Sensitivity of Simulated Boreal Fire Dynamics to Uncertainties in Climate Drivers

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ABSTRACT: Projected climatic warming has direct implications for future disturbance regimes, particularly fire-dominated ecosystems at high latitudes, where climate warming is expected to be most dramatic. It is important to ascertain the potential range of climate change impacts on terrestrial ecosystems, which is relevant to making projections of the response of the Earth system and to decisions by policymakers and land managers. Computer simulation models that explicitly model climate–fire relationships represent an important research tool for understanding and projecting future relationships. Retrospective model analyses of ecological models are important for evaluating how to effectively couple ecological models of fire dynamics with climate system models. This paper uses a transient landscape-level model of vegetation dynamics, Alaskan Frame-based Ecosystem Code (ALFRESCO), to evaluate

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the influence of different driving datasets of climate on simulation results. Our analysis included the use of climate data based on first-order weather station observations from the Climate Research Unit (CRU), a statistical reanalysis from the NCEP–NCAR reanalysis project (NCEP), and the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5). Model simulations of annual area burned for Alaska and western Canada were compared to historical fire activity (1950–2000). ALFRESCO was only able to generate reasonable simulation results when driven by the CRU climate data. Simulations driven by the NCEP and MM5 climate data produced almost no annual area burned because of substantially colder and wetter growing seasons (May–September) in comparison with the CRU climate data. The results of this study identify the importance of conducting retrospective analyses prior to coupling ecological models of fire dynamics with climate system models. The authors' suggestion is to develop coupling methodologies that involve the use of anomalies from future climate model simulations to alter the climate data of more trusted historical climate datasets.

KEYWORDS: Boreal forest; Climate–fire relationships; Transient vegetation model; Vegetation dynamics

1. Introduction

Understanding fire's linkage to climate and influence on land cover, as well as associated feedbacks, is critical for accurate forecasts of global change impacts. Fire is the keystone disturbance in terrestrial ecosystems globally (Clark et al. 1997; Pyne 2001; Lavorel et al. 2005), burning 200–500 × 10^6 hectares (Mha) annually (Goldammer and Mutch 2001). Fire represents the primary reinitiation mechanism throughout much of the boreal biome and is responsible for the annual burning of 5–15 Mha of boreal forest (Stocks et al. 2002; Lavorel et al. 2005; Flannigan et al. 2006).

Current estimates are that an average of 2.3 Mha burn annually across the North American boreal forest, with the amount of annual area burned ranging between 0.5 and 8 Mha (Amiro et al. 2001; Kasischke et al. 2006; Csiszar et al. 2004), and there is a growing awareness of the importance and vulnerability of the region to forecast climatic change (Weber and Flannigan 1997; Flannigan et al. 2001; Lavorel et al. 2005). A relationship between area burned in Canada in the past 40 yr and human-induced climatic warming has been shown (Gillett et al. 2004). Specifically, temperature has been identified as the most important predictor of annual area burned in Canada (Flannigan et al. 2005) and Alaska (Duffy et al. 2005), driven by El Niño–influenced summer temperature increases (Hess et al. 2001; Duffy et al. 2005).

Strong linkages between climate, fire, and vegetation imply that fire's sensitivity to global change could be more important than the direct effects of climatic warming on terrestrial ecosystems (Rupp et al. 2000a; Houghton 2001; Lavorel et al. 2005). Studies of future responses of fire weather severity (Flannigan and Van Wagner 1991; Flannigan et al. 1998; Stocks et al. 1998) and area burned (Price and Rind 1994; Flannigan et al. 2005) indicate strong increases for many regions of the boreal forest but are characterized with large variation among regions (Bergeron and Flannigan 1995; Flannigan et al. 2000; Flannigan et al. 2006). A more frequent fire regime has implications for regional hydrology in high latitudes (McClelland et al. 2004) because postfire thaw of permafrost (Zhuang et al. 2003) has the potential to release water locked up in ice-rich permafrost. Also, lower transpiration associated with vegetation with low leaf area can lead to higher runoff for a number of years after fire (Bayley et al. 1992; Lamontagne et al. 2000; Schindler et al. 1980). A more frequent fire regime also has the potential to release carbon to the atmosphere from high-latitude soils that are rich in carbon (McGuire et al. 2004). Therefore, it is important to couple ecological models of fire regime into climate models to better understand how future responses of the fire regime in high latitudes may influence hydrologic and trace gas feedbacks to the climate system.

Global climate models (GCMs) agree that the effects of anthropogenic climate warming will occur first and most dramatically at high latitudes (Houghton 2001; ACIA 2005). Surface air temperatures measured across high-latitude sites of western North America show an increase of approximately 0.3°C decade^{-1} over the past century (Keyser et al. 2000) and show that current temperatures are the highest experienced in the last 400 yr (Jacoby and D'Arrigo 1995; Jacoby et al. 1996; Overpeck et al. 1997). Precipitation has increased, primarily during winter and spring (Serreze et al. 2000), but the limited ability by climate models to simulate precipitation and large underestimates of precipitation at high-latitude weather stations greatly reduce the certainty of these estimates (Chapin et al. 2000). Conservative predictions of 4°–7°C increases in average annual temperature for regions above 60°N by 2100 have been simulated by numerous GCMs (Houghton 2001; ACIA 2005). These models also predict increasing precipitation (10%–30%); however, the increased evaporation caused by warmer temperatures will likely offset higher precipitation and actually make conditions drier (Flannigan et al. 2005; Flannigan et al. 2006). The general conclusion of research to date indicates that the severity, number, season length, and total area burned will increase throughout much of the boreal biome (Csiszar et al. 2004; Lavorel et al. 2005; Flannigan et al. 2006).

Models of transient vegetation and fire dynamics (Lenihan et al. 1998; Thonicke et al. 2001) are currently being applied (Bachelet et al. 2000; Venevsky et al. 2002; Bachelet et al. 2005) to evaluate regional responses of fire regime to projections of future climate change. These models are important tools for identifying important processes, thresholds, and feedbacks, as well as providing forecast changes in fire regime and the associated impacts under scenarios of climate change. There has been growing interest in coupling ecological models of fire regime dynamics into climate system models. To understand how to incorporate fire regime dynamics into climate system models, we argue that it is important to evaluate the dynamics of ecological models in retrospective studies involving climate models as well as observationally based datasets. As the number of driving climate datasets grows (both observation and modeled) there is an increasing need to assess the degree to which the responses of ecological models to a particular dataset make sense, as simulation results may serve as a basis for projections of changes in landscape dynamics and consequent recommendations for policy development.

The primary goal of the Western Arctic Linkage Experiment (WALE) was to evaluate uncertainties in regional hydrology and carbon estimates in Alaska and the adjacent Yukon Territory associated with 1) alternative driving datasets and 2) alternative simulation models (McGuire 2006, manuscript submitted to *Earth Interactions*, hereafter MCG). The sensitivity of regional hydrology and carbon dynamics in recent decades to alternative historical climate datasets was assessed, respectively, by Rawlins et al. (Rawlins et al. 2006) and Clein et al. (Clein et al. 2006). Uncertainties in regional hydrology and regional carbon dynamics among alternative simulation models were assessed, respectively, by Lammers et al. (Lammers et al. 2006, manuscript submitted to *Earth Interactions*) and Kimball et al. (Kimball et al. 2006). Future projections of hydrology and carbon dynamics will require both an understanding of the effects of different driving data as well as the consideration of projections of fire dynamics. In this paper we address the latter issue by assessing the sensitivity of simulated fire dynamics to different driving climate datasets. Our focus is the response of a transient vegetation dynamics model, Alaskan Frame-based Ecosystem Code (ALFRESCO) (Rupp et al. 2000b; Rupp et al. 2002), to the same driving datasets evaluated by Clein et al. (Clein et al. 2006). We evaluate both simulated and prescribed fire ignition and spread to assess vegetation response differences. We discuss the implications of our modeling results for efforts to couple models of fire dynamics with the output of climate system models.

2. Methods

2.1. Study area

Our simulation domain was defined as the entire Yukon River drainage basin and the surrounding regions (3 937 500 km^2 total area; 692 715 km^2 forested area). The domain includes all of Alaska (except the extreme southeastern panhandle), the Yukon Territory, and portions of British Columbia and the Northwest Territories. The study region includes strong gradients in climate, vegetation, topography, and parent material (see MCG for details). Historical fire occurrence within the simulation domain is restricted almost exclusively to boreal forest and primarily within the more continental interior regions (Figure 1; see also Csiszar et al. 2004; Kasischke et al. 2002; Stocks et al. 2002). Interannual variation in total area burned is substantial (Figure 2); the average annual area burned (1950–2000) for the study area was approximately 426 000 ha and ranged between approximately 1600 and 2 331 000 ha.

2.2. Description of ALFRESCO model

ALFRESCO was originally developed to simulate the response of subarctic vegetation to a changing climate and disturbance regime (Rupp et al. 2000a; Rupp et al. 2000b). Previous research has highlighted both direct and indirect (through changes in fire regime) effects of climate on the expansion rate, species composition, and extent of tree line in Alaska (Rupp et al. 2000a; Rupp et al. 2001). Additional research, focused on boreal forest vegetation dynamics, has emphasized that fire frequency changes—both direct (climate driven or anthropogenic) and indirect (as a result of vegetation succession and species composition)—

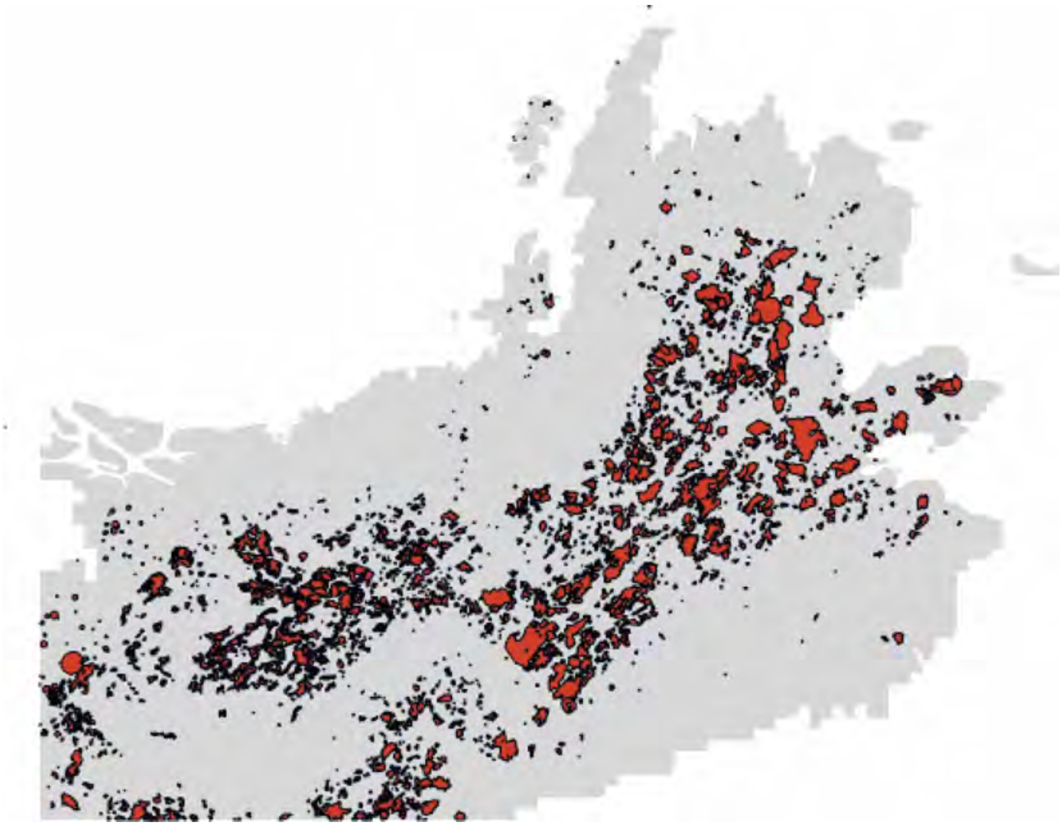


Figure 1. Map showing study domain and the perimeters of all large fires that occurred during the period 1950–2000. The map is projected in the EASE projection format.

strongly influence landscape-level vegetation patterns and associated feedbacks to future fire regime (Rupp et al. 2002; Chapin et al. 2003; Turner et al. 2003).

Here we focus our description on the fire routine and other issues specific to this research. We refer the reader to Rupp et al. (Rupp et al. 2000a; Rupp et al. 2000b; Rupp et al. 2001; Rupp et al. 2002) for all other relevant discussion of the model. For this research we modified ALFRESCO to operate on an annual time step and 1 km × 1 km pixel resolution to better incorporate climate–fire–vegetation dynamics and facilitate the incorporation of regional climate model data. ALFRESCO is a state-and-transition model of successional dynamics that explicitly represents the spatial processes of fire and vegetation recruitment across the landscape (Rupp et al. 2000b). ALFRESCO does not model fire behavior but rather models the empirical relationship between growing-season (May–September) climate (e.g., average temperature and total precipitation) and total annual area burned (i.e., the footprint of fire on the landscape). ALFRESCO also models the changes in vegetation flammability that occur during succession through a flammability coefficient that changes with vegetation type and stand age (i.e., succession) (Chapin et al. 2003).

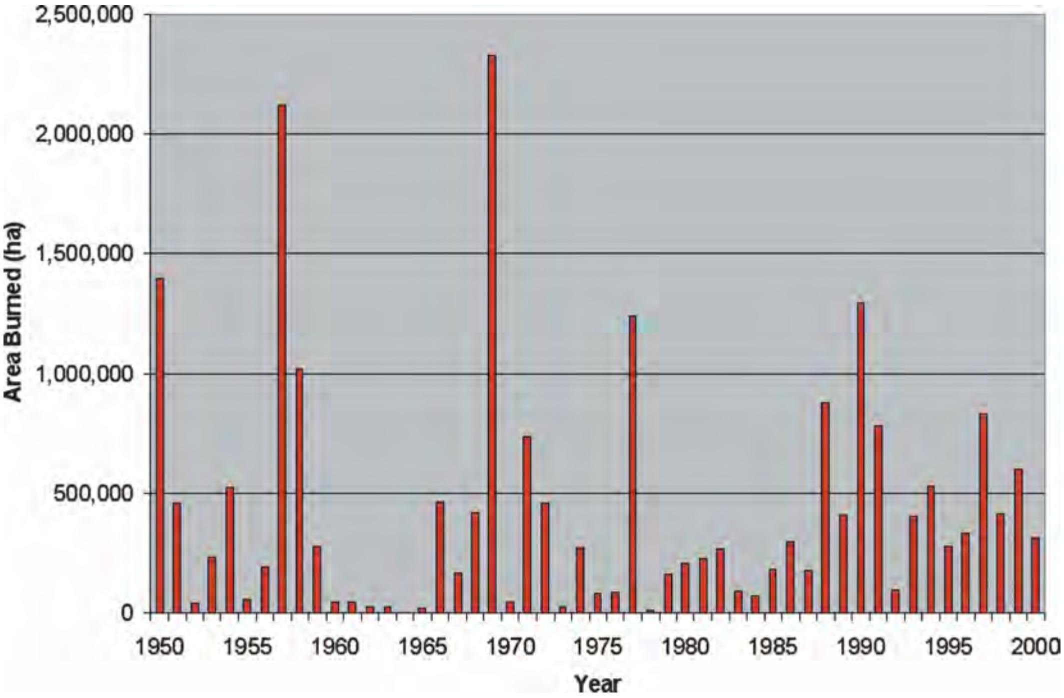


Figure 2. Histogram showing observed total area burned (ha) within the study domain for the period 1950–2000.

The fire regime is simulated stochastically and is driven by climate, vegetation type, and time since last fire (Rupp et al. 2000b). ALFRESCO employs a cellular automaton approach, where an "ignited" pixel may "spread" to any of the eight surrounding pixels. "Ignition" of a pixel is determined using a random number generator and as a function of the flammability value of that pixel (Rupp et al. 2000b; Rupp et al. 2002). The flammability value of each pixel is a function of vegetation type and age (i.e., fuel loading/structure) and growing-season climate (i.e., fuel moisture). Therefore, random ignitions will be concentrated in pixels with the highest fuel loads and experiencing the driest climate conditions for any given time step. For this research we simulated only lightning ignitions. Human ignitions were not simulated and were omitted from the observational dataset. Fire spread depends on the flammability (i.e., fuel loading and moisture) of the receptor pixel and any effects of natural firebreaks including nonvegetated mountain slopes and large water bodies, which do not burn. Suppression activities were not simulated, and large fires that were suppressed were also omitted from the observational dataset.

The relative effects of growing-season climate on fire were computed using a two-parameter regression analysis similar to that used by Kasischke et al. (Kasischke et al. 2002). We stratified interior Alaska by ecoregion (Gallant et al. 1995), growing-season climate (Fleming et al. 2000), and fire frequency (Kasischke et al. 2002). We assumed the Canadian portion of our domain to be similar and therefore did not incorporate region-specific data for the analysis. Fire frequencies and climate variables were computed directly (and respectively) from the Bureau of Land Management, Alaska Fire Service (AFS) large-fire database (Kasischke et al. 2002; http://agdc.usgs.gov/data/blm/fire/index.html) and monthly statewide maps of precipitation and temperature (Fleming et al. 2000; http://agdc.usgs.gov/data/projects/hlct/hlct.html). We performed this analysis statewide to ensure that we captured the full spectrum of climate variability and to provide the future ability to accurately simulate the response of the fire regime to a changing climate in a specific region.

We relied upon the literature for computation of the rate at which tundra and deciduous and white and black spruce stands burn (Starfield and Chapin 1996; Cumming 2001). In addition, we utilized stand age data of Yarie (1981), collected in a region of interior Alaska—generally representative of our fire-dominated portion of the study domain. This analysis provided relative burn rates for each vegetation type. A sensitivity analysis of the model revealed that area burned is highly nonlinear with a flammability factor (Rupp et al. 2000b). As a result, we performed baseline calibration runs to compute the actual flammability factors required by the model to produce the computed burn rates for each vegetation type.

The other component modeled by ALFRESCO is vegetation succession. This model version has five general vegetation types: upland tundra, black spruce forest, white spruce forest, deciduous vegetation, and coastal forest. The details of the first four vegetation types and transitional pathways are discussed in Rupp et al. (Rupp et al. 2000a; Rupp et al. 2000b; Rupp et al. 2002). For this retrospective analysis the coastal forest type, a forest type that does not readily burn (Lertzman et al. 2002) and represents a minor component of our study domain was modeled statically.

2.3. Climate datasets

We utilized three different spatially and temporally defined climate datasets to drive the ALFRESCO simulations. These datasets were chosen based on the WALE study design (MCG) with respect to the objective of evaluating driving data with fields developed using three different approaches: 1) an observationally based approach, 2) a data assimilation approach using a climate model, and 3) a regional climate modeling approach forced with only boundary conditions (see Drobot et al. 2006; Clein et al. 2006). Because the datasets were not on common grids, the datasets were first converted to the Northern Hemisphere 25 km × 25 km Equal-Area Scalable Earth (EASE) grid (Drobot et al. 2006). Because ALFRESCO operates at a resolution of 1 km to simulate interactions between fire and vegetation heterogeneity across the landscape, it requires driving data at 1-km resolution. For this analysis we used a simple resampling algorithm to process each dataset and generate climate data for a grid of 1 km × 1 km pixels. No interpolation (i.e., downscaling) methodology was employed in this analysis as we simply populated the six hundred twenty-five 1 km × 1 km pixels within an EASE pixel with the climate data of the EASE pixel. The first dataset is from the Climate Research Unit (CRU) in East Anglia. The CRU dataset is based on first-order weather station observations, which are updated monthly based on the currently available station network (Mitchell et al. 2004). The CRU dataset covers the period 1950–2000 (Clein et al. 2006). The second dataset is the product of the National Centers for

Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis project (hereafter NCEP; Kistler et al. 2001). The NCEP data are a statistical reanalysis of historical climate observations based on a static data assimilation scheme, and in this study the NCEP data we used span the period 1980–2000. The third dataset is the product of the fifth-generation Pennsylvania State University–NCAR Mesoscale Model (MM5). The MM5 data provide simulated climate based on defined boundary conditions (see Wu et al. 2006 for details), and in this study the MM5 data we used span the period 1990–2000. Additional details regarding these three climate datasets are provided by Drobot et al. (Drobet et al. 2006), Herzfeld et al. (Herzfeld et al. 2006), and Wu et al. (Wu et al. 2006).

The three climate datasets produced significant spatial and temporal differences within the period of overlap (Drobot et al. 2006; Herzfeld et al. 2006). Previous analyses have reported a severe overestimation of summer precipitation in the NCEP data (Serreze and Hurst 2000). These differences have direct implications for our simulation results (see sections 3 and 4 for details). The common period of overlap (1990–2000) among the simulations driven by the different driving data was limited by the practical limitations imposed in conducting the MM5 simulations over the WALE region.

2.4. Model simulations

All input datasets were organized on the EASE grid domain (MCG; http://wale.unh.edu/data.shtml). The initial vegetation dataset (representing 1950) was developed by reclassifying Advanced Very High Resolution Radiometer (AVHRR) satellite data into our five general vegetation types following the methodology of Calef et al. (Calef et al. 2005) and Rupp et al. (Rupp et al. 2000a) (see MCG for details related to input datasets).

A 500-yr "spinup" was performed to allow for realistic patch size and age-class distributions to be generated over multiple fire cycles. We chose 500 yr because that represents at least a doubling of the length of the longest reported fire frequency for these ecosystem types (30–200 yr; Yarie 1981; Van Cleve et al. 1991; Chapin et al. 2003). We used monthly fields of surface temperature and precipitation (1860–1995) developed by McGuire et al. (McGuire et al. 2001) to generate annual average growing-season temperature values and total precipitation values. The simple resampling procedure that was previously described was used to process the data to a grid of 1 km × 1 km pixels. We generated a 500-yr driving climate data stream by randomly choosing and assembling individual years of paired surface temperature and precipitation. The spinup ensures ecologically realistic initial conditions for our scenario simulations. Without this step the initial distribution and composition of vegetation and their associated ages may not conform to observations and/or basic ecological principles (Rupp et al. 2000b). The final (year 500) vegetation and age maps from the spinup were used as the initial input for our simulations.

We first performed a prescribed fire simulation driven by the CRU climate data for the period 1950–2000 (five realizations). In the prescribed fire simulation we input the historically observed fire perimeters (Figure 1; Kasischke et al. 2002; Stocks et al. 2002) at each time step. The results of this simulation provided two things. First, we compared 1992 vegetation distribution simulated by the model with vegetation distribution derived from 1992 AVHRR satellite data. This analysis allowed us to assess the simulated successional dynamics independent of any stochastic effects of a simulated fire regime. Second, we used the "best fit" realization as the initial model input for the NCEP (year 1980) and MM5 (year 1990) simulations. This simulation scheme was followed because it provided us with the most accurate initial model conditions based on historical climate and fire observations, and ecologically realistic patch size and age-class distributions.

We then performed an ensemble simulation for each of the three driving climates with simulated fire (100 realizations each). All model results were output as both vector (i.e., time series) and raster (i.e., maps) data. We analyzed the response and sensitivity of ALFRESCO to the different climate datasets and investigated vegetation-driven feedbacks to the fire regime.

3. Results

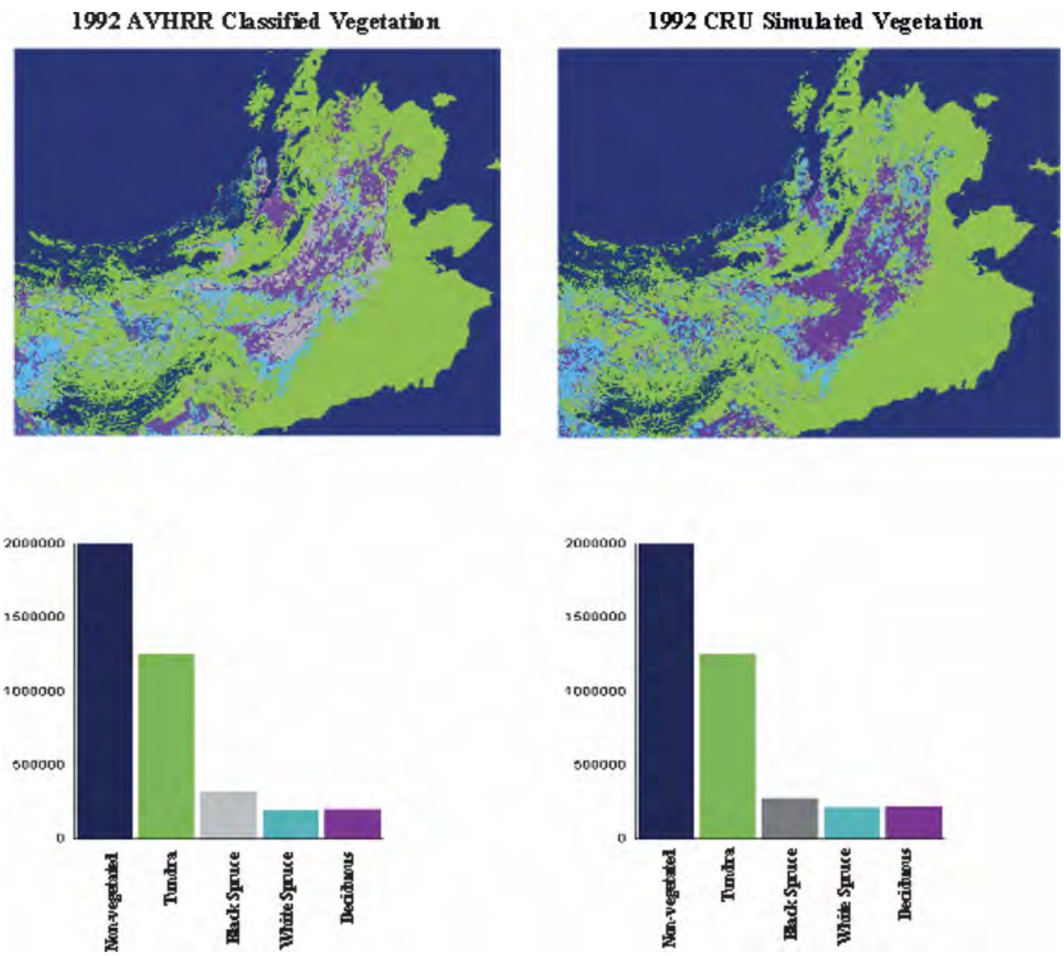
3.1. Prescribed fire

The results indicate relatively close agreement between the CRU simulated 1992 vegetation distribution and the reclassified 1992 AVHRR satellite data, although regional differences in the spatial composition were apparent (Figure 3). Relative to the AVHRR-derived vegetation, the simulation results were characterized by 13% less black spruce forest, 12.3% more white spruce forest, and 9% more deciduous vegetation.

3.2. Simulated fire

Periods of overlap between the CRU, NCEP, and MM5 simulations were minimal, with only the period of 1990–2000 providing a common comparison period among the three datasets. Within that comparison period there were large differences between the CRU simulation results and the NCEP and MM5 simulation results (Figure 4). The NCEP- and MM5-driven results were similar, but in both cases ALFRESCO was unable to reasonably simulate observed historic fire activity. In fact, both simulations produced virtually no area burned through the entire simulation period (NCEP: 1980–2000; MM5: 1990–2000).

The inability to simulate historical fire trends using the NCEP and MM5 driving climates resulted because of substantial decreases in growing-season (May–September) average temperature and increases in total precipitation (Table 1; Figure 5; see also Drobot et al. 2006; Herzfeld et al. 2006). Both the NCEP and MM5 climate data consistently showed differences of 100 mm or more of total growing-season precipitation. These differences occurred across 42%–62% of the landscape with the NCEP data and 21%–38% for the MM5 data. Similarly, both datasets consistently showed differences of −2°C or more in average growing-season temperature. These differences occurred across 45%–54% of the landscape with the NCEP data and 94%–97% for the MM5 data. The general trends for both driving climate datasets identify a substantially cooler and wetter climate than the CRU dataset.



1992 AVHRR Classified Vegetation

1992 CRU Simulated Vegetation

Figure 3. Comparison of observed vegetation pattern in 1992 (based on an AVHRR classification) vs simulated vegetation at 1992 for the CRU climate dataset and prescribed fire. Histogram presents the number of pixels (1 km × 1 km) in each vegetation type. Maps are projected in the EASE projection format.

The CRU simulations performed reasonably when compared to the observed annual area burned (Figure 4). Simulation results performed well for the period 1950–90 with relatively minor deviations between simulated averages ($n = 100$) and historic observations. However, large deviations occurred in several years between 1991 and 2000. The overall Spearman's rank correlation value was 0.4952. Comparison of simulated and observed fire size distribution showed general agreement with ALFRESCO simulating more, smaller fires (Figures 6a–b). Approximately half the total area burned from 1950 to 2000 resulted from fires larger than 50 000 ha (500 1-km^2 pixels; Figure 6c). However, fires greater than 50 000 ha accounted for less than 5% of the total number of fires that occurred during this same period (Figure 6d).

Analysis of the individual realizations from the CRU ensemble simulation iden-

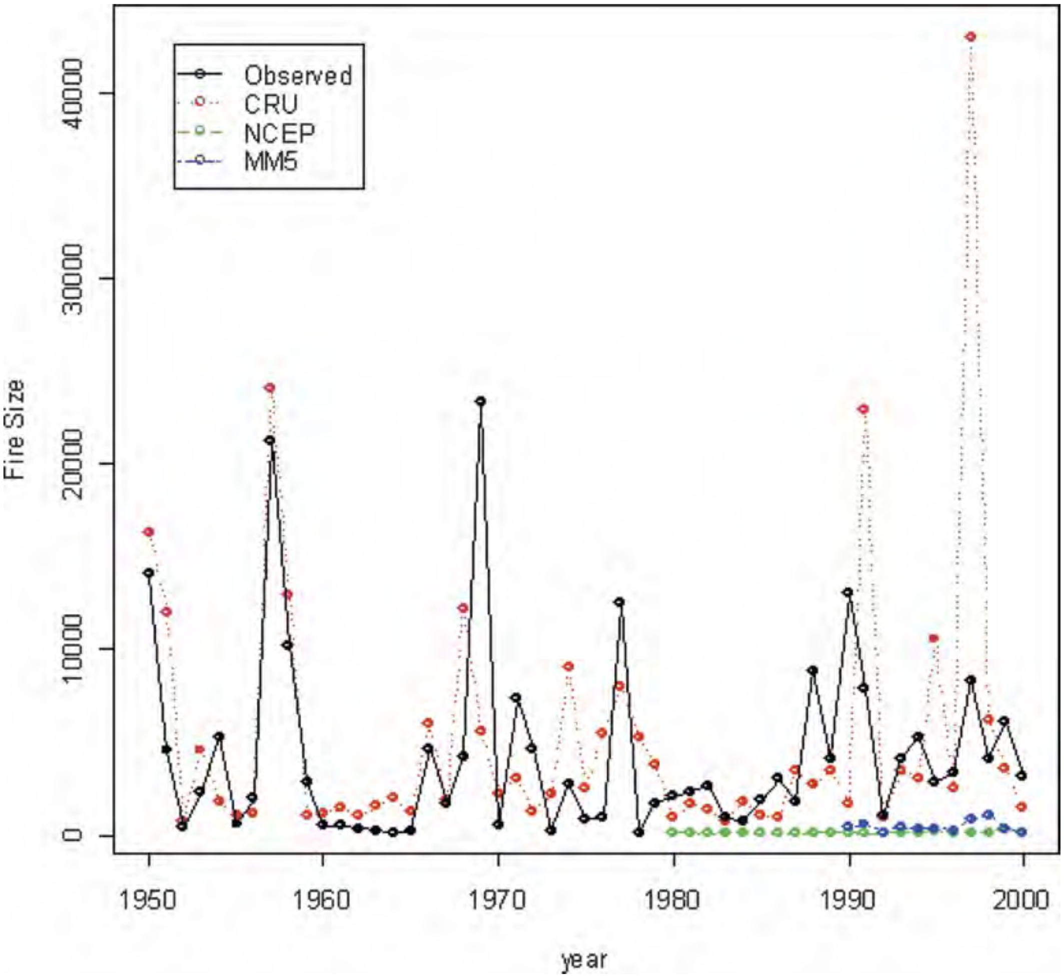


Figure 4. Time series comparing observed annual area burned to that simulated by ALFRESCO for the three different climate datasets. Simulated results presented as averages across realizations ($n = 100$): CRU (red), NCEP (green), and MM5 (blue).

Table 1. Summary of selected years showing the difference between the NCEP and MM5 climate datasets vs the CRU climate data. Results presented as the percent of pixels from NCEP and MM5 datasets that had precipitation values 100 mm or greater (i.e., substantially wetter) and temperature values −2°C or greater (i.e., substantially colder) compared to the CRU data values. Analysis was performed on the entire simulation domain.

	1982	1988	1990	1997	1999
Precipitation >100 mm					
NCEP	53.5%	54.6%	49.5%	62.0%	41.7%
MM5	—	—	20.6%	30.4%	37.8%
Temperature <−2°C					
NCEP	50.8%	53.1%	53.8%	44.7%	46.1%
MM5	—	—	94.6%	94.2%	96.7%

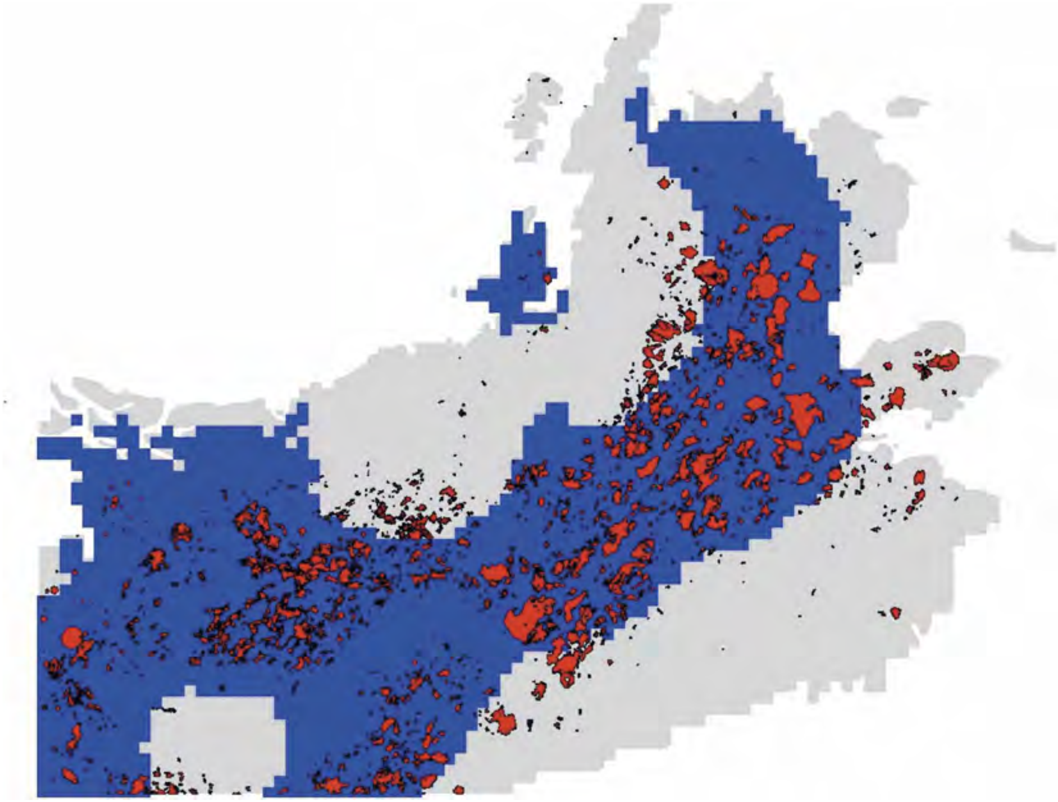


Figure 5. Climate data evaluation showing comparison between CRU and NCEP datasets for a representative year (1987). Shaded (blue) areas identify pixels where the NCEP data showed 100 mm or greater precipitation values compared to the CRU data. Historical fire perimeters (red polygons) are superimposed to illustrate the spatial correlation between areas of greatest climate divergence and occurrence of fires. Map is projected in the EASE projection format.

tified large differences in the temporal (Figure 7) and spatial (not presented) patterns of annual area burned. We identified the realization that resulted in the minimum and maximum deviation over the entire simulation period and with specific years removed. Regardless of the combination of years analyzed the same minimum and maximum realizations were identified. Additionally, we iteratively chose the best (i.e., closest to the observed) realization at each time step and used it as input for the next time step. This methodology produced a more accurate historical reconstruction of annual area burned, relative to the minimum deviation realization, for the period 1950–90, but produced less accurate results from 1991 to 2000.

The temporal vegetation dynamics simulated by the CRU climate show general agreement across realizations. The realizations with the minimum and maximum deviation (1950–2000) produced minor differences during the simulation period and produced virtually identical endpoint distributions of pixels by vegetation type (Figure 8). The general trend suggests small decreases in spruce cover (both white

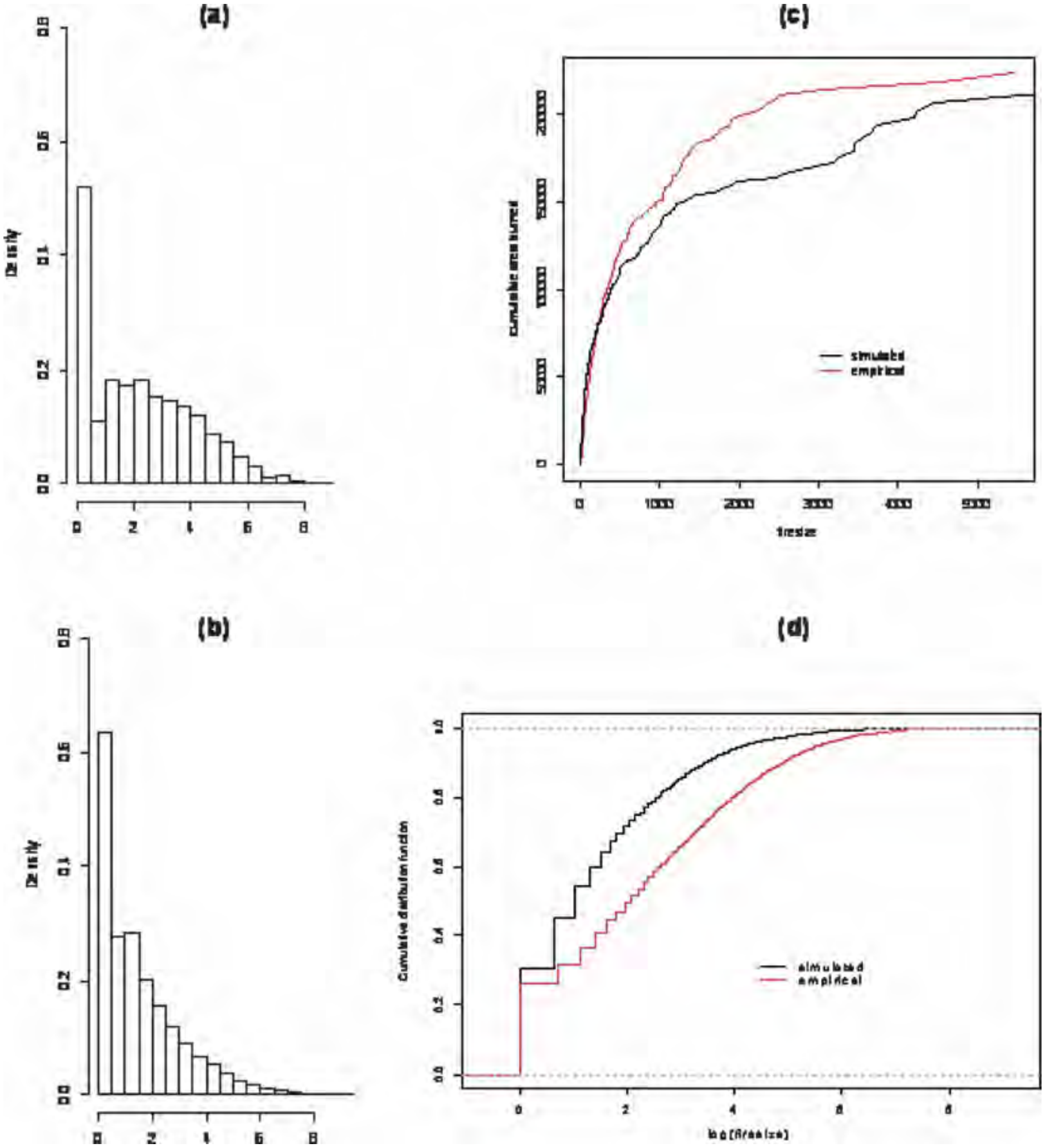


Figure 6. Fire size distribution plots for historical (red) and simulated (black) data. (a) Histogram of the logarithm of fire sizes from the historical record, (b) histogram of the logarithm of fire sizes from ALFRESCO, (c) cumulative area burned as a function of fire size for both historical and simulated data, and (d) cumulative distribution functions for both historical and simulated data (logarithm of fire size). ALFRESCO results correspond to a single set of representative realizations from 1950 to 2000. Fire size and logarithm of fire size are expressed as number of 1 km × 1 km pixels (1 pixel = 100 ha).

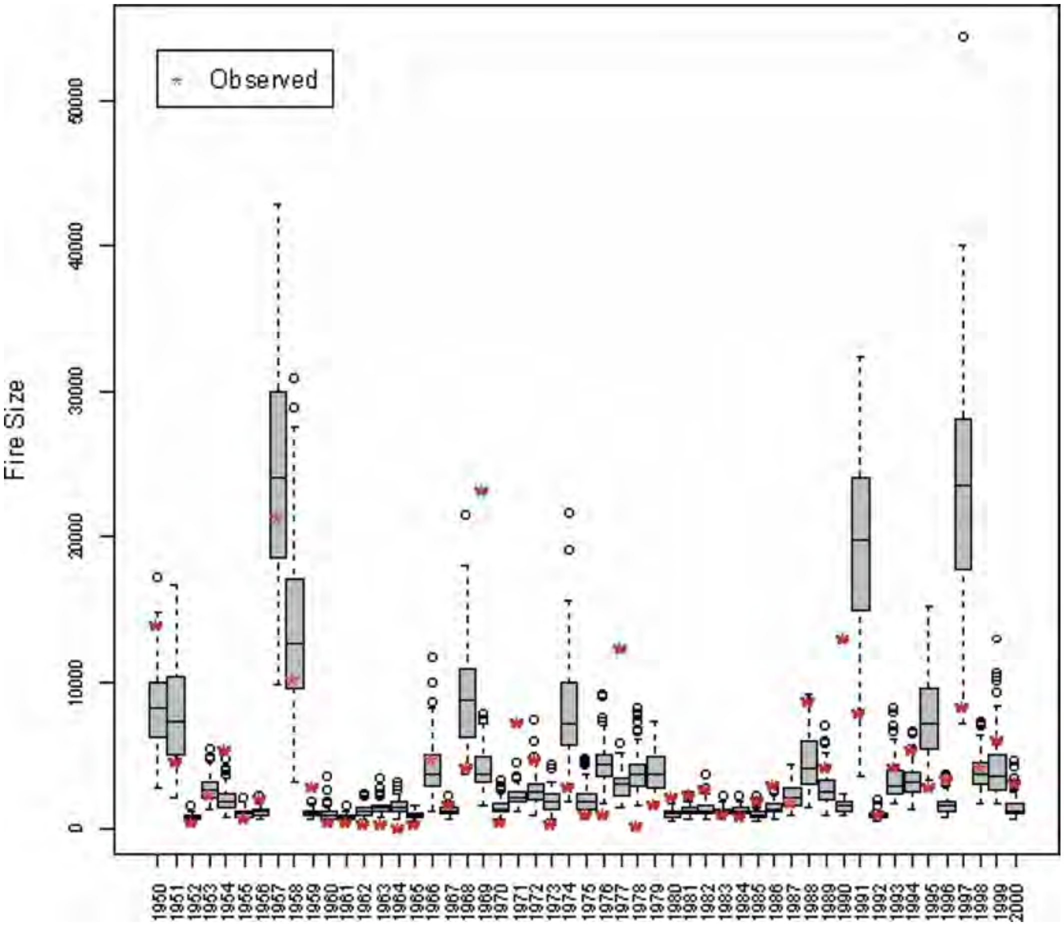


Figure 7. Time series box plot of the CRU climate data ensemble ($n = 100$). Red stars indicate observed values. The solid line represents the median. The shaded box around the median represents the inner quartile range (IQR), which identifies the region between the 25th and 75th percentiles. The whiskers extending from the IQR represent the largest/smallest value that is still within the median ±1.5(IQR). Any value beyond the whiskers is subjectively considered to be an outlier, and as such is marked with an "o."

and black spruce) and a concomitant increase in deciduous vegetation cover over the simulation period (1950–2000). Simulation results from the NCAR and MM5 climates produced the opposite trend. Both climates simulated small increases in spruce cover and concomitant decreases in deciduous vegetation cover as a function of succession in the absence of simulated fire.

4. Discussion

The results of our simulation study identified major differences in ALFRESCO's response to different driving datasets of growing-season average temperature and

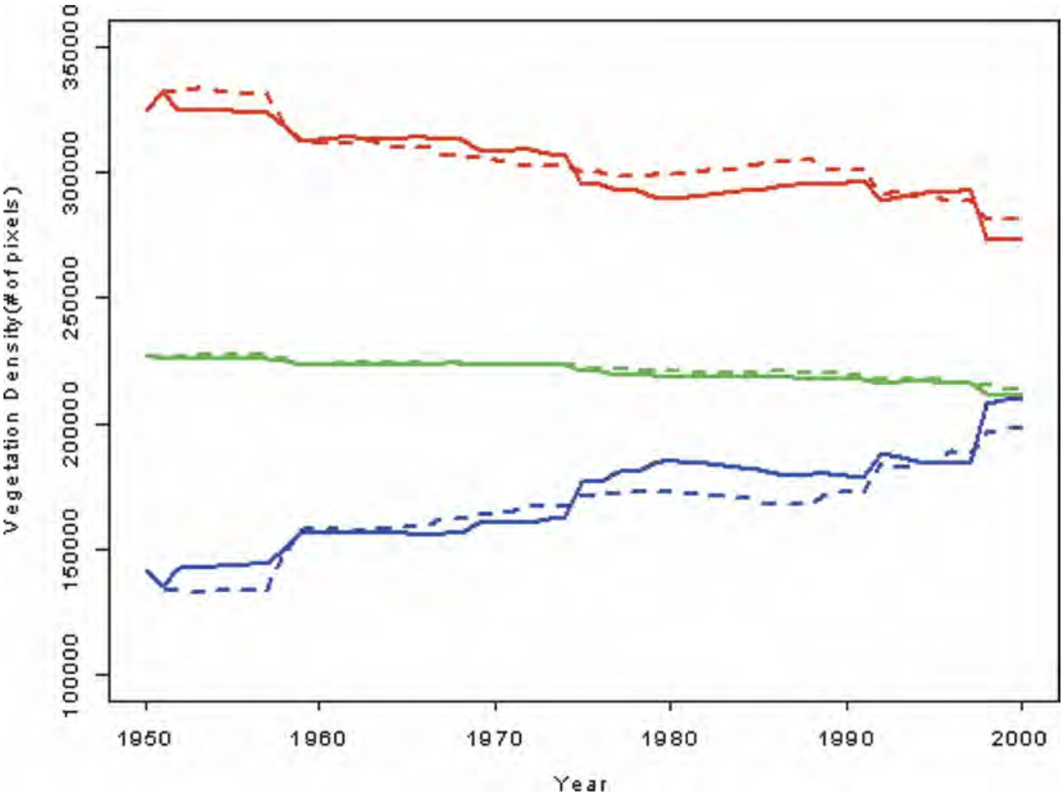


Figure 8. Time series of vegetation distribution (number of 1 km × 1 km pixels) for the CRU simulations. Comparison between the minimum (solid line) and maximum (dashed line) deviation realizations: black spruce (red), white spruce (green), and deciduous (blue).

total precipitation. ALFRESCO was reasonably able to simulate historic observations of annual area burned (1950–2000) across the study domain using the CRU data. In contrast, the model simulated almost no area burned when driven by either the NCEP or MM5 climate data (Figure 4). Even during years of observed high fire activity (e.g., 1991 or 1997) the model simulated almost no area burned for these two climates.

There is a clear case to be made for the linkage between climate/weather and fire (Swetnam 1993; Flannigan et al. 2005; Gillett et al. 2004; Duffy et al. 2005). Our modeled climate–fire relationship reflects this supposition. The documented observations between climate and fire, where hotter and dryer conditions are associated with increases in the number and extent of fires in the boreal forest (Flannigan et al. 2005; Duffy et al. 2005), and the empirical data utilized to develop ALFRESCO's climate–fire relationship (Kasischke et al. 2002; see section 2) clearly explain why ALFRESCO was unable to simulate historical fire regime trends using the NCEP and MM5 climate data. Large deviations in both these climate data streams compared to the CRU data (see Drobot et al. 2006; Herzfeld et al. 2006; Wu et al. 2006) resulted in growing-season conditions not conducive to burning (i.e., cool and wet fire seasons). In most years mean growing-season temperatures were at least 2°C colder and total growing-season precipitation was 100 mm or more wetter (Table 1) across a large portion of the study domain (Figure 5), as compared to the CRU dataset. Our results highlight a simple, but very important modeling issue—climate-driven contagion processes, such as wildfire, cannot be realistically simulated without temporally and spatially accurate driving datasets.

ALFRESCO was able to provide reasonable estimates of annual area burned and fire size distribution when driven by the CRU dataset. Less than 3% of the total number of fires accounted for roughly half of the total cumulative area burned from 1950 to 2000 (Figure 6). These results agree with separate findings from both Alaska (Kasischke et al. 2006) and Canada (Stocks et al. 2002). Average annual area burned across realizations showed relative agreement (Figure 4), but differences among realizations were substantial in some years (Figure 7). These individual realization differences were expected because of the stochastic nature of the fire routine and its random ignition component (Rupp et al. 2000b). An analysis of individual realizations consistently identified the same maximum and minimum deviation realizations. Although within-year differences in area burned between the maximum and minimum realizations were 50% or greater for some years (results not presented), only minor differences in vegetation response (Figure 8), due to the specific fire history of the realizations, were simulated. The spatial composition of vegetation among realizations was different, but this too was expected because of the stochastic nature of the fire routine (Rupp et al. 2000b).

We attribute ALFRESCO's overall success when using the CRU data to the fact that the CRU data are based on first-order weather station observations. Although the CRU data are not without shortcomings, they provide a direct spatiotemporal linkage to past fire seasons (i.e., fire–climate relationships). The climate weighting factor developed in ALFRESCO, based on the analysis of Kasischke et al. (Kasischke et al. 2002), increases the probability of ignition and spread under warming and drying conditions. Kasischke et al. (Kasischke et al. 2002) showed a doubling or more in fire rotation times where temperatures differed by approximately 2°C. Given these differences, we are not surprised that ALFRESCO simulated very little area burned for either the NCEP or MM5 climates.

ALFRESCO has two primary limitations with respect to the accurate simulation of the fire regime. First, ALFRESCO randomly ignites fires based on the same probability function as utilized for fire spread. The relationship between lightning strikes and growing-season climate is weak (Gardner et al. 1996; Li 2000) and so may lead to overestimations in ignition density and/or location (Knight 1987). Second, the coarse nature of the climate–fire linkage likely misses important seasonal patterns. Duffy et al. (Duffy et al. 2005) were able to explain approximately 80% of the variability in total annual area burned in Alaska based on monthly climate data—June average temperature accounted for approximately 38% of the variability alone—and larger-scale atmospheric circulation anomalies. These relationships warrant further investigation and offer real possibilities for future model improvement.

Transient vegetation models that include the representation and simulation of spatial processes (e.g., contagion process of fire ignition and spread) also require accurate temporal and spatial input vegetation data. The linked climate fire regime also interacts with land cover via the differential flammability of vegetation types (Lavorel et al. 2005) and the spatial connectivity of fuels (Turner and Romme 1994; Gardner et al. 1996; Rupp et al. 2000b; Turner et al. 2003). Not knowing the actual distribution and condition of vegetation types on the landscape at the beginning of our retrospective analysis (1950) limits the accuracy to which the fire routine can simulate the historical fire record. In our case, the initial age structure of the landscape, specifically of the deciduous vegetation, directly influences successional transition rates and therefore influences the simulated fire regime because as deciduous stands transition to spruce, the differential flammability increases (Rupp et al. 2000b; Cumming 2001).

5. Conclusions

It is important to ascertain the potential range of climate change impacts on terrestrial ecosystems, which is relevant to making projections of the response of the Earth system and to decisions by policymakers and land managers. Ecological models of fire dynamics offer a tool for identifying the role of disturbance for high-latitude regions and the regional hydrologic and trace gas feedbacks to the climate system. The results of our study identified the importance of conducting retrospective analyses prior to coupling ecological models of fire dynamics with climate system models. It is clear that directly using the climate variables simulated by prognostic climate models may lead to biased inferences about the vulnerability of the fire regime in high latitudes to future climate change. Drobot et al. (Drobot et al. 2006) found significant differences among all six climate datasets (including the three used in this study) evaluated in the Western Arctic Linkages Experiment but noted that the temporal anomalies among the datasets are highly correlated. Our suggestion is to develop coupling methodologies that involve the use of anomalies from future climate model simulations to alter the climate of more trusted historical climate datasets (e.g., the CRU climate datasets used in this study). This approach offers real potential for simulating realistic fire–climate interactions and at the same time assessing the sensitivity of the fire regime to alternate scenarios of future climate change.

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