

Postfire response of North American boreal forest net primary productivity analyzed with satellite observations

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Abstract

Fire is a major disturbance in the boreal forest, and has been shown to release significant amounts of carbon (C) to the atmosphere through combustion. However, less is known about the effects on ecosystems following fire, which include reduced productivity and changes in decomposition in the decade immediately following the disturbance. In this study, we assessed the impact of fire on net primary productivity (NPP) in the North American boreal forest using a 17-year record of satellite NDVI observations at 8-km spatial resolution together with a light-use efficiency model. We identified 61 fire scars in the satellite observations using digitized fire burn perimeters from a database of large fires. We studied the postfire response of NPP by analyzing the most impacted pixel within each burned area. NPP decreased in the year following the fire by 60–260 g C m⁻² yr⁻¹ (30–80%). By comparing pre- and postfire observations, we estimated a mean NPP recovery period for boreal forests of about 9 years, with substantial variability among fires. We incorporated this behavior into a carbon cycle model simulation to demonstrate these effects on net ecosystem production. The disturbance resulted in a release of C to the atmosphere during the first 8 years, followed by a small, but long-lived, sink lasting 150 years. Postfire net emissions were three times as large as from a model run without changing NPP. However, only small differences in the C cycle occurred between runs after 8 years due to the rapid recovery of NPP. We conclude by discussing the effects of fire on the long-term continental trends in satellite NDVI observed across boreal North America during the 1980s and 1990s.

Keywords: boreal forest, carbon cycle, emissions, fire, NDVI, net primary productivity

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Introduction

Fires are an integral component of the global carbon (C) cycle, releasing ~4 Pg C yr⁻¹ through combustion to the atmosphere globally (Andreae & Merlet, 2001). Global net primary productivity (NPP), the net amount of C fixed by vegetation, is about 55 Pg C yr⁻¹ (Cramer *et al.*, 1999), implying that about 7% of NPP is returned to the atmosphere via combustion. These carbon

emissions occur in addition to the effects of reduced productivity and changes in decomposing carbon pools caused by fire-induced mortality. Modeled estimates have found that these decomposition losses following fire often exceed the combustion loss (Auclair & Carter, 1993; Kurz & Apps, 1999). Auclair & Carter (1993) estimated that gross carbon fluxes from decomposition in temperate and boreal forests are greater than combustion losses by a factor of seven, and can last for 100 years. Net fluxes, including carbon accumulation through regrowth, reduce these estimated large losses. Field studies of net losses from biomass

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(Slaughter *et al.*, 1998) and paired-tower (Amiro, 2001) measurements reveal little net emissions within a decade following disturbance by fire.

Fire has the potential of affecting ecosystems for many years, and the combined legacy of multiple fires critically determines the C balance of terrestrial ecosystems at regional and continental scales. In North America, fire exclusion in the first half of the 20th century may be partly responsible for a contemporary C sink (Houghton *et al.*, 2000, Pacala *et al.*, 2001, Hurtt *et al.*, 2002). Kurz & Apps (1999) found that increased disturbances associated with fire and insects are responsible for a shift in Canadian forests from a carbon sink to a source in recent years. Interannual variability in combustion emissions and postfire recovery may also play a role in the observed variability of global atmospheric carbon (Langenfelds *et al.*, 2002).

In many temperate and boreal regions of North America, fires represent a major form of ecosystem disturbance. Statistics from Canada and Alaska show an average of 2.9 million ha yr⁻¹ burned during the 1990s (Kasischke *et al.*, 2002, Stocks *et al.*, 2002), and over 6 million ha have burned during high fire years (Murphy *et al.*, 2000). The total boreal forest area in North America is 412 million ha (excluding 143 million ha of nonforest area from boreal ecozones; Bourgeau-Chavez *et al.*, 2000), implying that fires burn an average of about 1% of this biome per year. At a regional scale, fire tends to be episodic in nature, with a substantial portion of the landscape affected by fire when drought conditions prevail. For example, 2–5% of some ecozones in Canada and Alaska has been burned during a single year (Murphy *et al.*, 2000).

Nine years after a 1988 fire in Yellowstone National Park, USA, field measurements of leaf area index and above-ground NPP (ANPP) revealed that values of high-density pine stands were within the range of other published values for mature forests, suggesting a rapid recovery of NPP within the burned ecosystem (Reed *et al.*, 1999). Amiro *et al.* (2000) conducted an NPP study following fires in Canadian forests using a model driven by satellite observations. Using satellite data from a single year (1994), these authors substituted space for time in their analysis and found that NPP increased for 7–20 years following a fire, depending on the region. Kasischke & French (1997) studied the behavior of satellite-based normalized difference vegetation index (NDVI) in Alaska, showing the substantial effect of fires on NDVI. Using observations from different forest types in a postfire successional chronosequence, the authors found that NDVI increased for 20–50 years after a fire, followed by a decline. Kasischke & French (1997) also analyzed the annual cycle of NDVI

after a fire using 2 years of satellite observations, finding a 50% reduction in postfire NDVI.

Since NPP is the pathway by which C enters the terrestrial biosphere, understanding postfire C dynamics requires accurate estimates of NPP response and recovery. A central goal of this study was to investigate the NPP response following fire to increase our understanding of the global carbon cycle. Several large-scale biogeochemical models have recently incorporated the effects of fire on ecosystem processes (e.g., Peng & Apps, 1999; McGuire *et al.*, 2001; Lucht *et al.*, 2002). Our results provide an observational constraint on postfire NPP dynamics for validation of these models. For C cycle models based on forest inventory data (e.g., Kurz & Apps, 1999), our results provide a means of parameterizing the NPP dynamics after a fire.

Here, we used 17 years (1982–1998) of satellite-driven NPP estimates from a carbon cycle model, together with an independent data set of large fire burn areas, to assess the effects of fire on NPP and net ecosystem productivity (NEP). Multiple years of NDVI and digitized fire perimeters allowed us to track how NPP responded over time in the burned areas. We then modeled C losses from combustion and decomposition and analyzed the long-term NEP behavior for typical boreal forest conditions.

Materials and methods

Modeled NPP and input data

To calculate NPP, we used the Carnegie–Ames–Stanford Approach (CASA) carbon cycle model discussed in detail by Potter *et al.* (1993) and Field *et al.* (1995). Briefly, CASA calculates the fraction of absorbed photosynthetically active radiation (fAPAR) from NDVI and the simple ratio (SR), which are defined as

$$\text{NDVI} = (\text{NIR} - \text{VIS}) / (\text{NIR} + \text{VIS}), \quad (1)$$

$$\text{SR} = \text{NIR} / \text{VIS}, \quad (2)$$

using the visible (VIS) and near-infrared (NIR) bands of the NOAA advanced very high resolution radiometer (AVHRR). Los *et al.* (2000) found that an average of the linear relationships between fAPAR and NDVI and fAPAR and SR yielded the best results compared to field observations of fAPAR. The parameters of these relationships varied by biome and were determined from the continental scale distribution of NDVI following Los *et al.* (2000).

NPP was computed from fAPAR, solar radiation, and down-regulators that represent plant stresses due to suboptimal temperature (T_e) and soil moisture (W_e):

$$\text{NPP} = \text{fAPAR} \times \text{PAR} \times \varepsilon^* \times T_e \times W_e, \quad (3)$$

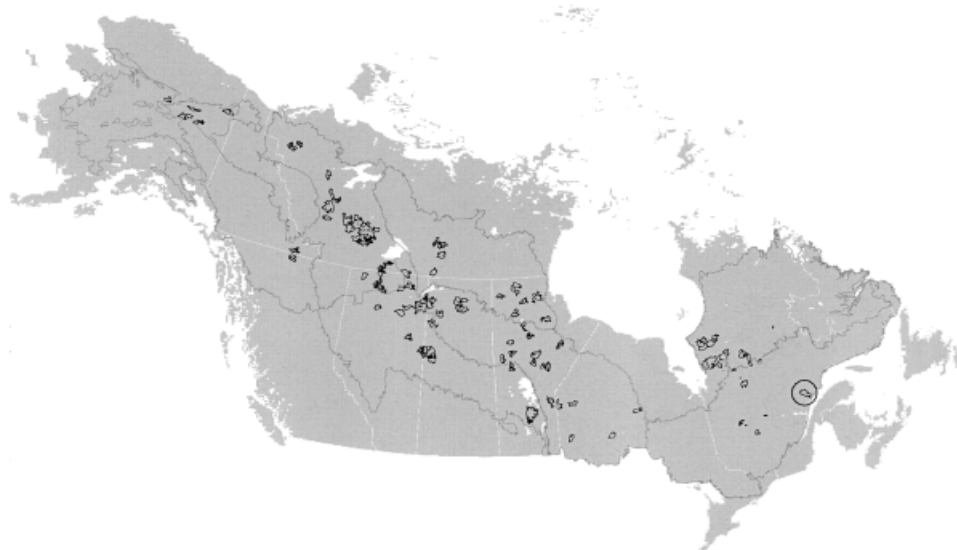


Fig. 1 Map of fire boundaries (in black) used in this study. Also shown are ecozones of the boreal forest containing fires (gray borders) (Bourgeau-Chavez *et al.*, 2000). The circled fire is discussed as a case study.

where PAR is the photosynthetically active radiation and was calculated from the total solar radiation, and ϵ^* is the maximum light-use efficiency set by comparison with field measurements of NPP (Potter *et al.*, 1993). T_e consists of two factors: one reduces plant growth for temperatures different from a globally defined optimum temperature; the other reduces production for temperatures different from an optimum temperature determined for each pixel. W_e is computed using the ratio of actual to potential evapotranspiration as calculated from a simple soil moisture model that incorporates precipitation and temperature data.

We utilized a 17-year (1982–1998) record of NDVI produced for North America (Tucker *et al.*, 2001); this NDVI record was corrected for artifacts such as solar zenith angle drift and instrument calibration (Los *et al.*, 2000, Tucker *et al.*, 2001). We averaged the semi-monthly composited NDVI into monthly values. The spatial resolution of the data is 8 km, resulting in a pixel size of 64 km² (6400 ha).

Interannually varying temperatures and solar radiation from the National Centers for Environmental Prediction (Kistler *et al.*, 2001) and precipitation from the Global Precipitation Climatology Project (Huffman *et al.*, 1997) were used to calculate the plant stressors (T_e or W_e). The three datasets were interpolated from 2.5° to 8 km spatial resolution.

CASA also requires soil texture and the land cover maps as input. The soil texture was taken from the FAO/UNESCO soil map (FAO/UNESCO, 1971). For land cover, we aggregated the 1 km land cover classification of Hansen *et al.* (2000) to 8 km and added a tundra class. This land cover classification was generated using

AVHRR data from 1992–1993, and was assumed to be representative over the entire period of our analysis. Implications of this assumption are discussed below.

Fire perimeters

Burn perimeters were used to identify fire locations in the NDVI observations and modeled NPP (Fig. 1). Boreal forest fires in Alaska and Canada from 1980–1995 with an area greater than 200 ha were mapped using fire records from the national fire management agencies and satellite observations (Stocks *et al.*, 1996, Murphy *et al.*, 2000). For this analysis, we focused on the 61 fires with areas greater than 100 000 ha. The average area of these fires was 191 000 ha, corresponding to ~30 satellite pixels, and ranged from 101 000 to 797 000 ha (15–125 pixels).

NPP decrease and recovery

A major strength of our methodology is the relatively long temporal extent of the satellite observations (1982–1998), allowing us to examine NPP behavior both before (in most cases) and after fire. To assess the immediate effect of each fire on modeled NPP, we compared annual NPP in the year before the fire to the annual NPP in the year of or immediately following fire. The timing of the fire influenced which year was selected: fires early in the season had the largest impact in the year of the fire, whereas late season fires had the largest impact during the following year.

To quantify the recovery of NPP, we calculated differences between prefire NPP and NPP for each year of the satellite record. Similarly, we computed

differences between prefire growing season NDVI (May through October) and each year's growing season NDVI. We included all prefire years when computing prefire values to reduce spurious results due to interannual variability. Fires before 1983 were not analyzed with this method since no NDVI observations were available to compute NPP.

Maps of the postfire NPP decrease and recovery were useful in analyzing case studies. However, we also sought a method of assessing the mean behavior across all fires. To accomplish this, for each fire we determined the pixel within the burn area with the maximum postfire NPP decrease. Then, the NPP time series of these pixels were shifted to align the fire years of all fires considered. 'Relative year zero' is the fire year, negative values are prefire years and positive values are postfire years. An equation defining the NPP recovery

$$\frac{\text{NPP}(t)}{\text{NPP}(\text{prefire})} = 1 - ae^{bt} \quad (4)$$

was fit to the data using least-squares regression. a and b are constants resulting from the fit; t being the time since fire and ≥ 1 ; and $\text{NPP}(t)$ is the net primary production at time t .

Although the burn scar database included 1980–1982, the lack of NDVI data did not permit direct analysis of NPP recovery for this period. Instead, we first identified the most impacted pixel within the fire scar as described above. We then rearranged Eqn (4) to estimate prefire NPP from (1) satellite-derived NPP in the year after the disturbance, and (2) a and b derived from the analysis of fires after 1982. Finally, we applied Eqn (4) to calculate postfire NPP for the entire time period to compare with the satellite-derived NPP. This method allowed verification of the recovery rate against independent observations for a longer time period. If the recovery based on NDVI was faster or slower than the recovery predicted by Eqn (4), we would see an increase in the difference between the methods with time.

Modeled NEP

CASA also estimates heterotrophic respiration (R_h) by allocating NPP among biomass pools and modeling C transfers among multiple pools, each with potentially different turnover times. Decomposition depends on temperature following an exponential (Q10) relationship. Soil moisture influences on decomposition were computed using the stored soil moisture from the previous time step together with precipitation and potential evapotranspiration. In this system, water stress plays a minor role and temperature controls the seasonality of respiration. See Potter *et al.* (1993) and Randerson *et al.* (1996) for more details on the modeling algorithms.

Table 1 Parameters for CASA NEP model run

Parameter	Value
Month of fire	July
% wood killed	80
% consumed by fire (lost to atmosphere)	25
% moved to coarse woody debris pool	75
% leaves killed	90
% consumed by fire	90
% moved to surface structural pool	10
% coarse woody debris consumed by fire	60
% roots killed	80
% moved to soil structural pool	100
% surface pools consumed by fire	90

To demonstrate the effect of fires on the carbon cycle, we ran a version of CASA for mean boreal forest conditions (temperature, precipitation, solar radiation and NDVI). The model was first run to equilibrium (i.e. $\text{NPP} \cong R_h$) with a constant NPP. We then simulated a fire in July by decreasing NPP based on the mean of the satellite observations, releasing C to the atmosphere due to combustion, and transferring C between pools to account for biomass killed, but not combusted. Table 1 summarizes our prescribed model response of the carbon pools to the fire. Our choice of these values was guided by the stand-replacing nature of boreal forest fires, which leads to widespread mortality of trees. The wood mortality numbers, which greatly influenced the postfire dynamics, were broadly consistent with those of Harden *et al.* (1997) and Shvidenko and Nilsson (2000).

We scaled the mean monthly prefire NPP using Eqn (4) to specify postfire NPP. Although we defined $t \geq 1$ in Eqn (4), by specifying the fire in July and using $t \geq 0$ we were able to simulate the mean observed NPP decrease in the year of the fire as well. NEP was defined here as the difference between NPP and R_h ; we ignored other terms such as losses of soil organic carbon through leaching or herbivory. We did not model such postfire ecosystem changes as increases in soil temperature that affect decomposition (Burke *et al.*, 1997); instead we focused on the differences in NEP behavior resulting solely from including postfire NPP dynamics.

Results

Quebec fire

Analysis of a specific fire event illustrates our approach. In 1991, a forest fire burned over 200 000 ha in southeast Quebec (circled fire boundary in Fig. 1). The burned area stands out clearly from the surrounding area (Fig.

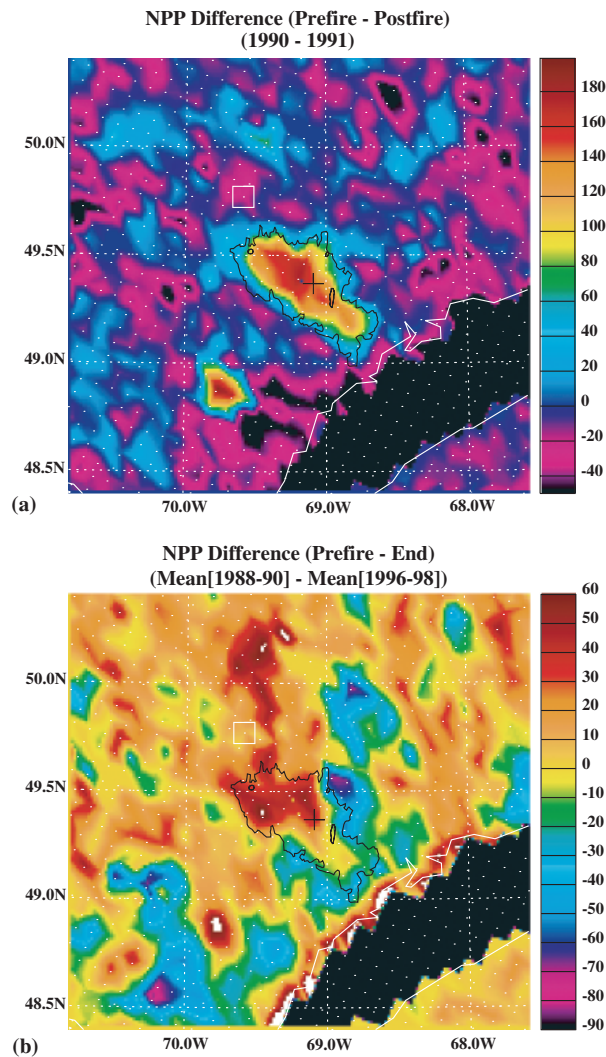


Fig. 2 (a) Net primary productivity (NPP) difference ($\text{g C m}^{-2} \text{yr}^{-1}$) between 1990 and 1991 for a 1991 fire in Quebec. (b) NPP difference ($\text{g C m}^{-2} \text{yr}^{-1}$) between pre- and postfire years. The mean of three years prior to the fire year (1991) and the mean of the last 3 years of the satellite record (1996–1998) were used in calculating the difference. Fire occurred in June 1991 as determined from the satellite imagery, and is located in southern Quebec near the mouth of the St Lawrence River (visible in the lower right). The black outline is fire perimeter. White dots indicate centers of satellite pixels. The black cross indicates pixel selected to represent burned areas in (Fig. 3); the white square indicates the pixel selected to represent unburned areas. A smaller fire $<100\,000$ ha (not analyzed) also occurred to the southwest.

2a). Whereas surrounding unburned areas showed modeled NPP changes of $40 \text{ g C m}^{-2} \text{yr}^{-1}$ or less, areas within the fire boundary (outlined in black) had NPP decreases of over $140 \text{ g C m}^{-2} \text{yr}^{-1}$ (60%). To assess NPP recovery, we compared NPP for prefire years with NPP at the end of the satellite record (1996–1998) (Fig. 2b). NPP differences were $\sim 10\text{--}15\%$ of the prefire NPP,

suggesting that much of the burned site had returned to preburn levels.

Annual production (Fig. 3) of selected unburned and burned locations behaved similarly in prefire years, but postfire NPP was reduced to $100 \text{ g C m}^{-2} \text{yr}^{-1}$. NPP recovered quickly, however, with a difference between burned and unburned pixels of only about $30 \text{ g C m}^{-2} \text{yr}^{-1}$ after 8 years (12%).

Modeled postfire NPP for all fires

Maximum NPP difference of each fire

Fires resulted in NPP decreases of $60\text{--}260 \text{ g C m}^{-2} \text{yr}^{-1}$, corresponding to a relative decrease of 30–80% (Fig. 4). Eighty percent of the fires displayed NPP reductions of at least $100 \text{ g C m}^{-2} \text{yr}^{-1}$ (a relative decrease of 40%).

The boreal cordillera ecozone had the lowest postfire NPP decrease ($70 \text{ g C m}^{-2} \text{yr}^{-1}$), whereas the east boreal shield had the largest ($180 \text{ g C m}^{-2} \text{yr}^{-1}$) (Fig. 5a). The remaining ecozones displayed relatively uniform decreases in NPP, between 110 and $140 \text{ g C m}^{-2} \text{yr}^{-1}$. Only differences between the east boreal shield and other ecozones, and between Alaska boreal interior and boreal cordillera ecozones, were statistically significant at the 95% level (Student's *t*-test of samples with unequal numbers). Mean relative decreases of $\sim 50\%$ occurred in most ecozones (Fig. 5b), with little variation.

Postfire NPP recovery

The average recovery time for NPP for all fires was 9 years (Fig. 6). Similar postfire behavior is apparent between growing season NDVI and NPP, implying that modeled NPP was primarily driven by the satellite observations. Maximum differences of $\sim 50\%$ occurred either in the fire year (relative year 0) or in the year following. At relative year 9, when the number of fires decreased below ten, the mean NPP ratio increased to about one (i.e., postfire NPP recovered to prefire values). While there is some hint that postfire NPP might have exceeded prefire NPP after a period of about 10 years, the sparseness of the data prevents us from drawing any firm conclusions.

The small number of fires in each ecozone, together with variability in number of postfire years, precluded quantitative analysis of mean recovery times by ecozone (Fig. 7). However, two qualitative differences can be seen. Postfire NPP in Alaska boreal interior appeared to recover more slowly than average, whereas NPP in the taiga plains recovered more rapidly.

NPP recovery of fires before 1983

Figure 8a shows an example of NPP of the most impacted pixel within an area that burned in 1982. The

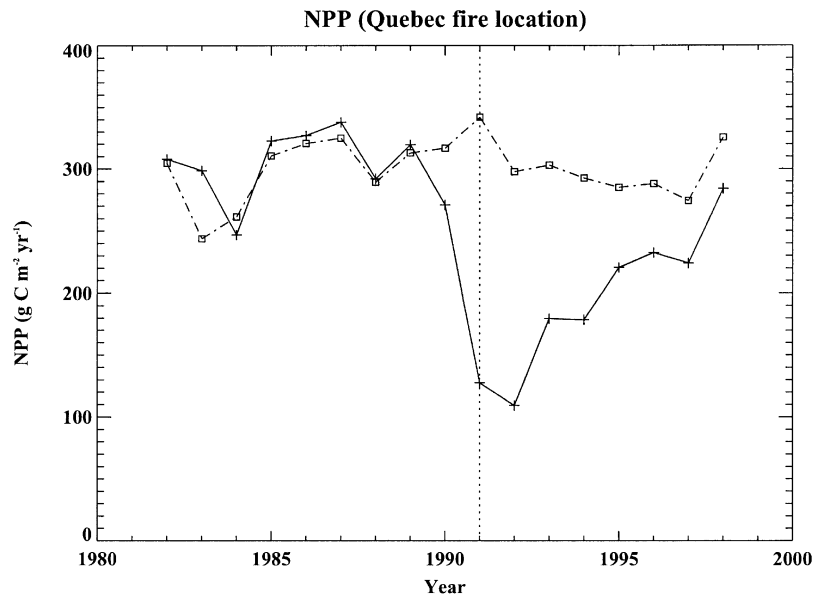


Fig. 3 Unburned (squares, dotted-dashed curve) and burned (crosses, solid curve) values of annual net primary production (NPP; $\text{g C m}^{-2} \text{yr}^{-1}$) for locations in and around the Quebec fire shown in (Fig. 2). Fire year indicated by vertical dotted line.

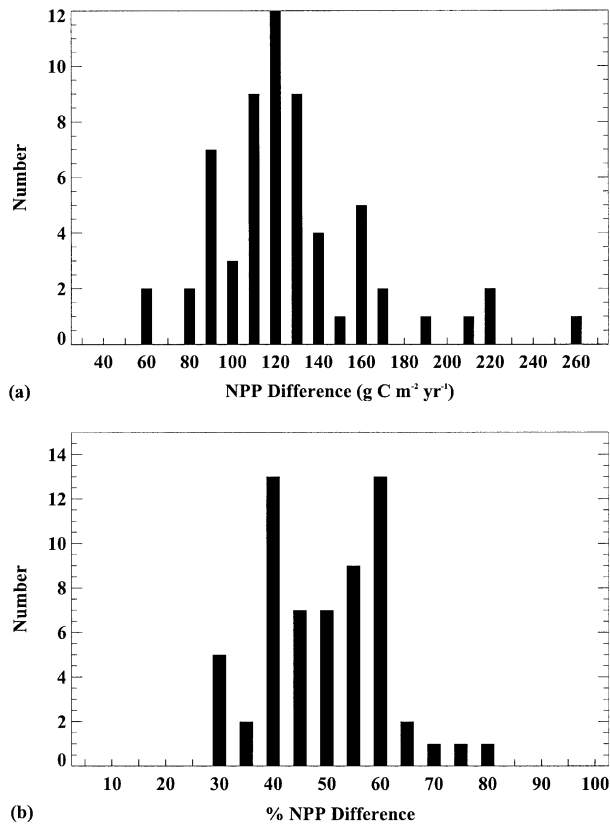


Fig. 4 Distribution of maximum pre- and postfire net primary productivity difference (year before fire minus fire year or fire year plus 1) within each burn area. (a) Absolute difference ($\text{g C m}^{-2} \text{yr}^{-1}$). (b) Relative difference (%).

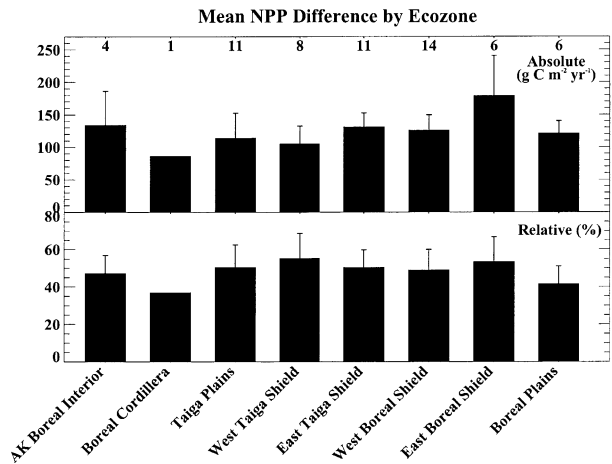


Fig. 5 Maximum net primary productivity (NPP) difference (fire year or fire year plus 1 minus year before fire) within each burn area average by boreal ecozone (ecozones shown in Fig. 1). The top panel shows the mean absolute difference ($\text{g C m}^{-2} \text{yr}^{-1}$), the bottom panel shows the mean difference relative to prefire NPP (%). Whiskers show one standard deviation; numbers across the top of the plot indicate number of fires in each ecozone.

predicted NPP (Eqn (4)) for this fire was slightly less than the satellite-driven NPP, but captured the general pattern of recovery. A wide range of differences exist between satellite-derived and predicted NPP for all 26 fires from 1980 to 1982 in the large-fire data set (Fig. 8b), indicating considerable variation in recovery. The mean

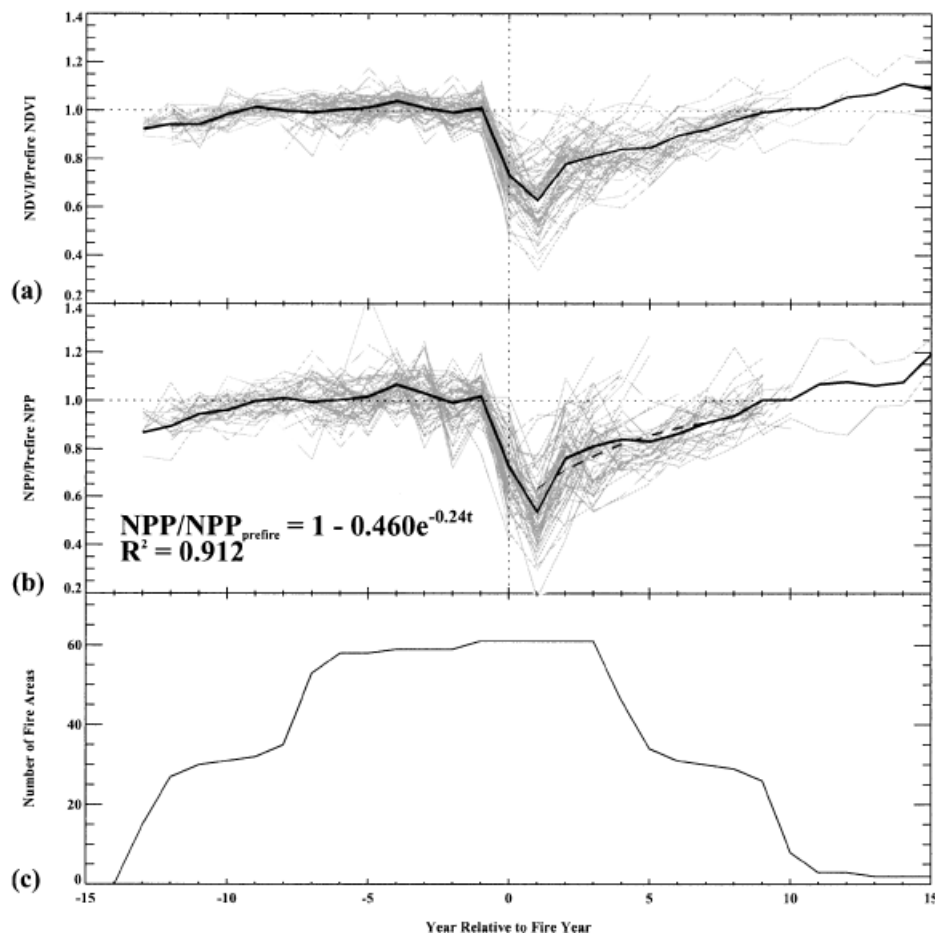


Fig. 6 (a) Recovery of growing season NDVI plotted as a function of year relative to fire year. Mean difference shown as thick curve. (b) Recovery of net primary productivity (NPP). The dashed line shows fitted equation; note that $t \geq 1$. (c) Number of fires used in calculating means in (a) and (b) for each relative year.

difference was slightly positive, suggesting that NPP predicted with Eqn (4) was too low and hence recovery was too slow compared to the satellite-derived NPP. The generalized NPP response probably does not capture regional, longer-term influences on NPP such as climate change that may be responsible for the more rapid observed recovery of the 1980–1982 fires (Zhou *et al.*, 2001; Hicke *et al.*, 2002a; Lucht *et al.*, 2002).

Modeled postfire NEP

The simulated combustion C loss from a typical boreal forest fire was 23% of the total ecosystem carbon, and transfers among pools affected 30% of the total (Table 2). The biomass killed by the fire, but not burned, generated an immediate increase in R_h following the fire, although by ~ 5 years after the fire, R_h was less than prefire R_h (Fig. 9). The resulting NEP shifted from a net C source to the atmosphere during the first 8 years after the fire to a net sink that continued for many

decades afterward as carbon accumulated in living wood and coarse woody debris pools. The cumulative loss of NPP after the disturbance was about 11% of the total carbon stocks altered by fire.

Reduced NPP following fire resulted in a faster decrease of R_h beginning 2 years after the fire due to decreased C inputs. NEP was three times larger during the period when the ecosystem was a net C source to the atmosphere compared to the simulation where only mortality (and not NPP) was allowed to respond.

Discussion

Reduction of NPP immediately following fire

Most fires in the North American boreal forest are stand-replacement events, where all the overstorey trees are killed (Rowe & Scotter, 1973; Viereck, 1983; Weber & Stocks, 1998). Why then do we see postfire annual production values greater than $0 \text{ g C m}^{-2} \text{ yr}^{-1}$? A

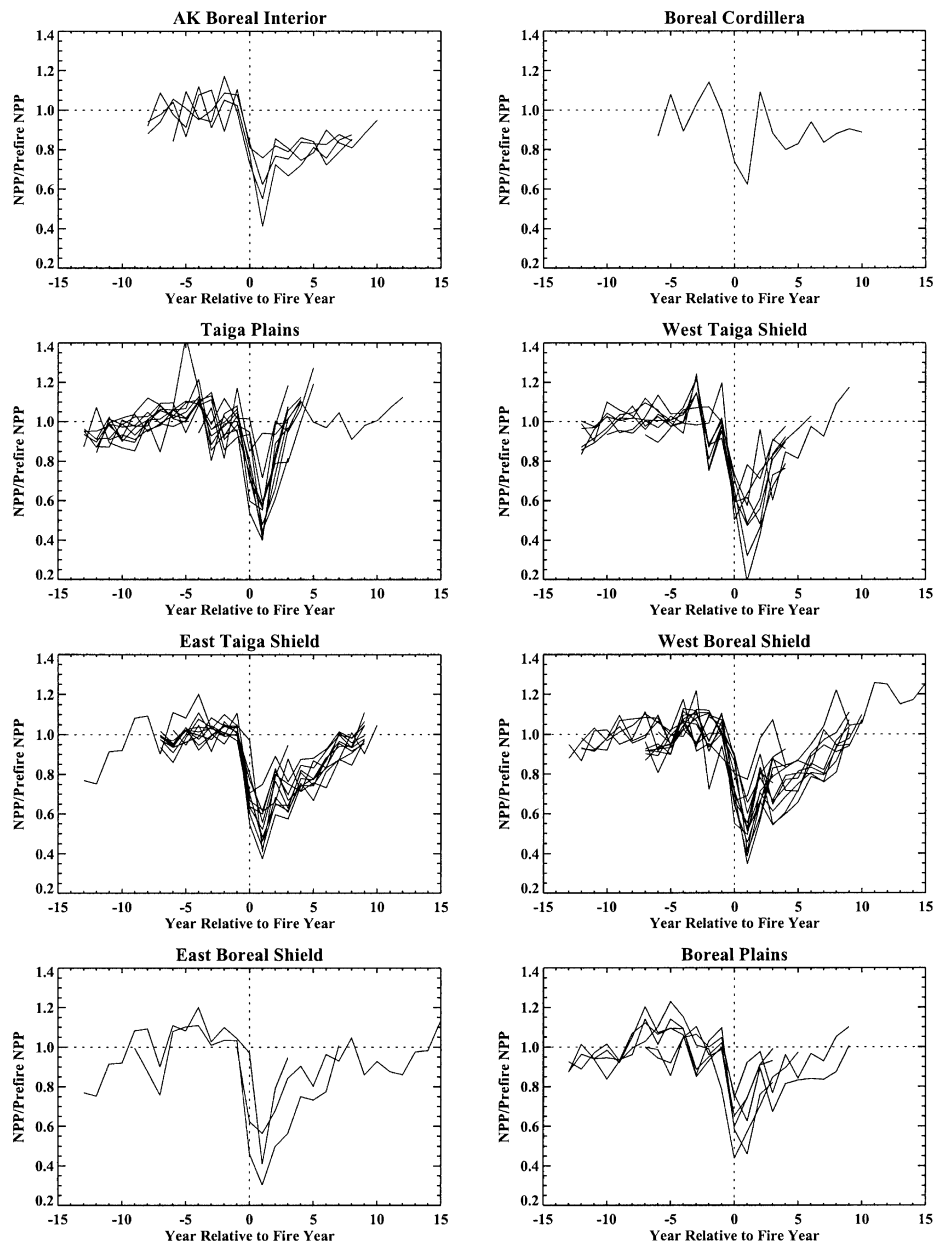


Fig. 7 Same as Fig. 6b for the ecoregions shown in (Fig. 1). Note the apparent longer recovery than average in Alaska boreal interior ecoregion, and shorter recovery than average in taiga plains ecoregion.

contributing factor is the coarse resolution of our satellite data. Substantial spatial heterogeneity in fire intensity occurs even for stand-replacement fires. NPP in the month after the fire was 20–70% of the prefire monthly value, depending on the fire, indicating that pixels typically did not burn completely. This was confirmed by Landsat satellite images at 30 m spatial resolution (not shown), and similar results were found by Kasischke & French (1997) and Michalek *et al.* (2000). It is likely that wetlands and fens within these large fires remained intact, also contributing to patchiness in

the NPP response. Thus, we likely underestimated the immediate NPP decrease following fire compared to a completely burned region, implying a scale-dependence to the decrease.

Part of the explanation for this discrepancy also lies in the timing of the fires within the season. Early season fires, such as in June for the Quebec fire, occurred after some production had occurred (Fig. 2), and also allowed for some vegetation regeneration in the late summer (Dyrness *et al.*, 1986; Kasischke *et al.*, 1993; Kasischke & French, 1997). Kasischke & French (1997)

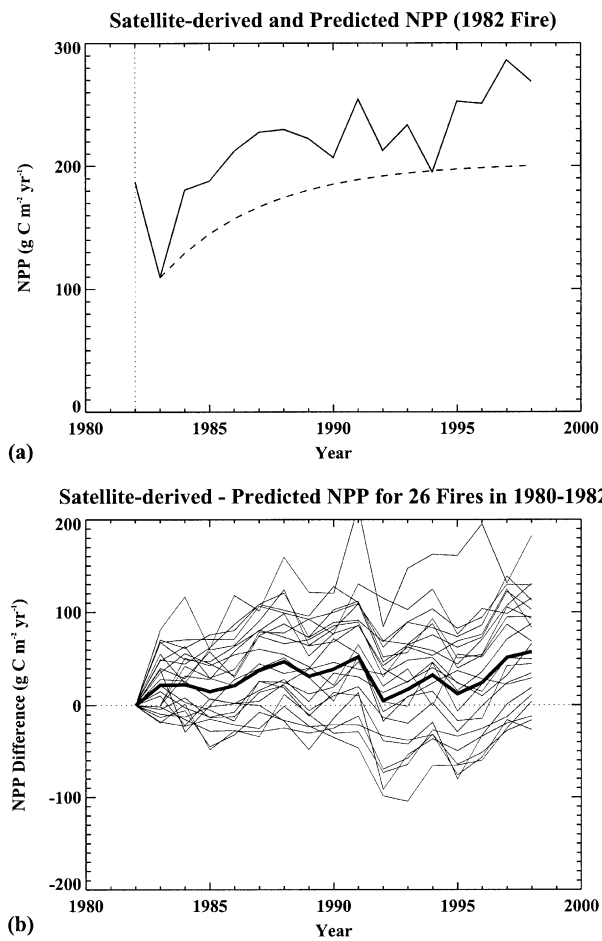


Fig. 8 (a) Satellite-derived (solid curve) and predicted (dashed curve) net primary production (NPP; $\text{g C m}^{-2} \text{yr}^{-1}$) for an area burned in 1982 (the vertical dotted line indicates fire year). (b) NPP difference (satellite-derived minus predicted) of all 26 fires before 1983. The thick line indicates the mean difference. Note that predicted NPP was less than satellite-derived NPP, indicating that the predicted recovery was too slow.

noted that early season fires in Alaska occur in higher soil moisture conditions, leading to less root kill and more vigorous vegetative reproduction than do later season fires. Late season fires took place after the majority of the annual production occurred.

Trajectories of postfire NPP

Our NPP recovery time of ~ 9 years for boreal forests is similar to that reported by Reed *et al.* (1999), who suggested that ANPP recovered 9 years after a 1988 Yellowstone fire. However, they defined 'recovery' as ANPP relative to other published values of ANPP for 'similar mature coniferous forests'. Here, we define recovery as total NPP relative to prefire NPP at the same location.

Table 2 Modeled fire effects on carbon stocks and fluxes

Parameter	Value (g C m^{-2})
<i>Stocks</i>	
prefire total	9360
emissions from combustion	2185
transfers among pools*	2844
<i>Fluxes</i>	
cumulative lost NPP	564
cumulative C source to atmosphere†:	
model run with NPP affected by fire	590
model run with NPP unaffected by fire	195

*Resulting from biomass killed, but not burned.

†Summed NEP over time when NEP < 0 (excluding emissions from combustion).

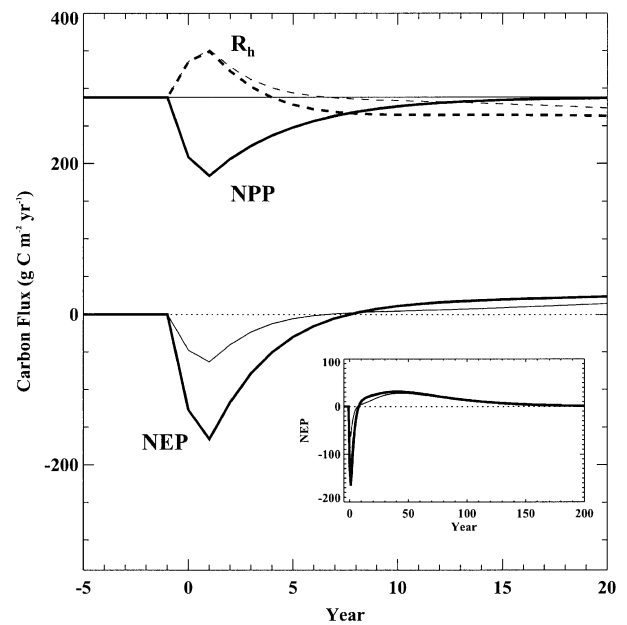


Fig. 9 Long-term responses of modeled net primary production (NPP), heterotrophic respiration (R_h), and net ecosystem production (NEP; $\text{g C m}^{-2} \text{yr}^{-1}$). Thick lines show results from a model simulation using postfire NPP recovery as prescribed by the generalized function shown in (Fig. 6). Thin lines show results from a model run using unchanging NPP. The inset shows extended time series of NEP.

Amiro *et al.* (2000) used chronosequences together with finer scale satellite observations (1 km) to study NPP recovery in the Canadian boreal forest, and found similar recovery times to those of this study. Also, using satellite observations of a postfire successional chronosequence, Kasischke & French (1997) found increasing NDVI for 20–50 years after a fire, longer than our mean

value for the boreal forest. However, our estimated recovery for fires in Alaska appears longer than the mean boreal forest recovery (Fig. 7), although the lack of postfire NPP precluded quantifying the NPP behavior beyond about 8 years.

Two additional factors must be considered when comparing our results to those of Amiro *et al.* (2000) and Kasischke & French (1997). Chronosequences allow a longer postfire time period to be studied; however, decadal increases in NPP may also confound analysis of older fires. For example, Hicke *et al.* (2002a) showed increases in satellite-derived NPP of >20% over 17 years in some boreal forest regions.

Secondly, both the above studies used 1 km NDVI observations in contrast to the 8-km spatial resolution used in this study, and the recovery times may be scale-dependent. Possible nonlinearities in aggregating NDVI over an 8 km pixel may result in a faster predicted recovery than actually occurs for a smaller, completely burned region. Further research is required to address this issue.

Postfire NEP behavior

The simulation of a typical boreal forest fire that included a postfire NPP decrease resulted in a net C source to the atmosphere, summed over the initial 8 years after the fire, that was 27% of the combusted C. These emissions occurred for two reasons. The first was an increase in the amount of C available for decomposition from biomass killed by the fire. The second was a reduction in NPP following the fire; this process also had subsequent effects on R_h through reduced inputs to decomposing C pools. Nearly all the carbon lost by the ecosystem was regained in 200 years, although this C sink occurred over many decades in contrast to the source behavior. We recognize that other postfire effects not modeled will also influence NEP (e.g. increases in soil temperature, Burke *et al.*, 1997).

Our results were similar to a study of plot-level C stocks by Slaughter *et al.* (1998) that revealed only small changes in aboveground carbon 23 years following fire. They found no change in surface soil carbon; we calculated a 4% loss after 23 years. However, our modeled wood pool stocks recovered somewhat more slowly (44% of prefire values compared to ~60%). We also estimated C flux behavior similar to that of Amiro (2001), who used paired-tower flux measurements in the Canadian boreal forest to study carbon dynamics after fire. Amiro (2001) found that a 1-year-old jack pine forest was a C source, in contrast to a measured sink at a mature jack pine forest. A 10-year-old burned mixed forest had similar C uptake values compared to a mature mixed forest, indicating recovery.

Impacts of fire on decadal trends in satellite NDVI

The North American boreal forest region includes 412 million ha of forest and 143 million ha of nonforest (e.g. bogs) (Bourgeau-Chavez *et al.*, 2000). Using our calculated mean NPP recovery time, together with the total forested and burned areas (2.59 million ha yr⁻¹ from 1980 to 1994; Bourgeau-Chavez *et al.*, 2000), we estimated that ~6% of the North American boreal forest is experiencing reduced levels of NPP immediately following fire. Studies of longer-term satellite observations have reported increasing vegetation activity (Myneni *et al.*, 1997; Zhou *et al.*, 2001) and NPP (Hicke *et al.*, 2002b) in North American high latitudes. Our analysis suggests that at regional scales, fires influence these trends. However, at the continental scale, it appears that other mechanisms, principally climate (Hicke *et al.*, 2002a; Lucht *et al.*, 2002), are driving these changes, due in part to the relatively small area burned and rapid recovery of NPP. However, if we assume that the effects on NEP last 100 years after a fire (Fig. 9), then about 63% of this biome is affected by fire. We recognize that these are crude estimates with large uncertainties, but present the values to highlight the potentially important effects of fire in the boreal region.

Within some ecozones in the North America boreal forest, 2–5% of the landscape can burn in major fire years (Murphy *et al.*, 2000). In such areas, decadal increases in NDVI (Zhou *et al.*, 2001) and NPP (Hicke *et al.*, 2002b) are responding to fire. Changes in the decadal magnitude of area burned, such as the two-fold increase in the 1980s and 1990s compared to earlier decades or the potential increase due to climate change (Murphy *et al.*, 2000), will have important implications for the regional carbon budget.

Assumptions

As discussed above, decadal trends in NPP could confound our recovery time estimates. A slight positive trend occurred in the mean prefire NPP (Fig. 6), possibly implying that our calculated recovery times may be too short compared to the productivity of surrounding ecosystems. To assess this possible effect, we repeated our analysis by comparing subjectively defined pixels, one inside and one outside of each fire. This method required the burned pixel NPP to recover to the unburned pixel NPP, not to the prefire NPP of the burned pixel. Both methods resulted in similar recovery times.

The calculation of fAPAR from NDVI depends in part on leaf morphology, canopy structure, and soil optical properties (Sellers *et al.*, 1986). These parameters are

assigned in CASA using a map of land cover classes (Hansen *et al.*, 2000). The derived classification of the pixel from the Quebec fire was 'woodland', since the classification was based on 1992–1993 observations, several years after the fire. To test the sensitivity to prescribed land cover, we reran CASA after changing the classification 'evergreen needleleaf', the vegetation type of the surrounding unburned regions. The resulting prefire NPP was lower in the forest cover runs by 20%, indicating that our results were not overly sensitive to possible vegetation misclassifications or temporal shifts in cover type. DeFries & Los (1999) also found a low NPP sensitivity to land classification. However, we recognize that uncertainty in the cover class could lead to some uncertainty in the initial NPP decrease and the recovery rates.

CASA relies on the assumption that productivity is proportional to the total amount of light harvested by the green canopy. However, changing allocation schemes, such as increases of C to aboveground structures relative to roots early in a tree's life cycle, are not captured with this assumption. Additional research is needed to assess whether this will substantially affect our results.

Our use of only the most impacted pixel to characterize the postfire NPP behavior resulted in larger NPP decreases than pixels with less burned area (e.g. the 'mean' pixel within the burn perimeter), although the influence of burned fraction on recovery time is less clear. Similarly, when studying the postfire ecosystem response across all pixels of a fire, the sensitivity of the results to the choice of spatial resolution is likely greater for pixels that have more unburned area than for the most impacted pixel.

Conclusions

In this study, we employed a long-term satellite record of NDVI (1982–1998) to study the effects of fire on NPP. The 17-year results together with known locations of burned areas allowed us to explore the postfire decrease of NPP as well as to analyze the vegetation recovery. We found that fires can have large impacts within a burned area, with as much as an 80% drop in annual production, but NPP recovered to prefire values within 9 years. The large range of estimated responses among fires was not surprising, given variations in fire intensity, fire burn area within the selected pixel, climate, wetland area, species composition, and other factors affecting ecosystem responses (Rowe & Scotter, 1973), but highlights the difficulty of modeling individual responses.

With a model that included fire impacts on production and carbon pools for mean boreal forest conditions,

we found that the amount of carbon affected by reduced NPP and unburned but killed biomass after a fire was over 1.5 times larger than the combustion emissions from the fire. Accounting for postfire NPP behavior led to a much greater C source to the atmosphere compared to a model run without varying NPP. The relatively small net loss we computed following fire was similar to field observations (Slaughter *et al.*, 1998; Amiro, 2001).

Other studies have analyzed longer-term NDVI variability in temperate and boreal northern latitude regions. These studies have primarily focused on the fact that longer-term NDVI increases may be an indicator of NPP increases driven by climate warming (e.g. Myneni *et al.*, 1997) or that interannual variations in NPP are correlated to variations in climate (temperature and precipitation) (e.g. Braswell *et al.*, 1997). In this paper, we show that fire is an important factor determining spatial and temporal variations in modeled NPP at regional scales. By combining large fire databases, satellite observations, and biogeochemical models, we may better understand the contributions of fire to interannual variations and long-term trends in NPP.

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