Research Article

Wildfire Consumption and Interannual Impacts by Land Cover in Alaskan Boreal Forest

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ABSTRACT

Boreal forest fires are an important source of terrestrial carbon emissions, particularly during years of widespread wildfires. Most carbon emission models parameterize wildfire impacts and carbon flux to area burned by fires, therein making the assumption that fires consume a spatiotemporally homogeneous landscape composed of predominantly spruce forests and peat bogs with deep duff layers. While recent efforts have demonstrated that boreal forest fires heterogeneously consume aboveground vegetation, little remains known about the vegetation consumed during such fires. We examined climate, land cover, area burned, and fire impacts for large fires (2002 to 2009) across the Alaskan boreal landscape to address the validity of assumptions made by carbon emissions models for boreal fires. Results indicated that while coniferous vegetation, particularly spruce forests and spruce bogs, comprised the majority of the area burned in all years, shrub land cover comprised a substantial proportion (up to 35%) of the area burned during warmer years of the study period. Interannual climate variability significantly influenced both the proportion of vegetation classes burned and the distribution of fire impacts across years and vegetation classes. We found that surface fuel modifications were sensitive to both the vegetation type that burned and climatic conditions. Area burned is an inadequate input metric for increasingly refined carbon emissions models, and consideration of heterogeneous fire impacts may improve carbon emissions modeling.

Keywords: Alaska, boreal forest, carbon, climate, dNBR, NLCD

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INTRODUCTION

Wildfire activity is widely expected to increase across boreal ecosystems in response to climate change (Flannigan *et al.* 2005, Higuera *et al.* 2008, Balshi *et al.* 2009*a*, Flannigan *et al.* 2009). Such projected increases in wildfire extent, frequency, and intensity would have numerous impacts at local to global scales (EPA 2007, Flannigan *et al.* 2009). Boreal forests store an estimated one-third of global terrestrial carbon stocks (Apps *et al.* 1993, Kasischke *et al.* 1995, Kasischke 2000), primarily as undecomposed organic material in the surface soil horizon of late succession forests and bogs (Kasischke *et al.* 1995). Carbon in boreal forests is released both directly during wildfire consumption and indirectly in the subsequent

years following wildfire due to increased soil respiration (Kasischke *et al.* 1995, Richter *et al.* 2000). Potential implications of changing wildfire activity in boreal regions include increased levels of carbon consumption associated with greater area burned, increased rates of post-fire soil respiration, and the potential for alternative fire regimes and succession processes to reduce carbon storage capacity (Kasischke and Stocks 2000, Balshi *et al.* 2009*b*, Kasischke *et al.* 2010). To date, carbon research in boreal ecosystems has focused primarily on estimation of emissions for past years (Amiro *et al.* 2001, Kasischke and Bruhwiler 2002, Soja *et al.* 2004, Turquety *et al.* 2007, Turetsky *et al*. 2011). Some recent efforts, however, have focused on future emissions, producing estimates that boreal wildfires will emit 2.5 to 4.4 times more carbon by the end of the twenty-first century based on changing climate conditions and a projected 200 to 300 percent increase in area burned from the twentieth century (Balshi *et al.* 2009*b*).

Carbon emissions models to date parameterize fire activity using area burned (e.g., Measurements of Pollution in the Troposphere [MOPITT]; Turquety *et al.* 2007) and assume spatial homogeneity of fuel and fire severity within the burned area (Balshi *et al.* 2009*b*). The failure of this approach to account for the heterogeneity of biomass consumed (i.e., vegetation type and fuel volume), fire intensity, and post-fire effects (e.g., rates of vegetation regeneration and soil respiration) within the fire perimeter has been noted and addressed by several previous studies (Mihalek *et al*. 2000, Balshi *et al*. 2009*b*, Kasischke *et al.* 2010, Turestsky *et al*. 2011). To maximize accuracy in projections of future carbon emissions, process-based models must account for both spatial and temporal variability of wildfire impacts across a landscape (i.e., the range and distribution of fire frequency and severity in different vegetation types across years and decades) (Mihalek *et al.* 2000, French *et al.* 2004, Balshi *et al.* 2009*b*, Turetsky *et al.* 2011).

In Alaska, an extensive body of research has been compiled that explores the characteristics and processes of fire in boreal forests. However, much of this research has focused on a few active long-term data collection sites (e.g., Bonanza Creek Long-Term Ecological Research site, near Fairbanks) due to the general inaccessibility of Alaska and the lack of high quality proxy records such as tree-rings (Kasischke *et al.* 2006). Recent efforts have begun to address how boreal fire processes vary across the entire state and at larger spatial extents, but most existing research utilizing remotely sensed data to study wildfire regimes has been limited to either a few fires or the area of a single Landsat scene (Epting *et al.* 2005, Hoy *et al.* 2008, Murphy *et al.* 2008, Verbyla *et al.* 2008), or to a coarse-scale analysis (Kasischke *et al.* 2002, Kasischke and Turetsky 2006).

The primary focus of most previous wildfire research in the interior Alaska boreal forest has been on spruce forest (*Picea* spp.), the dominant land cover type in the Alaskan interior, and the primary, fire-adapted ecosystem type consumed by wildfire (Van Cleve *et al.* 1986). This focus is justified due to the potential liberation of soil carbon stocks in black spruce (*Picea mariana* [Mill.] Britton, Sterns and Poggenb.) forests under a changing climate with increased wildfire activity from projected warmer summer temperatures (Turetsky *et al.* 2011). Historically, larger fires have burned later in the season during years of above-average summer temperatures and a prolonged summer drought that carries into August (Kasishke *et al.* 2002, Kasischke and Turetsky 2006, Abatzoglou and Kolden 2011). These larger fires also consume more soil carbon through prolonged deep burning (Turetsky *et al.* 2011).

To date, limited efforts have been made to quantify Alaska fire regimes at landscape scales across land cover types beyond spruce forest (but, see Kasischke *et al.* 2002), as the first state-wide high-resolution (30 m) land

cover map was not released until 2006 (Selkowitz and Stehman 2011). Anecdotal observations from fire management and previous studies outside of Alaska indicate that deciduous cover types (i.e., herbaceous grass, shrubs, and deciduous forest) simply do not burn in significant quantities due to the lack of resinous needles that characterize spruce forest (Schimmel and Granström 1997, Todd and Jewkes 2006, Krawchuk and Cumming 2009). However, observations of anomalous fire consumption patterns in Alaska during record regional fire years in 2004 and 2007 (Jones *et al.* 2009, Kasischke *et al.* 2010) suggest otherwise. The release of the high-resolution 2001 National Land Cover Database (NLCD) in 2006 and the questions raised by these recent observations allow for a more thorough analysis of fire-vegetation patterns in the region.

Previous work has assumed that spruce forest is both the dominant ecosystem and, due to its flammability, the primary vegetation burned by wildfires across the interior (Chapin *et al.* 2006), but there has been no regional, high-resolution assessment of either land cover burned or interannual variability in vegetation type burned. Similarly, there has been no prior assessment of the interannual variability of surface fire impacts across vegetation types; fire impacts here being defined as the surface fuel modification detected by the differenced Normalized Burn Ratio (dNBR). This definition acknowledges that, while dNBR represents burn severity in contiguous US (CONUS) forest ecosystems where fire impacts are primarily aboveground, it does not capture the depth of subsurface soil horizon consumption that defines burn severity in boreal forests (Kasischke *et al.* 2008, 2010), and is instead meant to assess general surface change. To increase the accuracy of carbon emissions models and increase understanding of the role cover type plays in Alaskan boreal forest fire regimes, our primary goal in this study was to explore regional variability of fire characteristics (i.e., area burned and surface fire impacts) across different vegetation types in the Alaskan boreal forest. Specifically, the objectives were to assess: 1) whether certain land cover types burn preferentially in the Alaskan interior (e. g., spruce forest); 2) whether the proportion of vegetation and area burned vary in response to climatic conditions; and 3) if surface fire impacts are significantly different across years and across vegetation types.

METHODS

Studies outside of Alaska addressing wildfire regimes stratified vegetation type from one of two sources: historic land cover maps that were created prior to any recorded fire disturbance (Miller *et al.* 2008), or recent land cover maps that identify a potential climax vegetation cover based on disturbance history and abiotic factors (e.g., the LANDFIRE Potential Natural Vegetation map). In Alaska, however, wildfires are primarily stand-replacing and multiple decades often pass before a spruce forest regenerates (Chapin *et al.* 2006). Thus, a fire "footprint" of early-succession vegetation from fires occurring in the last three to four decades is evident on the NLCD, and renders it useless for multi-decadal fire assessments that pre-date the acquisition of Landsat imagery used in its creation (i.e., 2001). Given this temporal limitation, this study utilizes two types of fire data (fire perimeters and dNBR) spanning the period 2002 to 2009, NLCD, and a suite of climate and weather variables to assess fire and vegetation relationships through a multifaceted approach.

Data

We obtained wildfire perimeters for 2002 to 2009 from the Alaska Large Fire Database (ALFD) (BLM 2009), including 282 large (>400 ha) boreal summer (May to August) fires that fall within Bailey's Boreal forest ecoregion (Bailey 1998) of the Yukon River Basin (Figure 1). Surface fire impacts were

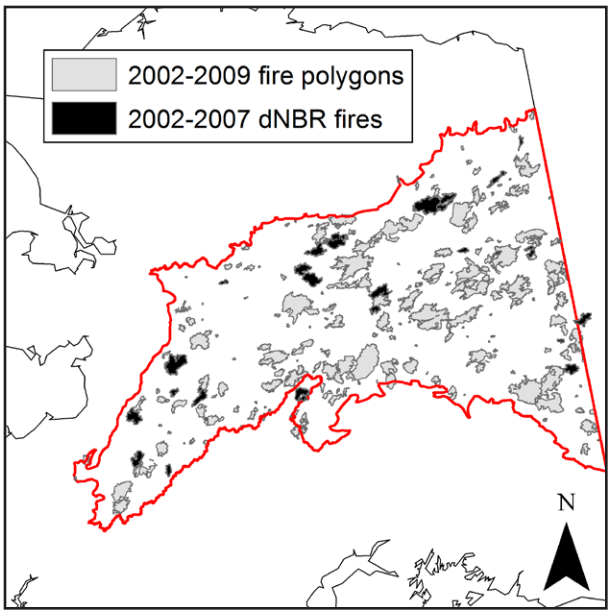

Figure 1. The boreal forest ecoregion of the Alaskan interior, the Yukon River Basin, showing the 282 fires from 2002 to 2009 that were stratified by proportion of vegetation burned (grey), and the 30 fires from 2002 to 2007 for which dNBR was produced (black).

represented by a 30 m dNBR atlas for a subset of 30 randomly selected large wildfires occurring between 2002 and 2007 (Kolden 2010). The dNBR atlas was produced from Landsat Thematic Mapper/Enhanced Thematic Mapper-plus (TM/ETM+) imagery following methods from Key and Benson (2006) and using best practices from Key (2006) as outlined in Kolden (2010). We specifically refer to dNBR as representing 'surface fire impacts' and not 'burn severity' in this study, and we define 'surface fire impacts' as the consumption and immediate post-fire regeneration (from fire termination to post-fire image acquisition) of vegetation on the soil surface (described by Key 2006). We describe it thus to acknowledge that Kasischke *et al.* (2008) specifically defined wildfire burn severity in boreal forests as the depth of duff consumption, and several studies have shown inconsistent and inconclusive relationships between soil consumption and both NBR and dNBR (Epting *et al.* 2005, French *et al.* 2008, Verbyla and Lord 2008), while dNBR was specifically developed to measure change in surface vegetation due to fire (Key and Benson 2006). We also specifically chose to use dNBR over its relative version, the RdNBR (Miller and Thode 2007). While Miller and Thode (2007) developed the RdNBR to address pre-fire differences in canopy cover and structure, they did so to address bare soil in the understory. This is less of a concern in the densely vegetated Alaskan landscape, and RdNBR has not shown greater accuracy in portraying fire impacts than dNBR here (Hoy *et al.* 2008, Kolden 2010).

Previous efforts relating fire regime characteristics to vegetation in Alaska (i.e., Kasischke *et al*. 2002, Duffy *et al*. 2007) used coarse-resolution (≥1 km), unvalidated land cover data (USGS 1992, Bailey 1998). We desired finer-scale land cover data for this analysis to match the resolution of dNBR (30 m) and capture localized variability of the landscape (e.g., topography). The National Land Cover Database (NLCD) is the first high-resolution vegetation map covering the entire Alaskan interior, and was classified from 1998-2001 Landsat TM/ETM+ images with an overall accuracy of 76 percent (Selkowitz and Stehman 2011). Consistent with NLCD efforts in CONUS, the Alaska NLCD represents 19 vegetation classes. For this study, we removed non-vegetated classes and classes with too few pixels burned to be significant (less than one percent) from the analysis. The remaining six NLCD classes were cross-walked to the dominant Alaska vegetation classes described by Viereck *et al.* (1992) in order to identify key species of the class (D. Selkowitz, USGS Alaska Science Center, Anchorage, personal communication).

Class 41 (Deciduous) includes the broadleaf deciduous species that characterize the middle succession stages of boreal forest, including aspen (*Populus tremuloides* Michx.), balsam poplar (*P. balsamifera* L.), willow (*Salix* spp.), and birch (*Betula* spp.). Class 42 (Evergreen) is dominated in the interior region

by open- and closed-canopy spruce forest, with no distinction between black spruce and white spruce (*P. glauca* [Moench] Voss), and is hereafter referred to as Conifer. Class 43 (Mixed) is a heterogeneous mix of deciduous and conifer forest. Classes 51 (Dwarf Scrub) and 52 (Scrub-Shrub) are comprised of shrub versions of the deciduous trees (e.g., *Populus* spp., *Betula* spp.), willow (*Salix* spp.), and shrubs (*Vaccinium* spp.). Class 90 (Wooded wetlands) represents the dwarf black spruce and peat bogs that typically occur atop poorly drained sites, where sphagnum mosses abound and a shallow active permafrost layer can support less than only 25 percent canopy cover of dwarf trees (Viereck *et al.* 1992), and is hereafter referred to as Bog. Classes 71 through 74 (here aggregated to a single 'Herbaceous' class) comprise the myriad of grasses, sedges, lichens, and moss found throughout the study area.

We calculated the percent of area burned in each NLCD class for each fire, and then aggregated and stratified by year and by NLCD class. To determine whether certain ecosystem types burn preferentially in interior Alaska, we also calculated the percentage of the study area covered by each NLCD class. This allowed us to normalize NLCD classes burned and more formally test assumptions that more 'flammable' ecosystem types are predisposed to fire (i.e., we expected the percent of area burned comprised of spruce forest to exceed the percent of the study area comprised of spruce forest). In addition, we extracted the NLCD class and the dNBR value for each burned pixel within the perimeter of the 30 randomly selected fires to examine surface fire impacts.

Monthly and seasonal temperature and precipitation data derived from Alaskan weather stations have been used in previous studies of Alaska fire-climate relationships (e.g., Duffy *et al.* 2005), but are spatiotemporally limited. Abatzoglou and Kolden (2011) found sub-monthly meteorological conditions after fire ignition were key factors in allowing for fire growth and suggested the need to more thoroughly analyze climate data using monthly and seasonal timescales in addition to data temporally specific to the burning period. For this study, we used meteorological data from Abatzoglou and Kolden (2011), who incorporated climatological normals from 2 km PRISM (Parameter-elevation Regressions on Independent Slopes Model; Daly *et al.* 1994), gridded monthly precipitation and temperature data from 25 km Arctic RIMS (Rapid Integrated Monitoring System, http://rims.unh.edu/data/data.cgi, last accessed 10 October 2011), and sub-daily temperature, precipitation, and relative humidity data from 32 km NARR (North American Regional Reanalysis, http://dss.ucar.edu/pub/narr). Daily temperature (Temp), precipitation (Prec), and relative humidity (RH) were extracted and aggregated within the perimeter of each of the 282 fires. From this set of variables, we calculated the Duff Moisture Code (DMC). The DMC is a component of the Canadian Forest Fire Danger Rating System that incorporates several variables into a long-term indicator of the capacity for the organic soil horizon to burn (Stocks *et al.* 1989), and is commonly used in Alaska as a proxy for fire potential (Alexander and Cole 2001).

In addition to seasonal timescales commonly used in climate analyses (e.g., June to August), we examined timescales strictly tied to the individual fires. For this study, we defined the 'Start Date' for each fire as the date of fire ignition, as recorded in the ALFD. We calculated the 'Fire Length' for each fire as the number of days from the Start Date to the date when the Alaska Fire Service recorded the fire as contained, or "out." In practice, "out" dates may occur weeks after significant fire growth has ceased, so we also calculated a 'Burning Period' for each fire. We defined the Burning Period as the period between the Start Date and the first subsequent date when a "fire-ending event" occurred. A fire-ending event is defined by the Alaska Fire Service as recording at least 12.5 mm of precipitation over a 5-day

period that includes at least a 25-hour duration of precipitation (determined using 3-hour NARR data) and the 5-day mean RH exceeds 50 % (AFS 2008).

A total of 10 variables were identified for each fire. These included four seasonal (denoted as Temp JJA [June-August], Prec JJA, RH JJA, and DMC JJA) climate anomalies (herein defined as departures from the 1979 to 2009 period), four Burning Period climate anomalies (denoted as Temp Fire, Prec Fire, RH Fire, and DMC Fire), the Start Date, and the Fire Length.

Analysis

We undertook three analyses. First, we compared the annual percentage of area burned attributed to each NLCD class relative to its percentage within the study area to determine if land cover classes were comparatively more or less 'flammable.' Our null hypothesis was that the proportion of land cover classes in burned areas is similar to the proportion of land cover classes across the Alaskan interior as a whole.

Second, we examined the influence of climate on the amount and proportion of the six different vegetation types burned. This analysis aimed to address whether climate differentially alters the flammability of vegetation classes. To address this question we used a Monte Carlo resampling (10 000 iterations) of climate and vegetation classes burned where we randomly sampled 200 of the 282 fires from 2002 to 2009, ranked the subset by its associated climate variable value, and placed the top and bottom 20 percent of fires into 'Higher' and 'Lower' categories, respectively (e.g., Higher JJA Temp, Lower JJA Temp). Although only comprising an eight-year period, the spatiotemporal variability in meteorological conditions across the study area allowed one to examine, for example, whether a given land cover class (e.g., Shrub) burned preferentially during wet or dry conditions. Our null hypothesis was that climate has no influence on the ratio of vegetation burned; specifically, that there was no significant difference ($P < 0.05$, assessed using resampling confidence intervals) between the Higher and Lower datasets for each variable.

Third, we assessed the relationship between the land cover composition and dNBR (as a proxy for surface fire impacts) to test the null hypotheses that, 1) different land cover types do not burn across significantly different dNBR distributions, and 2) individual land cover types do not burn at significantly different dNBR distributions across years. We stratified the sampled dNBR and NLCD pixel values first by land cover class and then by year, and binned them by their dNBR value (bin size of 40). For each dNBR bin, we calculated the mean area burned (hectares) and percent of area burned values and created a histogram for the comparison of interest: all NLCD classes (no stratification by year), each NLCD class individually (stratified by year), and each year individually (stratified by NLCD class). We calculated 95 percent confidence interval bounds to test for significant difference between curves at the $P < 0.05$ level.

RESULTS

Conifer (NLCD Class 42) comprised the greatest portion of area burned in all years (Figure 2). This is not unexpected as the distribution of Conifer on the landscape is also larger than any other class; however, every year, the proportion of total area burned in the Conifer class exceeded the proportion of total land area in that class, making Conifer the most flammable class over the study period. In contrast, the proportion of area burned in Deciduous was less than the proportion of Deciduous across the study area for all years, making Deciduous the least flammable class. For the other five classes, the occurrence of the NLCD class across the landscape was within the range of the proportion of area burned

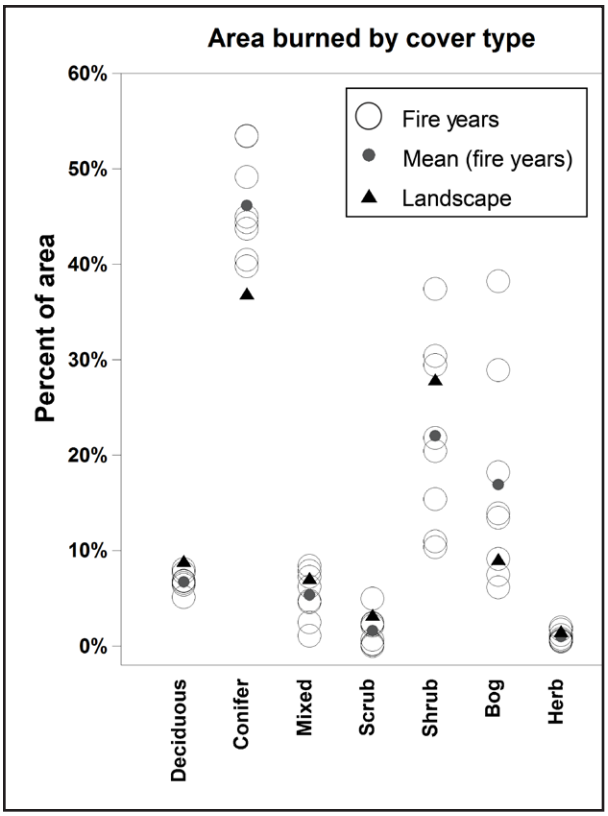

Figure 2. Percent of area burned in each NLCD vegetation class for the years 2002 to 2009 (large, open grey circles), with the mean percent of area burned over that period (small, closed grey circles), and the percent of the study area covered by the NLCD class as of 2001 (black triangles).

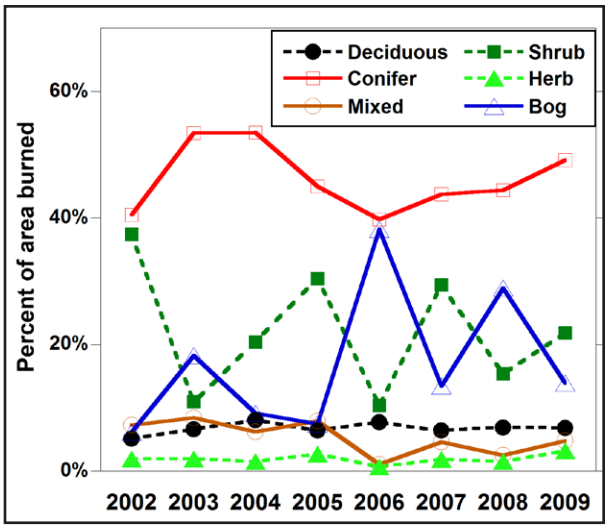

Figure 3. Time series of proportion of area burned each year attributed to each NLCD class for Deciduous (black dashed line with solid circle), Conifer (red solid line with open square), Mixed (brown solid line with open circle), Shrub (dark green dashed line with solid square), Herbaceous (light green dashed line with solid triangle), and Bog (blue solid line with open triangle).

across the study period. A time series of the proportion of each NLCD class burning each year from 2002 to 2009 indicated strong interannual variability (Figure 3). While Conifer dominates the burned vegetation each year, there is an inverse relationship between the percent of area burned in the Shrub and Bog classes. Shrubs, although not typically considered a highly flammable ecosystem in interior Alaska due to their high live fuel moisture and lack of soil duff (Todd and Jewkes 2006), account for over 30 percent of the burned area in 2002, 2005, and 2007.

The proportion of the fire burning each land cover class was significantly impacted by climate and timing (Table 1). For the Conifer class, higher JJA temperature, JJA DMC, and a longer Fire Length were associated with both a significantly greater percent of area burned per fire (Figure 4a) and a significantly greater total area burned (Figure 4b). For the Shrub class, lower precipitation, higher temperature, and lower RH during the Burning Period were associated with a significantly greater percent of the area burned per fire (Figure 4c) and significantly greater area burned (Figure 4d). No single climate variable was significant across all six land cover classes, although Fire Length was a predictor of significantly higher area burned for all six classes, which is consistent with previous findings (Kasischke *et al.* 2002, Abatzoglou and Kolden 2011).

Preliminary assessment of dNBR stratified by land cover class indicated that the dNBR distributions of the Deciduous and Mixed classes were not significantly different, suggesting that they should be merged into a single class for the fire impacts assessment. This was not surprising since the Mixed class is a combination of Deciduous and Conifer. The

Table 1. Relationships between climate variables and percent of area burned (top) and total area burned (bottom) for the six primary land cover types in the study area. An 'H' indicates that either a greater percent of area or total area burned associated with comparatively higher values for the top portion of the resampled data (e.g., relatively higher temperature or longer fire length), while an 'L' indicates a greater percent of area or greater total area burned associated with comparatively lower values. Bold letters in grey boxes indicate a significant difference at the 95% level. See Figure 4 for a visual representation.

	Deciduous	Conifer	Mixed	Shrub	Herb	Bog
			Percent area burned			
PPT Fire	**H**	H	H	**L**	H	**H**
PPT JJA	**L**	L	L	L	L	**H**
Temp Fire	H	H	H	**H**	**L**	**L**
Temp JJA	H	**H**	**H**	**L**	L	**L**
RH Fire	L	**H**	**L**	**L**	H	**H**
RH JJA	**H**	**H**	L	**L**	H	**H**
DMC Fire	H	L	**H**	**H**	**L**	**L**
DMC JJA	H	**H**	**H**	L	L	**L**
Fire Length	**H**	**H**	L	**L**	L	H
Start Date	**L**	L	**H**	**H**	H	**L**
			Area burned			
PPT Fire	L	**L**	L	**L**	H	L
PPT JJA	**L**	**L**	L	**L**	H	H
Temp Fire	H	H	H	**H**	L	L
Temp JJA	**H**	**H**	**H**	**H**	L	H
RH Fire	H	**H**	**L**	**L**	H	H
RH JJA	**H**	**H**	H	**L**	L	**H**
DMC Fire	H	H	H	H	L	H
DMC JJA	**H**	**H**	**H**	**H**	H	H
Fire Length	**H**	**H**	**H**	**H**	**H**	**H**
Start Date	**L**	**L**	L	H	H	L

dNBR distribution curves for the resulting five primary land cover groups (Deciduous-Mixed, Conifer, Shrub, Herbaceous, and Bog) indicate that when all burned area is aggregated by vegetation type, the NLCD classes produce significantly different dNBR distribution curves (Figure 5). All five of the land cover types displayed a bimodal dNBR curve, particularly when the data were normalized by area burned (Figure 5a).

The three most widely burned land cover groups (Conifer, Shrub, and Bog) all exhibited significantly different dNBR curves when stratified by year. First, dNBR for each type varied significantly across the 2002 to 2007 study period (Figure 6). For example, Conifer dNBR values (Figure 6a) were left-skewed in 2003, right-skewed in 2006, bi-modal in 2005, and more normally distributed in 2002, 2004, and 2007. When the three classes were compared to each other but stratified by year (Figure 7), significant differences between the dNBR curves of the individual land cover classes were noted for all years. For example, curves for 2004 and 2006 were right-skewed towards lower dNBR (i.e., lower fire impacts) for all three land cover classes, whereas dNBR values for fires in 2005 exhibited bimodality for Conifer and Bog classes and a left-skewed distribution for Shrubs. The 2003, 2006, and 2007 curves showed the greatest overlap in dNBR distribution between the three types; these were also years when the lowest amount of area burned. When dNBR curves were not normalized by area, years of lower burned area had a high proportion of Conifer pixels burned.

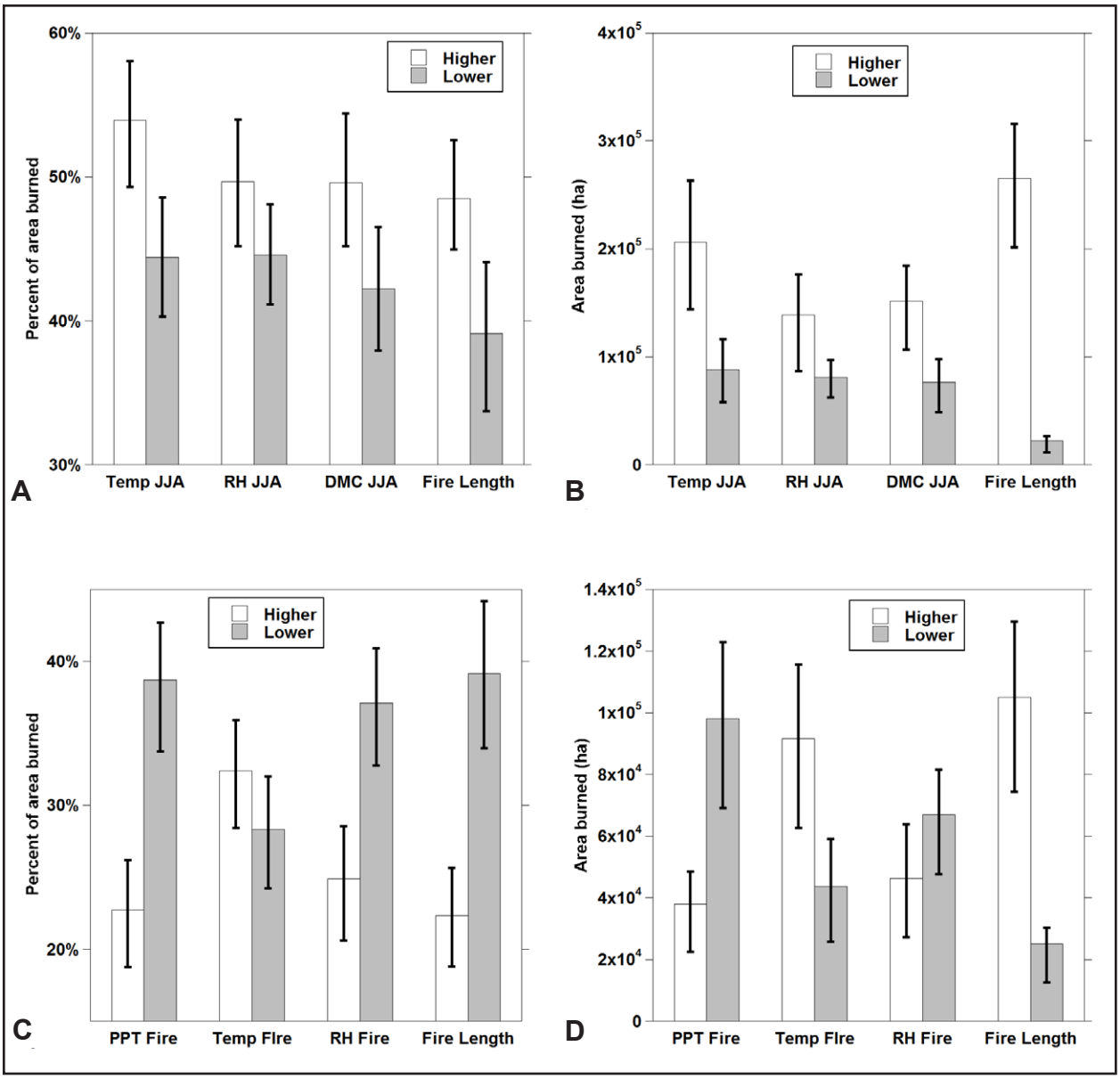

Figure 4. Climate variables that have a significant influence on the percent of area burned (A and C) and the total area burned (B and D) for Conifer (A and B, respectively) and Shrub (C and D, respectively) vegetation. White columns indicate comparatively higher fire danger conditions for the top portion of the resampled data (e.g., relatively higher temperature, lower RH, or longer fire length), while grey columns indicate comparatively lower fire danger conditions. Error bars indicate the 95% confidence interval.

In years with greater area burned, more Shrub pixels burned and there were significant differences in the dNBR curves between the two types (Figure 8). For example, Shrubs, which comprised 35 percent of the area burned during 2005, exhibited a left-skewed dNBR curve (i.e., higher fire impacts), whereas the dNBR curve for the Conifer class exhibited bimodality that was weighted more heavily to lower dNBR values.

DISCUSSION

The results indicate that fire impacts and vegetation burning in the Alaskan boreal forest were significantly different from year to year,

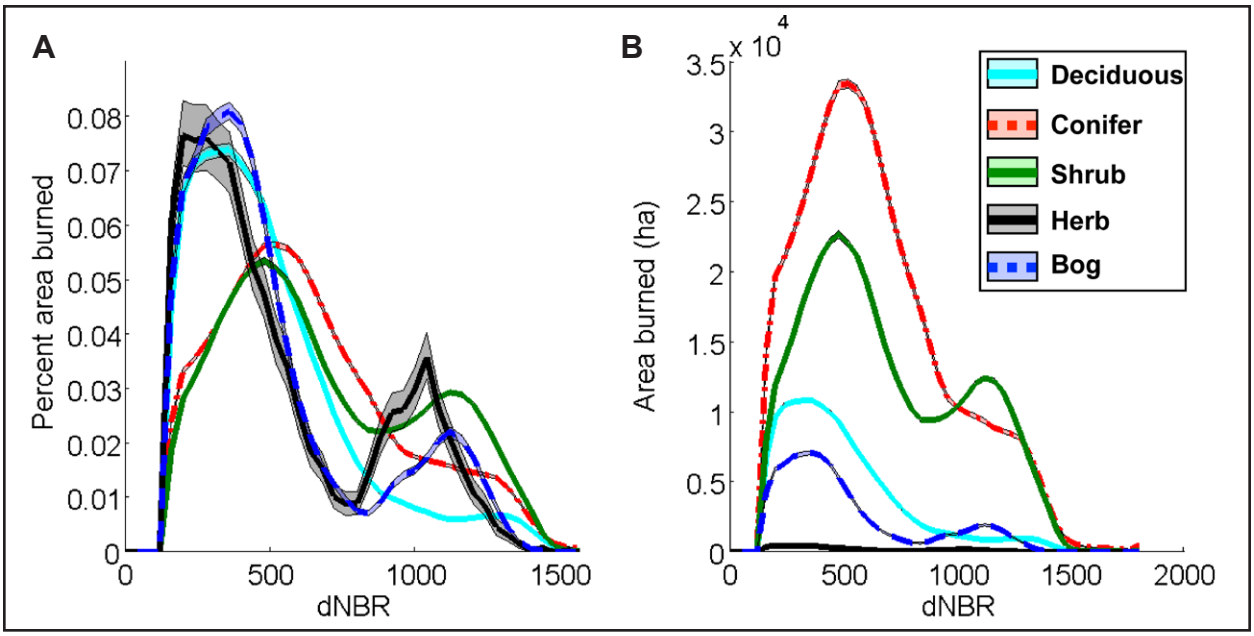

Figure 5. The dNBR distribution (binned by 40) of all pixels burned from 2002 to 2007 for 30 fires in each of the five primary vegetation classes: Deciduous-Mixed forest (light blue solid line), Conifer forest (red dashed line), Shrub-Scrub (green solid line), Herbaceous (black solid line), and Bog (dark blue dashed line). (A) percent of area burned per bin. (B) total area burned (ha). For each class, the shaded area represents the 95 % confidence interval.

in part as a product of climate conditions. The overall distribution of burned land cover supports the considerable body of research that describes the coniferous species found in late-succession boreal forest, such as black and white spruce and spruce bogs, as the primary fire carriers in interior Alaska. However, the interannual distribution of land cover burned (Figure 2) also points out the occurrence of years when a substantial proportion of the vegetation burned is shrub and dwarf scrub, which have previously received comparatively less attention as fire carriers in the forest boreal interior. Very little research has been conducted on fire in shrub ecosystems in interior Alaska, and the bulk of the literature available indicates that fire does not burn in the shrub cover types (reviewed in Chapin *et al.* 2006), in part because there is substantially less fuel available compared to late-succession spruce forests and bogs, where fire carries primarily in the thick duff and moss layers. This result shows that there is considerable interannual variability in the composition of vegetation burned, and while Conifer is the most flammable ecosystem, Shrub and other classes can be quite flammable, especially under certain climatic conditions.

While the study only covers eight years, the significant relationships between climatic anomalies and the land cover burned indicate that interannual climate variability dictates what fuel and vegetation types are available to burn. While it is not surprising that more area is burned for all land cover types during a longer lasting fire as compared to a shorter one, the contrasts between meteorological conditions conducive to fire in some land cover types but not others provide insight into how climate controls fire regimes in Alaska. For example, Bog burned preferentially when RH was higher and conditions were cooler and wetter during the Burning Period, but Shrubs burned preferentially when RH was lower and conditions were warmer and drier during the Burning Period (Table 1). When this observa-

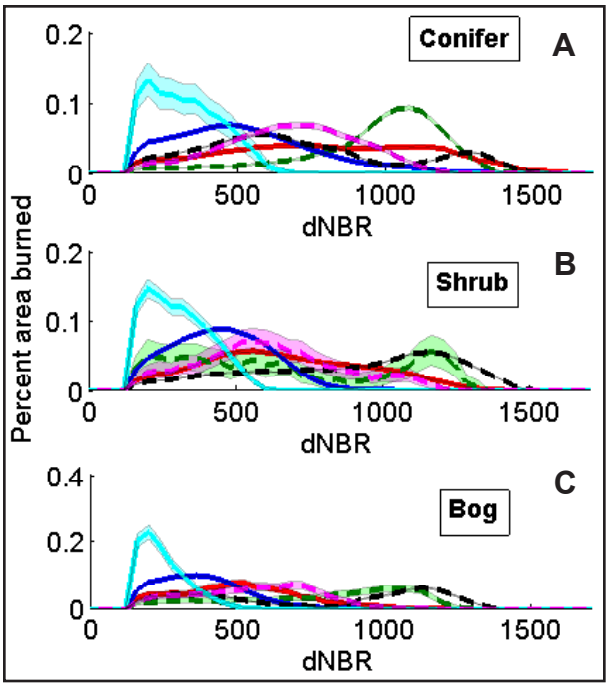

Figure 6. Distribution of dNBR (binned by 40) by percent of area burned for the three vegetation types with the greatest area burned: (A) Conifer, (B) Shrub, (C) Bog by year for 2002 (red solid line), 2003 (green dashed line), 2004 (blue solid line), 2005 (black dashed line), 2006 (teal solid line), 2007 (pink dashed line). Shaded envelope represents the 95% confidence interval.

tion is taken in context with the total area burned across the study years, it indicates that while a substantial extent of area burned every year is Conifer and Bog land cover, anomalously warm and dry conditions are conducive to increased fire consumption of the Shrub class. This increased Shrub consumption is potentially associated with increased drought stress on live fuels and the lower RH dropping fuel moistures below the moisture of extinction threshold. These same warm and dry conditions are also conducive to fires burning a greater extent of Deciduous forest.

This difference in what cover types burn under climatically warmer and drier versus cooler and wetter conditions has considerable implications for carbon emissions models. Our results indicate that in warmer, drier conditions, a greater proportion of the area burned is shrub cover. This will likely produce lower carbon emissions than are currently projected, as shrub-dominated sites store significantly less carbon than spruce-dominated sites. Any kind of shift in the area burned between the cover types due to climate change would also have significant implications for fire suppression efforts. For example, realized projections of warmer boreal summer conditions may induce increased burning of Deciduous forest and Shrub, which fire management has historically used as natural, high fuel moisture fire breaks for fire suppression.

The significantly different distributions of dNBR by year across the NLCD classes indicate that fire has variable interannual impacts on different land cover types in Alaska. From the period 2002 to 2007, the distribution of dNBR for all land cover types was bi-modal (Figure 5). This bi-modality is significantly different from other landscape-scale assessments of dNBR that have found multi-year dNBR composites following a predominantly normal or uni-modal curve (Lutz *et al.* 2011, Thode *et al.* 2011). However, a predominantly bi-modal dNBR distribution indicates that fire impacts are falling primarily into just two classes: Low and High. This agrees with findings from a single-fire case study in Alaska by Michalek *et al.* (2000), but has not yet been addressed at a regional level.

Since the dNBR is a proxy for surface fuel modification one year post-fire, it includes any regeneration that has occurred in the interim between the fire event and the post-fire imagery acquisition date (Key 2006); that regeneration rate is dependent upon the pre-fire vegetation type. Regeneration has not been widely addressed in burn severity studies using dNBR because most burn severity studies have been conducted in regions where no regeneration takes place prior to acquisition of the post-fire data. However, if climate had no significant influence on fire impacts, we would expect no significant differences between the regional

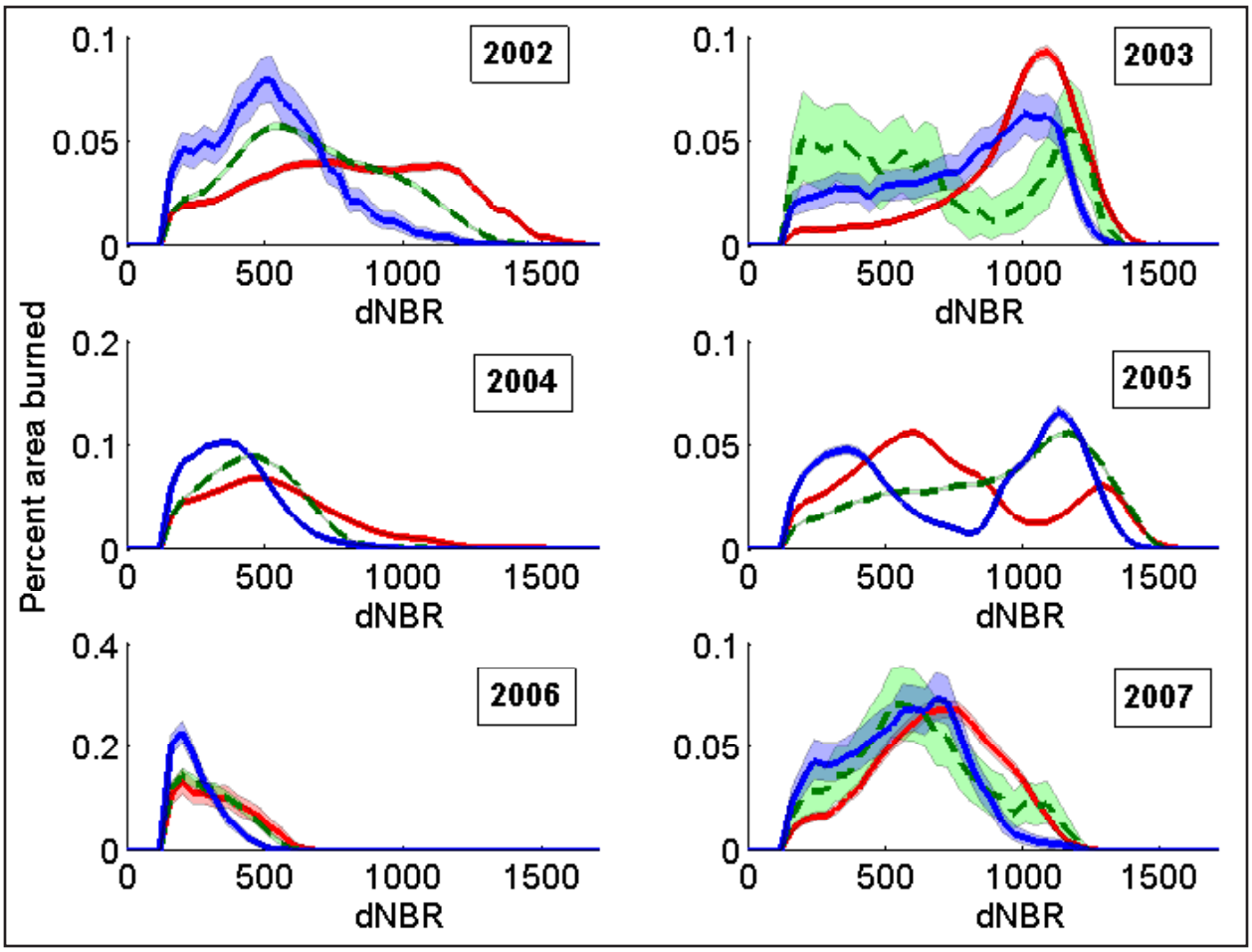

Figure 7. Distribution of dNBR (binned by 40) by percent of area burned for the three vegetation types with the greatest area burned (conifer [red solid line], shrub [green dashed line], spruce bog [blue solid line]) by year. Shaded envelope represents the 95 % confidence interval.

dNBR curves for a single land cover type from year to year. Instead, the three most widely burned land cover types (Conifer, Shrub, and Bog) produce significantly different interannual dNBR distributions (Figure 6), including right-skew years of predominantly lower dNBR values (e.g., 2006 for all three types), left-skew years of predominantly higher dNBR (e.g., 2003 for Conifer), bi-modal, and normally distributed years (e.g., 2007 for all three types). These preliminary results will require additional analysis of a greater number of fires and years to refine, but initially they confirm that climate impacts the type of vegetation consumed across the landscape, as opposed to the homogenous impacts assumed by carbon emissions models.

Results of this study confirm that there is significant interannual and spatial variability in both what land cover type is burning and the impacts of the fire. Assumptions of homogeneous land cover burning (i.e., spruce forest) and fire impacts in modeling carbon emissions may therefore produce a worst-case emissions scenario that has implications for developing carbon emissions policies. These results also suggest that considerable research on fire in boreal shrubs is warranted, as anecdotal evidence tends to classify shrub and deciduous forest as non-flammable land cover types that are often utilized by managers as natural fire breaks (R. Jandt, Fire Ecologist, Alaska Fire Service, personal communication, October 2008). Warmer and drier conditions result in

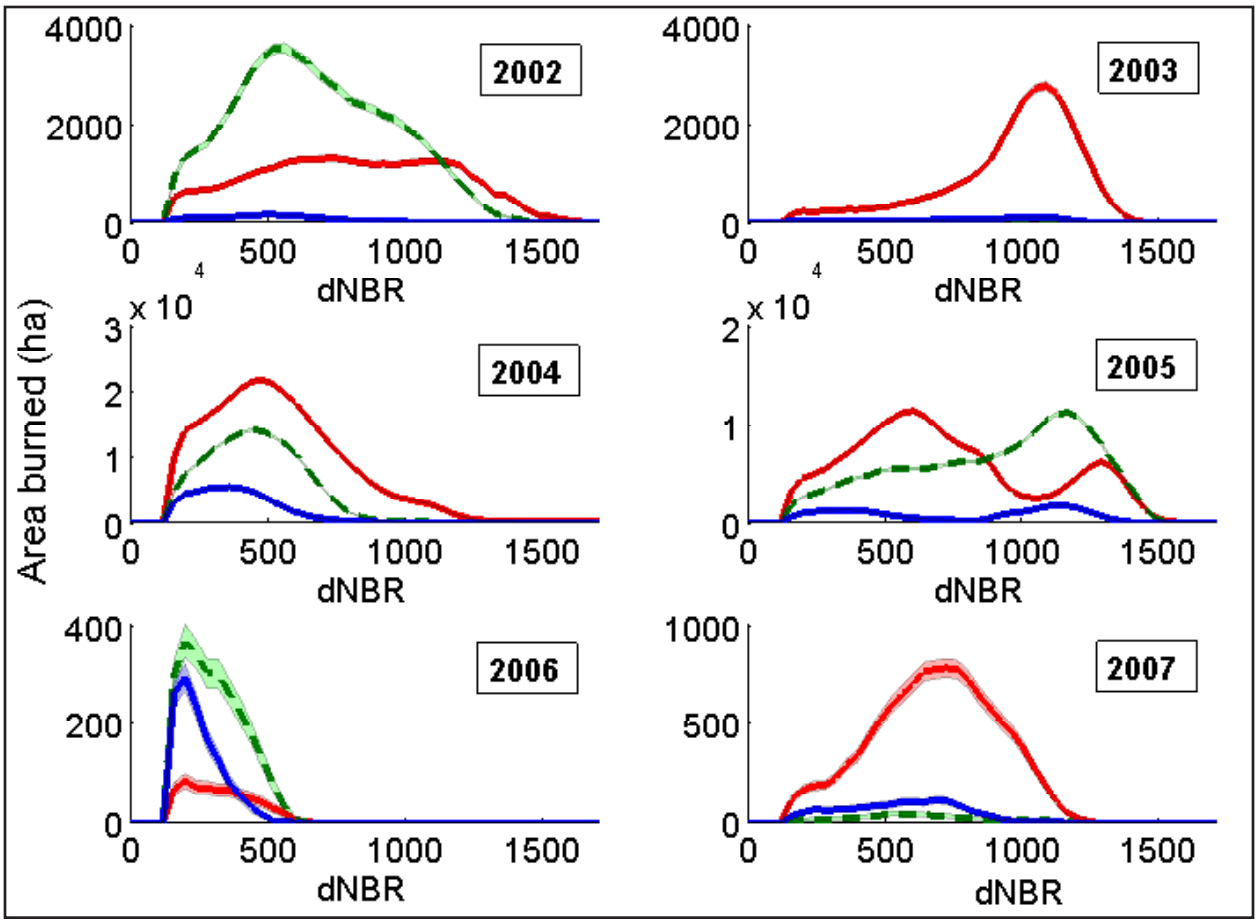

Figure 8. Distribution of dNBR (binned by 40) by area burned for the three vegetation types with the greatest area burned (conifer [red solid line], shrub [green dashed line], spruce bog [blue solid line]) by year. Shaded envelope represents the 95% confidence interval.

lower live fuel moistures and make deciduous vegetation more available to burn; if projected warming in Alaska induces increased burning of shrub types, this may have a more broad range of implications for the boreal forest. Johnstone *et al.* (2011) recently suggested that increased fire in the boreal forest would produce a negative feedback by increasing deciduous cover, which they describe as less flammable. However, our results suggest that this increased deciduous cover will be more flammable under future conditions, thus countering the suggested negative feedback.

CONCLUSION

Carbon emissions models assume homogeneous fire impacts in boreal forests, based on nearly a half-century of research on fire in Alaska boreal forest that has identified the primary fire regime as black spruce forest burning infrequently (i.e., 100+ years) at stand-replacing, high severity. Our results suggest that there is significant interannual variability in the composition of vegetation burning, and significant spatiotemporal variability in fire impacts. Heterogeneity of fire impacts is determined both by vegetation type burned and by climate, although it is difficult to disaggregate the influence of each component at the landscape scale utilizing dNBR as a proxy for fire impacts, both because dNBR utilizes one year post-fire information and because there is no high-resolution vegetation classification for Alaska prior to 2001. This complexity challenges the assumptions of carbon emissions

models by indicating that there may be multiple fire regimes in interior Alaska emitting considerably different quantities of carbon. It also indicates that model assumptions of homogeneity may lead to significantly overestimated carbon emissions from boreal wildfires.

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