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Potential shifts in dominant forest cover in interior Alaska driven by variations in fire severity

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Abstract. Large fire years in which >1% of the landscape burns are becoming more frequent in the Alaskan (USA) interior, with four large fire years in the past 10 years, and 79 000 km^2 (17% of the region) burned since 2000. We modeled fire severity conditions for the entire area burned in large fires during a large fire year (2004) to determine the factors that are most important in estimating severity and to identify areas affected by deep-burning fires. In addition to standard methods of assessing severity using spectral information, we incorporated information regarding topography, spatial pattern of burning, and instantaneous characteristics such as fire weather and fire radiative power. Ensemble techniques using regression trees as a base learner were able to determine fire severity successfully using spectral data in concert with other relevant geospatial data. This method was successful in estimating average conditions, but it underestimated the range of severity.

This new approach was used to identify black spruce stands that experienced intermediate- to high-severity fires in 2004 and are therefore susceptible to a shift in regrowth toward deciduous dominance or mixed dominance. Based on the output of the severity model, we estimate that 39% (~4000 km^2) of all burned black spruce stands in 2004 had <10 cm of residual organic layer and may be susceptible a postfire shift in plant functional type dominance, as well as permafrost loss. If the fraction of area susceptible to deciduous regeneration is constant for large fire years, the effect of such years in the most recent decade has been to reduce black spruce stands by 4.2% and to increase areas dominated or co-dominated by deciduous forest stands by 20%. Such disturbance-driven modifications have the potential to affect the carbon cycle and climate system at regional to global scales.

Key words: Alaska; black spruce; boreal forest; climate change; fire severity; land cover change; organic layer of soil; Picea mariana; *successional shifts.*

Introduction

Fire is the dominant disturbance type in the Alaskan boreal forest (Payette 1992, Esseen et al. 1997), causing changes in edaphic conditions that result in permafrost degradation (Brown 1983, Burn 1998), changes in vegetation composition (Johnstone and Kasischke 2005, Johnstone and Chapin 2006, Johnstone et al. 2010*b*, Shenoy et al. 2011), and subsequent changes in energy exchanges (Chambers et al. 2005, Randerson et al. 2006) and wildlife populations (Irwin 1985, MacCracken and Viereck 1990, Fisher and Wilkinson 2005) on which native Alaskans depend for subsistence hunting (Nelson et al. 2008). There are two primary postfire successional trajectories in fire-disturbed black spruce stands in the Alaskan interior (USA). In a less severe fire, much of the surface organic layer remains and favors conifer self-replacement (Van Cleve et al. 1983, Viereck 1983). On exposed mineral soils or a thin organic layer mat resulting from more severe fires, deciduous species such as trembling aspen (*Populus tremuloides*) and white birch (*Betula papyrifera*) may dominate the secondary successional stages (Johnstone and Kasischke 2005, Johnstone et al. 2010*b*) and may persist in mature stands (Zackrisson 1985, Cumming 2001). We focus on postfire successional trajectories in black spruce stands in the Alaskan interior to infer the likely impact of severity on land cover in the region. The ecosystem dynamics described in this analysis are generally relevant to dynamics in the boreal forest region (Bonan and Shugart 1989), although the findings of this analysis are confined to Alaska.

Increases in fire activity (Kasischke and Turetsky 2006, Kasischke et al. 2010) and severity (Turetsky et al. 2011) in the Alaskan boreal forest in recent decades have altered the structure and function of black spruce stands, the dominant forest type in the region. Fire regime characteristics such as severity, fire return intervals, and fire seasonality, respond to variations in climate, particularly warmer (McGuire et al. 2006) and drier (Flannigan et al. 2005, 2006; Scenarios Network

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for Alaska Planning, data *available online*)[5] conditions (Rupp et al. 2000, Kasischke et al. 2002, 2008, 2010, Duffy et al. 2005, Soja et al. 2007, Jones et al. 2009). Fires also contribute to climate change by influencing carbon and energy fluxes (Chapin et al. 2000, Liu et al. 2004, Randerson et al. 2006, Turetsky et al. 2011). If fires become more severe due to warmer and drier conditions predicted for interior Alaska, they may cause a region-wide shift in dominant forest cover if the mechanisms of recruitment, establishment, and competition are affected at a broad spatial scale (Johnstone and Kasischke 2005, Johnstone and Chapin 2006). Such a shift would have far-reaching consequences for carbon cycling (Harden et al. 2000, 2006, Kane et al. 2007, Amiro et al. 2009, Balshi et al. 2009, Turetsky et al. 2011), wildlife habitat (Rupp et al. 2007), energy exchange (Chambers et al. 2005, Randerson et al. 2006, Lyons et al. 2008), and potential feedbacks that may exacerbate or mitigate regional and global climate change (Randerson et al. 2006, Bonan 2008, Chapin et al. 2008, Euskirchen et al. 2009, 2010, Johnstone et al. 2010*a*, Turetsky et al. 2011).

Black spruce (*Picea mariana*) is the dominant tree species in the forest ecosystems of the North American boreal region because they are not only well suited to the cold climate of this region, but they can survive across a broad range of soil drainage conditions (Hollingsworth et al. 2006). Black spruce are well adapted to fire (Viereck 1983), with their stand age distribution across a region being controlled by fire frequency (Yarie 1981). Although black spruce cones are semi-serotinous, the thin bark is not particularly fire resistant, and most trees will not survive a fire of even moderate severity. An important general characteristic of black spruce forests is a deep organic soil layer underlying a nearly continuous layer of mosses and lichens (K. D. Johnson et al., *unpublished manuscript*). This organic layer not only serves as a large reservoir of carbon (Harden et al. 2000), but is an important control on the formation of permafrost (Yoshikawa et al. 2003).

The deep organic layer (OL) common to black spruce forests can and does burn during fires, and data on depth of burning are important measures of fire severity (Kasischke et al. 2008). The deep surface organic material of low bulk density in black spruce stands generally precludes deciduous boreal species from establishing seedlings (Johnstone and Kasischke 2005, Johnstone et al. 2010*b*). Black spruce seeds, which are larger than seeds of aspen (*Populus tremuloides*) and other deciduous species, have more resources to withstand the very dry surface organic layers during the establishment phase of regrowth (Johnstone et al. 2010*b*). A very severe fire can remove most or all of the surface organic material; however, in that case the deciduous seeds are at an advantage on exposed mineral soils and are more successful at establishment (Johnstone and Chapin 2006). Furthermore, given the high proportion of mixed or deciduous dominated stands in the interior, proximity to a deciduous seed source has not been a limiting factor in determining where such shifts occur (Johnstone et al. 2010*a*). In some cases black spruce will outcompete the deciduous trees and become dominant after a few decades (Johnstone and Chapin 2006), but the deciduous stands in areas that we have studied that are >60 years old show no sign of such competition. Depth of burning also plays an important role in postfire soil moisture and temperature (Burn and Smith 1988, Yoshikawa et al. 2003, Kasischke and Johnstone 2005, Harden et al. 2006, Yi et al. 2009, 2010), emissions from fire consumption (Kasischke et al. 2005), changes in nutrient availability (Brais et al. 1995, Neary et al. 1999, Wan et al. 2001, DeLuca et al. 2002), and removal of plant material for species that are capable of vegetative reproduction (Greene and Johnson 1999, Johnstone and Chapin 2006).

Field-based research has provided key insights on the factors that control depth of burning in black spruce forests. Studies have shown that higher severity, deeper burning fires occur on sloping (and therefore, better drained) surfaces compared to flat lowlands (Kane et al. 2007, Turetsky et al. 2011), and that higher severity fires occur during late season fires (Kasischke and Johnstone 2005, Turetsky et al. 2011). Fire severity, however, is a characteristic of the boreal forest fire regime that has yet to be studied at a landscape scale, for lack of consistent and reliable methods to determine severity through analysis of satellite imagery (French et al. 2008). A previous study (Barrett et al. 2010) developed a model of fire severity for use in the Alaskan boreal forest. The present study refines and extends the severity model to study the effect of an extreme fire year and infers from these findings the effect of four large fire years that occurred in the previous decade.

Because of the potential impacts of fire severity on forest composition, our objective was to better characterize fire severity and to determine its effect on land cover in the Alaskan interior.

To this end we addressed the following research questions in this study: (1) How severe were the fires in 2004 (the largest fire year on record in Alaska), and how much of the burned area is susceptible to a successional shift? (2) Based on the proportion of the burned area in 2004 that is susceptible to a shift in succession, how may large fire years during the most recent decade have affected coniferous land cover in the Alaskan boreal forest?

Methods

A model that adequately describes fire severity at a landscape scale is useful for many ecological applications relevant to land management efforts. Using satellite data, severity is typically described in compar-

[5] ⟨http://www.snap.uaf.edu⟩

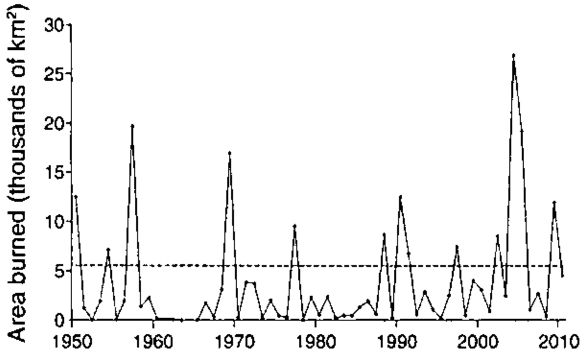

FIG. 1. Area burned in Alaska, USA, from 1950 to 2010. The dashed line indicates the threshold for "large fire years" or years during which burned area > 5500 km^2.

ison to some prefire state (e.g., Normalized Burn Ratio [data *available online*][6] and related indices; Epting et al. 2005, Loboda et al. 2007, Verbyla et al. 2008). Certain applications may not require information on prefire conditions, but are primarily concerned with the disturbance event itself, as in the case of estimating fire emissions (Harden et al. 2000, Kasischke et al. 2005, Turquety et al. 2007). Finally, severity information may describe the postfire condition, which is a useful indicator of possible changes to the structure and function of the disturbed ecosystem. To account for these different user requirements, three severity models were developed in the course of this analysis to estimate relative organic layer (OL) depth reduction, absolute depth reduction, and postfire organic layer depth. The severity models were created using a random forest technique, which averages the output of hundreds of decision trees created using a jackknife approach (Breiman 2001).

The use of different metrics allows us to test the effectiveness of severity models for a multiple purposes and provides an opportunity to compare outputs. Reduction of the surface organic layer is useful for calculating the loss of material via combustion during the disturbance event. To estimate biomass-burning emissions in boreal forests, models require information on the depth of burn in addition to area burned and fuel type. The reduction of the surface OL relative to prefire depth may be a better indication of severity conditions, as it explicitly relates pre- and postfire conditions. Subtracting the fraction of material removed from the ecosystem indicates how much of the material is available for recovery, particularly in the case of plant propagules and vegetative reproduction of aspen and shrubs. The reduction of the surface OL removes the less dense layers that are important to ecosystem functioning in terms of soil moisture and temperature. Deep burning that occurs in the dry, low bulk density OL influences the species that become dominant during establishment (Johnstone and Chapin 2006). Finally, the postfire OL depth is better suited to predicting postfire successional shifts in black spruce stands, as well as other important ecosystem properties such as the insulating effect of low-bulk density material on the soil surface.

To develop the severity model we used a combination of field data, satellite data, and non-spectral geospatial data sets from the 2004 fire season, which was the largest fire season on record for Alaska since 1940 (Fig. 1; Kasischke et al. 2010). The framework for data, processing, and analysis used in this study is illustrated in Fig. 2. The first step in our analysis was to develop the input variables for the fire severity model that describe topography, spectral properties of the burn, spatial properties of the burn area, and fire characteristics measured at the time of the fire. The random forest technique was chosen to develop the model because of its ability to characterize severity with a high degree of accuracy, gauged from comparison of modeled values with a holdout sample (Barrett et al. 2010). The impact of fire severity on successional shifts for the 2004 fires was evaluated using two thresholds for the postfire OL depth. The areas with <3 cm of surface OL after the fire will be susceptible deciduous-dominated regeneration and permafrost loss, while areas with 3–10 cm of OL depth will be susceptible to codominant regeneration with significant fractions of both coniferous and deciduous trees in which the degradation of permafrost is probable (Yoshikawa et al. 2003, Johnstone et al. 2010*b*, Shenoy et al. 2011). Finally, we used the fraction of area that was susceptible to a shift toward deciduous dominance or codominance in 2004 fires to model the impacts of the four large fire years during the past decade (2000–2009).

Independent variables

The independent variables used as input to the severity models represent four distinct types of information: topography, spectral information, spatial information, and those variables related to the active disturbance event that we refer to here as instantaneous-fire characteristics (Table 1). The data were obtained from measurements made in the field, derived from satellite imagery, and collected from neighboring weather stations in the Remote Automated Weather Stations (RAWS) network (operated by the U.S. Bureau of Land Management, the State of Alaska, the U.S. Fish and Wildlife Service, the National Park Service, and the U.S. Forest Service). While it is recognized that many of these variables are correlated, the regression tree technique employed does not require that input variables are uncorrelated as in a least squares regression model (Breiman 2001).

Topography.—Topography, and more specifically local drainage conditions, is an important control on fire susceptibility in Alaska (Johnson 1992, Kane et al. 2007, Turetsky et al. 2011). Convex surfaces are better drained, whereas low, flat areas or concave surfaces tend

[6] ⟨http://www.nrmsc.usgs.gov/research/ndbr.htm⟩

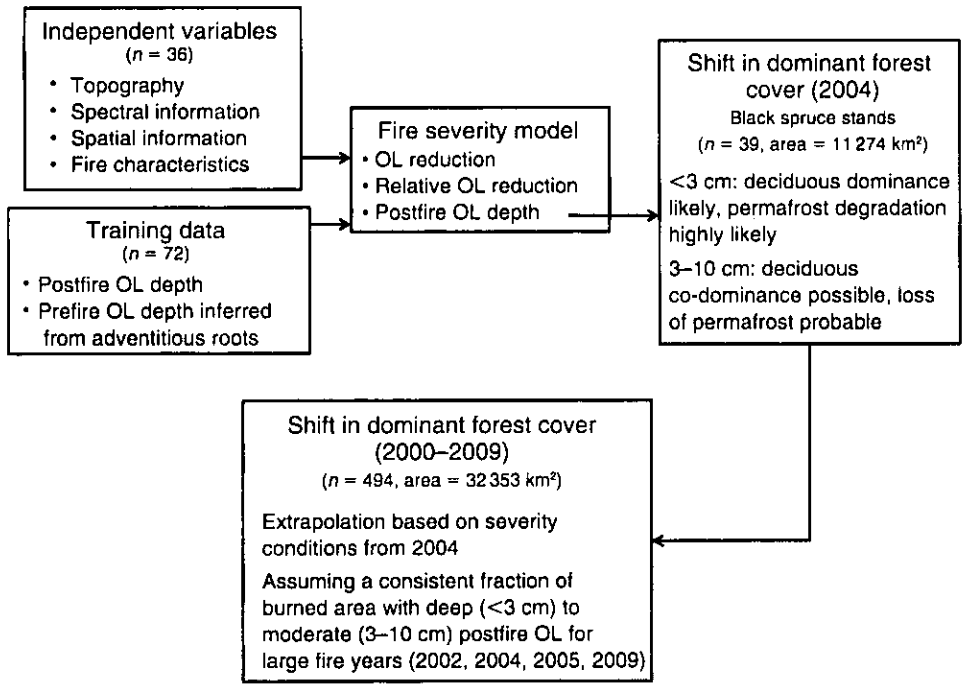

FIG. 2. Flow diagram of data, processing, and analysis. The organic layer is abbreviated as OL.

to have wetter soils where fire is likely to be extinguished or occur at very low severity (Rowe and Scotter 1973). The topographic information used in the analysis was derived from a 60-m digital elevation model (DEM) from the U.S. Geological Survey. Using the DEM, slope, aspect, and elevation were calculated and included as independent variables, as well as two indices derived from topography (topographic convergence index and fire resistance). The topographic convergence index (Beven and Kirkby 1979) was used as a measure to determine the local area and slope that contribute to flow accumulation for a given pixel, and provided an indication of drainage conditions that may mitigate burn severity.

The fire resistance scale (Table 2), described in a previous analysis (Barrett et al. 2010), reflects the tendency of certain topographic positions to be more resistant to burning. Fire resistance was ranked from 1 to 5 in order of most to least resistant. Flat, lowland areas are typically poorly drained and have cool, wet soils that are highly resistant to deep burning (Rowe and Scotter 1973, Turetsky et al. 2011). North-facing slopes are less resistant to burning than flat lowlands because the soils are better drained. East- and west-facing back slopes are more prone to deep burns because of better drainage and increased insolation. South-facing back slopes, which receive the most solar radiation and are well drained due to the absence of permafrost, are the most likely to experience deep-burning fires.

The threshold for "lowland" areas differs between fire scars because drainage conditions depend on surrounding topographic features and subsequent drainage characteristics. Lowland areas are those locations where runoff collects and are characterized by flat terrain, cool, wet soils, and the presence of black spruce forests that are able to survive such conditions. Upland and lowland categories were created based on geospatial analysis of each fire event. Both topographic information (Gesch et al. 2002) and a spatial land cover data set (Homer et al. 2004) were used in the determination. First, flat (<2% grade), evergreen areas were isolated within each fire perimeter. Then the elevation of those sites in valleys or flat plains of low elevation was used as a threshold to distinguish lowland from upland regions within the individual fire event.

Spectral information.—All spectral data used in the analysis came from the Monitoring Trends in Burn Severity (MTBS) project (information *available online*),[7] a collaboration among the U.S. Geological Survey, National Park Service, and U.S. Forest Service. The data products provided by this project are based on the analysis of Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper+ (ETM+) data. The postfire spectral data and Normalized Burn Ratio family products were all provided directly, while the tasseled cap brightness, greenness, and wetness indices (Kauth and Thomas 1976) were derived from the different spectral bands of the Landsat TM and ETM+ data sets (Huang et al. 2002). The spectral reflectance data provide information on pre- and postfire scene elements related to severity such as live and dead or damaged

[7] (http://www.mtbs.gov)

TABLE 1. Input variables for severity models of fire severity in the Alaskan boreal forest (USA).

Independent variable by category	Units	Source
Topography		
Elevation	meters	NED
Slope	percent	NED
Aspect	degrees	NED
TCI (topographic convergence index)		NED-derived
Fire resistance		NED-derived
Spectral information		
Landsat Band 4 (near infrared)	reflectance	MTBS
Landsat Band 5 (mid-infrared)	reflectance	MTBS
Landsat Band 7 (mid-infrared)	reflectance	MTBS
Band 7/Band 5		MTBS
Normalized Differenced Vegetation Index (NDVI)		MTBS
Normalized Burn Ratio (NBR)		MTBS
Differenced NBR (dNBR)		MTBS
Relativized dNBR (RdNBR)		MTBS
Kauth Thomas "brightness"		MTBS
Kauth Thomas "greenness"		MTBS
Kauth Thomas "wetness"		MTBS
Spatial information		
Area burned	$meters^2$	MTBS
Distance to burn perimeter	meters	MTBS
Fractal dimension of burned area		MTBS-derived
Percentage of unburned "islands" within perimeter	percent	MTBS
Fire characteristics		
Fire radiative power	megawatts	MODIS-Aqua
Fire radiative power	megawatts	MODIS-Terra
Duration of fire detection	hours	MODIS
Number of fire detections	frequency	MODIS
Burn date	Julian day	MODIS
Air temperature	degrees Fahrenheit	RAWS
Precipitation	inches	RAWS
Relative humidity	percent	RAWS
Wind speed	miles per hour	RAWS
Duff moisture code		RAWS
Drought code		RAWS
Fine-fuel moisture code		RAWS
Initial spread index		RAWS
Build-up index		RAWS
Fire weather index		RAWS
Daily severity rating		RAWS

Note: Abbreviations are: NED, National Elevation Dataset; MTBS, Monitoring Trend in Burn Severity; MODIS, Moderate Resolution Imaging Spectroradiometer; and RAWS, Remote Automated Weather Stations. MODIS-Aqua and MODIS-Terra are two satellite platforms that collect data using MODIS.

vegetation, exposed mineral soils, and char and ash (Rogan and Franklin 2001, Rogan et al. 2002). The indices derived from spectral data such as the Normalized Burn Ratio family (*available online*; see footnote 6) were designed to detect variations in the scene elements that reflect severity conditions (Lopez-Garcia and Caselles 1991). The tasseled cap transformation, which provides information on vegetation greenness, moisture, and brightness of scene elements, has in previous studies been shown to be also correlated with surface measures of fire severity (Miller and Yool 2002, Epting et al. 2005).

Spatial information.—The spatial data for individual fire events and test sites were derived from the MTBS categorization of burned area and unburned areas within the burn perimeter. Recent studies (Turetsky et al. 2011) have shown that depth of burning during early- and mid-season fires in black spruce forests is correlated to the size of the fire event. Fractal dimension of burned area has been used to examine disturbance properties (Skinner 1995, Díaz-Delgado et al. 2004, Kellogg et al. 2008) and to propagate models of fire spread (Porteric et al. 2007, Rodriguez Gonzalez et al. 2008). It is possible that a similar relationship exists

TABLE 2. Fire resistance score as a function of topographic position related to drainage.

Fire resistance score	Topographic position
1	flat, lowland areas and toe slopes
2	north-facing back slopes
3	flat upland areas
4	east- and west-facing back slopes
5	south-facing back slopes

between fractal dimension and severity, given that a severe fire is less selective in terms of the vegetation that it is capable of consuming. It is hypothesized that the perimeter of a severe burn may therefore be less complex than a burn scar whose shape results from variations in vegetation cover. The percentage of area burned within a perimeter may be indicative of the severity of the fire. A less severe fire may only burn the driest fuel types, while a more severe event is likely to consume a greater range of fuel types, including those with higher moisture content. The percentage of area burned and fractal dimension of the burned area were included in the severity model even though there was only one value for the entire fire because these factors were assumed to create variation in severity between fires.

Instantaneous-fire characteristics.—The variables that reflect the conditions under which the fire burned or characteristics of the fire itself at the time of the fire came from remote-sensing data as well as remote automated weather stations (RAWS). Remote-sensing data from the Moderate Resolution Imaging Spectroradiometer (MODIS) provided information on Fire Radiative Power (megawatts), frequency (count), and duration of fire detection (hours), and date of burn. The burn date information was used to create fire progression maps of burn date for an entire burn.

Burn date being thus available for the entire burned area, corresponding weather information and fire weather indices were derived for the date that a specific site burned. The effect of meteorological conditions on fire behavior is well documented (Cohen and Deeming 1985, Van Wagner 1987, Johnson 1992, Renkin and Despain 1992, Bessie and Johnson 1995, Nelson 2002, Chuvieco et al. 2004), and such factors are likely to affect severity as well by controlling fire behavior (such as the spread of fire by wind) and the moisture content of fuels (dependent on precipitation levels and relative humidity). The weather information was derived from the closest weather stations using methods described in Barrett et al. (2010). Temperature, relative humidity, and wind speed were collected at the remote automated weather stations, and this information was used to create metrics such as the fine-fuel moisture code, drought code, and duff moisture code, based on the Canadian Forest Fire Danger Rating System (Stocks et al. 1998). Comprehensive indices of fire weather such as fire weather index and daily severity rating integrate the information from RAWS to estimate fire conditions for a given date (see, e.g., Flannigan et al. 2005).

Fire severity model

The dependent variables used in the three models of severity (relative and absolute OL depth reduction and postfire OL depth) were estimates of changes in the surface organic layer. The relative and absolute OL depth reduction models are based on estimating a prefire depth, while the postfire OL depth is independent of prefire levels. For the development of the fire severity model, pre- and postfire organic layer depths were obtained from field measurements that were collected in a stratified sampling design across landscape positions. Measurements of residual OL depth were made at 72 sites in five large fire events totaling nearly 7000 km^2. The relative depth reduction was estimated using adventitious root depth, an indicator of the prefire depth of the surface organic material (Kasischke et al. 2008, Boby et al. 2010).

Classification and regression trees (CART) are frequently used to link ecosystem properties with remote-sensing data, particularly in the context of image classification (e.g., Friedl and Brodley 1997, Friedl et al. 1999, DeFries and Chan 2000, Ham et al. 2005, Pal 2005, Gislason et al. 2006). Additional uses of CART in ecological studies include habitat modeling (Andersen et al. 2000, Patten et al. 2006), forest successional dynamics (Bigler and Bugmann 2004), drivers of disturbance (Archibald et al. 2009, Barrett et al. 2010) and disturbance impacts (Golubiewski 2006, Orr et al. 2007, Johnstone et al. 2010*b*), and species distribution (Thuiller 2003, 2004, Lawler et al. 2006, Fitzpatrick et al. 2008, Randin et al. 2009). Regression trees are attractive given their ability to incorporate disparate data types including categorical variables and those with a nonlinear effect on the dependent variable. Regression trees can handle large data sets efficiently and can accept as many independent variables as the researcher cares to include (Breiman 2001). In cases where the relationship between independent and dependent variables is non-linear, these characteristics make regression trees a better choice than traditional ordinary least-squares regression models (OLS). Unlike OLS regressions, regression trees do not require a numeric variable, a linear (in some cases transformed) relationship with the dependent variable, or parsimony of independent variables.

One of the challenges of using regression trees is the lack of robustness, where every step (or node) in the model depends on the sequence of preceding steps. As a result, small changes in values above the terminal nodes can lead to significant differences in the model output. This difficulty can be addressed by creating hundreds of trees using a subset of the data with replacement and using the average of the trees as the final output. The creation of multiple trees to improve the robustness of the regression tree output is known as an ensemble technique, of which there are many varieties.

Random forests, similar to other ensemble techniques, use hundreds of regression trees created from a subset of the input data (Breiman 1996, Breiman 2001). The tree structure in a random forest model is limited by how many independent variables are permitted in each tree (Breiman 2001, Liaw and Wiener 2002). The number of independent variables used in every tree influences the explanatory power of the model as well as the correlation between each tree (Breiman 2001). The random forest model attempts to balance these two

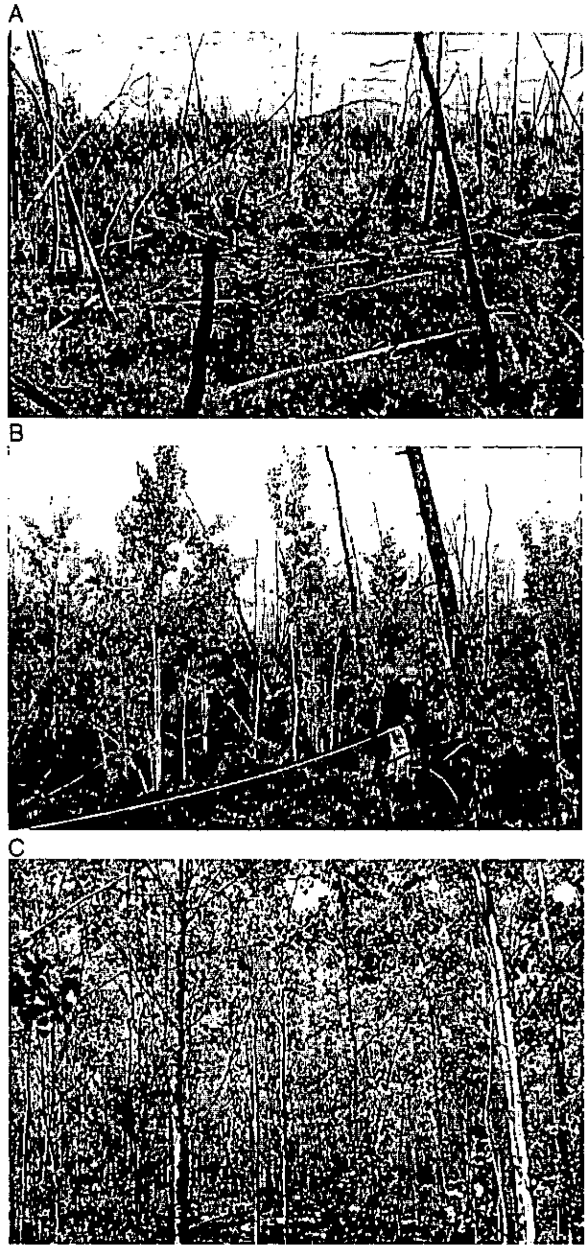

FIG. 3. Variations in patterns of regrowth as a function of depth of the residual organic layer depth. (A) A site with >10 cm of organic matter. The vegetation in this site is dominated by a shrub layer resulting from vegetative reproduction and spruce saplings. (B) A site with ~8 cm of organic soil (photo taken in the summer of 2009 in a site that burned in 1987). The vegetation in this site includes a shrub layer resulting from vegetative reproduction and both aspen and spruce saplings (photo taken in the summer of 2009 in a site that burned in 1990). (C) A site with <2 cm of organic soil. The vegetation in this site is dominated by aspen saplings. Also note the absence of a shrub layer. Photos credits: E. Kasischke.

factors by comparing the training error of the model with the correlation between input trees (Breiman 2001, Liaw and Wiener 2002). About one-third of the observations were withheld in the creation of each tree (Liaw and Wiener 2002). The model attempts to maximize the explanatory power of the model (minimize training error) and minimize the inter-tree correlation by constraining the number of explanatory variables permitted in each tree (Breiman 2001). In this case, 500 iterations were performed, a sufficiently large number to minimize generalization error (Breiman 2001). The default number of explanatory variables in the models of this study is one-third the number of inputs, or 11.

For this study, the random forest model was run for each dependent variable to produce estimates of severity for all of the large fires in 2004. The accuracy of each model was determined from a cross-validation wherein one observation was withheld from each model run and compared with the model output, similar to jackknifing. The relative contribution of independent variables was ranked according to the percentage decrease in accuracy (Breiman 2001). Independent variables are selected by the model based on their ability to split the remaining dataset into two groups with greatest difference of means.

Potential impacts of fire severity

The model of fire severity (postfire OL depth) makes possible an assessment of the likely impact of the 2004 fire season on postfire succession in the region, specifically the area that is susceptible to a shift from conifer to deciduous dominance or co-dominance. We estimated the cumulative impact of the previous decade of large fire years assuming that the same fraction of area burned experiences a shift in vegetation type as a function of burn severity.

We categorized expected patterns of vegetation and ecosystem recovery as a function of postfire organic layer depth based on recent field observations and modeling studies (Yoshikawa et al. 2003, Johnstone and Kasischke 2005, Kasischke and Johnstone 2005, Johnstone et al. 2010*b*, Shenoy et al. 2011). Sites with >10 cm of organic soil remaining after the fire are expected to come back as black spruce stands, with permafrost recovering to prefire conditions at some point (Fig. 3A). Sites with 3–10 cm of organic soil remaining after the fire are expected to recover as mixed deciduous–spruce stands, with permafrost taking longer to recover and having deeper active layers than the prefire conditions (Fig. 3B). Sites with <3 cm of organic soil remaining after the fire are expected to recover as deciduous-dominated stands, with permafrost being absent (Fig. 3C).

The perimeter locations of the 39 largest fires that burned in 2004 were obtained from the Alaska Large Fire Database (ALFD) from the Bureau of Land Management (Kasischke et al. 2002). The area that was spruce prior to the burn was determined from the "evergeen" category in the National Land Cover Database (NLCD; Vogelmann et al. 2001) map of the study area. The map is of sufficient accuracy to be used in this analysis (overall accuracy = 76%, accuracy of evergreen category = 84%; Selkowitz and Stehman 2011). The burned spruce areas (created by intersecting the ALFD with the NLCD data sets) were used to mask the study area to exclude other vegetation types.

According to the NLCD, which was compiled in 2001, ~8.4% of the interior is mature deciduous forest stands, and 7.8% of the area is mature mixed-forest stands co-dominated by coniferous and deciduous trees. The NLCD, based on remote-sensing imagery, does not differentiate the area of young aspen and black spruce stands that appear similar to shrubs in remote-sensing imagery. We used Yarie and Billings (2002: Table 2) to estimate the fraction of black spruce and aspen stands that are too young to be detected using remote sensing (50 years for black spruce and 20 years in the case of aspen). Using this approach, we determined that 20% of black spruce and aspen stands were in an early-successional phase, and therefore, were not included in the NLCD categories. We added these fractions to the estimates of fractional cover from 2001 and found that the total deciduous area including immature stands was 10.5% of the landscape, and that of mixed-forest stands was 9.8%.

In determining the impact of 2004 and large fire years from 2000 to 2009, we used the burned area estimates from the Alaska Large Fire Database. To determine the area of burned black spruce, we multiplied the total burned area estimate by 0.5, the typical fraction of burned area that is black spruce (Kasischke et al. 2010). This value was then multiplied by 0.8 to remove the fraction of area within a burn perimeter that is typically unburned (Kasischke et al. 2010).

Impact of large fires in 2004.—To analyze the severity of total area burned during the 2004 fire season, we used various geospatial data sets, including spectral and non-spectral data from remote-sensing platforms and fire weather data from weather stations. Fires smaller than 40 km^2 were excluded from the analysis. The total fire impacted area from the 39 fire events used in this study (~25 600 km^2 out of a total of 27 122 km^2 for all fires) was masked to only include mature spruce stands and to exclude areas that were missing reflectance data (i.e., due to cloud cover or from SLC-off ETM+ imagery) to yield a total sample area of 11 274 km^2 at 60-m resolution. Dependent variables used to determine fire severity were relative and absolute OL reduction and postfire residual OL depth. Thirty-six independent variables were incorporated in the severity model, broadly categorized as topographic, spectral, spatial, and instantaneous-fire characteristics.

Large fires between 2000 and 2009.—During the four large fire years of the 2000s, some 66 900 km^2 were impacted by fires, which represents 16% of the forested area in interior Alaska (Fig. 4). It has been determined that nearly 40% of the burned area in Alaska during the 2000s occurred during late-season fires (after July 31), compared to 17% in the previous four decades

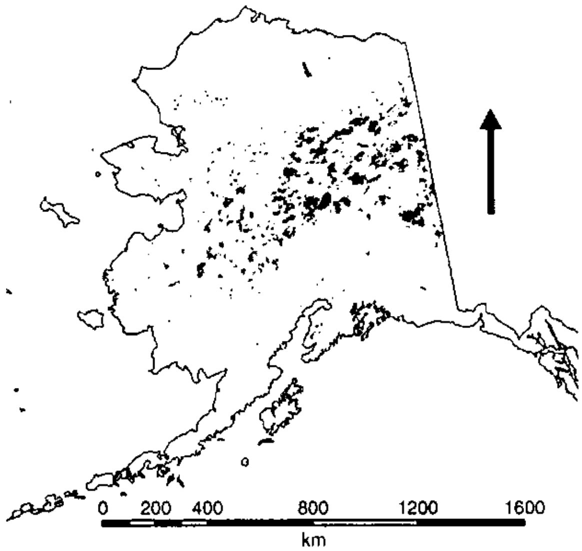

FIG. 4. Areas that burned in the Alaskan boreal forest during large fire years from 2000 to 2009.

(Kasischke et al. 2010). Because deeper burning of the surface organic layer in black spruce forests increases during late-season fires, this recent change in the fire regime has the potential for causing significant changes to these ecosystems.

The impact of the previous decade (2000–2009) on vegetation composition was estimated based on the results from 2004. From 2000 to 2009 there were four large fire years (defined as those years in which >1% of the total area burned), which consumed an estimated 25 000 km^2 of black spruce. We assume that the fraction of area burned that is severe to intermediate in severity is constant across large fire years for the most recent decade (2002, 2004, 2005, and 2009). We used this information to estimate the changes in the fraction of deciduous dominant or codominant stands vs. spruce in the Alaskan boreal forest that may result from moderate and deep-burning fires.

In determining the areas with low to intermediate values of postfire OL depth, two versions of the dependent variable were used. Given the tendency of the random forest model to underestimate the range of data, in estimating the area with <3 cm postfire OL depth the log of the dependent variable was used and the antilog of the output was evaluated.

RESULTS

The jackknifing cross-validation method indicated that the performance of all three fire severity models was satisfactory (Fig. 5). The explanatory power of the model was high for all three models ($R^2 = 0.94$, 0.96, 0.95) for absolute reduction, relative reduction, and postfire OL depth, respectively), and while the mean of each output is close to the model-predicted mean, the range of values for each metric are somewhat smaller

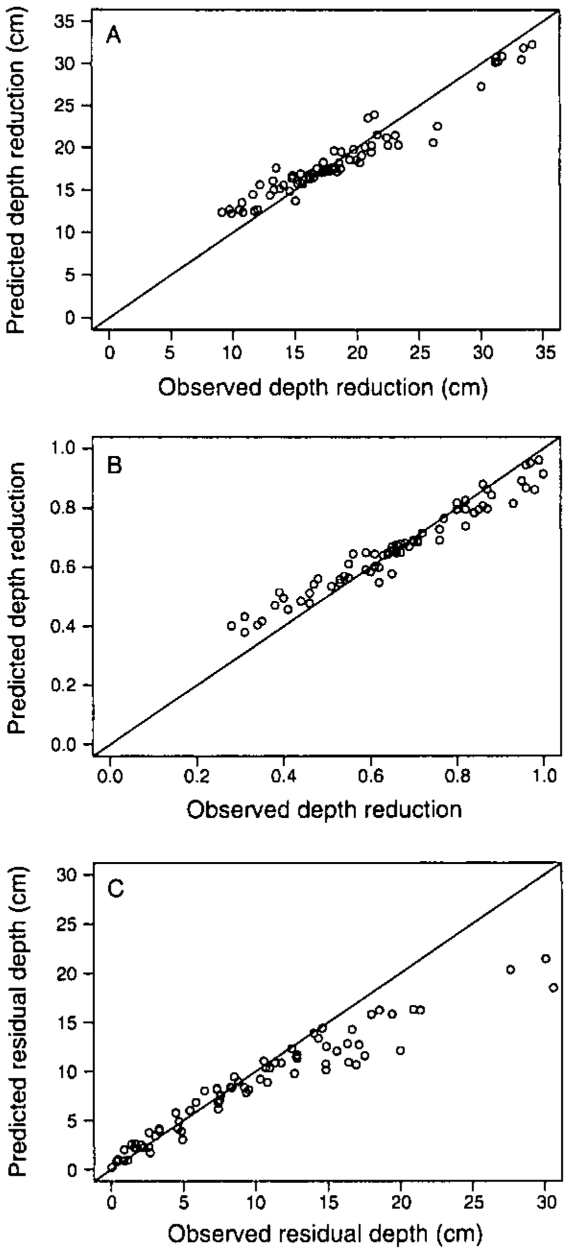

FIG. 5. Scatterplots of modeled vs. observed (A) OL depth reduction values, (B) relative OL depth reduction values (unitless), and (C) postfire OL depth values.

than the observed data. Outliers occur at high and low extreme values, where the models tend to underestimate high values and overestimate low ones. The decrease in the range of modeled values may be the result the ensemble technique used in this study, which takes the average of many runs. Examples of the outputs for the Boundary Fire provided in Fig. 6 illustrate absolute reduction, relative reduction, and postfire OL depth, respectively.

The importance of each input to each model, based on the mean decrease in percentage accuracy, is shown in Fig. 7. The ranking of variables is not consistent across models, which may be a function of the large number of independent variables included in the analysis. The average rank of each variable type (topography, instantaneous-fire characteristics, spectral information, and spatial information) is displayed in Fig. 8. By summarizing the importance of each variable type, a general pattern emerges wherein variables related to topography are most important, followed by fire characteristics, and to a lesser degree, spectral data and spatial characteristics. In one model, absolute depth reduction, the spatial information was as important as topography.

In the model of postfire OL depth, the model output was the log of the independent variable for values <3 cm. The log transformation yielded an R^2 of 0.74 for values <5 cm, while the model of untransformed values had an R^2 of just 0.42. The proportion of the study area that had and OL <3 cm was 14%. If we include burned areas that were not included in the study (e.g., due to cloud cover or that burned in smaller fires) this amounts to 1520 km^2 of burned black spruce stands from 2004 that have a strong potential to regenerate as deciduous-dominated stands and lose permafrost as a result of the shallow postfire OL. In the case of intermediate OL depth, the untransformed OL depth was used as the dependent variable, and the proportion of area burned with 3–10 cm of OL depth was 25%. The area that was susceptible to deciduous co-dominance and permafrost loss as a result of intermediate fire severity in 2004 was, therefore, 2710 km^2.

Based on the model results, the effect of large fire years in the past decade has been to potentially increase areas dominated by deciduous regrowth from 10.5% to 11.2%, and to increase areas with codominant conifer and deciduous vegetation from 9.8% to 11.1% (Table 3). The entire area affected by these potential changes amounts to ~10 100 km^2 (Table 4), which is ~2.0% of the entire boreal forest in the interior Alaska region or 4.2% of areas dominated by black spruce in the region.

DISCUSSION

In the course of this study we sought to determine what types of information are most important in estimating fire severity (organic layer depth reduction) at a regional scale, and to model the extent of spruce forests that may experience a high enough severity to impact recovery from the disturbance. Changes in dominant forest type from fire disturbance are critical baseline information for modeling the interactions between disturbance, climate, and vegetation characteristics at the regional to global scale. Models of fire severity are useful for investigating the potential for ecological shifts to a novel mix of coniferous and deciduous stands that will affect important climate drivers such as albedo and carbon cycling. Regionally, such changes are likely to affect wildlife populations (and, consequently human use of these resources) in terms of the vegetation available for forage and habitat. Fire management agencies may wish to use a model of severity to determine which fires are more likely to lead to a shift in dominant forest type and therefore merit greater efforts toward preventing fire spread. The results of this study suggest that shifts in stand-level composition in the Alaskan boreal forest are significant and that these changes are likely to accelerate if fire activity increases in response to warming trends as predicted in some studies (Flannigan et al. 2005).

Contribution of independent variables

The rank of variables by type (topography, instantaneous-fire characteristics, spectral information, and spatial information; Fig. 8) was generally consistent among the three models of severity. The importance of spatial characteristics in determining absolute depth reduction appears to be an anomaly cause by the high importance of fractal dimension, though it is unclear why the input is so highly ranked in only one of the severity models. That the rank of variable importance varies by type was noticed in an earlier analysis of fire severity with a smaller area of study in interior Alaska (Barrett et al. 2010). We can divide the variable types according to those that constitute the spatial context of the event (topography variables) and those that contain information regarding the disturbance (spectral data, spatial data, and instantaneous-fire characteristics).

Interestingly, the most important variable type (topography) in determining severity was unaltered by the disturbance event. That is, unlike spectral or spatial data, the topographic information is not a direct reflection of the postfire environment. Topography forms the context of fire severity, in that it occurs at scales greater than that of the analysis. The next most important data type, the fire-related variables, represent the mechanisms (occurring at a finer scale) by which the organic layer is reduced Notably, the fire resistance score highlights the importance of landscape position and resulting drainage characteristics in affecting burn severity (Kane et al. 2007, Johnstone et al. 2010*a*, Yi et al. 2010, Turetsky et al. 2011). The variables related to the causes of fire severity are, therefore, more important than those that describe the postfire conditions. This finding is significant in the context of efforts to use spectral data to determine fire severity in the Alaskan interior (e.g., Epting et al. 2005, Duffy et al. 2005, 2007, Allen and Sorbel 2008). The performance of spectral indices designed to detect variations in fire severity have performed poorly in the Alaskan boreal forest (French et al. 2008, Hoy et al. 2008, Murphy et al. 2008, Verbyla et al. 2008), most likely because the most important aspect of severity, OL reduction, does not usually modify the surface reflectance properties except for deep-burning fires where mineral soil is exposed. The rank of input variables that reflect the causes of fire severity demonstrate the usefulness of including non-spectral data in determining fire severity in black spruce stands (Beck et al. 2011).

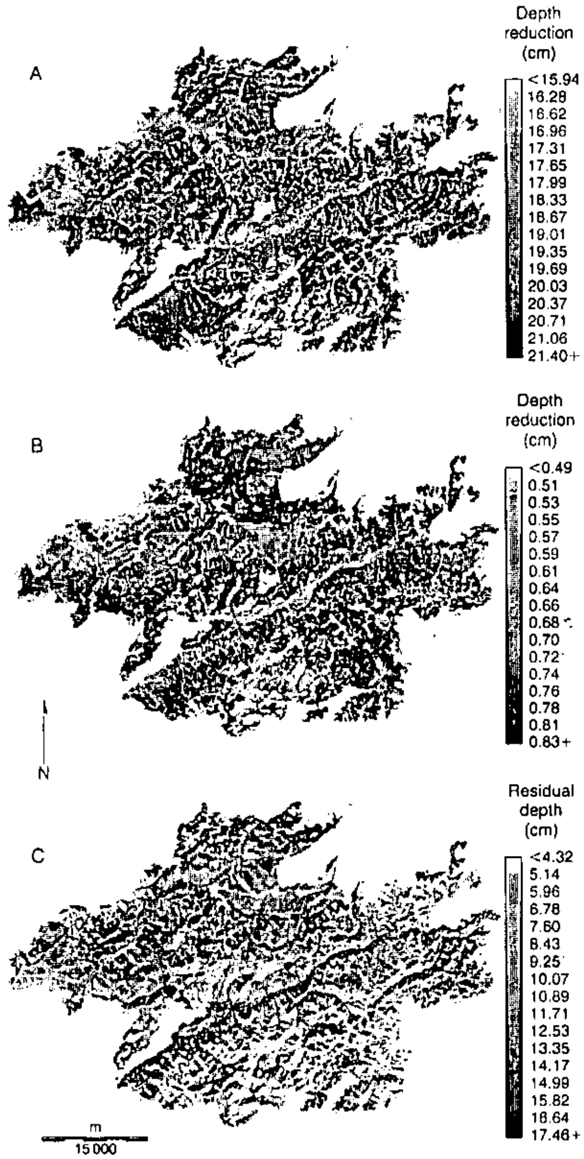

FIG. 6. Modeled severity conditions in the Boundary Fire burn scar: (A) OL depth reduction, (B) relative OL depth reduction (unitless), and (C) postfire OL depth.

Severity model outputs

Fig. 6 shows an example of the three severity model outputs: absolute OL depth reduction, relative OL depth reduction, and postfire OL depth for the Boundary Fire event. The lightning-caused fire began in mid-June 2004, and burned until late August. Fig. 6C (residual organic layer depth) shows nearly the opposite spatial pattern from the first two. This follows logically from the fact that the first two are essentially maps of removal of organic material and the last is a map of what was not

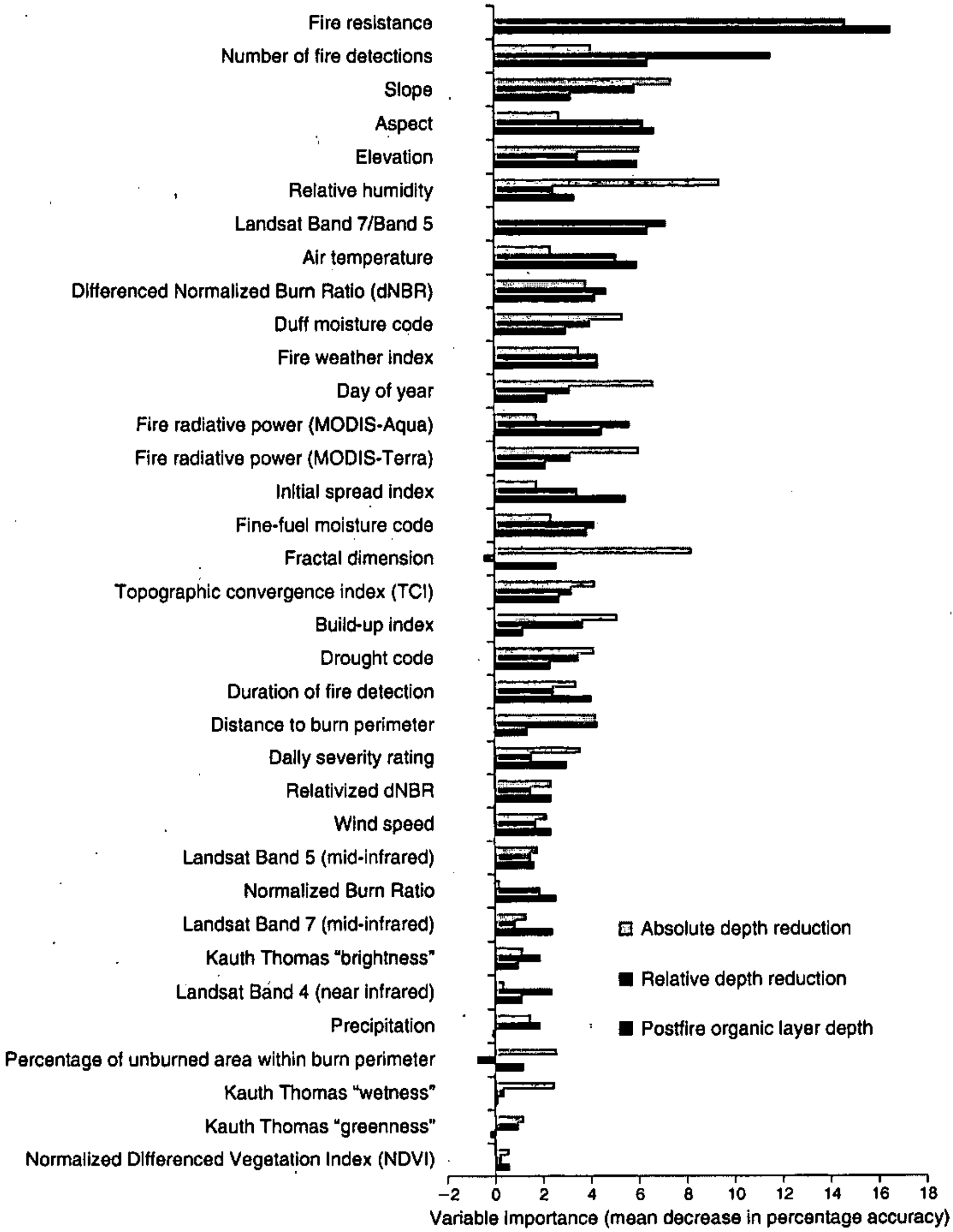

FIG. 7. Variable importance for each model. MODIS-Aqua and MODIS-Terra are two satellite platforms that collect data using the Moderate Resolution Imaging Spectroradiometer.

removed by fire. The maps of OL depth reduction appear similar in the spatial distribution of severe burning. The center of the scar, which burned earliest in the season, is not as severe as those areas close to the perimeter, which burned much later. The differences between relative and absolute depth reduction likely reflect differences in prefire OL depth, as the same burn depth will represent a different relative amount based on prefire conditions.

Increased boreal deciduousness

The proportion of the Alaskan interior that is deciduous has fluctuated over geological time scales, from co-dominance with shrubs and grasses during the

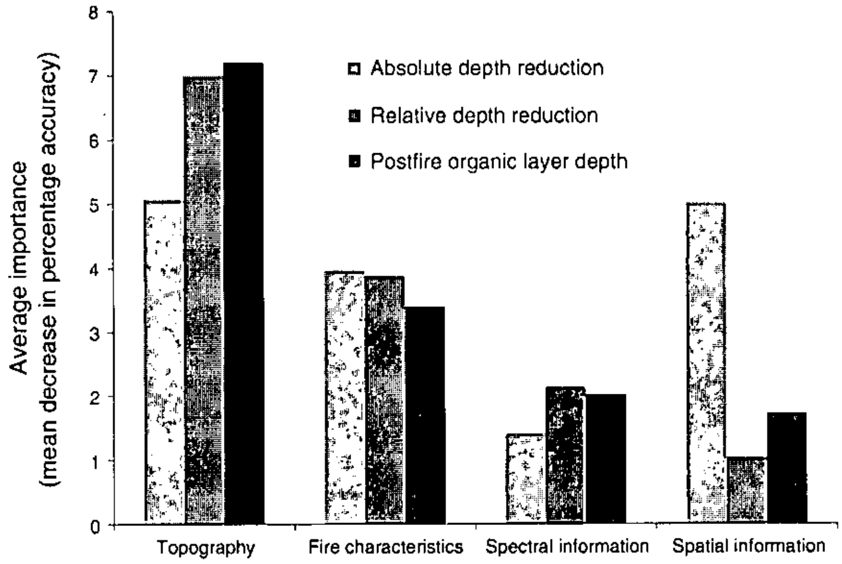

FIG. 8. Variable importance by type.

early Holocene to an expansion of alder during warmer and drier conditions about 8000 YBP to the present landscape dominated by black spruce (Lloyd et al. 2006). Warmer temperatures in the interior have generally been associated with more deciduousness, but not necessarily greater fire activity (Barber and Finney 2000, Lynch et al. 2003, Lloyd et al. 2006). It is likely, however, that increased fire activity and the associated impact on surface organic layers will cause a shift towards increased deciduousness in the interior in the context of warmer and drier climate conditions (Johnstone and Kasischke 2005, Johnstone and Chapin 2006).

Increases to the area occupied by deciduous and mixed stands that may result from large fire years in the most recent decade are modest compared to the entire boreal forest of interior Alaska (2.5%), but they represent major gains as a fraction of the landscape covered by deciduous dominated or codominant forest stands (a relative increase of 20%). Analyses that have tracked or modeled changes in albedo resulting from postfire succession have speculated that postfire changes related to increased deciduousness are significant (Randerson et al. 2006, Lyons et al. 2008). Postfire OL depth represents a fundamental biophysical control on the vulnerability of the landscape to shifts in species dominance (Johnstone et al. 2010*b*), and successional growth will likely respond to such controls over the medium term (Johnstone et al. 2004, Lyons et al. 2008, Shenoy et al. 2011).

In addition to the successional trajectories evaluated in this analysis, there is the possibility of recruitment failure of arboreal species, likely to be associated with low soil moisture (Kasischke et al. 2007, Johnstone et al. 2010*a*). In the event of recruitment failure, the burned area is typically dominated by graminoids such as *Calamagrostis canadensis* and shrubs such as *Salix* and *Betula nana*. For this reason it is possible that the fraction of area that is susceptible to deciduous regeneration after a fire may be overestimated. Some of the black spruce stands burned in 2004 and other large fire years may be vulnerable to recruitment failure, in which case some of the ecosystem impacts will be similar to those resulting from a shift to greater deciduousness (such as the loss of soil carbon), while

TABLE 3. Observed fractional cover of plant functional types in the Alaskan boreal forest in 2001 and estimated changes as a function of severity of fire disturbance.

Cover type	Percent cover in 2001	Estimated percent cover in 2001	Change (%)
Deciduous forest	10.50	11.23	6.90
Evergreen forest	48.61	46.59	−4.15
Mixed forest	9.81	11.11	13.19

Source: National Land Cover Database (NLCD; Vogelmann et al. 2001).

TABLE 4. Area of black spruce stands (*Picea mariana*) burned in large fire years from 2000 to 2009.

	Area burned (km^2)		
Year	Total burned	Severe burn	Moderate burn
2002	3351	469	838
2004	10 250	1435	2563
2005	7607	1065	1902
2009	4674	654	1169
Total	25 882	3624	6471

Note: The fraction of area that is severely burned (postfire OL < 3 cm) is 14%, and the fraction that is moderately burned (3 cm < OL < 10 cm) is 25%.

others may be very different (such as storage of carbon in aboveground biomass).

Small fire years that occur during cooler, wetter years are likely to be dissimilar to large fire years in terms of severity. Fire severity during small fire years is an important area of research that deserves the same attention given to large fire years in this analysis. While the frequency of large fire years in interior Alaska appears to be changing in response to drying and warming trends (Kasischke et al. 2010), another complicating factor is the possibility that recovery from more severe fires is likely to modify the fire regime (Johnstone et al. 2010*a*) because deciduous forest stands are generally less flammable than coniferous forest stands. Deciduous species, having a higher moisture content in the aboveground biomass and lacking the ladder fuels present in spruce stands, are more fire resistant, and therefore should decrease fire frequency. This feedback of plant functional type dominance precludes extrapolation from observations of severity conditions very far into the future, even for multiple years of observation.

While the rates of increases in mixed forest and deciduous forests are large on a relative scale, the large fires in 2000 produced only a modest loss in spruce forest: 4.2% of the total. This result raises questions as to the rate at which changes in Alaska's fire regime will impact dominant forest cover type within Alaska through losses to its dominant forest cover of black spruce. Recent modeling studies have attempted to predict how changes to Alaska's fire regime will affect the distribution of dominant forest cover. The results from Rupp et al. (2006) suggest that a reduction in fire return interval in black spruce forests from 95 to 75 years would result in a 20–25% loss in areas dominated by black spruce within 50 to 100 years. It is unlikely, however, that the interior region of Alaska could sustain the level of burning observed in the 2000s for four to five decades. At some point, the loss of mature black spruce forests and the increase in early successional stands across the landscape will eventually have a negative feedback on fire activity and lower the frequency of large fire years. Thus, the rate of loss of black spruce forests is likely to be more gradual than shown by the modeling studies of Rupp et al. (2006).

Postfire deciduous dominance

The models performed well in terms of explanatory power and approximating fire severity. If the primary interest of an inquiry regarding severity is the general characteristics at a regional scale, the random forest model is adequate. If the focus of the analysis is on extremes of severity conditions, such as this analysis, it may be necessary to transform the dependent variable to "force" the algorithm to spend more computing resources on the range of interest. In this case, the log-transformation of the postfire OL depth yielded a satisfactory R^2 for the lowest range of values.

The increase in area that is susceptible to dominance or co-dominance by deciduous arboreal species such as *Populus tremuloides* and *Betula papyrifera* and decreases in the area dominated by black spruce will have a range of impacts on carbon cycling and energy exchange beyond the likely increase in fire return interval. Because the deciduous stands will have a higher albedo in summer and winter, the local radiative forcing effect in the absence of other factors would be cooling (Chapin et al. 2000, Randerson et al. 2006). Canopy surface area in a deciduous stand is lower than in conifer stands, however, providing less area for energy exchange than there would be in a conifer forest (Chambers et al. 2005). Warmer soils may result in increased production of aboveground biomass in trees, but the presence of leaf litter on the ground surface will reduce the presence of moss. Mosses and deep surface organic layers store large amounts carbon and transfer carbon to deeper, frozen soil layers as well as insulate and maintain ice-rich permafrost (Van Cleve et al. 1983, Burn and Smith 1988). The net effect on radiative forcing from increase in albedo, less frequent combustion, and an overall decrease in carbon storage is unknown (Bonan 2008).

The combustion of insulating organic layers is associated with permafrost degradation. The results of the modeling study of Yoshikawa et al. (2003) showed that areas with <10 cm of surface organic material are likely to lose permafrost, and are likely to experience additional changes in ecosystem structure and function beyond changes in dominant tree cover. In the case that there is a significant amount of ground ice present, the deepening of the active layer may serve to increase soil moisture. This is particularly true in the years immediately following fire disturbance when evapotranspiration is low. An additional possibility for areas with a deeper active layer is that there will be a greater volume available for holding moisture, which may shift soil moisture conditions to be generally drier (Hinzman et al. 2006). In the case that the permafrost thaws completely, the loss of the aquatard allows groundwater to drain vertically and the areas affected by more severe fires are likely to become drier. An important consideration for long-term implications of deep burning is whether or not permafrost will re-form, and if this will result in an eventual return to conifer dominance.

Conclusions

The methods outlined in this approach are effective at modeling broad-scale severity conditions and ecosystem response in terms of shifts in terms of dominant plant functional types. While the model performed reasonably well with respect to characterizing medium-range severity conditions, the range of the output was smaller than the observed data. The decrease in the data range may complicate estimating severity in very severe or very light burns.

The ranking of independent variables by type demonstrates the usefulness of incorporating data on the mechanisms and context of severity into the modeling framework. Remotely sensed data from the postfire reflectance characteristics and spatial pattern are likely to be secondary to information on the causes of severity in determining postfire organic layer depth in black spruce stands. The suitability of the random forest method has proven adequate for mapping OL depth reduction and postfire residual OL depth at a regional scale, an important consideration for land and natural resource management agencies and researchers. The data requirements for replicating this analysis however are large, and future research should focus on which data types are necessary to achieve a reliable accuracy for specific research goals.

The fraction of black spruce stands that are susceptible to a shift in successional type as the result of deep-burning fires over the last decade is ~4.2%. If subsequent decades exhibit the same fraction of black spruce vulnerable to fire-driven successional shifts, it will take ~200 years for the boreal forest to become a mixed conifer and deciduous ecosystem. Complete loss of spruce from the landscape is unlikely, however, because spruce stands on lowland areas are resistant to deep burning (Turetsky et al. 2011). Key questions that merit more detailed analysis are the fraction of deep-burning fires during small fire years and longer term competition between conifers and deciduous species in mixed stands.

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