Arctic tundra fires: natural variability and responses to climate change

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Anthropogenic climate change may result in novel disturbances to Arctic tundra ecosystems. Understanding the natural variability of tundra-fire regimes and their linkages to climate is essential in evaluating whether tundra burning has increased in recent years. Historical observations and charcoal records from lake sediments reveal a wide range of fire regimes in Arctic tundra, with fire-return intervals varying from decades to millennia. Analysis of historical data shows strong climate–fire relationships, with threshold effects of summer temperature and precipitation. Projections based on 21st-century climate scenarios suggest that annual area burned will approximately double in Alaskan tundra by the end of the century. Fires can release ancient carbon from tundra ecosystems and catalyze other biogeochemical and biophysical changes, with local to global consequences. Given the increased likelihood of tundra burning in coming decades, land managers and policy makers need to consider the ecological and socioeconomic impacts of fire in the Far North.

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After surveying scientists working in the Far North for tundra-fire observations and examining Canadian Government fire records, pioneer Arctic ecologist Ross Wein concluded that "tundra fires occurred infrequently, and were invariably small in areal extent... Little is known about the ecological significance of tundra fires" (Wein 1976). Modern satellite data have greatly enhanced scientists' ability to detect tundra fires in remote high-latitude regions, but Wein's conclusion holds for the biome as a whole: only 0.12% of vegetated circumpolar Arctic tundra has burned over the past decade (Figure 1a). Thus, the tundra biome is historically characterized by a general lack of burning, reflecting its location in one of the coldest environments on Earth (Figure 1, a and b) and its limited biomass.

In a nutshell:

- Anthropogenic climate change in the Arctic will increase tundra fires, with far-reaching ecological and socioeconomic implications
- Historical observations and paleorecords reveal a wide range of fire frequencies in tundra ecosystems, suggesting that tundra can sustain frequent burns under particular climate and fuel conditions
- Annual variability in tundra burning is primarily determined by summer temperature and precipitation, with threshold effects
- Tundra fires alter ecosystem processes and may release ancient soil carbon to the atmosphere, but their long-term consequences remain unclear
- Tundra-fire management should take into account trade-offs among preserving fire's ecological roles, protecting resources, and maximizing tundra's carbon-storage capacity as an ecosystem service

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Against this historical backdrop, the frequency of tundra fires in recent years in some areas of the Arctic has been unexpectedly high. For example, during the summer of 2010, ~40 fires occurred in tundra ecosystems of the Noatak River Watershed in northwestern Alaska (AICC 2014) – a record-setting annual number for this area. Furthermore, tundra fires may have increased over time in terms of size and biomass consumed. On the North Slope of Alaska, where fires have been extremely rare over the past 10 000 years (Hu *et al.* 2010; Chipman *et al.* 2015), the Anaktuvuk River Fire (AR Fire) occurred in 2007, at a time when the region was unusually warm and dry (Jones *et al.* 2009; Hu *et al.* 2010). This single fire burned a 1039-km^2 area, more than doubling the total area burned during the previous 60 years in the region. These recent fires suggest that the future disturbance regime of tundra ecosystems will differ greatly from that of today if the trend of Arctic climate warming (Kaufman *et al.* 2009) continues, with far-reaching ecological and socioeconomic consequences (Mack *et al.* 2011; Joly *et al.* 2012).

Are these recent tundra fires unprecedented or part of the natural fire cycle? How is tundra-fire occurrence related to climate conditions? What are some of the ecological and ecosystem-management implications of tundra burning? Recent fire events in tundra ecosystems have motivated scientists to address these questions (eg Hu *et al.* 2010; Mack *et al.* 2011; Rocha and Shaver 2011a; Bret-Harte *et al.* 2013). This paper highlights some of the new findings about tundra-fire regimes – focusing on Alaska, where tundra-fire research efforts have accelerated. We aim to (1) provide a long-term context for recent tundra burning using historical and paleofire records; (2) elucidate how the spatial extent of tundra fires is related to climatic variability over the past 60 years, and apply these relationships to estimate tundra burning in the 21st century; (3) describe the impacts of tundra fires on biogeochemical and biophysical processes; and (4) discuss the management implications of tundra fires in the Arctic.

Highly variable fire regimes in tundra ecosystems

Circumpolar tundra fires have primarily occurred in the portions of the Arctic with warmer summer conditions, especially Alaska and northeastern Siberia (Figure 1). Satellite-based estimates (Giglio *et al.* 2010; Global Fire Emissions Database 2015) show that for the period of 2002–2013, 0.48% of the Alaskan tundra has burned, which is four times the estimate for the Arctic as a whole (0.12%; Figure 1). These estimates encompass tundra ecoregions with a wide range of fire regimes. For instance, within Alaska, the observational record of the past 60 years indicates that only 1.4% of the North Slope ecoregion has burned (Rocha *et al.* 2012); 68% of the total burned area in this ecoregion was associated with a single event, the 2007 AR Fire (Jones *et al.* 2009). This rate of burning corresponds to an estimated fire rotation period (also termed the "fire cycle") of 4400 years (Rocha *et al.* 2012). During the same period, 14% of the tundra has burned in both the Noatak and Seward Peninsula ecoregions, corresponding to fire rotation periods of ~420 years (Rocha *et al.* 2012). These latter ecoregions are the most flammable of the tundra biome, and both contain areas that have experienced multiple fires within the past 60 years (Rocha *et al.* 2012). This high level of fire activity suggests that fuel availability has not been a major limiting factor for fire occurrence in some tundra regions, probably because of the rapid post-fire recovery of tundra vegetation (Racine *et al.* 1987; Bret-Harte *et al.* 2013) and the abundance of peaty soils.

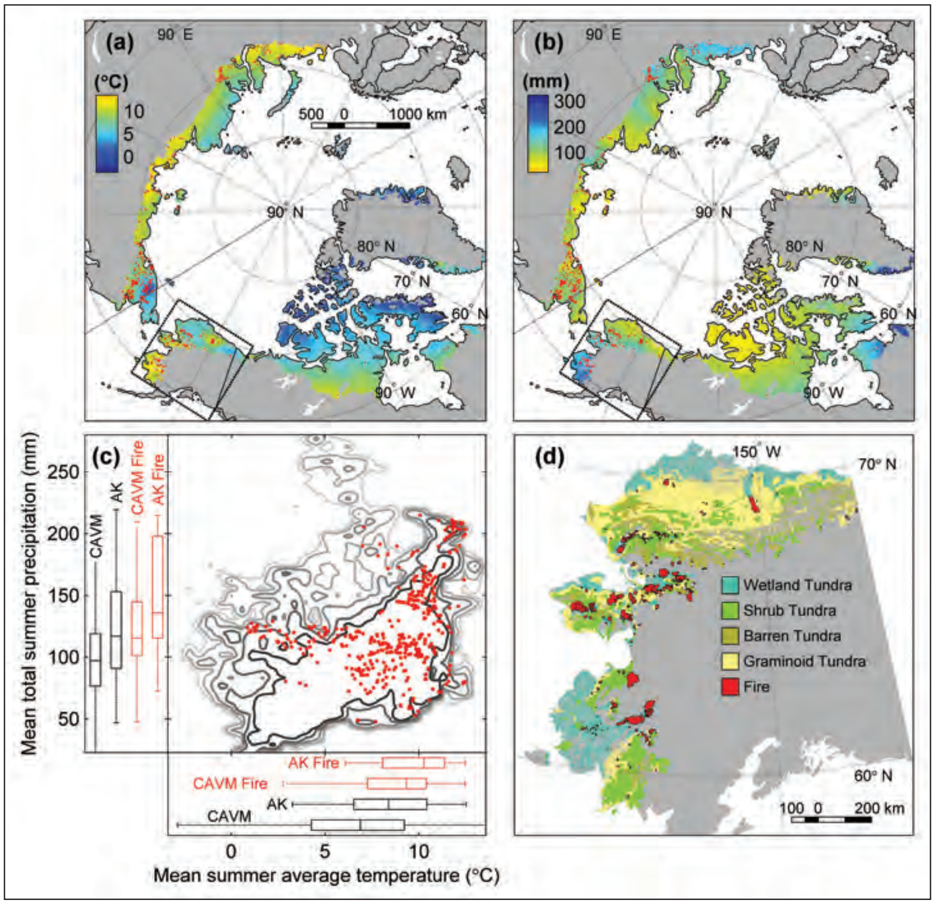


Figure 1. *Fire and climate in circumpolar Arctic tundra (CAVM Team 2003; Walker* et al. *2005; Harris* et al. *2014). (a) Mean summer average temperature and (b) mean total summer precipitation (both 2000–2012 CE); (c) climate space (ie range of temperature and precipitation) occupied by circumpolar Arctic and Alaskan tundra, and fire occurrence. Lighter (darker) contour lines depict infrequently (frequently) occurring climate space for Arctic tundra; (d) spatial distribution of Alaskan tundra fires from 1950–2013 CE (AICC 2014). Red points in panels (a), (b), and (c) represent pixels with nonzero burned-area estimates between 2002 and 2013 by the MCD64A1burned-area-data product, taken from the GFED4 dataset.*

Charcoal analysis of lake-sediment cores provides reliable information on tundra-fire regime variability spanning thousands of years (Hu *et al.* 2010; Higuera *et al.* 2011a). Consistent with observations from the past 60 years, charcoal data from Alaska show that the frequency of wildfires has varied greatly across space and time (Figure 2). Within the extent of the AR Fire, no fire occurred in the previous 6500 years (Chipman *et al.* 2015). This extreme rarity of tundra burning is supported by data from other sites; at Tungak Lake in southwestern Alaska, only five fires occurred in the past 35 000 years (Chipman *et al.* 2015). In stark contrast, in the Noatak ecoregion tundra fires have occurred regularly, with mean fire-return intervals (the time interval between individual fire events) at four lakes ranging from 135 to 309 years over the past 2000 years (Higuera *et al.* 2011a). Similarly, the late-glacial (14 000–10 000 years ago) tundra in north-central Alaska burned at frequencies close to those of the modern boreal forests, with mean return intervals of 140–150 years (Higuera *et al.* 2008). A notable feature that has emerged from the accumulating paleofire records is that the broad spatial patterns of tundra fires observed in recent decades have been in place for thousands of years (Chipman *et al.* 2015).

Factors driving the spatiotemporal variation in paleofire occurrence are difficult to decipher. Despite their abundance, paleoclimate records from Alaska fail to provide temperature and precipitation information at spatial and temporal resolutions adequate for interpreting the climatic drivers of paleofires. However, the wide range of tundra-fire regimes in the modern record results from spatial variations in climate and fuel conditions among ecoregions. For example, frequent tundra burning in the Noatak ecoregion reflects relatively warm/dry climate conditions, whereas the extreme rarity of tundra fires in southwestern Alaska reflects a wet regional climate and abundant lakes that act as natural firebreaks. Although fuels may not have been the main limitation leading to rare tundra fires in the observational record of the past several decades, vegetation change seems to have played an important role in tundra burning preserved in the paleorecord. In particular, the late-glacial shift from herb to shrub tundra and an associated increase in biomass coincided with a marked increase in the frequency of tundra fires (Higuera *et al.* 2008).

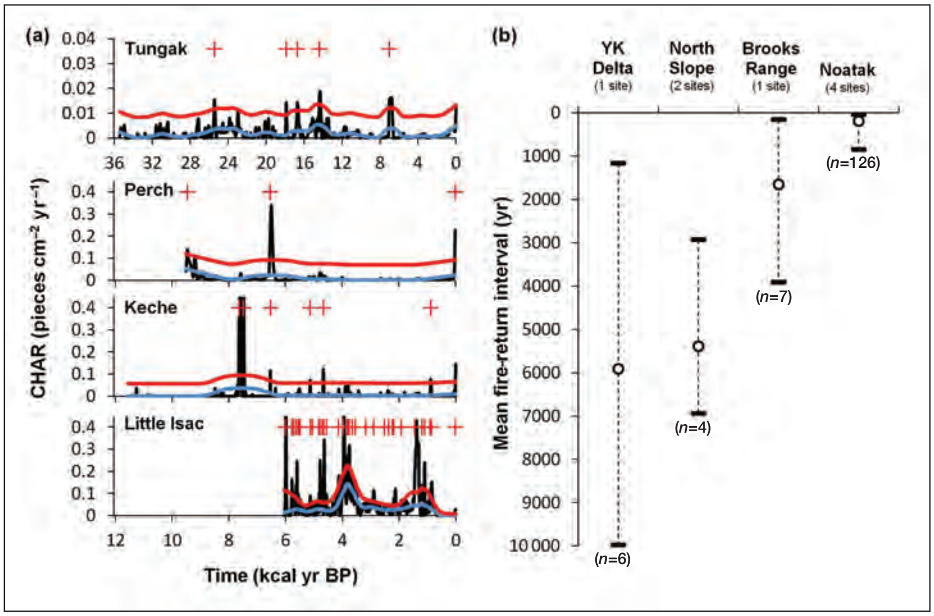


Figure 2. *Paleofire records from Alaskan tundra. (a) Charcoal accumulation rates (CHAR; black lines), background CHAR (blue lines), thresholds for peak detection (red lines), and fire events (red "+") in lake-sediment records from four ecoregions: Tungak (Yukon–Kuskokwim [YK] Delta), Perch (North Slope), Keche (Brooks Range), and Little Isac (Noatak River Valley); (b) minimum, maximum, and mean fire-return intervals calculated from data in (a), plus other paleofire records, over the past ~35 500 (YK Delta), 11 500 (North Slope), 12 100 (Brooks Range), and 6000 (Noatak River Watershed) years. All data are from Chipman* et al. *(2015) except for the data for Noatak (Higuera* et al. *2011b). kcal yr BP = thousand calibrated ^{14}C years before the present.*

Taken together, the historical and paleofire data show unambiguously that Arctic tundra can sustain an extremely wide range of fire regimes, with individual fire-return intervals spanning several orders of magnitude. These data imply that this historically non-flammable biome could become highly flammable if climate limitations to fire occurrence are reduced. Historical observations of tundra fires reveal that tundra burning has increased in northern Alaska and decreased farther south over the past few decades (Rocha *et al.* 2012). No unambiguous evidence exists to demonstrate that fire frequencies were higher in the past 60 years as compared with fire frequencies during the late Quaternary; tundra-fire frequencies overlap statistically between those two periods for each of the ecoregions where charcoal records have been obtained for paleofire reconstruction (Chipman *et al.* 2015). Nonetheless, some tundra ecoregions have not experienced burning for several centuries or even millennia (Chipman *et al.* 2015). In that context, increased fire frequency in Arctic tundra as a result of anthropogenic climate change can be considered a novel disturbance that may greatly alter the structure and function of these ecosystems.

Climatic controls of tundra burning: threshold effects and future estimates

Statistical analysis of historical data reveals strong climate–fire linkages in tundra regions. A generalized boosting model based on average temperature and total precipitation in June–August (SNAP 2014) alone explains ~90% of the variance in annual area burned from 1950–2009 in Alaska, with apparent thresholds at ~11°C and ~150 mm (Figure 3). Below the temperature threshold and above the precipitation threshold, climate variability has minimal effects on tundra burning. Yet if these thresholds are crossed, the extent of tundra burning increases markedly (ie exhibiting what we term a "threshold effect"), as was the case in 2007, when exceptionally warm and dry conditions facilitated the AR Fire (Hu *et al.* 2010).

Climate warming during the 21st century is anticipated to be more pronounced in the Arctic than in other regions. Climate projections (IPCC 2013; SNAP 2014) based on five global climate models most representative of Alaska (Walsh *et al.* 2008) and driven by the AR5 RCP 6.0 exhibit rising mean summer temperatures (WebFigure 1), which will favor tundra-fire occurrence. This effect may be offset by the projected increase in total summer precipitation (WebFigure 1). However, the pro-

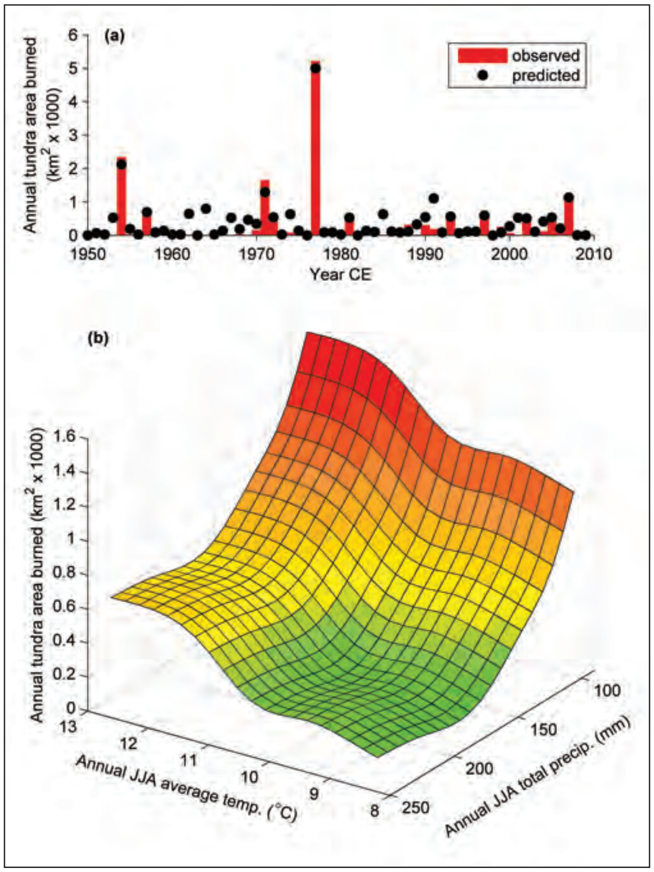


Figure 3. *(a) Observed and predicted annual tundra area burned and (b) smoothed response surface summarizing fire–climate relationships in Alaskan tundra. Small changes in the response surface reflect the variability of tundra-area-burned estimates across the climate space. Methods are identical to those described in Hu* et al. *(2010), with the exception that here we use (1) an updated fire dataset from the Alaska Fire Service (http://afs.ak.blm.gov/afs.php) and (2) a tundra vegetation map that excludes water bodies and barrens by overlaying the North American Land Change Monitoring System map (http://landcover.usgs.gov/nalcms.php) with the Circumpolar Arctic Vegetation Map (Walker* et al. *2005). JJA = June, July, and August.*

jected increase in precipitation is less pronounced than the projected increase in temperature, and several climate scenarios indicate that interannual variability in precipitation will rise. Thus, warm and dry conditions may coincide more frequently, leading to a greater likelihood of tundra burning.

We use future climate scenarios to estimate the annual area of tundra burning in Alaska for coming decades (Figure 4), based on historical climate–fire relationships (Figure 3). The climate scenarios are the downscaled projections (SNAP 2014) from the five different global climate models driven by the AR5 RCP 6.0, mentioned above (IPCC 2013). Each projection of tundra area burned displays high interannual variability, similar to that in the historical record of 1950–2009, with substantial differences among the scenarios. Yet the collective result is an elevated mean area of tundra burned annually. Whereas the average annual area burned from 1950–2009 was 270 km^2, the projected value for the 21st century ranges from 500–610 km^2 (Figure 4a). Thus, the consensus among the models is that the rate of tundra burning will approximately double in Alaska. In addition, the frequency of "large" tundra-fire seasons (defined as those in which the annual area burned exceeds 1000 km^2 across Alaskan tundra) will also increase; the annual probability of a large fire season was 6.7% over the past 60 years but is projected to increase to 13–23% in the remaining decades of the 21st century (Figure 4b).

These future fire estimates must be interpreted with caution for a number of reasons. Climate variability associated with large-scale ocean circulation patterns, such as the El Niño–Southern Oscillation and the Pacific Decadal Oscillation, played an important role in driving historical variability in boreal forest fire regimes (Hess *et al.* 2001; Duffy *et al.* 2005). Such variability will likely affect tundra burning at multi-annual to decadal scales, but is inadequately represented in the 21st-century climate scenarios that drive our future tundra-fire estimates (Ault *et al.* 2012). As a result, the variability in our tundra-fire projections is probably underestimated, adding uncertainty to our comparison of the rates of tundra burning between the 21st century and the historical record. In addition, the use of historical climate–fire relationships to estimate future area burned may not be appropriate because future climate is anticipated to exceed the historical domain (WebFigure 2; Williams *et al.* 2007). Furthermore, the spatial pattern of tundra burning will likely be highly variable because of spatial variability in climate and the stochastic nature of fire ignition.

In the analysis, we grouped all tundra vegetation types into one category because climate exerts the primary control on tundra burning, and thus large-scale patterns are generally consistent among different tundra types (eg Hu *et al.* 2010). However, at smaller scales, the historical record of the past 60 years from Alaska reveals that tundra burning has been biased toward certain vegetation types (Rocha *et al.* 2012). Graminoid (grassy) tussock tundra makes up 42% of the Alaskan tundra but accounts for 55% of the tundra burned. Within shrub tundra types, erect dwarf shrub burns significantly more and low shrub tundra significantly less than expected by chance. Isolating the independent impact of vegetation on tundra burning is difficult, because the warmer regions where tundra burning tends to occur also support more productive tundra vegetation types (Walker *et al.* 2005), which provide more biomass to fuel fires.

Ecosystem consequences of tundra burning

Fire alters the surface properties, energy balance, and carbon (C) storage of many terrestrial ecosystems. These effects are particularly marked in Arctic tundra (Figure 5), where fires can catalyze biogeochemical and energetic processes that have historically been limited by low temperatures. The cold environment and permafrost soils impede microbial degradation of plant litter in the Arctic, resulting in abundant soil organic matter, which represents a C pool twice as large as that of the atmosphere (Zimov *et al.* 2006). Tundra fires can remove ≥30% of organic soils by depth (Liljedahl *et al.* 2007; Mack *et al.* 2011) and release large amounts of C from tundra ecosystems into the atmosphere. Mack *et al.* (2011) estimated that the AR Fire resulted in a loss of 2.016 ± 0.435 kilograms of C per square meter, for a total of ~2.1 teragrams of C. This amount equals approximately 25 years of C accumulation and 50–60% of the average annual C sequestration in the entire Arctic tundra biome. The magnitude of this C loss suggests that increases in fire frequency, severity, and extent have the potential to switch tundra from a net C sink to a source, creating a positive feedback with anthropogenic climate warming.

Fires also affect energy partitioning in tundra ecosystems. After a fire event, available energy for sensible (temperature-related), latent (evapotranspiration), and ground heat fluxes increases as a result of surface charring and decreased albedo (Chambers *et al.* 2005; Rocha and Shaver 2011b). A portion of this energy goes toward warming soils. Ground heat flux is also enhanced by the reduction of the soil organic layer, which extends the depth that surface heat can penetrate into soils (Brown 1983; Liljedahl *et al.* 2007). These changes collectively elevate soil temperatures, leading to permafrost thaw. For instance, post-fire soils were 1–4°C warmer, and had active layers (ie seasonally thawed upper soil) up to 15 cm deeper as compared with nearby unburned soils (Rocha and Shaver 2011b). Even after albedo and surface greenness had recovered, these changes persisted (Figure 6).

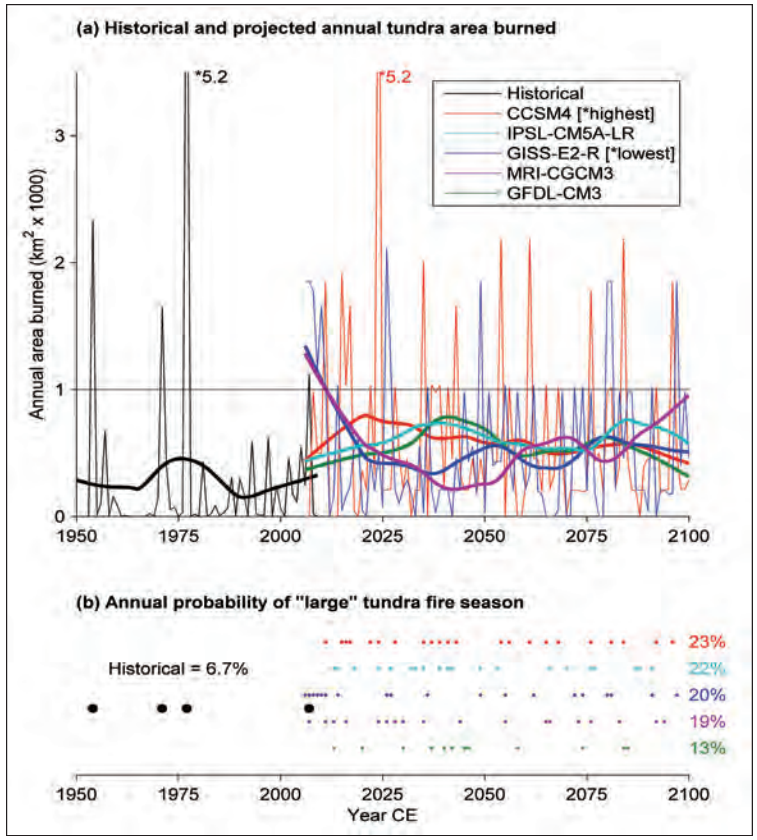


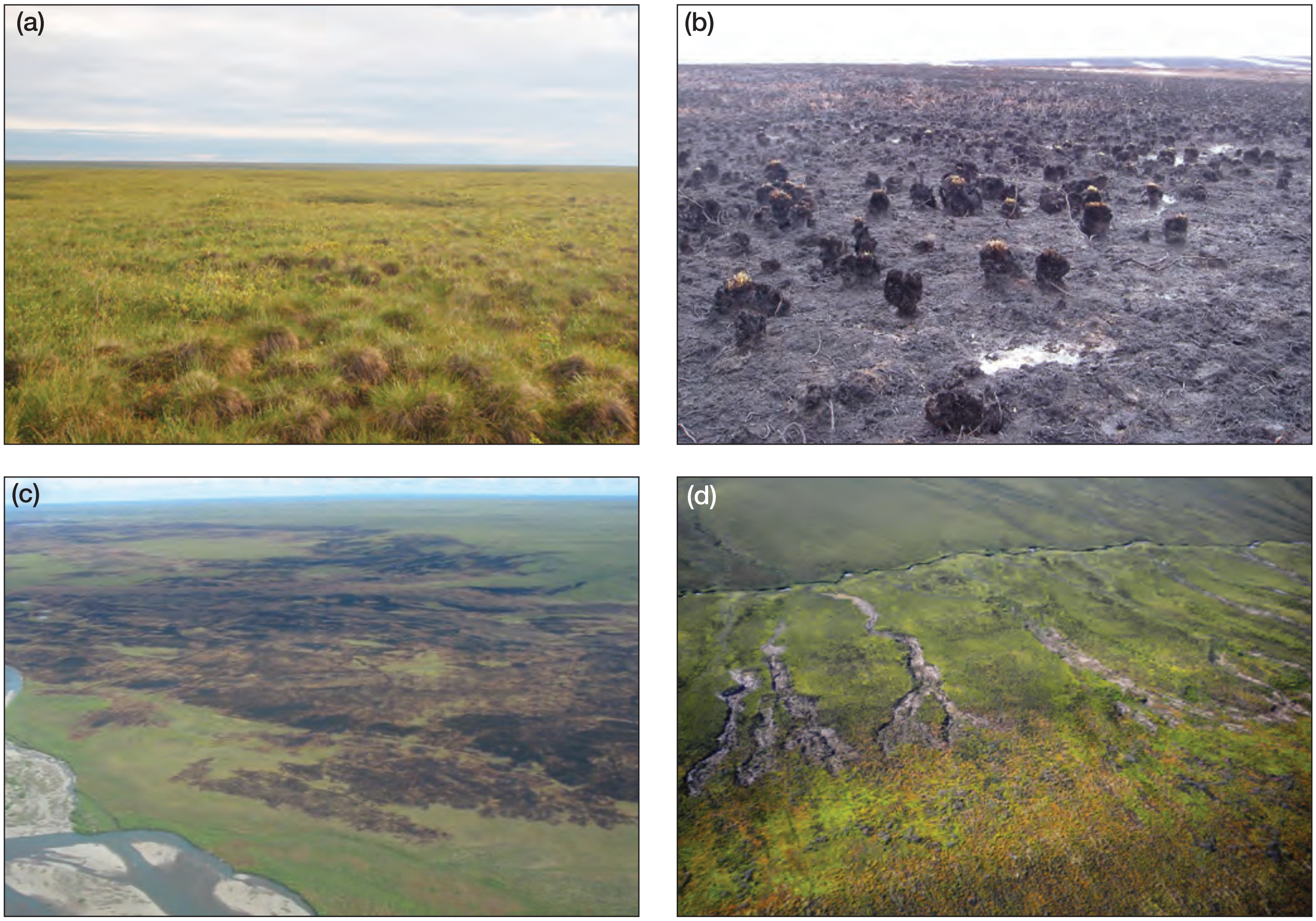
Figure 4. *Tundra area burned in Alaska. (a) Historical (1950–2009; AICC 2014) and projected annual area burned and 30-year locally weighted regression (thick lines). Projected area burned is based on downscaled scenarios (SNAP 2014) from five general circulation models (GCMs) driven by the AR5 RCP 6.0 (IPCC 2013). Annual projections are shown only for models with the highest and lowest averages of annual area burned for 2006–2100 CE. (b) Years with historical (black dots) or projected (colored dots) tundra area burned greater than 1000 km^2, arbitrarily defined as a "large" tundra-fire season.*

Following fire events, increases in soil active-layer thickness and moisture may lead to thermokarst, which develops when permafrost thaws and soils collapse under their own mass (Bowden 2010). In sloping terrain, saturated, warm soils can be carried by gravity above permafrost, resulting in active-layer detachments or thaw slumps (Figure 5d). When thermokarst occurs around lakes and streams, sediment transport substantially increases water turbidity and alters aquatic biogeochemistry (Mann *et al.* 2010). Thermokarst also exposes deep soils that are rich in ancient C to ambient air temperatures. Once exposed, this C is vulnerable to photochemical or microbial degradation (Schuur *et al.* 2009; Cory *et al.* 2013), potentially releasing greenhouse gases into the atmosphere.

In contrast to the long-term impacts of tundra fires on soil processes, post-fire vegetation recovery is unexpectedly rapid. Across all burned areas in the Alaskan tundra, surface greenness recovered within a decade after burning (Figure 6; Rocha *et al.* 2012). This rapid recovery was fueled by belowground C reserves in roots and rhizomes, increased nutrient availability from ash, and elevated soil temperatures (Rocha and Shaver 2011b; Jiang *et al.* 2015). The recovery of total ecosystem C stocks probably lags behind vegetation recovery because soil C derives from many years of vegetation productivity (Bret-Harte *et al.* 2013). Ultimately, ecosystem C storage after fire may be limited by nutrient availability. For example, an estimated loss of 400 years of accumulated ecosystem nitrogen (N) occurred in the AR Fire (Mack *et al.* 2011). Such a large N loss may prevent total ecosystem C stocks from returning to their pre-fire levels.

Discussion

The balance of evidence strongly suggests that climate limitations characteristic of historical tundra-fire regimes will be relaxed, resulting in increased tundra burning in the Arctic in the coming decades. A number of other factors – especially the rapid loss of summer sea ice in the



GR Shaver

WB Bowden

Figure 5. *Landscape effects of tundra fire. (a) Unburned tundra; (b) burned tundra immediately after fire; (c) mosaic of patches of variable burn severity; (d) active-layer-detachment thermokarst at the Anaktuvuk River Fire.*

Arctic Ocean – may interact synergistically with greenhouse warming to accelerate tundra burning over the 21st century. The three-decade-long record of summer sea-ice extent in the Arctic Ocean indicates that Arctic sea ice is moderately correlated with tundra area burned in Alaska (Hu *et al.* 2010), and some of the largest tundra-fire years in the past decade occurred when sea-ice extent decreased precipitously. Summer sea ice may vanish throughout much of the Arctic Ocean within the next several decades (Wang and Overland 2012), leading to major increases in surface air temperature, in addition to greenhouse warming within the Arctic and beyond (Lawrence *et al.* 2008; Bhatt *et al.* 2010). Given the strong climate–fire relationships in tundra regions (Figures 1 and 3), this additional warming should substantially elevate tundra-fire activity. Greater frequency of lightning is also expected as a result of Arctic warming because of increased convective energy in the atmosphere (Romps *et al.* 2014), which may increase the likelihood of tundra ignitions given sufficient dry fuels. Furthermore, the disappearance or shrinkage of ponds and wetlands in some Arctic regions (Smith *et al.* 2005; Riordan *et al.* 2006) may enhance fuel connectivity, facilitating tundra-fire spread. However, other changes, such as increased precipitation associated with greenhouse warming and sea-ice retreat, may reduce the probability of tundra fires. Reliable projections of future tundra-fire regimes require an integrative modeling approach that takes into consideration all major drivers of and feedbacks with tundra burning.

The long-term impacts of fires on tundra ecosystem structure and function are only beginning to be understood. Among the major concerns are the emissions of C stored in tundra ecosystems into the atmosphere (Mack *et al.* 2011). The direct impacts of fires on the C balance of tundra ecosystems may be more effective than warming- or drying-induced stimulation of microbial degradation of soil organic matter per se (Oechel *et al.* 2000). However, the role of tundra fires in the C cycle is poorly understood (Sitch *et al.* 2007). Tundra burning may primarily consume biomass that has accumulated over the past several decades, as was the case in the AR Fire (Mack *et al.* 2011). Coupled with the rapid post-fire recovery of tundra vegetation, this would diminish the long-term impacts of tundra fires on C storage. A sustained increase in fire frequency or severity is required to shift tundra regions from a net C sink to a source. The pronounced threshold effects of summer temperature and precipitation on tundra burning, combined with climate change, suggest that such changes will likely occur in the

21st century. Tundra burning may also exert long-lasting indirect effects on C storage by altering other ecosystem properties, such as permafrost thaw depths and thermal erosion of soils.

Post-fire increases in soil temperature and the depth of the active layer may induce a vegetation shift from tussock to shrub tundra (Landhäusser and Wein 1993; Racine *et al.* 2004), with important implications for C cycling, energy fluxes, fuel loading, and climate feedbacks. Jones *et al.* (2013) reported greater shrub abundance at tundra sites that burned more than 100 years ago, relative to an unburned site and sites that burned within the past several decades, although this pattern has yet to be verified in other areas. Shrub tundra has higher aboveground biomass than tussock tundra, which would influence C cycling by increasing woody material and litter fall. Greater aboveground biomass would increase fuel loads and fire hazard over the long term, and the potential positive feedback to shrubby vegetation may contribute to "Arctic greening" – the expansion of shrubs in the Arctic as a result of climate warming (Goetz *et al.* 2005; Myers-Smith *et al.* 2011). Shrubs increase absorption of solar energy (Loranty *et al.* 2011), and the associated regional warming is similar in magnitude to that expected from doubled atmospheric CO_2 and decreased Arctic sea ice (Chapin *et al.* 2005; Swann *et al.* 2010). Understanding the consequences of shrub expansion is an active area of research that promises to provide important insights into the future of the Arctic system.

Given the likelihood of more frequent tundra burning in the near future, land managers and policy makers should consider the ecological and socioeconomic impacts of tundra fires. Empirical information required for tundra fire and resource management is limited. National fire initiatives such as the LANDFIRE (www.landfire.gov) and Fire Regime Condition Class (www.frcc.gov) programs in the US require knowledge of historical fire-return intervals. However, even for this basic metric, information remains scarce because of the rarity of tundra fires and the short time span of observational fire data. The accumulating paleofire records therefore provide key knowledge for land managers on the historical range of variability (Higuera *et al.* 2011b). This knowledge is necessary for evaluating potential increases in tundra-fire frequency as a result of anthropogenic climate change, and for guiding tundra-fire management.

A major aspect of tundra burning that has societal ramifications is its impact on fruticose lichens, a key source of winter forage for the economically and culturally valuable caribou *Rangifer tarandus* (eg Jandt *et al.* 2008; Vors and Boyce 2009). Unlike tundra graminoids and shrubs, these highly flammable lichens take several decades to recover after burning (Jandt *et al.* 2008). The possibility of increased tundra burning has prompted discussions about fire suppression as a way to mitigate negative impacts on caribou (Joly *et al.* 2007, 2012). At regional to biome scales, tundra fires are unlikely to affect the overall size of

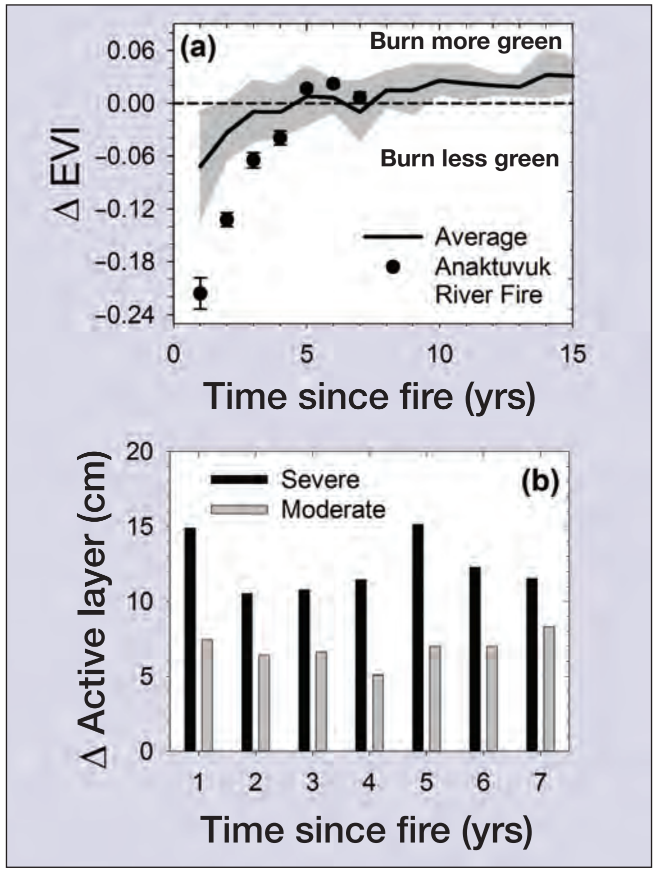


Figure 6. *Post-fire changes (Δ) in (a) tundra surface greenness (MODIS EVI) after all fires in the past decade (solid line with 90% confidence interval [gray area]) and the Anaktuvuk River Fire (solid circles, with error bars indicating 90% confidence intervals), and (b) depth of active layer at the Anaktuvuk River Fire at moderately and severely burned sites. Δ calculated as burned minus unburned values.*

the caribou winter range, given the high spatial variability of fire occurrence and the unlikely scenario that mean fire-return intervals will decrease to less than several decades in most tundra. Indeed, Higuera *et al.* (2011a) pointed out that fire and caribou have coexisted for at least 2000 years in the Noatak ecoregion, which has experienced relatively frequent tundra burning. At more local scales, however, increased burning will reduce the accessibility to caribou hunting areas and will therefore affect socioeconomic dynamics of native communities inhabiting the Far North (Joly *et al.* 2012; Gustine *et al.* 2014).

At present, the primary objective for wildland fire management in tundra ecosystems is to maintain biodiversity through wildland fires while also protecting life, property, and sensitive resources. In Alaska, the majority of Arctic tundra is managed under the "Limited Protection" option, and most natural ignitions are managed for the purpose of preserving fire in its natural role in ecosystems. Under future scenarios of climate and tundra burning, managing tundra fire is likely to become increasingly complex. Land managers and policy makers will need to consider trade-offs between fire's ecological roles and its socioeconomic impacts. For example, Alaskan tundra regions encompass >60 human communities and 348 Native allotments (ie land where title is held by Alaskan Natives), requiring fire management for resource and property protection as well as planning for the considerable health and safety impacts of smoke. The need to preserve fire's natural roles also presents a conflict with maximizing the ecosystem services of C storage. Meeting these competing demands is an emerging challenge for fire management in the 21st century as tundra burning increases in response to anthropogenic climate change.

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