

RESEARCH ARTICLE

Modeling impacts of fire severity on successional trajectories and future fire behavior in Alaskan boreal forests

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Abstract Much of the boreal forest in western North America and Alaska experiences frequent, stand-replacing wildfires. Secondary succession after fire initiates most forest stands and variations in fire characteristics can have strong effects on pathways of succession. Variations in surface fire severity that influence whether regenerating forests are dominated by coniferous or deciduous species can feedback to influence future fire behaviour because of differences in forest flammability. We used a landscape model of fire and forest dynamics to explore the effects of different scenarios of surface fire severity on subsequent forest succession and potential fire activity in interior Alaska. Model simulations indicated that high levels of surface fire severity leading to a prolonged phase of deciduous forest dominance caused a reduction in landscape flammability and fewer large fire events. Under low surface fire severity, larger patches

of contiguous conifer forest promoted fire spread and resulted in landscapes with shorter fire return intervals compared to scenarios of high surface severity. Nevertheless, these negative feedbacks between fire severity, deciduous forest cover, and landscape flammability were unable to fully compensate for greater fire activity under scenarios of severe climate warming. Model simulations suggest that the effects of climate warming on fire activity in Alaska's boreal forests may be partially but not completely mitigated by changes in fire severity that alter landscape patterns of forest composition and subsequent fire behaviour.

Keywords ALFRESCO · Black spruce · Boreal forest · Climate change · Disturbance · Fire regime · Forest regeneration · Simulation model · *Picea mariana*

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Introduction

The boreal forests of Alaska and northern Canada are dominated by a mix of deciduous and conifer forest cover types (Van Cleve et al. 1991). Stand-replacing wildfires are the main form of disturbance, and most forest stands are of wildfire origin (Payette 1992). Consequently, processes of secondary succession exert a dominant control over the temporal and spatial dynamics of these boreal forests (Van Cleve et al. 1991; Payette 1992).

The primary factors driving patterns of post-fire succession have typically been related to variations in topography or soils that affect site moisture and temperature (Van Cleve et al. 1991). In interior Alaska, forests of black spruce (*Picea mariana*) are a dominant cover type and are most frequent in areas of cool, moist soils (Calef et al. 2005). Post-fire succession in black spruce forests typically results in a fairly simple cycle of spruce self-replacement, with fire causing few changes in the composition of pre- versus post-fire vegetation (Van Cleve and Viereck 1981). However, differences in disturbance history can lead to stands of similar age and environmental conditions having very different patterns of forest composition (Turner et al. 1999; Johnstone et al. 2010).

Fire severity is an important aspect of the fire regime that can shape post-fire trajectories of vegetation recovery in many ecosystems (Turner et al. 1999; e.g. Keeley et al. 2005). Conifer-dominated boreal forests with extensive ladder fuels typically experience fires that burn both the forest floor and the tree canopy, resulting in high mortality of canopy trees (Johnson 1992). Although very severe canopy fires can destroy the aerial seedbanks of boreal conifers and thereby affect post-fire tree regeneration (Arseneault 2001), it is the fire severity on the forest floor that typically has the largest impacts on plant regeneration (Greene et al. 2007; Johnstone et al. 2010). In particular, the degree of fire consumption of soil organic layers has strong effects on patterns of tree seedling establishment (Johnstone and Chapin 2006a; e.g. Greene et al. 2007). Initial effects on tree recruitment can strongly influence subsequent patterns of stand development, or successional trajectories (Gutsell and Johnson 2002; Johnstone et al. 2004).

Typically, post-fire succession in black spruce leads to rapid replacement of the spruce on organic seedbed and recovery of the spruce canopy (Van Cleve and Viereck 1981). However, alternative trajectories dominated by deciduous trees may be initiated when severe combustion of the organic soil exposes mineral seedbeds and favors the recruitment of deciduous hardwoods (Johnstone et al. 2010). As fires become larger and more frequent in response to regional climate warming (Kasischke and Turetsky 2006; Duffy et al. 2007), corresponding increases in surface fire severity could contribute to changes in

forest cover via altered successional pathways (Johnstone et al. 2010). Thus, projecting the future impacts of changing climate and fire regimes on forest composition requires consideration of not only the changing distribution of stand ages and successional stages (e.g. Kurz and Apps 1994; Suffling 1995), but also of fire effects on successional trajectories.

Interactions between fire severity and successional trajectories could play an important role in regulating future climate effects on boreal fire regimes if shifts in forest cover feed back to affect future disturbance probability (Higuera et al. 2009). The initiation of deciduous or mixed deciduous-conifer successional trajectories on sites previously dominated by self-replacement cycles of black spruce has important implications for forest fuel types and potential fire behavior (Hély et al. 2000; Cumming 2001; Krawchuk et al. 2006). Black spruce stands represent a highly flammable configuration of fuels because of the large amounts of fine twigs and needles, high resin content, low moisture content, and large quantities of fine ground fuels that are connected to the canopy by low-lying tree branches. Lichens and feather mosses in the understory of black spruce communities are also highly flammable (Johnson 1992). In contrast, stands with increasing components of hardwoods have lower canopy bulk density, less flammable resins, increased moisture content of the canopy and fine fuels, and reduced ground and ladder fuels, all factors that contribute to lower flammability (Johnson 1992; Hély et al. 2000). The potential for deciduous stands to act as fire breaks makes transitions from conifer- to deciduous-dominated stands one of the main goals for fire hazard reduction in boreal forests (Chapin et al. 2008). Understanding the factors that can shift spruce-dominated forests to successional pathways dominated by deciduous species is a key element in developing adaptive fire management in the boreal forest and in predicting how changing fire regimes may shape future forest composition.

Here, we use a landscape model of fire and forest succession to investigate the impacts of fire severity on forest composition and future fire activity within a boreal forest landscape in interior Alaska. We use empirical relationships between fire size and severity from a 2004 fire to calibrate the simulation of spatial patterns of fire severity and develop plausible simulations of fire severity for burned landscapes. Using

the landscape simulation model ALFRESCO (Rupp et al. 2000, 2007), we perform simulation experiments to quantify the impact of fire severity scenarios on patterns of secondary succession, landscape forest composition, and future fire dynamics in a boreal forest landscape. The results of these simulation experiments provide insight into how interactions among forest succession, fuel types, and fire behavior may regulate the responses of boreal forests to changing climate and fire regimes.

Methods

Study area

This modeling study focuses on boreal forests of interior Alaska, a region bounded by the Brooks Range mountains to the North, the Alaska Range mountains to the South, maritime tundra to the West, and the Yukon border to the East. This region is composed of forests dominated by a mix of deciduous broadleaf and conifer tree species that are distributed based on broad and partially overlapping environmental requirements (Calef et al. 2005). The most common and widespread forest type is dominated by black spruce (*Picea mariana*), which occurs in cool and moist areas, particularly valley bottoms and uplands underlain by permafrost. Conifer forests dominated by white spruce (*Picea glauca*) are common in river floodplains and well-drained uplands, where soils are warm and mesic. Forest types dominated by deciduous trees such as aspen (*Populus tremuloides*) and birch (*Betula neoalaskana*) are also associated with areas of warmer soils (Kurkowski et al. 2008) and often occur as transitional forests in succession to white spruce dominance (Chapin et al. 2006). Fire is the major type of landscape disturbance in these forests and is the primary initiator of secondary succession (Van Cleve et al. 1991; Chapin et al. 2006).

We used detailed information from the 2004 Boundary Fire in interior Alaska (Fig. 1) as a case study from which to build representative scenarios of fire severity and successional trajectories within simulated fire scars. The Boundary Fire ignited from a lightning storm and was first reported on 13 June 2004 and expanded into September, eventually burning a total area of over 217,000 hectares. This large

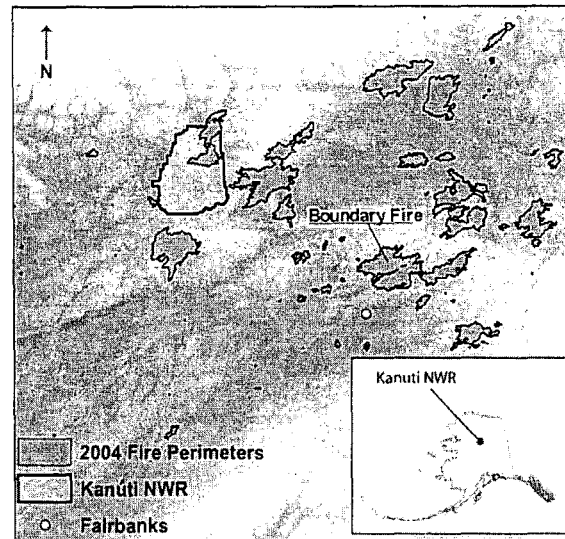


Fig. 1 Map of the study area in central Alaska showing the location of 2004 fire perimeters, including the 2004 Boundary Fire, as well as the focus area for modelling simulations within the Kanuti National Wildlife Refuge (NWR). The location of the city of Fairbanks, Alaska is shown as a unfilled circle in the central part of the study area

fire represented a wide range of fire severity and pre-fire vegetation due to the long duration of fire activity and high topographic variation within the fire perimeter. We used a remotely sensed index, the differenced normalized burn ratio (dNBR) to classify severities within the perimeter of the Boundary Fire. This index has been used successfully to estimate boreal fire severity (Epting et al. 2005; Duffy et al. 2007), although the index appears to saturate and become less informative at very high severities (Hoy et al. 2008). For this study, we used Landsat sensor spectral reflectance data from 18 July 2003 and 6 September 2004 to compute dNBR for each 100-m pixel within the fire perimeter. Severity classes of unburned, low severity, moderate severity, and high severity were then assigned to each pixel based on a its dNBR value (Epting et al. 2005).

Summary of the model

ALFRESCO is a landscape simulation model that was originally developed to simulate responses of subarctic vegetation to changes in climate and disturbance regime (Rupp et al. 2000). Subsequent model developments have created a boreal forest version of ALFRESCO that specifically explores the

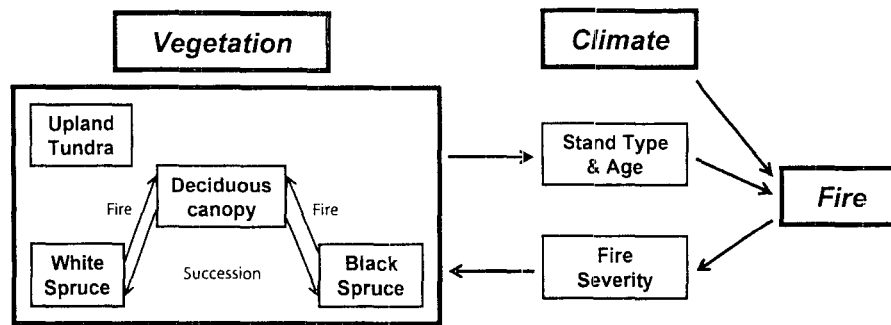


Fig. 2 A conceptual diagram of the ALFRESCO simulation model used in this study. The model simulates changes in vegetation states (*left box*) as a function of fire and succession, and fire activity as a function of vegetation and climate. The variables shown in *boxes* in the figure represent variables characterized for each pixel in the model at each time step.

Spatial datasets used to parameterize the model are: down-scaled climate patterns, which include topographic effects on climate, initial land vegetation cover (also influenced by topography), and classification of the landscape into flat and complex terrain forms to parameterize spatial correlation in fire severity (see the text for more details)

interactions and feedbacks between fire, climate, and vegetation in interior Alaska (Rupp et al. 2002, 2007). Previous research with the model has emphasized that fire-frequency changes—both direct (climate-driven or anthropogenic) and indirect (as a result of vegetation succession and species composition)—strongly influence landscape-level vegetation patterns and associated feedbacks to future fire regime (Rupp et al. 2002; Brubaker et al. 2009). A detailed description of ALFRESCO can be found in earlier references (Rupp et al. 2000, 2002). Here we provide a brief summary of the model and focus on details pertinent to this specific study.

ALFRESCO is a spatially explicit state-and-transition model that simulates vegetation succession and fire spread in Alaska's boreal forest at scales of 1×1 km and at annual time steps (Rupp et al. 2000, 2007). The primary spatial process is the stochastic simulation of fire regime. Fire initiation and subsequent spread are simulated based on a flammability coefficient that is determined by climate and modified according to vegetation type and successional age (Fig. 2; Table 1). Vegetation and succession effects mimic changes in forest flammability resulting from different forest fuels (e.g. Hély et al. 2000; Cumming 2001; Krawchuk et al. 2006), but fuel loads are not simulated directly. Climate effects on flammability are a weighted function of monthly average temperatures for March–June, and monthly precipitation totals for June–July. The form of this equation follows a statistical model that explains 79% of the variability in logarithm of annual area burned by Alaska fires from 1950 to 2004 (Duffy et al. 2005).

ALFRESCO uses a cellular automaton approach in which an ignited pixel can spread fire to any of its eight neighbouring pixels. Ignition of a pixel is determined using a random number generator and is a function of its flammability. Multiple pixels may be ignited in a single annual time step. Fire spread to neighbour pixels depends on their flammability and the presence of firebreaks such as non-vegetated mountain slopes, rivers, and lakes. The rate at which different vegetation types burn in ALFRESCO was parameterized from published records of stand ages and fire activity rates (Yarie 1981; Cumming 2001). A sensitivity analysis of the model revealed that area burned was highly nonlinear with flammability factor (Rupp et al. 2000). As a result, baseline calibration runs were used to compute the actual flammability factors needed to produce the computed burn rates for each vegetation type (Rupp et al. 2007). Previous applications of the model have shown a strong agreement between simulated fire patterns and both historic and paleoecological fire records in Alaska (Rupp et al. 2007; Brubaker et al. 2009).

The other landscape component modeled by ALFRESCO is vegetation cover and succession (Fig. 2; Table 1). An initial vegetation map was constructed by aggregating vegetation classes from the National Land Cover Database (Homer et al. 2004). ALFRESCO has three vegetation classes: upland tundra, deciduous forest, and black or white spruce forest (Table 1). Spruce forests were differentiated into stands dominated by black or white spruce based on empirical relationships between site topography and forest composition (Calef et al. 2005;

Table 1 Summary of states and transition dependencies that define the state-and-transition dynamics in the ALFRESCO model simulations

Variable type	Possible states	Transition dependencies
Fire status	Burned	Ignition or adjacent to burned cell
	Unburned	Climate Current forest type Stand age
Fire severity	Low severity	Fire status
	High severity	Fire size Topographic complexity
Stand age	Time (years) since last fire	Number of time steps since burned
Current forest type	Deciduous	Successional endpoint
	Black spruce	Stand age
	White spruce	Fire severity
	Tundra	
Successional endpoint	Black spruce	Initial land cover classification
	White spruce	Topography (black spruce vs. white spruce)
Topographic complexity	Tundra	
	Flat	Static
	Complex	

Kurkowski et al. 2008). Fire causes a transition from spruce forest to early successional deciduous vegetation as a result of fire-induced tree mortality (Fig. 2). Deciduous vegetation was modeled as an early stage in succession to spruce forest that conceptually includes initial herbaceous and shrub-dominated stages of succession (Chapin et al. 2006). Consequently, all deciduous stands in the model eventually succeed to spruce forest, except when interrupted by fire. The time required to transition to spruce forest is shorter for black spruce than white spruce forests, as black spruce forests generally self-replace after fire with only a short intervening stage of shrub dominance (Van Cleve and Viereck 1981; Chapin et al. 2006). The ages of stand transitions from deciduous to spruce-dominated stands were identified from the literature (Van Cleve and Viereck 1981; Chapin et al. 2006), and were modeled with a small stochastic element to include variability in transition times. For simplicity in this modeling exercise, cells designated as tundra vegetation were assumed to be static.

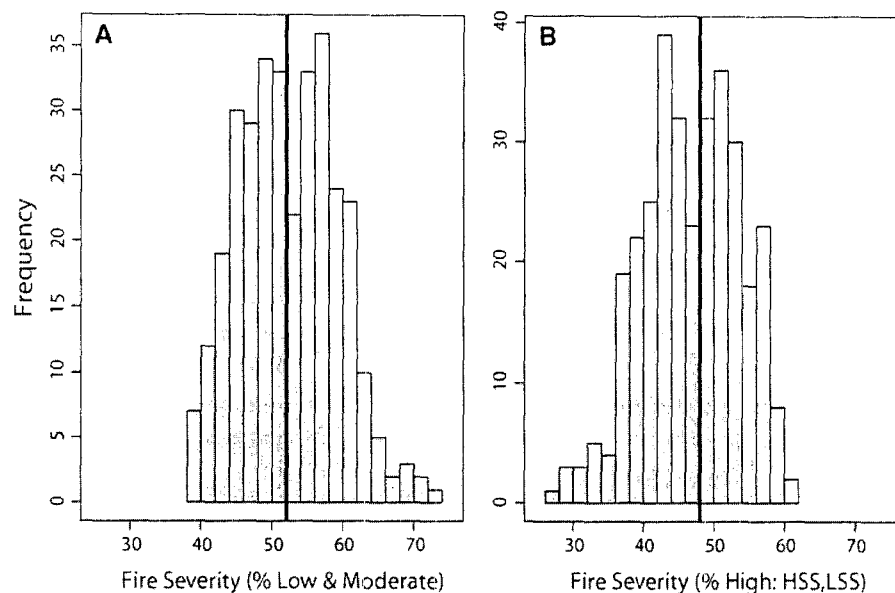
Fire severity implementation and calibration

Simulated patterns of fire severity were applied to ALFRESCO fire scars based on previously described

statistical relationships between fire size and fire severity in Alaska (Duffy et al. 2007). First, the proportion of severely burned pixels increased with fire size to reflect that larger fires typically occur during long drought periods or late in season when soils have thawed, leading to a greater potential for high consumption of biomass (Skinner et al. 2006; Kane et al. 2007). Second, fires burning in flat areas had greater spatial correlation in fire severity than those burning in complex topography (Duffy et al. 2007). In ALFRESCO, a burned pixel would first be assigned a fire severity classes as a function of fire size and then pixels in flat areas would have their severity class adjusted probabilistically based on the pixel the fire spread from (Table 1). Incorporation of these rules in the model resulted in larger fires having a larger proportion of pixels classed as high severity and lower heterogeneity in fire severity in flat portions of the landscape.

The scenarios of fire severity used in our simulations were calibrated based on the remote sensing classification of fire severity using dNBR (Epting et al. 2005) applied to the 2004 Boundary Fire. Our fire severity scenarios explicitly accounted for different levels of canopy and surface fire severity that are important for vegetation succession (Johnson

Fig. 3 Histograms of the frequency of pixels classed as **a** low to moderate canopy fire severity and **b** high canopy fire severity in ALFRESCO simulations for fire sizes between 1500 and 2500 km². The vertical line in each panel shows the actual proportion of pixels in different fire severity classes observed in the Boundary Fire using remote sensing



1992). Simulation of the proportion of low, moderate, and high canopy severity were calibrated to the 2004 Boundary Fire such that the most common distribution of low vs. high canopy severities corresponded to the observed distribution in the Boundary Fire (Fig. 3). Although the dNBR index distinguishes low and high classes of canopy fire severity, it is less sensitive to surface fire severity, or the consumption of the soil organic layer (Hoy et al. 2008). To evaluate the impacts and sensitivity of the model to surface fuel consumption, we applied three scenarios of surface fire severity (SFS): (1) low SFS, where all areas mapped as having high crown severity were designated as having low surface severity; (2) high SFS, where areas with high crown severity were designated as also having high surface severity; and (3) mixed SFS, where 50% of the areas having high crown severity were designated as having low surface severity. These scenarios reflect that there can be large variations in surface fuel combustion even in stands with a high canopy mortality due to fire (e.g. Greene et al. 2005).

Mixed classification of SFS (the MIX scenario) was applied to the landscape in a non-random fashion, such that valley bottoms, northern aspects, and shallow slopes had low surface severity, and high severity occurred on south-facing aspects and steep slopes. This corresponds to expectations that high consumption of the organic layer is most likely to occur in more well-drained parts of the landscape,

especially areas without permafrost (Kane et al. 2007).

The simulation experiments required modifying the fire and vegetation states in ALFRESCO to use fire severity as a factor determining successional transitions within a pixel (Fig. 2; Table 1). Our parameterization was based on previous research showing that black spruce forests subjected to high severity fires have increased establishment of deciduous trees (e.g. Greene et al. 2007; Johnstone et al. 2010). This early post-fire establishment strongly influences subsequent canopy composition (Gutsell and Johnson 2002; Johnstone et al. 2004). Thus, black spruce sites with high deciduous recruitment after fire are likely to experience a prolonged period of deciduous dominance prior to returning to spruce canopy dominance. This alternative successional trajectory for black spruce forests is contingent on fire behavior and thus represents a potential feedback between changing fire regime and forest landscape composition.

The rules for recovery of black spruce forests after fire were modified from previous versions of ALFRESCO (Rupp et al. 2000, 2007) to incorporate the effects of fire severity on successional trajectories (Table 1). Black spruce pixels with low to moderate canopy severity were modeled as returning to black spruce canopy dominance following a short, 15–30 year period of deciduous (shrub) dominance. Pixels mapped as having high canopy severity were

assumed to have close to 100% canopy mortality, and therefore required a longer period of succession to return to spruce dominance. In this case, the amount of time to succeed to spruce dominance was modeled as a function of surface fire severity. Pixels with low surface severity followed the typical self-replacement successional trajectory used in ALFRESCO, in which pre-fire black spruce pixels returned to a canopy dominance of black spruce following an intermediate shrub phase lasting 30–50 years (Van Cleve and Viereck 1981; Chapin et al. 2006). In pixels with high surface severity, transitions from deciduous to black spruce dominance required 75–150 years, mimicking the timing of spruce emergence into the canopy (Bergeron 2000; Gutsell and Johnson 2002). State changes in forest cover types were modeled in a probabilistic fashion to occur within the specified age ranges. For example, only a few percent of pixels would be likely to transition to black spruce dominance 75 years after a severe surface fire, while 100% of pixels would have made this transition by the time they reached 150 years.

Simulation experiment

We used ALFRESCO to conduct a simulation experiment to assess the sensitivity of landscape vegetation composition and fire activity to the presence of alternative successional trajectories in black spruce forests following low vs. high severity fire. We used a simulation area encompassing the Kanuti National Wildlife Refuge (NWR), a large region of interior Alaska away from urban–wildland interfaces. The Kanuti NWR is located approximately 300 km to the northwest of Fairbanks and covers an area of 27700 km², roughly 13 times the size of the Boundary Fire (Fig. 1).

We performed a series of model runs for the Kanuti NWR region of interior Alaska with explicit simulation of fire severity and alternate successional trajectories for black spruce forests. We ran 500 simulation replicates for simulation periods of 800 years. We applied a factorial combination of simulation experiments to examine direct and interactive effects in ALFRESCO of scenarios of (1) fire severity and black spruce succession (low, mixed, and high surface fire severity) and (2) future climate conditions. The fire severity-succession experiment included: (a) a control scenario of low surface

severity (LSS), in which all burned pixels were modeled as having low surface severity and black spruce succession followed the original ALFRESCO parameterization; (b) a high surface severity (HSS) scenario, in which the maximum proportion of a fire polygon was modeled as having high surface fire severity and alternative successional trajectories for black spruce forest, and (c) an intermediate scenario (MIX), in which an intermediate proportion of the fire polygon was modeled with high surface fire severity and alternate succession for black spruce.

Two scenarios of future climate were used for the simulation experiments. Specifically, in conjunction with the A1B emission scenarios we used the years 2008–2099 from the CGCM3.1 and ECHAM5 models of the IPCC GCM suites (Solomon et al. 2007). These are 2 of the 5 best models for the state of Alaska (Walsh et al. 2008), and among the 5 best, the 2 selected have the greatest divergence of temperature predictions for the period chosen. Outputs from the CGCM3.1 and ECHAM5 models were regionally downscaled to a 1 × 1 km grid. Downscaling used the delta method (Hay et al. 2000) to superimpose climate predictions from the coarse-scale models onto finer-scale, observed spatial variations in the climate of interior Alaska. Observed climate patterns were derived from PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate maps (Daly et al. 2001). For each replicate simulation, an 800 year time series of climate was constructed from a randomly generated permutation of the downscaled model output. These climate scenarios did not include an impact of long-term changes in climate over time, as they were constructed to isolate the equilibrium effects of different fire severity scenarios under different climate conditions.

The effects of fire severity and vegetation succession scenarios on landscape fire hazard were assessed by comparing distributions of fire sizes from the fire simulation experiments. We also examined the size distribution of the 250 largest fires in each experiment, as it is the large fires that account for most of the area burned in a landscape (Kasischke and Turetsky 2006). We compared the cover frequency of different forest types and landscape patch metrics across simulation scenarios to evaluate how the different severity scenarios affected forest composition, patch configuration, and subsequent fire spread. We used the SDMTTools package in

R (R Development Core Team 2010) to characterize patch metrics. Responses to the different fire severity scenarios were compared among simulations with the climatic forcing from the two different GCMs to assess whether changes in successional trajectories influenced the simulated fire response to different climate signals.

Results

Simulations of forest types in ALFRESCO showed differences in average landscape composition between climate scenarios but not between severity scenarios. Deciduous forest cover averaged 49–50% in the CGCM3.1 scenario and 61–62% in the ECHAM5 scenario across all fire severity levels. However, variance over time in the proportion of the landscape occupied by deciduous versus spruce cover was greater in LSS compared to HSS scenarios under both climate scenarios (40.0 vs. 29.4 in the ECHAM5 scenario and 28.5 vs. 23.6 in the CGCM3.1 scenario).

Simulations under different scenarios of climate and fire severity showed clear effects of both climate

and successional trajectories on fire activity. Fire return intervals were always shorter in the warmer ECHAM5 climate compared to the CGCM3.1 climate within a given severity scenario (Table 2). Across fire severity scenarios, fire return intervals were longest in the HSS scenario, shortest in the LSS scenario, and intermediate in the MIX scenario. The effects of fire severity scenarios were largely additive and did not interact with climate effects in determining fire return intervals for pixels classed as black spruce forests. However, comparisons of fire return intervals within all forest pixels (including deciduous forest as well as black or white spruce forest) showed a non-linear interaction between climate and severity scenarios. Calculating fire return intervals for all forest pixels takes into account the lower flammability of deciduous forests. Within all forested pixels, fires occurred substantially more frequently under the LSS–ECHAM5 scenario than in any other scenario (Table 2). Switching from a low to high severity scenario in the ECHAM5 simulations lengthened the mean fire return interval by over 60%. However, although scenarios with more severe fires lengthened the mean fire return interval, this effect did not fully counterbalance the decreases in fire interval that were associated with a warmer climate (Table 2).

Simulations of fire ignition and spread under both climate scenarios showed clear differences in fire sizes and cumulative area burned between scenarios of low, mixed, and high surface fire severity (Fig. 4). Under both climate regimes, large fires occurred more frequently in the LSS scenario and less frequently in the HSS scenario. Differences between fire severity scenarios in the frequency of fires of different size classes were smallest for small fire sizes and greatest for intermediate to large fire sizes. The frequency distribution of fires in smaller size classes fully overlapped for the two climate scenarios. However, climate scenarios differed strongly in the simulated frequency of large fires, with many more large fires being simulated in the warmer ECHAM5 climate scenario than the scenario based on CGCM3.1 climate (Fig. 4). These differences resulted in different outcomes for cumulative area burned across both climate and fire severity scenarios within the 800-year model simulations (Fig. 5). Based on the slopes of the lines representing cumulative area burned, the annual rate of burning was 28% higher in the LSS vs. HSS scenarios under the

Table 2 Median fire return intervals (years between fires) simulated by ALFRESCO under two climate scenarios and three surface fire scenarios (N = 500 simulation replicates of 800 years each)

Pixel type	Climate scenario		
	Severity scenario	ECHAM5	CGCM3.1
Black spruce	LSS	55	71
	MIX	67	92
	HSS	82	106
All forests	LSS	67	103
	MIX	100	113
	HSS	109	118

Medians have been calculated for pixels classed as black spruce forest or a more inclusive grouping of all forested pixels, which include black spruce and white spruce pixels as well as deciduous pixels that are on a successional trajectory to spruce forest. The climate scenarios are based on scenarios of substantial vs. moderate warming for interior Alaska in 2100 from the ECHAM5 and CGCM3.1 models. Fire severity scenarios are based on the proportion of fire scars with severe surface burning and range from low surface severity (LSS) to high surface severity (HSS), with an intermediate mixed scenario (MIX)

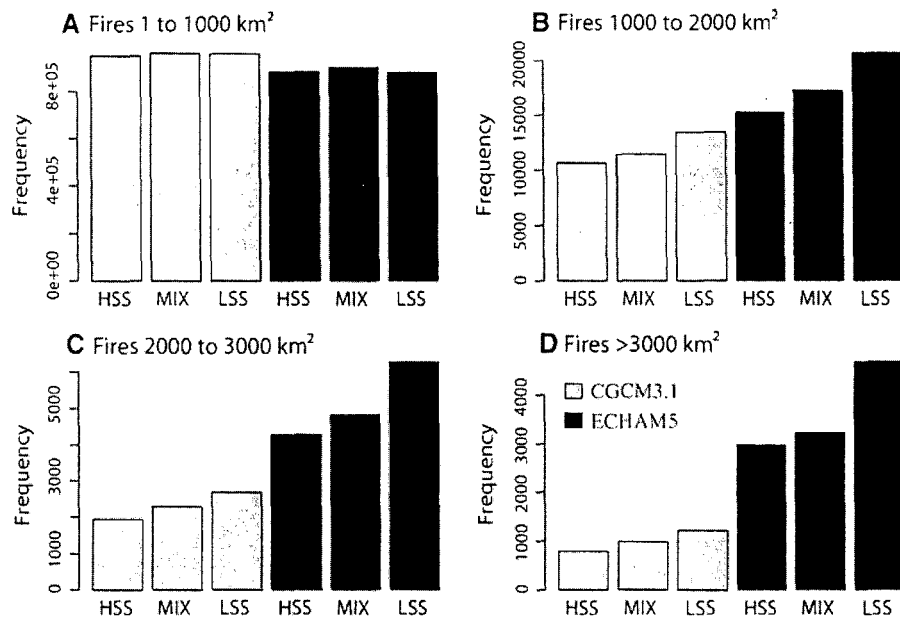


Fig. 4 Frequency of fires in different size classes (a–d, from smallest to largest) across different climate and severity scenarios (n = 500 replicate simulations of 800 years). Bars are ordered by fire severity scenarios along the x-axis (HSS

high surface severity, MIX intermediate surface severity, and LSS low surface severity) and color-coded by climate scenarios (grey bars = CGCM3.1 climate, black bars = ECHAM5 climate)

ECHAM5 climate, and 18% higher in the LSS vs. HSS scenarios under the CGCM3.1 climate.

Differences in fire sizes and cumulative area burned between the simulation scenarios were due to two factors: (a) differences in fire weather simulated under the two different climate scenarios, and (b) differences in forest composition and landscape configuration under the three different severity scenarios that lead to variations in overall landscape flammability. Because the low surface fire severity led to the most rapid timing of spruce self-replacement after fire, the LSS scenarios tended to have larger contiguous patches of flammable black spruce forest on the landscape (Table 3). This led to a higher potential for fire spread and a more frequent occurrence of large fire years (Fig. 6). Both the MIX and HSS scenarios generated more frequent but smaller and more fragmented spruce patches in which fire spread was more likely to be interrupted by less flammable deciduous patches (Table 3).

Fire activity was substantially increased under the severe but plausible scenarios of climate warming represented by the ECHAM5 model. This simulation outcome was due to the direct effect of climate on the probability of fire ignition and spread in the model. Climate scenarios also caused indirect effects on

landscape forest composition in the simulations, as black spruce stands were more likely to burn at a young age under warmer climate scenarios (Table 2). Consequently, within a given simulation, black spruce pixels were being burned by fire and transformed via post-fire succession into deciduous vegetation types at a faster rate in the ECHAM5 scenario than in the CGCM3.1 scenario (Fig. 6). Because large fires and annual area burned in ALFRESCO only occurred when deciduous vegetation occupied <50–60% of the landscape, the increased variability of deciduous cover under the LSS compared to HSS scenario resulted in the more frequent creation of landscapes that were able to sustain large fires (Fig. 6).

Discussion

The aim of this modeling exercise was to assess whether fire-initiated changes in the successional trajectories of black spruce forests could have important implications for subsequent fire behavior in boreal landscapes. In scenarios with extensive, severe surface fire severity (our HSS scenario), the increased potential for deciduous cover on the

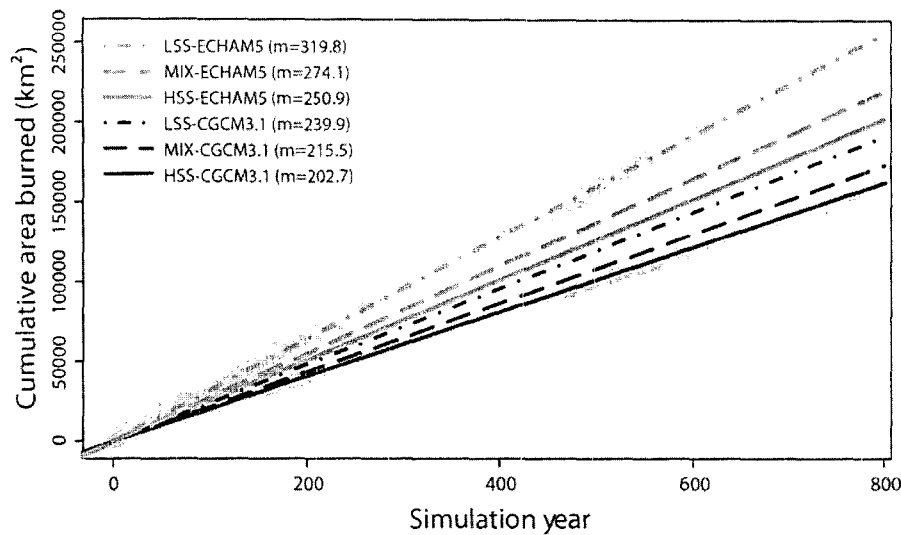


Fig. 5 Cumulative area burned plotted against year for each replicate simulation ($n = 500$) across the six simulation scenarios (see text for explanation of scenarios). Raw data (grey shading) have been included for the two bounding

scenarios. Lines were fit using simple linear regression with the intercept fixed to zero. The slopes of the fitted lines (m) provide an estimate of the different annual rates of accumulation in cumulative area burned

Table 3 Summary of landscape patch and connectivity metrics for different vegetation types simulated by ALFRESCO under two climate scenarios (ECHAM5 and CGCM3.1) and three surface fire scenarios ($N = 500$ simulation replicates of 800 years each)

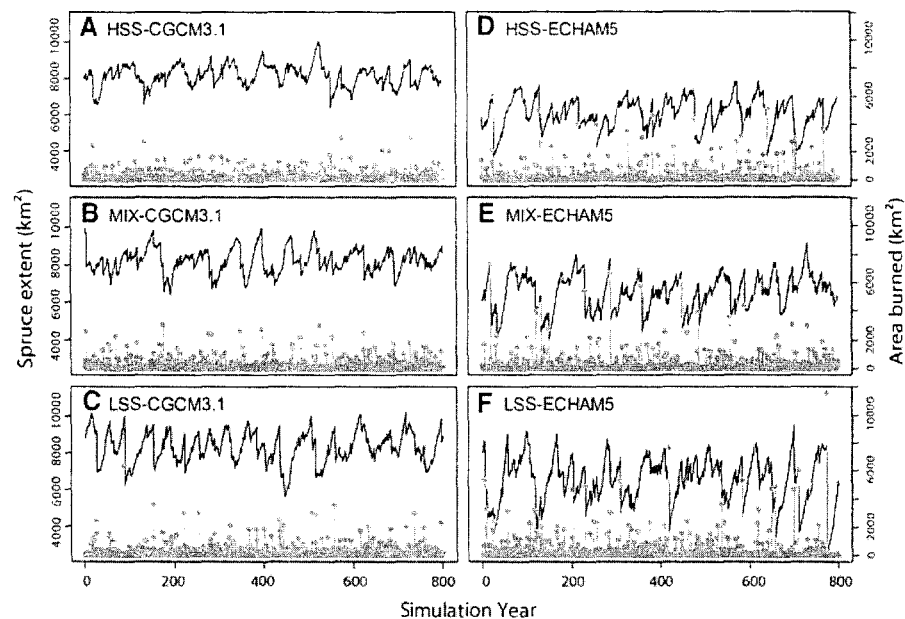
Pixel type	Severity scenario	ECHAM5				CGCM3.1			
		Patch size	Patch density (%)	Cohesion index	% Like adjacency	Patch size	Patch density (%)	Cohesion index	% Like adjacency
Black spruce	LSS	10	2.54	9.26	34.17	14	2.26	9.45	38.57
	MIX	9	2.73	9.12	31.64	13	2.35	9.40	36.72
	HSS	8	2.90	9.04	30.27	12	2.49	9.35	35.41
White spruce	LSS	3	2.78	7.99	22.04	5	2.86	8.51	27.67
	MIX	4	2.73	8.17	23.39	5	2.82	8.59	28.39
	HSS	4	2.67	8.31	24.33	5	2.77	8.65	29.04
Deciduous	LSS	55	1.08	9.84	57.44	34	1.33	9.79	52.35
	MIX	55	1.06	9.84	55.85	33	1.36	9.79	51.22
	HSS	59	1.00	9.85	56.70	35	1.32	9.80	51.65

Patch metrics: patch size is the mean number of pixels within a patch of a given vegetation type, and patch density is the number of patches of the corresponding patch type divided by the total landscape area. Connectivity metrics: Patch cohesion index measures the connectedness of the corresponding patch type (values increase as the patch type becomes more aggregated), and percent like adjacency is the frequency with which a pixel is adjacent to another pixel of the same patch type. The climate and severity scenarios used in the simulations are described in the methods

landscape led to negative effects on future fire hazard. This effect occurred primarily as the result of changes in the temporal variance and spatial configuration of flammable forest cover types, rather than due to changes in the average landscape composition. Deciduous stands had a lower potential of burning and thus acted as partial fire breaks, reducing the potential for fire disturbance to propagate across the

landscape. Nevertheless, this negative, stabilizing feedback between vegetation and fire behavior was not sufficient to compensate for increases in fire activity driven directly by climate warming. The more severe climate warming scenario that we modeled (ECHAM5) produced larger fires, more annual area burned, and shorter fire return intervals than the moderate warming scenario (CGCM3.1),

Fig. 6 Examples of individual simulations arising under the six different scenarios climate and severity scenarios (a–f). The black lines show the area occupied by black spruce on the landscape and grey circles on stalks show the area burned for each year across the 800 year simulation period



regardless of fire severity effects on patterns of vegetation succession. These simulations suggest that increases in the initiation of deciduous-dominated succession trajectories under conditions of high fire severity (Johnstone et al. 2010) can reduce but not eliminate the positive effects of climate warming on fire activity in Alaskan boreal forests.

The behavior of any model is a product of the assumptions that are built into it, and it is worth evaluating whether the assumptions we used here are likely to be realistic. Successional relationships in the model are based on stand self-replacement after fire as the most common successional pattern in Alaskan boreal forests (Van Cleve et al. 1991; Chapin et al. 2006). Although this may be a reasonable first approximation, there are clearly situations where this will not be the case. For example, in black spruce forests, fire appears to be an important trigger of shifts in successional trajectories (Johnstone et al. 2010). Variations in surface fire severity have been shown to affect the relative dominance of deciduous vs. conifer seedlings in regenerating stands (e.g. Johnstone and Chapin 2006a; Greene et al. 2007), with probable effects on subsequent canopy dominance (Johnstone et al. 2004, 2010). These relationships have been explicitly incorporated in our model by setting a prolonged phase of deciduous dominance for cells burned at high surface severity. However, the successional transitions in our model may also not

be entirely realistic with respect to the timing and deterministic pathways of transitions in forest canopy dominance. In our model, all deciduous stands eventually are succeeded in the canopy by conifers (white or black spruce). This model of canopy relay succession may be generally representative of boreal forests (Bergeron 2000; Chapin et al. 2006), but there is evidence to suggest that at least some deciduous forests may maintain themselves in a state of deciduous dominance for 200 years or more (Cumming et al. 2000; Kurkowski et al. 2008). Consequently, our model may underestimate the length of time over which deciduous forests are able to persist without a successional transition to conifer canopy dominance.

The frequency of fire events is also likely to affect successional trajectories and patterns of forest dominance (Suffling 1995). In particular, short return intervals of disturbance can disrupt the mechanisms that support conifer self-replacement, leading to a reduction in conifer cover and replacement by deciduous species (Johnstone and Chapin 2006b). However, under current fire regimes, such events appear to be relatively rare (Johnstone and Chapin 2006b), and were not included in our simulations. Similarly, our model does not deal with directional changes in climate and environmental conditions that may lead to long-term changes in forest cover (Calef et al. 2005). In general, these factors are likely to lead

to a greater frequency of deciduous-dominated forest stands. Thus, our model may be conservative in its estimates of deciduous forest cover under different climate and fire scenarios.

Fire behavior in the model follows algorithms that determine the probability of a pixel burning as a function of annual fire weather and vegetation type. These algorithms have been used in previous versions of ALFRESCO and validated for simulations carried out on a 1×1 km grid (Rupp et al. 2007; Brubaker et al. 2009). The fire spread algorithm is designed to capture known empirical relationships between fire weather and annual area burned in boreal forests (Duffy et al. 2005; Skinner et al. 2006) and observed decreases in fire hazard of deciduous vs. coniferous forests (Hély et al. 2000; Cumming 2001; Krawchuk et al. 2006; Duffy et al. 2007). Although the general nature of these effects seems well established, the relative importance of fire weather, vegetation type, and other controls, such as topography, is less certain (e.g. Bessie and Johnson 1995; Duffy et al. 2007). Alternative parameterization of fire algorithms in ALFRESCO to reflect different levels of sensitivity to weather vs. fuel types would change our estimates of fire size, but would be unlikely to qualitatively alter our results unless vegetation effects on flammability were removed completely.

Climate change projections for boreal Alaska and western North America predict that substantial climate warming will occur due to anthropogenic effects in the 21st century and beyond (Solomon et al. 2007). Weather conditions and fire behavior are strongly linked in the boreal forest (Duffy et al. 2005; Skinner et al. 2006). Thus, increased warming is likely to lead to increases in the severity and spatial extent of fires (Flannigan et al. 2005; Balshi et al. 2009). Indeed, historical records of fire occurrence suggest that there has already been an increase in fire activity associated with recent warming in North American boreal forests (Kasischke and Turetsky 2006). Although less is known about possible future changes in fire severity, positive relations between fire size and severity in Alaska (Duffy et al. 2007) suggest that increases in fire activity will be associated with increases in fire severity.

Outcomes from this relatively simple model of forest and fire dynamics suggest that changes in landscape flammability associated with increased deciduous forest cover can act as a negative feedback

to future fire activity. This is important because, so far, many of the feedbacks identified between climate change and ecosystem change in boreal and arctic regions have been positive (Chapin et al. 2008). Examples of positive feedbacks include increased carbon emissions from larger, more frequent, or more severe fires (Bond-Lamberty et al. 2007), loss of soil carbon due to increased decomposition in warmer soils (Kane and Vogel 2009), and decreased albedo and increased sensible heat associated with expansion of forest and shrubs into tundra regions (Chapin et al. 2005). However, when burned spruce forests are replaced by deciduous broadleaves, important negative feedbacks to climate warming and increased fire can occur. For example, early successional deciduous canopies have a higher albedo that reduces heating of the land surface for several decades after fire (Randerson et al. 2006). The model simulations reported here also suggest that if climate warming leads to more severe fires, consequent increases in the cover of deciduous forests may help constrain increases in fire activity caused directly by climate warming. However, these simulations also indicate that changes in landscape vegetation are unlikely to fully compensate for climate effects on fire behavior and increased area burned is a likely outcome of continued warming in Alaskan boreal forests.

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