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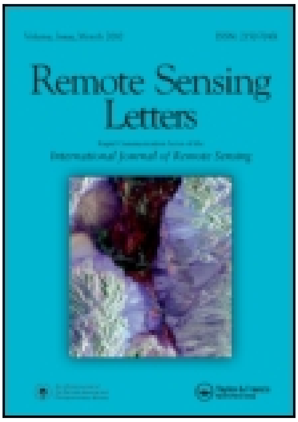

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Kirsten Barrett [a] , Adrian V. Rocha [b] , Martine Janet van de Weg [b] & Gaius Shaver [b]

[a] US Geological Survey, Alaska Science Center, Anchorage, AK, 99508, USA

[b] Marine Biological Laboratory, The Ecosystems Center, Woods Hole, MA, 02543, USA

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Vegetation shifts observed in arctic tundra 17 years after fire

KIRSTEN BARRETT*†, ADRIAN V. ROCHA‡,
MARTINE JANET VAN DE WEG‡ and GAIUS SHAVER‡
†US Geological Survey, Alaska Science Center, Anchorage, AK 99508, USA
‡Marine Biological Laboratory, The Ecosystems Center, Woods Hole, MA 02543, USA

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With anticipated climate change, tundra fires are expected to occur more frequently in the future, but data on the long-term effects of fire on tundra vegetation composition are scarce. This study 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 with the control site, whereas the late-season signal is slightly higher. The range and maximum vegetation index are greater in the burn scar, although the mean annual values do not differ among the sites. Ground observations revealed a greater abundance of moss in the unburned site, which may account for the high early growing season normalized difference vegetation index (NDVI) anomaly relative to the burn. The abundance of graminoid species and an absence of *Betula nana* in the post-fire tundra sites may also be responsible for the spectral differences observed in the remotely sensed imagery. The partial replacement of tundra by graminoid-dominated ecosystems has been predicted by the ALFRESCO model of disturbance, climate and vegetation succession.

1. Introduction

The effects of wildfire on tundra vegetation are poorly understood primarily due to low fire return intervals and remote sampling locations. Although areas such as the Seward Peninsula and Noatak region of Alaska experience burning once every few years, tundra fires in western Alaska and the North Slope are generally smaller and less frequent (Hu *et al.* 2010). However, in the near to intermediate future, global warming trends are likely to reduce vegetation and soil moisture levels and the resistance of tundra to wildfire (Serreze *et al.* 2000, ACIA 2004, Hinzman *et al.* 2005, Mcguire *et al.* 2006). At the end of an uncommonly hot and dry summer in 2007, an anomalously large tundra fire was recorded on the North Slope in an area that had not experienced fire for at least 5000 years (Jones *et al.* 2009, Hu *et al.* 2010). Tundra fires have profound effects on the surface and atmospheric carbon and energy exchange, with important implications for the entire arctic system (Mack *et al.* 2011, Rocha *et al*. 2011a). For example, the 2007 Anaktuvuk River fire resulted in a 2.1 Tg loss of carbon into the atmosphere, enough to offset the amount of C taken up by the entire

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*Corresponding author. Email: kbarrett@usgs.gov

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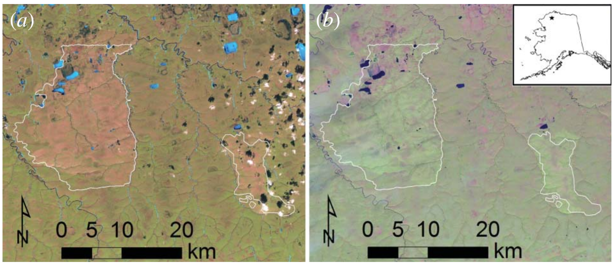

Figure 1. Landsat imagery of the burn scars (image composite, bands 543 as RGB) showing (*a*) lower top of atmosphere (TOA) reflectance in the near-infrared early in the season (12 June 2006) and (*b*) higher TOA reflectance in the near-infrared late in the season (27 July 2002). Note the area north of the eastern scar, where the burned area appears to extend beyond the mapped perimeter. Inset map shows the location of the study site in the state of Alaska.

biome (Mack *et al.* 2011). 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 above-ground biomass, tundra generally recovers from fire after only a few years (Wein and Bliss 1973, Racine *et al.* 1987, Vavrek *et al.* 1999), becoming indistinguishable from unburned areas in moderate-scale remotely sensed imagery 3–5 years after a burn (Rocha *et al*. 2011a). However, other ecosystem components such as moss and lichens, as well as animals such as caribou that are dependent on these slow-growing species, recover on longer time scales (Racine *et al.* 2004, Jandt *et al.* 2008). Unless the surface organic layer is entirely removed, the effect of fire on tundra plant communities and dominant plant functional types is a temporary suppression of 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* regrow 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. The largest losses of C by tundra fires are from the soil and may represent $>$50 years of net C accumulation (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. For 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 80 km south-west of Atqasuk (figure 1, inset). The fire scars stand out in moderate-to-fine scale remotely sensed imagery because the scars are (1) fairly large (total area $\approx$ 400 km^2) and (2) quite distinct in their spectral signature, particularly with respect to reflected near-infrared energy. We compared spectral data and field observations from the burn scar and an adjacent unburned area to determine the impact of the fire on the long-term vegetation composition and its spectral signature.

2. 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) data set (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 year data to characterize the pre-burn vegetation and 14 year post-burn data following the fire in 1993. Because NDVI changed rapidly for several years following the fire, we used only the last 4 year data (2004–2007) to assess the mature post-fire vegetation index. We used 12 year data from unburned vegetation (1996–2007) to compare with 2004–2007 data from the burned site.

The perimeter of the burned area was obtained from the Alaska Large Fire Database (ALFD; Kasischke *et al.* 2002), maintained by the US 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 pre- and post-fire NDVI anomalies (burned site minus control site NDVI) were calculated for the entire growing season (May, June, July and August) and individually for each month in the growing season.

Landsat Thematic Mapper (TM) data were used to identify field locations within the burn and the control area (path: 80, row: 11 and date: 12 June 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 seasonality, indicating the likelihood that differences in plant phenology were 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 burned 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 2010, we visited areas spectrally distinct in the Landsat imagery, and from the aircraft, we prioritized field locations that appeared homogeneous over a large area. Areas that exhibited a low NDVI early in the growing season covered 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-metre 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: *E. vaginatum*, other graminoids (i.e. other than *E. vaginatum*), *B. 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 *et al.* 2004). Thaw depth was recorded every 5 m along the transect.

3. 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 3 years after the burn, with occasional spikes that were much higher. Post-fire growing season NDVI anomalies exhibit a greater range of values compared

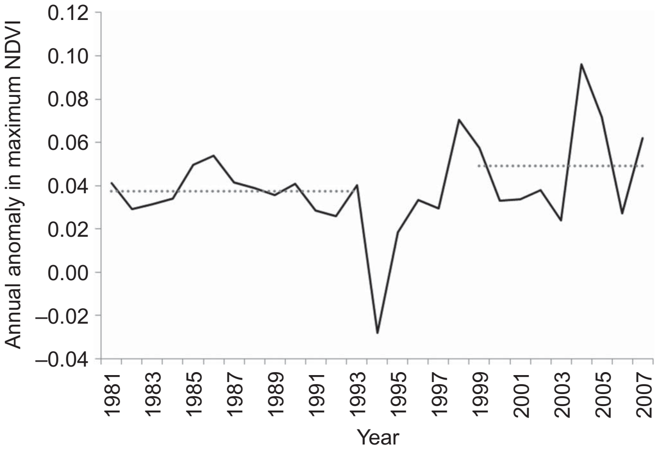

Figure 2. Annual anomaly (burned site minus control) in maximum NDVI. Dashed lines represent mean NDVI anomaly before and 5 years after the burn.

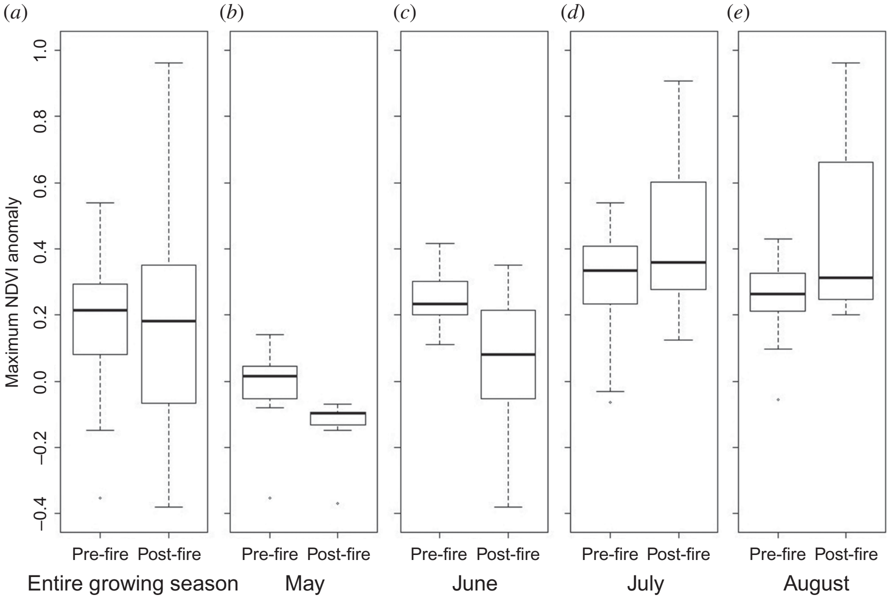

Figure 3. Box plots showing the distribution of pre- and mature (5 years) post-fire NDVI anomalies for the entire year (*a*) and monthly variation (*b*)–(*e*).

with pre-fire levels (figure 3). After 5 years of recovery, 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. Although there is considerable annual variation in post-fire monthly NDVI of mature vegetation, there was a general trend towards lower NDVI in June and higher levels in the burned site in July and August (figure 3).

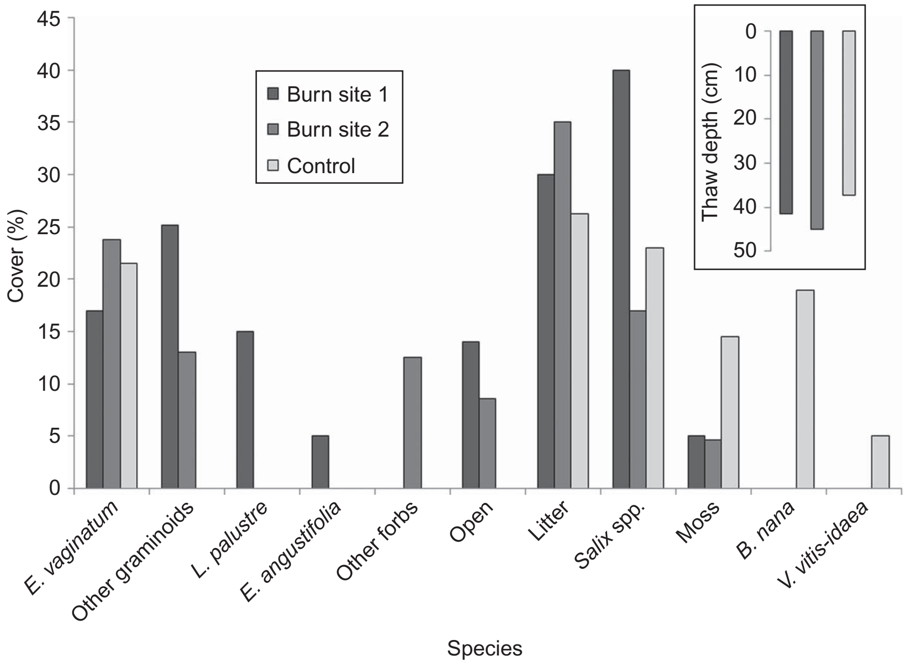

Figure 4. Average percent cover for each transect in the burned sites (dark grey) and the control site (light grey). Thaw depth shown in inset.

The burned sites were characterized by 86% and 91% ground cover, whereas the control site had 100% vegetation cover. The composition of the ground cover in the burned 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). Although *E. vaginatum*, *Salix* spp. and litter were major components of the burned site, moss and *B. nana* were considerably less abundant. In addition to grasses, ground cover that was found in the burned site but not the control includes *L. palustre*, forbs, fireweed and open ground. Tussock mortality was 0.43 in the burned sites and 0.03 in the control. The tussock mortality rate in the burned area is consistent with findings from more severely burned areas in the Anaktuvuk River Fire (Rocha *et al*. 2011b). Thaw depth was 43 cm at the burned sites and 37 cm at the control site.

4. 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 10 years after the burn. We did not observe a clear increase in evergreen shrubs or *Salix* spp. as reported for the 1977 burn. Moss cover is similarly low in the 1977 and 1993 burns, many years after the fire. The reduction in moss cover in the burn scar is notable given the role of mosses in buffering soil temperatures (Rocha *et al*. 2011b). Racine *et al.* (2004) note that moss recovery was slow in the 1977 burn. The rate of recovery cannot be reconstructed for the 1993 burn but appears to be slow given the amount of moss cover relative to the control site.

The changes in seasonal NDVI patterns in the 1993 burn indicate a likely link to differences in vegetation composition. Early in the growing season, the greater moss cover in the control site was likely responsible for the higher NDVI anomaly. At this time, the burned sites had a greater proportion of exposed soil and litter, which have a higher reflectance in the red band and lower reflectance in the near infrared band than photosynthetically active vegetation. Towards the middle of the growing season, the NDVI signals converge, indicating that as the leaf canopy develops, differences in ground cover contribute less to the signal. This factor may be responsible for the convergence of NDVI anomalies in July (figure 3(*d*)).

The different phenologies of graminoids and shrubs can explain the differences in community phenology (Chapin and Shaver 1996, Shaver and Laundre 1997, Boelman *et al.* 2011) 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 or is partially obscured. In the burned areas, we saw a greater volume of litter (unpublished data), through which graminoid leaves must grow in order to be detected by a remote-sensing instrument. The shrubs, which are more dominant in the control site, drop their leaves at the end of the growing season and, therefore, appear green as soon as the first new leaves begin 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.

Although 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 as indicated by tussock mortality and changes associated with the removal of insulating surface organic materials such as the increase in thaw depth and extreme degradation of ice wedges (figure 5). 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.*

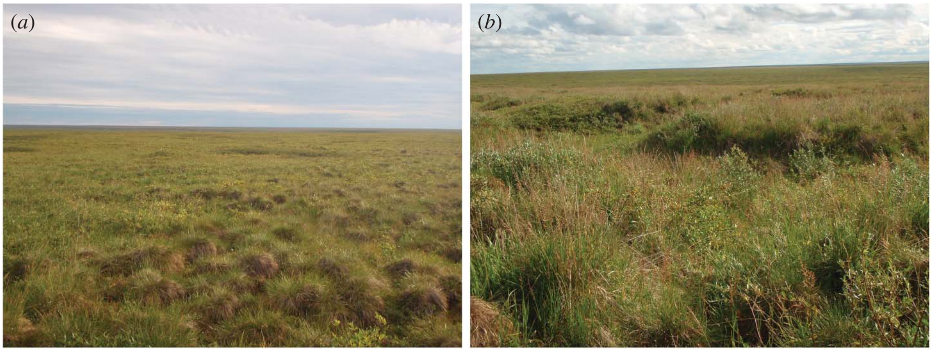

Figure 5. Photographs contrasting the stable unburned area (*a*, image date: 14 August 2010) with the deformation caused by degradation of ice wedges in the burned area (*b*, image date: 13 August 2010). Note the differences in vegetation composition and biomass.

2011). 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 towards 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.

Acknowledgements

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