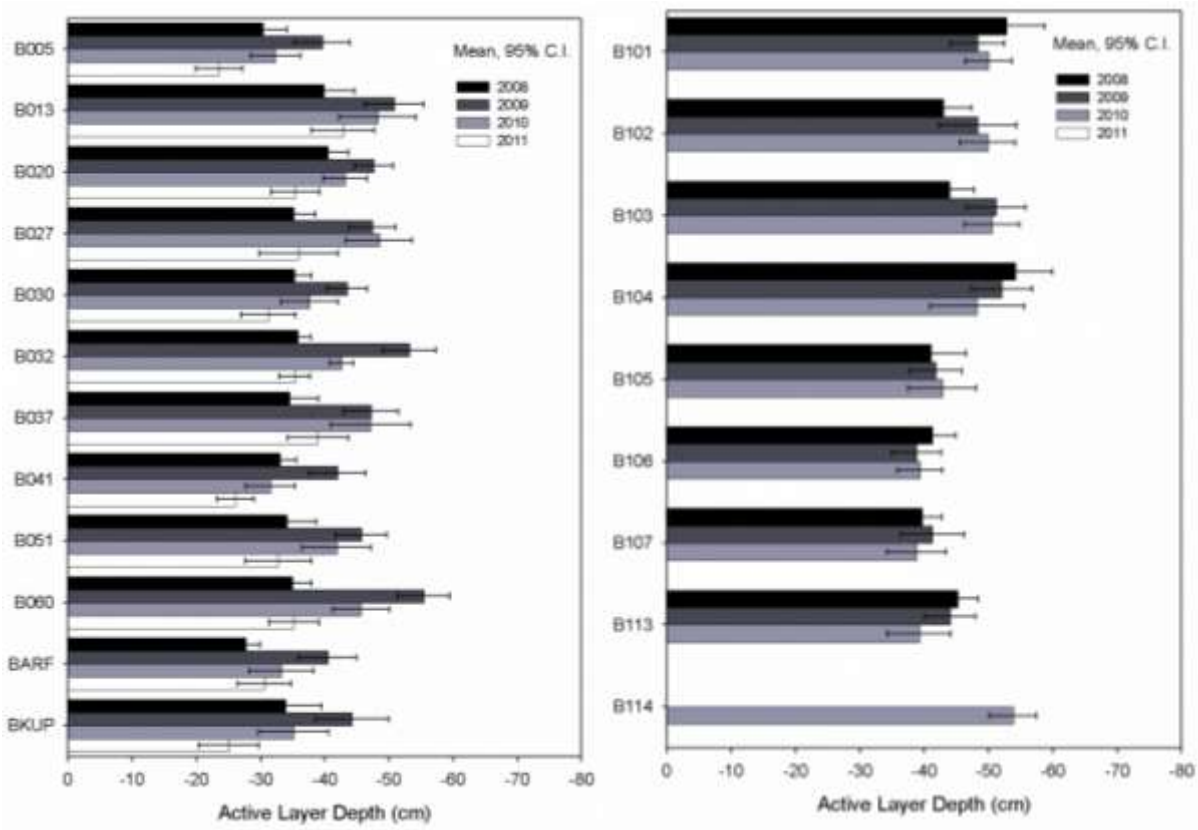

Figure D-1. Active layer measurements from burned transects, means with confidence interval (n=21).

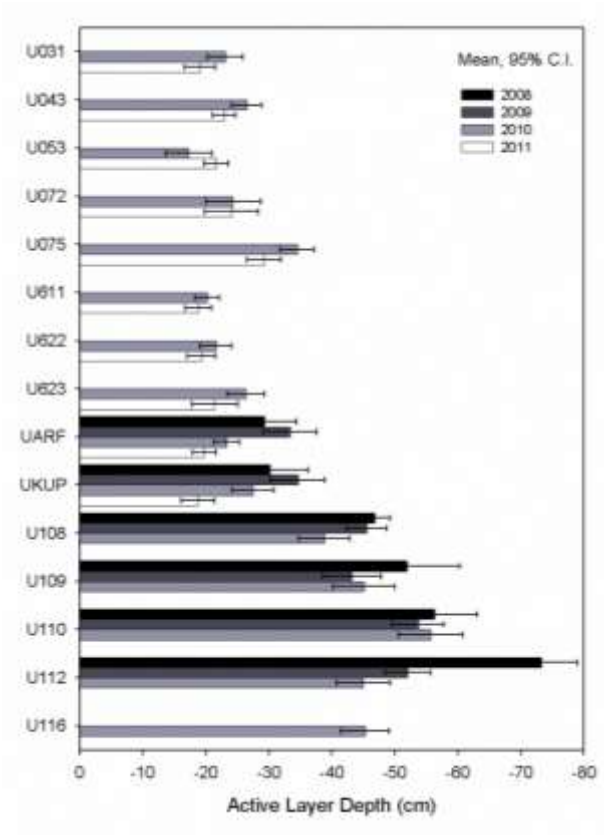

Figure D-2. Active layer measurements from unburned transects, means with confidence interval (n=15).

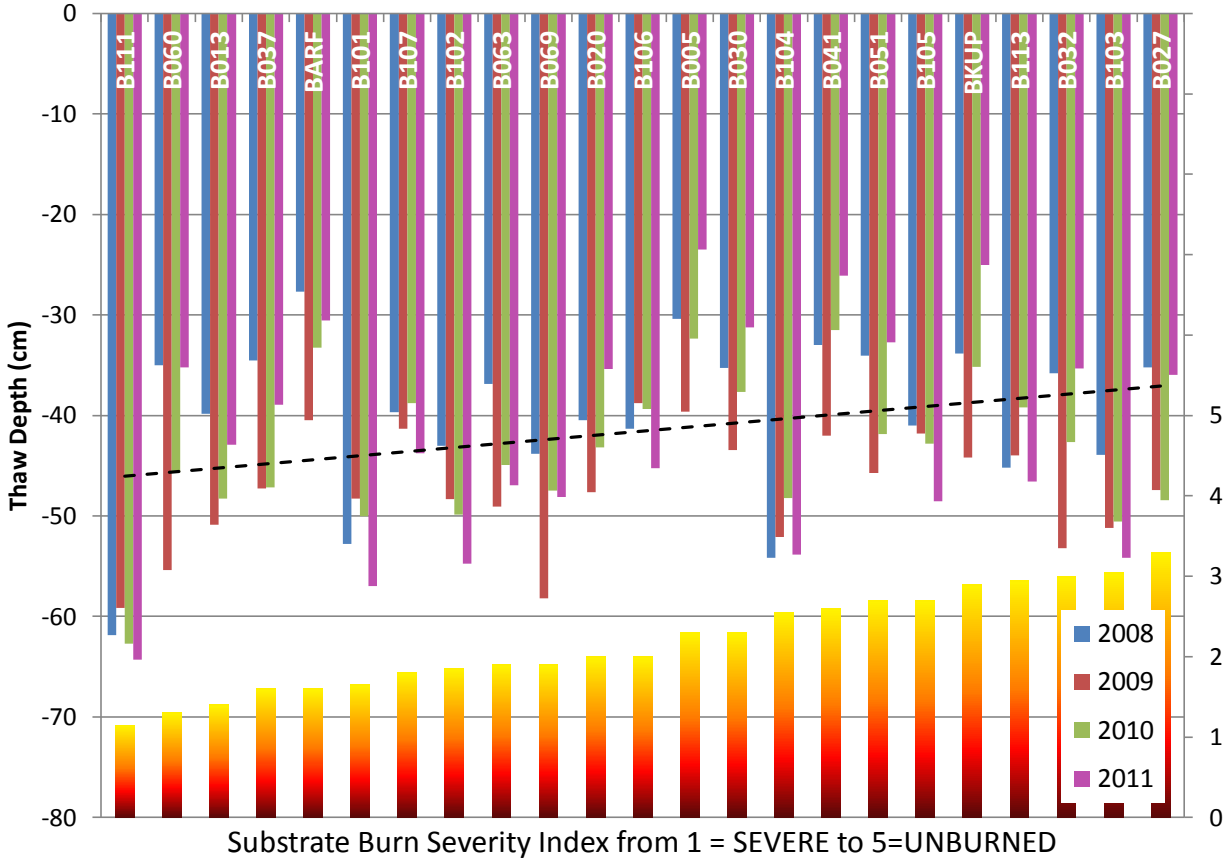

Figure D-3. Average active layer thaw depths by year (n=20 points/transect) for burned transects compared to average burn severity on substrate layer in quadrats (n=10 per transect). Trend line is for average thaw depth in 2011, which deepens with increased severity (highest severity has an index of 1) but not significantly.

Figure D-4. Severely burned quadrat (B060, 30m) in 2008.

Figure D-5. "Copper wire moss" and liverwort growing in dense mats on heavily burned soils in 2010, with dead tussock and grass/forbs.

Figure D-6. Heavy flowering of cottongrass on Transect B041, July 2010.

Figure D-7(a). Burned area on Transect B037, 5-m quadrat, in July 2008.

Figure D-7(b). Same B037 quadrat in July 2010, showing progress of vegetation, especially grass and shrub.

Figure D-7(c). Same B037 quadrat in July 2011, showing expansion of sedge and grass, especially *Calamagrostis inexpansa*.

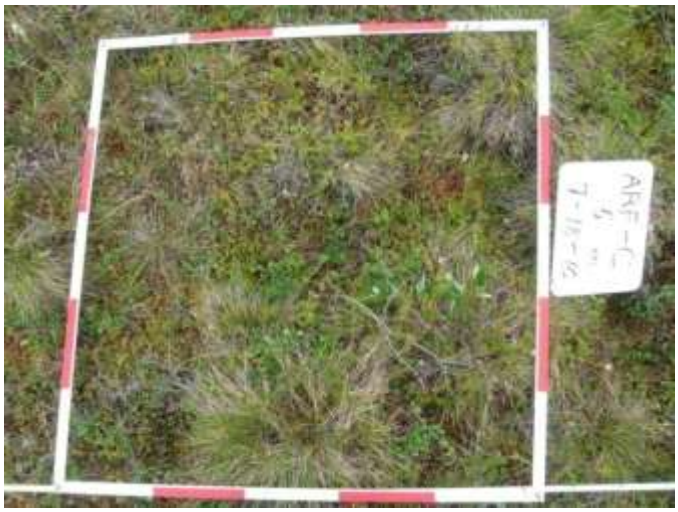

Figure D-8. Unburned reference transect (UARF) in shrub tussock tundra showing dominance of dwarf ericaceous shrubs and community complexity.

Figure D-9. Subsidence due to ice-rich soil melting on Transect BARF, 2010, looking east.

Figure D-10(a). Aerial view of one thermokarst area along the Nanushek River west-facing bluffs in 2011.

Figure D-10(b). Ground view of thermokarst area along the Nanushek River in 2011, showing slump and loss of soil.

D-11. Thermokarst area along Nanushek River, exposed ice wedge, 2011.

D-12. Silt outflow at the toe of a thermokarst (NAN2 photopoint looking 360°, 2011).

APPENDIX D. PHOTOGRAPHS FROM ANAKTUVUK RIVER FIRE STUDY 2008-2011

Cover photo: Active layer sampling in ARF burned area in 2011 (K. McNulty and E. Miller).