Vegetation shifts observed in arctic tundra 1.5 decades after fire

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ABSTRACT

With anticipated climate change, tundra fires are expected to occur more frequently in the future, but data on the longer term effects of fire on tundra vegetation composition are scarce. This study therefore addresses changes in vegetation structure that have persisted for 17 years after a tundra fire on the North Slope of Alaska. Fire-related shifts in vegetation composition were assessed from remote sensing imagery and ground observations of the burn scar and an adjacent control site. Early-season remotely sensed imagery from the burn scar exhibits a low vegetation index compared to the control site, while the late-season signal is slightly higher. The range and maximum vegetation index is greater in the burn scar, although the mean annual values do not differ among the sites. Ground observations revealed a greater abundance of graminoid species and an absence of *Betula nana* in the post-fire tundra sites, which is a likely explanation for the spectral differences observed in the remotely sensed imagery. Additional differences in vegetation composition in the burn scar include less moss cover and a greater cover of herbaceous species. The partial replacement of tundra by graminoid-dominated ecosystems has been predicted by the ALFRESCO model of disturbance, climate, and vegetation succession.

keywords: fire, tundra, North Slope, grass, NDVI, GIMMS, vegetation shift, succession

1.0 Introduction

The effects of wildfire on tundra vegetation are poorly understood due primarily to low fire return intervals and remote sampling locations. While areas such as the Seward Peninsula and Noatak region of Alaska experience burning once every few years, tundra fires in southwest Alaska and the North Slope are generally smaller and less frequent. In the near to intermediate future, however, climate warming trends (Serreze et al. 2000; ACIA 2004; Hinzman et al. 2005; McGuire et al. 2006) are likely to reduce vegetation and soil moisture levels and the resistance of tundra to wildfire occurrence. At the end of an uncommonly hot and dry summer in 2007, an anomalously large tundra fire was recorded on the North Slope (Jones et al. 2009) in an area that had not experienced fire for at least 5,000 years (Hu et al. 2010). Although tundra soils can store more carbon than is found in the aboveground biomass of tropical forests (Schuur et al. 2008), the impact of biomass burning and recovery in the tundra is poorly understood. The long term impacts of tundra fires remain an important question in the context of feedbacks between climate change and disturbance cycles.

In terms of aboveground biomass, tundra generally recovers from fire after only a few years (Wein and Bliss 1973, Racine et al. 1987, Vavrek et al. 1999), at least in terms of above ground biomass, becoming indistinguishable from unburned areas in moderate-scale remotely sensed imagery three to five years after a burn (Rocha and Shaver 2011a). However, other ecosystem components such as moss and lichens, as well as animals dependent on these slow-growing species such as caribou, and soil carbon recover on longer time scales (Racine et al. 2004, Jandt et al. 2008). The effect of fire on tundra plant communities and dominant plant functional types is usually to temporarily suppress plants that are unable to reproduce from vegetative material, while plants that are capable of re-sprouting such as *Salix spp.*, *Betula nana*, and *Eriophorum vaginatum* return within the following year. In addition to combustion of live biomass, combustion of the surface organic layer can be severe, exposing mineral soils in some areas. Generally the time needed to replace the carbon lost from the organic layer is not more than half a century, however (Mack et al. 2011).

Research on the impact of tundra fires on ecosystem functioning is hindered by the small area burned each year and by the remoteness of areas where the fires occur. In this analysis, we were able to visit a burn scar from a fire that burned in 1993 on the western North Slope of Alaska, about 50 miles southwest of Atqasuk (Figure 2, insert). The fire scars stand out in moderate-to-fine scale remotely sensed imagery because the scars are (1) fairly large (total area ≈ 400 km^2) and (2) quite distinct in their spectral signature, particularly with respect to reflected near infrared energy. We collected a limited amount of field data from the burn scar and an adjacent unburned area to compare with the spectral information to determine the impact of the fire on the long-term vegetation composition.

2.0 Materials and Methods

2. 1 Remotely sensed data

This study uses the Normalized Difference Vegetation Index (NDVI, Tucker 1979), a measure of vegetation ‘greenness’, derived from images collected by the Advanced Very High Resolution Radiometer (AVHRR) sensor. The data were collected daily at a 1.1 km spatial resolution, and were upscaled to an 8 km, bi-weekly composite to create the Global Inventory Modeling and Mapping Studies (GIMMS) dataset (Tucker et al. 2005).

The GIMMS data cover the period from 1981 to 2007, the longest time series of corrected global NDVI data. The long time-span of the data permitted 12 years of data to characterize the pre-burn vegetation, and 14 years of postburn data following the fire in 1993. Because NDVI changed rapidly for several years following the fire, we used only the last four years of data (2004-2007) to assess the mature post-fire vegetation index. We used 12 years of data from unburned vegetation (1996-2007) to compare with 2004-2007 data from the burned site.

The perimeter of the burned area came from the Alaska Large Fire Database (ALFD, Kasischke et al. 2002), maintained by the U.S. Bureau of Land Management. The perimeter of the burn scar was buffered to exclude edge pixels, which yielded 320 km^2 within the burned area used in the analysis. A control area of 384 km^2 was defined between the two burn scars to control for variations in NDVI not directly related to succession. The NDVI anomaly (burned site minus control site NDVI) was calculated for the entire growing season (May, June, July, and August) and for each month in the growing season individually, pre- and post-fire.

Landsat Thematic Mapper (TM) data were used to identify field locations within the burn and the control area (path:80 row:11 date: June 12, 2006. We chose an early season image to maximize the spectral differences between the burn and the control. The near infrared band (TM Band 4, 760 -900 nm) was most affected by the season difference, indicating the likelihood that vegetation composition was at least partly responsible for the changes observed in the burned area. An unsupervised classification of the study area was conducted to identify spectrally distinct areas in the imagery. We determined a number of possible sample locations in the burn sites and the control area that appeared from the imagery to be located in areas of patterned ground, exposed soils, green vegetation, and dead/non-photosynthetic vegetation.

2.2 Field data

In August of 2010, we visited areas spectrally distinct in the Landsat imagery and prioritized field locations that appeared homogeneous of the larger area from the aircraft. Areas that exhibited a low NDVI early in the growing season appeared to compose much of the burned area (Figure 1). Two burned areas and one control site were sampled for vegetation composition and thaw depth, with one transect per site for a total of three transects. One meter quadrats were located every 10 m along the 50 m transect of a random bearing. Within each quadrat, vegetation composition was recorded as percent cover (categories: *Eriophorum vaginatum*, other graminoids [i.e., other than *E. vaginatum*], *Betula nana*, *Salix spp.*, *Ledum palustre*, mosses [e.g., *Sphagnum spp.*, *Hylocomium splendens*], *Epilobium angustifolium*, other forbs [i.e., other than *E. angustifolium*], litter, *Vaccinium vitis-idaea*, and open ground). Additionally, the number of live and dead *E. vaginatum* tussocks was recorded within each quadrat as an indicator of fire severity (Racine, 2004). Thaw depth was recorded every 5 m along the transect.

3.0 RESULTS

The GIMMS maximum NDVI anomaly clearly indicates a reduction of surface greenness following the burn in 1993 (Figure 2). NDVI quickly recovered, reaching the range of pre-fire levels three years after the burn, with occasional spikes that were much higher. Post-fire growing season NDVI anomalies exhibit a greater range of values compared with pre-fire levels (Figure 3). After five years of recovery the burn, the maximum growing season NDVI anomaly was elevated in the burn scar although there was no difference in the average NDVI compared with pre-fire levels (Figures 2 and 3). The monthly NDVI anomalies exhibit intra-annual changes relative to pre-fire conditions. While there is considerable annual variation in post-fire monthly NDVI of mature vegetation, there was a general trend toward lower NDVI in June and higher levels in the burned site in July and August (Figure 3).

The ground cover of the burn sites was distinct from that of the control, which was composed primarily of *Salix*, leaf litter and, to a lesser extent, *E. vaginatum* and other graminoids (Figure 4). While *E. vaginatum*, *Salix spp*., and litter were major components of the burn site, moss and *B. nana* were considerably less abundant. In addition to grasses, ground cover that was found in the burn site but not the control includes *L. palustre*, forbs, fireweed, and open ground. The fraction of dead tussocks in the burned sites was around 0.5, about 12 times the level observed in the control site. Thaw depth in the burn sites averaged 43 cm, 37 cm in the control site.

Discussion

Comparison of the results of this analysis with a study of the long-term effects of wildfires in tundra vegetation on the Seward Peninsula (Racine et al. 2004) demonstrates some similarities in terms of shifts in vegetation composition. We limited this comparison to flat, lowland sites in the Seward Peninsula, which are topographically similar to conditions in the areas sampled in this analysis. Racine et al. found expansion of *E. vaginatum* in the lowland sites, but other graminoids did not increase significantly after the fire. Wein and Bliss (1973) found a similar increase in E. vaginatum as well as Calamagrostis canadensis in burned tussock tundra, and Fetcher et al. (1984) found that these increases persisted more than ten years after the burn. We did not observe a clear increase in evergreen shrubs or Salix spp. reported for the 1977 burn. Moss cover is similarly low in both burns, many years after the fire. Racine et al. note that moss recovery was slow in the 1977 burn. The rate of recovery cannot be reconstructed for this study, but appears to be slow given the amount of moss cover relative to the control site.

The changes in seasonal NDVI patterns indicate a likely link to phenological shifts related to vegetation composition. Field sampling revealed significant differences in vegetation composition that were most likely caused by the fire. The presence of graminoid species other than *E. vaginatum*, and the reduction of *B. nana* are two of the most important differences between the two sites. Plant phenology data from the Arctic Long Term Ecological Research station, located on the North Slope (149° 34' W, 68° 38' N) indicate divergent patterns in *B. nana* and graminoids commonly found on the North Slope (*E. vaginatum, Carex bigelowii, Carex microchaeta, and Hierochloe alpina*) (see Gough et al. 2007 for more detailed information). The data are from the 2004 growing season, over which the number of leaves (in the case of *B. nana*) or leaf length (in the case of graminoids were recorded weekly within a plot measuring 5 m by 20 m. We looked at two relative indicators of plant phenology based on these data, based on the ratio of the leaf length or number of leaves to the maximum amount for each 10 day period in the dataset (Figure 5).

The two graphs in figure 5 show the seasonal pattern in *B. nana* and graminoid leaves. The first measurement date was June 14 (Julian day 165), by which time many of the *B. nana* branches have already produced the maximum number of leaves. In contrast, the graminoid species do not reach the maximum until the end of June (around Julian day 180). It is possible that these differences in leaf exsertion (see Shaver and Laundre, 1997) are responsible for the differences seen in remotely sensed greenness inside the burn perimeter.

The physiology of graminoids and shrubs can explain the differences in phenology, and perhaps the spectral differences within the burned area. At the start of the growing season, before a new leaf can emerge, it must grow from the base to the top of the sheaths from the previous year. In the spring this means there is a period of time when the green vegetation is not visible. When the grass leaf is young it is usually oriented perpendicular to the ground, reflecting less solar radiation detected by remote sensing instruments. As the leaves age they become longer and heavier and therefore expose more area to be detected. The shrubs which are more dominant in the control site drop leaves from their branches at the end of the growing season, and therefore appear green as soon as the first new leaves begins to grow. *B. nana* and other shrubs are therefore likely to have a higher NDVI early in the season relative to *E. vaginatum* and other graminoids. The phenological trajectory of B. nana increases slightly in mid-July (around Julian day 200), whereas the mean graminoid leaf length has decreased by this time. This factor may be responsible for the convergence of NDVI anomalies in July (Figure 3, boxplot D).

While the mechanism behind the shift in the vegetation composition remains to be explored, it may be related to fire severity. The fire appears to have been severe from the increase in thaw depth and extreme degradation of ice wedges (Figure 6), changes associated with the removal of insulating surface organic materials. A more severe burn can facilitate colonization by new species when combustion of the pre-fire seedbed and plant propagules is high (Bernhardt et al. 2011). Fire frequency on the North Slope is very low making it unlikely that there will be a transition toward a graminoid-dominated ecosystems under the present fire regime. With the anticipated increase in temperature and decrease in moisture for the region, however, the vegetation succession model ALFRESCO has predicted at least a partial shift toward greater area of grassland in present-day Alaskan tundra (Rupp et al. 2000), an ecosystem type not seen on the landscape in the last 12,000 years (Hopkins et al. 1982). It is likely that, with an increase in fire activity and the conditions that contribute to increased fire severity, fire-related shifts in vegetation type will become more common.

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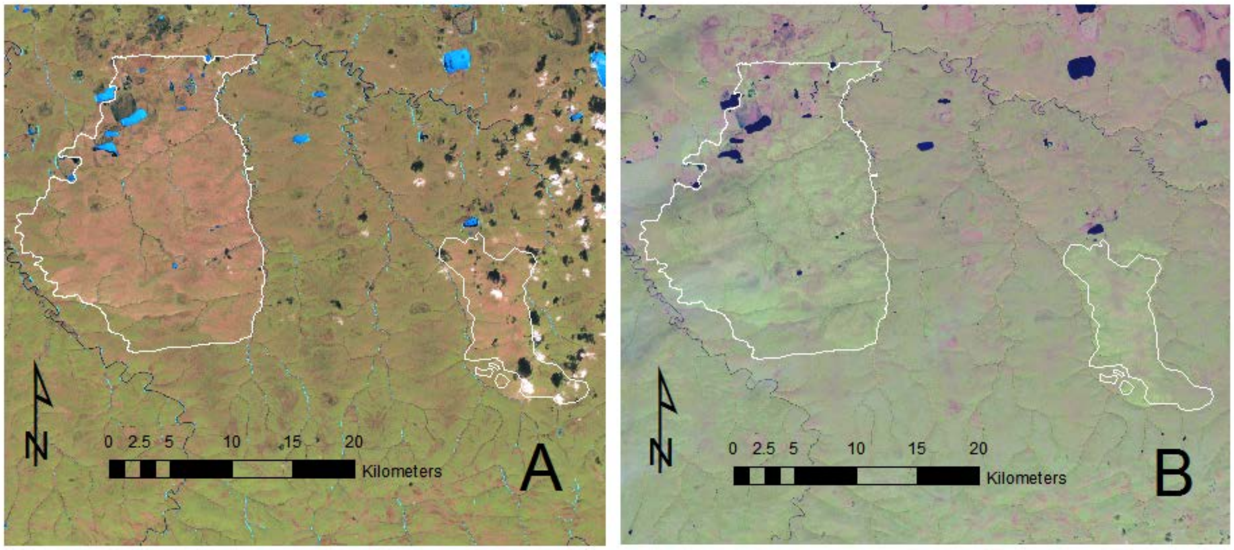

Figure 1. Landsat imagery of the burn scars (image composite, 543), showing (a) lower reflectance in the near-infrared early in the season (June 12, 2006) and (b) higher reflectance in the near-infrared late in the season (July 27, 2002). Note the area north of the eastern scar, which appears to be larger than the mapped perimeter.

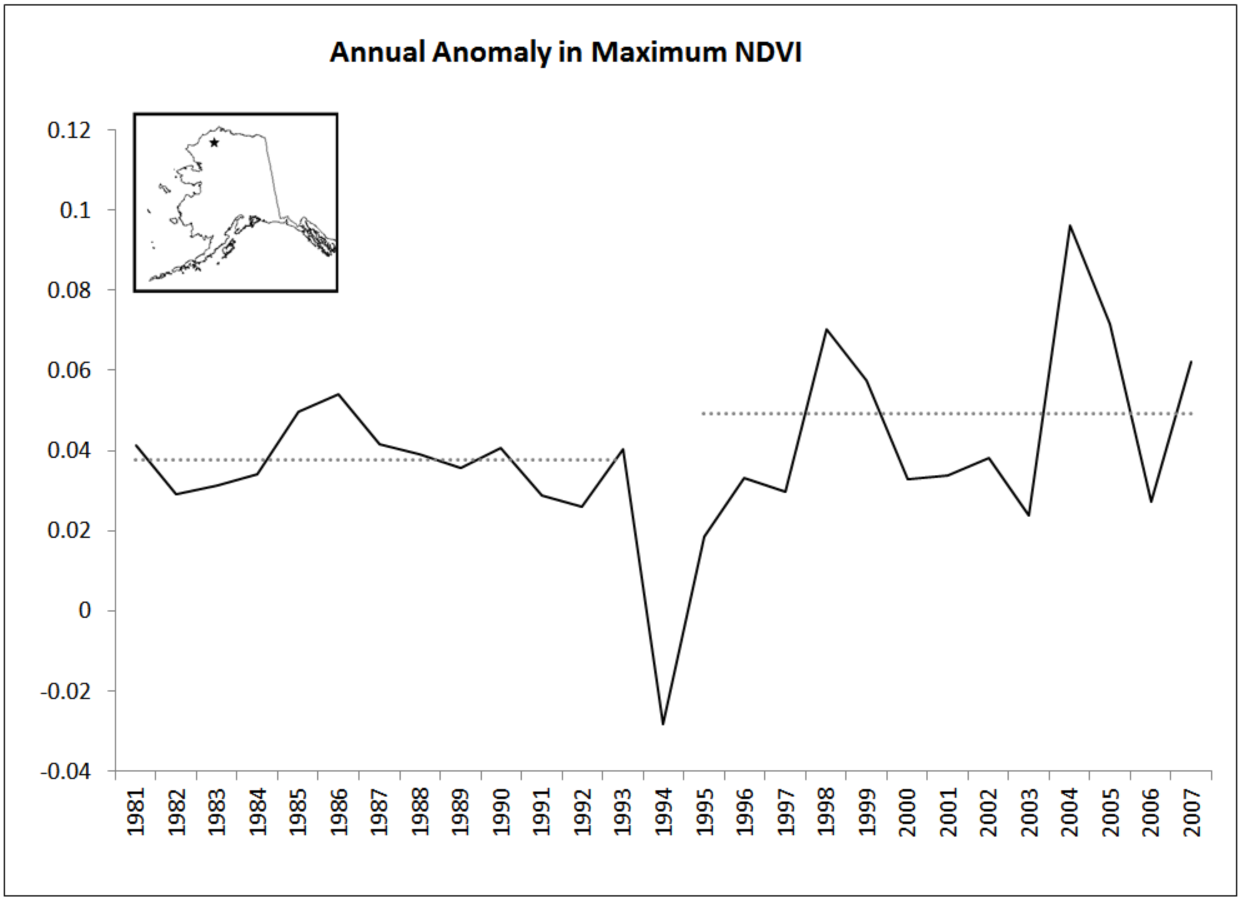

Figure 2. Annual anomaly (burn site minus control) in maximum NDVI. Dashed lines represent mean NDVI anomaly before and 5 years after the burn. Inset shows the location of the burn.

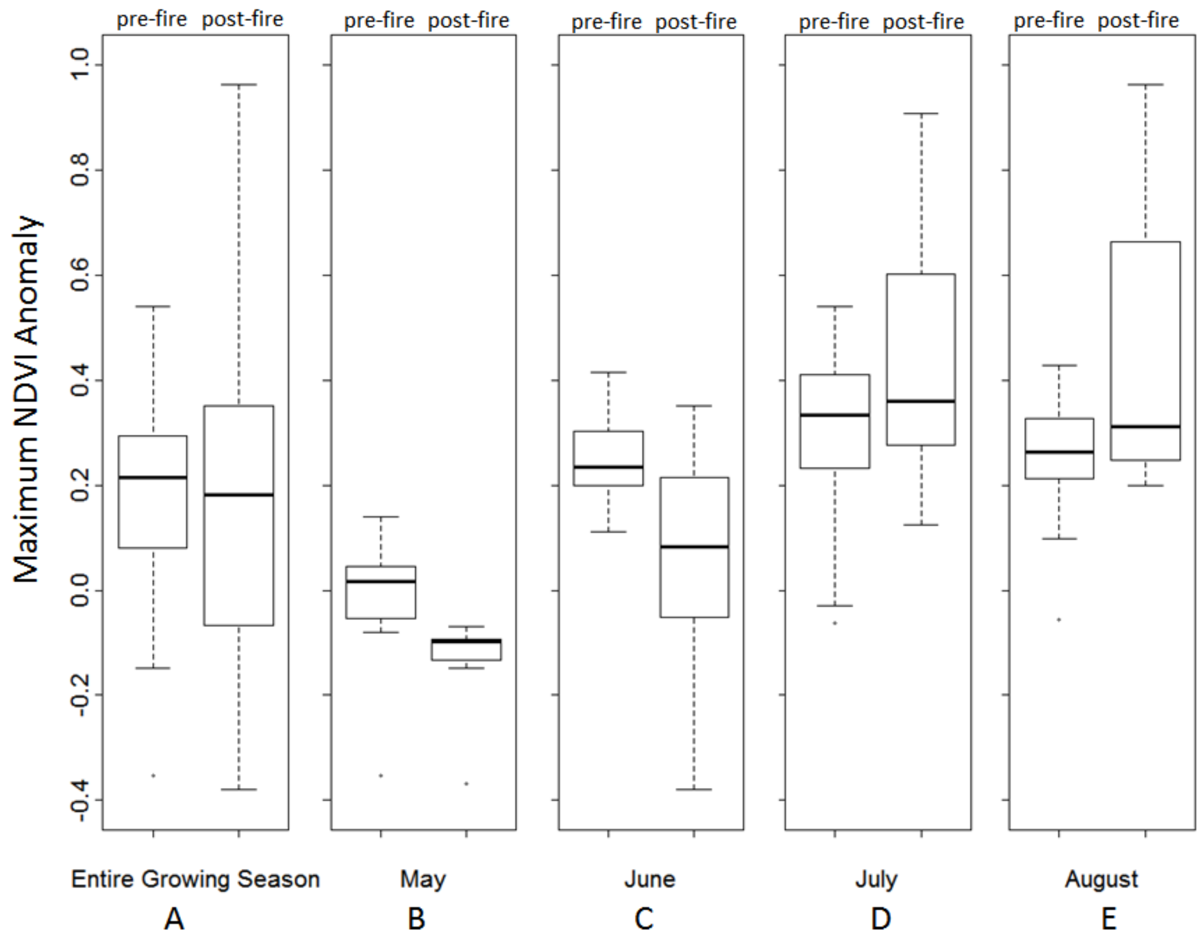

Figure 3. Boxplots showing the distribution of pre- and mature (five years) post-fire NDVI anomalies for the entire year (A), and monthly variation (B-E).

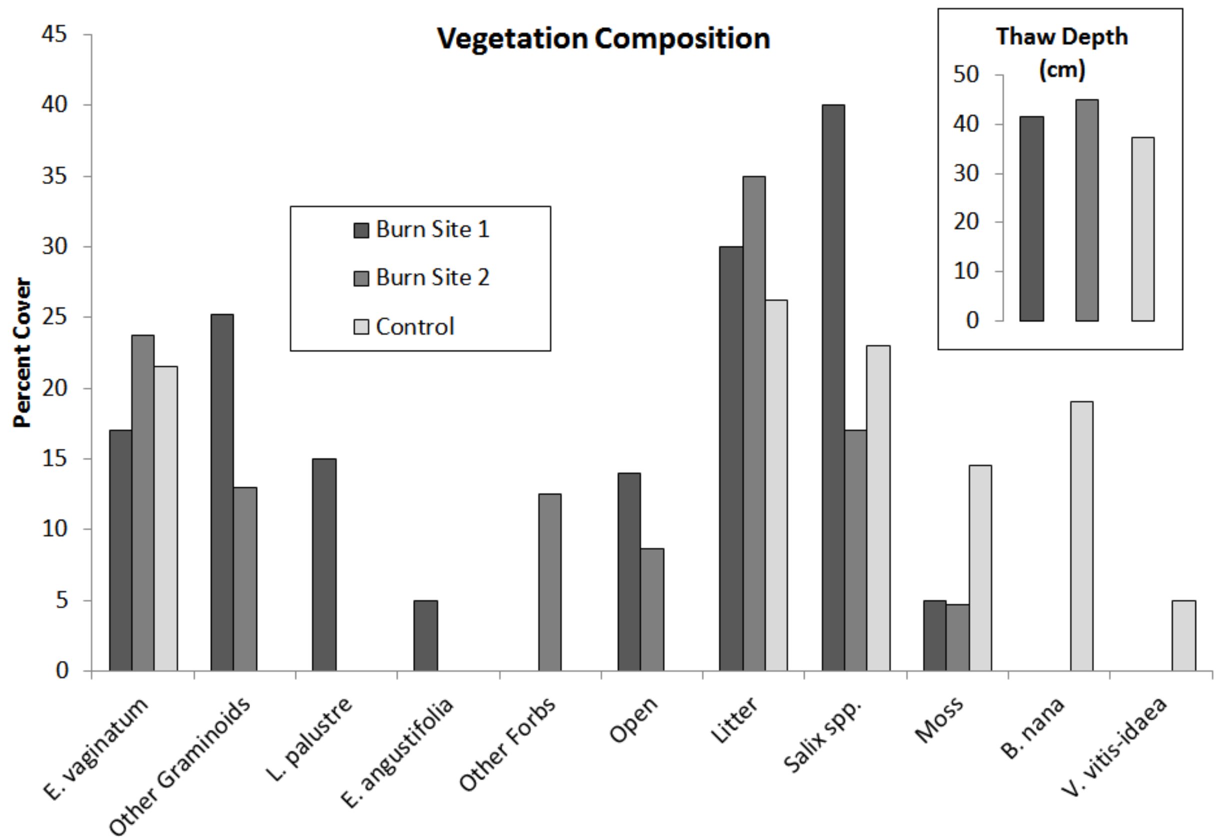

Figure 4. Average percent cover for each transect in the burn sites (dark grey) and the control site (light grey). Thaw depth shown in insert.

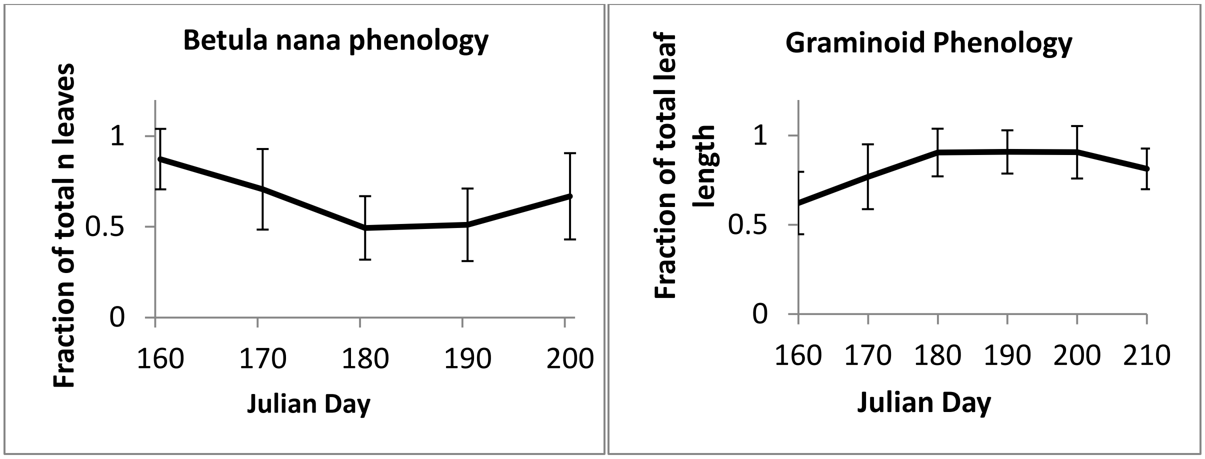

Figure 5. Differences in the phenological cycles of *B. nana* graminoid species commonly found on the North Slope (error bars represent 1 sigma). While *B. nana* typically has produced most of its maximum number of leaves by mid June (Julian day 160), the graminoids don’t reach peak leaf length until later in the season.

Figure 6. Photograph highlighting the degradation of ice wedges in the burned area (background), contrasted with the stable unburned area (foreground).