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## FOREST FIRES AND CLIMATE CHANGE IN THE 21<sup>ST</sup> CENTURY

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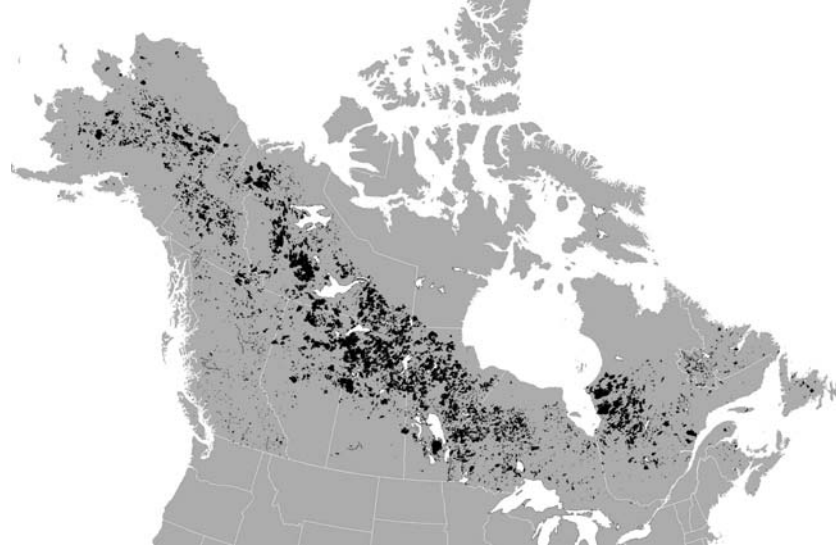
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**Abstract.** Fire is the major stand-renewing disturbance in the circumboreal forest. Weather and climate are the most important factors influencing fire activity and these factors are changing due to human-caused climate change. This paper discusses and synthesises the current state of fire and climate change research and the potential direction for future studies on fire and climate change. In the future, under a warmer climate, we expect more severe fire weather, more area burned, more ignitions and a longer fire season. Although there will be large spatial and temporal variation in the fire activity response to climate change. This field of research allows us to better understand the interactions and feedbacks between fire, climate, vegetation and humans and to identify vulnerable regions. Lastly, projections of fire activity for this century can be used to explore options for mitigation and adaptation.

**Keywords:** climate change, carbon, forest fires, GCMs, area burned

### 1. Introduction

Fire is the major stand-renewing agent for much of the circumboreal forest zone, greatly influencing forest structure and function. Current estimates are that an average of 5–15 million hectares burn annually in boreal forests, primarily in Siberia, Canada and Alaska (Figure 1; also see Stocks et al. 2002), and there is a growing global awareness of the importance, and vulnerability, of this region with respect to future climate change. Fire activity is strongly influenced by four factors – weather/climate, fuels, ignition agents and human activities (Johnson 1992; Swetnam 1993). Climate and the associated weather are dynamic due to changes in the earth's orbital parameters, solar output and atmospheric composition. Recently, our climate has been warming as a result of increases of radiatively active gases (carbon dioxide, methane etc.) in the atmosphere caused by human activities (IPCC 2001). Such warming is likely to have a rapid and profound impact on fire activity in the circumboreal forest zone. Gillett et al. (2004) have suggested that the observed increase in area burned in Canada during the last 4 decades is the result of human-induced climate change. Additionally, it appears that temperature is the most important predictor of area burned in Canada and Alaska with warmer temperatures associated with increased area burned (Duffy et al. 2005; Flannigan



*Figure 1.* Large fires for Alaska and Canada 1980–1999. Large fires were defined as greater than 1000 ha for Alaska and greater than 200 ha for Canada. The fire polygons were kindly provided by Canadian fire agencies (provinces, territories, national parks) and the State of Alaska.

et al. 2005). General Circulation Models (GCMs) are tools that can be used to model the current and future climates to give some insight into these changes.

The objective of this paper is to review and synthesise the present state of fire and climate change research with particular emphasis on the circumboreal forest zone with many examples drawn from the Canadian boreal forest. The relationship between fire and climate change could have significant implications for forests, forestry activities, community protection and carbon budgets. On average, fire management agencies in Canada alone spend 500 million dollars a year on direct suppression costs; if fire activity increases these suppression costs would likely rise dramatically. Additionally, fire management agencies operate with a narrow margin between success and failure, a disproportionate number of fires may escape initial attack under a warmer climate, resulting in an increase in area burned much greater than the corresponding increase in fire weather severity (Stocks 1993). This interplay between climate change and fire is also important in that it could overshadow the direct effects of global warming on plant species distribution and migration (Weber and Flannigan 1997). Thus, fire could be viewed as an agent of change in circumboreal forests (Stocks 1993). Additionally, we will look forward and discuss the future direction of fire and climate change research.

## **2. Forest Fires and Climate Change – Recent Studies**

A number of recent research studies have used GCMs to simulate the future climate. There are a number of GCMs in use; these models include three-dimensional

representations of the atmosphere, ocean, cryosphere and land surface and the parameterizations of the associated physical processes. Future climate scenarios are built based on the effects of various concentrations of greenhouse gases and other pollutants within the atmosphere on our earth-atmosphere system. Transient simulations are available from GCMs which allow examination of the possible rates of change in the climate. The major areas of uncertainty in GCMs include clouds and their radiative effects, the hydrological balance over land surfaces and the heat flux at the ocean surface. Despite these uncertainties, GCMs provide the best means available to estimate the impact of changes in the future climate on the fire regime at larger scales. Most models predict the greatest warming at high latitudes in winter. Confidence is lower for estimates of precipitation fields but many models suggest an increased moisture deficit particularly in the center of continents during summer. In addition to temperature and precipitation, other weather variables such as atmospheric moisture (e.g., relative humidity), wind, cloudiness, etc. will be altered in a changed climate. The variability of extreme events may also be altered (Mearns et al. 1989; Solomon and Leemans 1997) which could have a significant impact on fire activity as many of the largest fires occur on a few critical days with extreme fire weather (Flannigan and Wotton 2001).

Many studies have addressed the impact of climate change on fire weather severity. Flannigan and Van Wagner (1991) compared seasonal fire severity rating values (Seasonal Severity Rating – a rating index to provide a measure of fire control difficulty and is a component of the Canadian Forest Fire Weather Index System) from a  $2 \times \text{CO}_2$  scenario (mid 21st century) versus the  $1 \times \text{CO}_2$  scenario (approx. present day) across Canada. Their study used monthly anomalies of temperature and precipitation from three GCMs (Geophysical Fluid Dynamics Laboratory (GFDL), Goddard Institute for Space Studies (GISS), and Oregon State University (OSU)). The results suggest increases in the Seasonal Severity rating across all of Canada with an average increase of nearly 50%, translating roughly into a 50% increase of area burned. Stocks et al. (1998) used monthly data from four GCMs to examine climate change and forest fire potential in Russian and Canadian boreal forests. Forecast seasonal fire weather severity was similar for the four GCMs, indicating large increases in the spatial extent of extreme fire danger in both countries under a  $2 \times \text{CO}_2$  scenario. Stocks et al. (1998) also conducted a month-to-month analysis, which showed an earlier start to the fire season and significant increases in the area experiencing high to extreme fire danger in both Canada and Russia, particularly during June and July. Flannigan et al. (1998) used daily output from the Canadian GCM to model potential fire danger through the use of the Canadian Fire Weather Index (FWI)(the FWI is a dimensionless relative numerical rating of fire intensity used as a general index of fire danger) for both the  $1 \times \text{CO}_2$  and  $2 \times \text{CO}_2$  scenarios for North America (Figure 2) and Europe. Most of these studies showed large regional variation in the response of fire weather severity to climate change, ranging from significant increases to regions of no change or decreases in fire weather severity (e.g., Bergeron and Flannigan 1995; Flannigan et al. 2000). Consequences

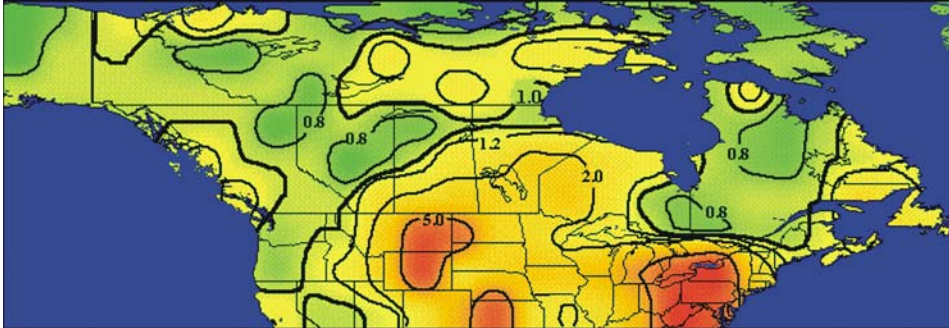


Figure 2. Mean FWI ratio ( $2 \times \text{CO}_2/1 \times \text{CO}_2$ ) for North America (Flannigan et al. 1998; reprinted with permission from Journal of Vegetation Science).

of climate change on fire disturbance must be viewed in a spatially dependent context.

Only a few studies have quantified the potential changes in area burned due to climate change. Flannigan et al. (2005) used historical relationships between weather/fire danger and area burned in tandem with two GCMs to estimate future area burned in Canada (Figure 3). The results suggest an increase of 74–118% increase in area burned by the end of this century. Price and Rind (1994) suggest that lightning-caused fires would increase by 44%, while the associated area burned would increase by nearly 80% by the end of the 21st century in the USA. Bergeron et al. (2004) discuss implications of a changing fire regime on sustainable forest management in Canada. They find that estimates of future fire activity this century are less than the historical fire activity (pre-industrial) for many sites across the boreal forest and suggest that forest management could potentially be used to recreate the forest age structure of fire-dominated pre-industrial landscapes. There are other factors such as ignition agents, length of the fire season and fire management policies that will likely greatly influence the impact of climate change on fire activity. Ignition probabilities may increase in a warming world due to increased cloud-to-ground lightning discharges (Price and Rind 1994), although they did not account for changes in vegetation, which may greatly influence the lightning ignitions and area burned. Recent results for people-caused ignitions suggest increases of 18% and 50% for 2050 and 2100, respectively, for Ontario (Wotton et al. 2003). These potential increases in people-caused ignitions are due to lower fuel moistures. Climate warming is expected to make fire seasons longer. Wotton and Flannigan (1993) estimated that the fire season length in Canada, on average, will increase by 22%, or 30 days in a  $2 \times \text{CO}_2$  world. Also, research has suggested that the persistence of blocking ridges in the upper atmosphere will increase in a  $2 \times \text{CO}_2$  climate (Lupo et al. 1997), which could have a significant impact on forest fires as these upper ridges are associated with dry and warm conditions at the surface and are conducive to the development of large forest fires (Skinner et al. 1999, 2001).

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Fire management policies and effectiveness will continue to change. Changes in prevention programs, initial attack capabilities and restricted access/fire restriction policies will influence potential fire activity in this century. These other factors are all confounding effects that may dampen or amplify the impact of a changing climate on the fire regime.

### 2.1. CARBON DYNAMICS

Fire plays a major role in carbon dynamics because it is the major stand-renewing agent throughout most of the boreal forest. The magnitude of the effect of fire on net biome productivity depends on three main processes. First, carbon is lost through direct combustion. Most of this is in the form of carbon dioxide, but quantities

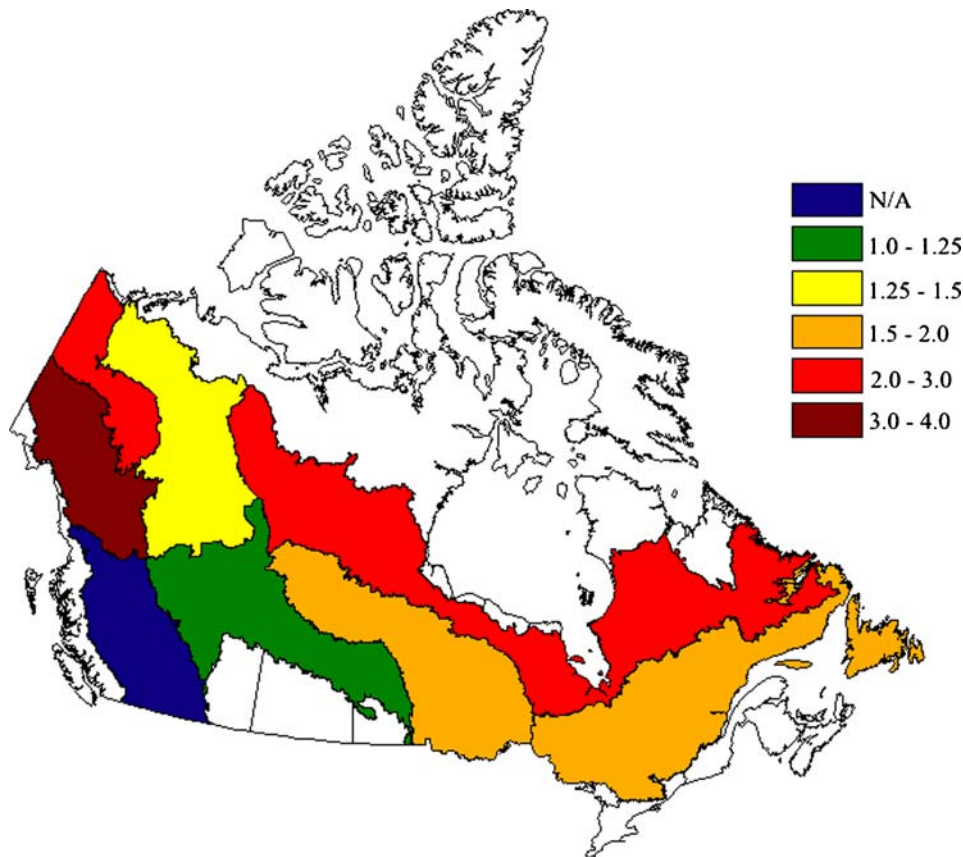


Figure 3. Ratio of  $3 \times \text{CO}_2/1 \times \text{CO}_2$  area burned by Ecozone using the Canadian and Hadley GCMs, respectively. N/A, not applicable. The area burned model did not work for one ecozone for the Canadian GCM (Flannigan et al. 2004; reprinted with permission from *Climatic Change*).  
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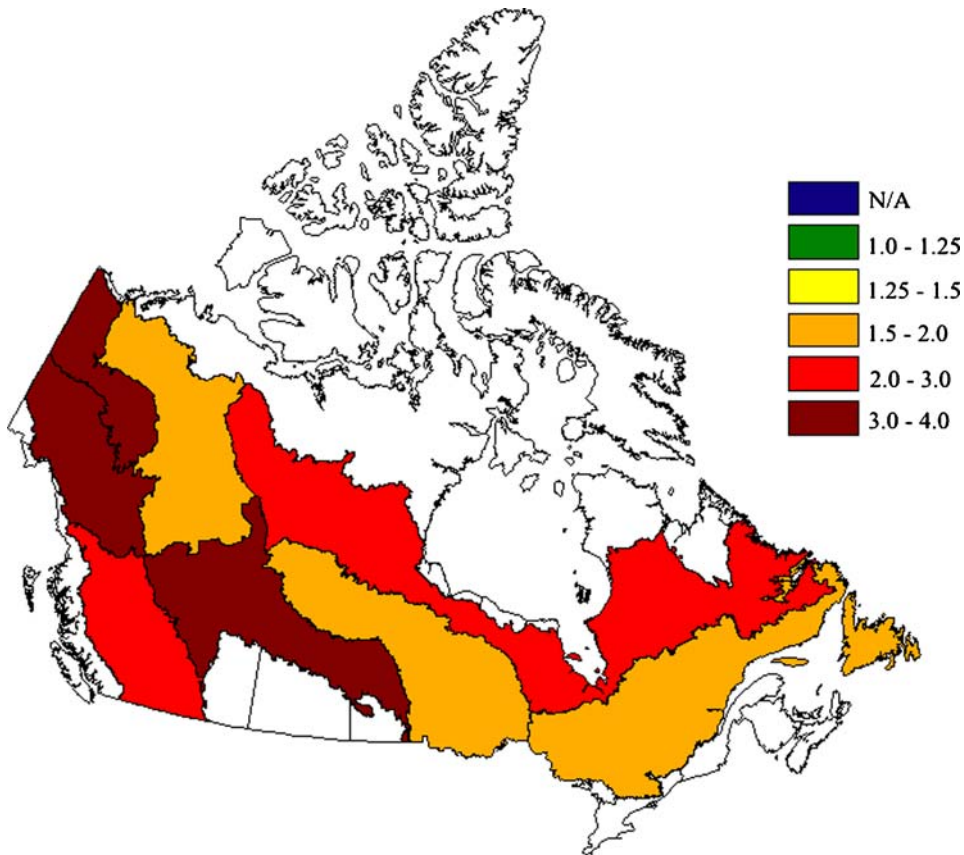


Figure 3. (Continued)

of carbon monoxide, methane, long-chain hydrocarbons, and carbon particulate matter are also emitted. Other greenhouse gases and elements (such as nitrogen compounds) are also released. A recent study determined that Canadian forest fires released an average of 27 Tg C per year, but in some years this exceeded 100 Tg C which is about the same amount of carbon as that is released by fossil fuel emissions in Canada (Amiro et al. 2001). The second process is decomposition of fire-killed vegetation. In severe fires, much of the finer vegetative materials, small twigs, and the top of the duff layer are consumed by the fire, leaving coarser materials behind. These materials decompose at a rate that depends on environmental factors, microbial populations, and the quality of the substrate for decomposition. A further complication is that charred material has chemical characteristics that are different from pre-fire vegetation. The effect of this is largely unknown, although we expect that the char changes the ion exchange capacity in the soil. The physical characteristics also change with the charred surface causing a decreased summer albedo. However the surface energy balance effect quickly changes as successional

vegetation develops, which increases albedo and changes partitioning between latent and sensible heat flux (Chambers et al. 2002; Liu et al. 2005). The third process is the dynamics of vegetation following the fire. Boreal vegetation has adapted to fire and there are a host of species that thrive in the post-fire environment. The vegetation is a photosynthetic sink for carbon.

The net ecosystem production (NEP) following fire is a combination of heterotrophic respiration (i.e., decomposition) and autotrophic fixation. Current research is underway measuring NEP at sites following fire in boreal forests of North America (Amiro 2001, 2003, 2005; Livak et al. 2003). These studies use the eddy covariance technique to measure net fluxes as part of the international FLUXNET community (Baldocchi et al. 2001). To date, this research has shown that forests are carbon sources soon after fire, becoming carbon sinks in the following decades. The magnitude of the flux depends on the successional nature of the forest and environmental factors, and research projects are investigating the interaction of processes to understand and model the net effects to the forest carbon balance.

What will the future look like with respect to fire activity? Research to date suggests that fire weather will be more severe, fire ignitions (people-caused and lightning-caused) and area burned will increase, and the fire season will lengthen. However, much work remains to obtain improved estimates of fire activity in the 21st century and to explore what options are available for mitigation and/or adaptation.

### **3. Forest Fires and Climate Change – Future Directions**

There are a number of subjects related to fire and climate change that require further research. Topics that will be discussed in this section include area burned, fire ignitions, fire intensity and adaptation to altered fire activity. Also, potential feedbacks between fire and greenhouse gases will be addressed. One final objective of this research area would be to have a simulation model(s) that would have dynamic modules of fire and other disturbances (including human-caused), vegetation, weather, and the appropriate interactions so that future fire activity could be simulated globally or for various regions of the world.

There are a number of methods available to obtain better estimates of future area burned. Two possible options involve using dynamic vegetation models (DVMs) that include a fire component in the model or a suite of landscape fire models that could be employed for a region like the circumboreal forest or globally. The approaches appear to be quite different at first glance with the dynamic vegetation models being a top-down approach and the landscape fire models a bottom-up approach. In this context, a top-down approach is where one model is being employed for all ecozones over a large area (continental or global) whereas the

bottom-up approach uses a suite of landscape fire models each developed for a specific ecosystem or ecozone. Both approaches have many similarities and can model vegetation, fire, weather and some human activities in a dynamic fashion with interactions. The primary difference is the spatial resolution and domain of the models with landscape models working at around 50 m on the landscape scale and DVMs operating at several kms on the continental or global scale. For larger regions, a suite of landscape models may have to be used as many landscape fire models can be vegetation-type specific. Research has begun on both approaches. Fire modules are present in two DVMs (Lenihan et al. 1998; Thonicke et al. 2001) and the landscape fire modelling effort has started (Keane et al. 2004, 2005). The rate of change in area burned in the future is of great interest. These simulations can use transient GCM data so the rate of change in area burned can be determined, and indications from historical area burned would suggest that the rate of change in area burned would not be linear (Stocks 1993). These modelling approaches will be able to handle aspects such as the changes in the length of fire season, vegetation, patterns of fire ignition and fire suppression efficiency and policies. Results from this simulation modelling exercise of future fire activity can be used to evaluate potential outcomes in terms of carbon and other GHG emissions and adaptation/mitigation options including the effectiveness of fuel treatment approaches.

These simulation models would require improved fire occurrence prediction models for spatially and temporally explicit information on lightning-caused and human-caused fires. A preliminary assessment of the impact of climate change on human-caused ignitions has been completed by Wotton et al. (2003). However, the model employed used static vegetation and did not alter human population and activities such as harvesting and access to the forest through improved road access etc. These would be the next steps in improving human-caused fire occurrence prediction models. Although, trying to anticipate future human activities and policies can be very difficult. Research into incorporating lightning activity into GCMs is underway. Estimates of future lightning activity along with dynamic vegetation would allow the use of existing lightning-caused fire occurrence prediction models (Anderson 2002) to develop scenarios of future lightning-caused fire starts.

The impacts of climate change on fire intensity levels is another area that requires additional research. Fire intensity is defined as the amount of energy being released by the flaming front of a fire per unit of length of fireline (kW/m). The influence of climate change on fire intensity may be a secondary effect as changes to fire intensity may be due to decreased fuel moisture, increased fuel load, increased wind speed, a change to more conducive fuel types or a combination of any of the above. Fire intensity is important for two reasons. First, the fire intensity often dictates the suppression strategy used on a fire. If a fire is too intense it is not safe to place fire crews on the fireline and aerial attack is required. Second, the intensity can be used to determine the mortality of vegetation in a fire (Hely et al. 2003). Some



preliminary work on the impact of climate change on head fire intensity has been done in Saskatchewan (Johnston 2001). The results suggest a significant increase in fire intensity in some fuel types. This approach should be conducted for the entire circumboreal forest zone, ideally with a dynamic vegetation component; Johnston (2001) used static vegetation.

Results from the fire and climate change research studies outlined thus far would allow us to ascertain which regions of the circumboreal zone, or the globe are potentially vulnerable to a climate change altered fire regime. This would encourage the development of plans and options to mitigate or adapt to the possible changes. One tool that could be used from a fire suppression perspective is a level of protection analysis model (McAlpine and Hirsch 1999). This model determines how many fires will escape initial attack based on fuels, weather and available suppression resources. Simulations can be used to explore the impact of changing climate and changing resource levels on escaped fires.

Lastly, feedbacks and interactions between fire and humans, climate, the atmosphere and ecosystems need to be understood. Lavorel et al. (2005) have proposed an integrated fire research framework (Figure 4) that could be employed to address

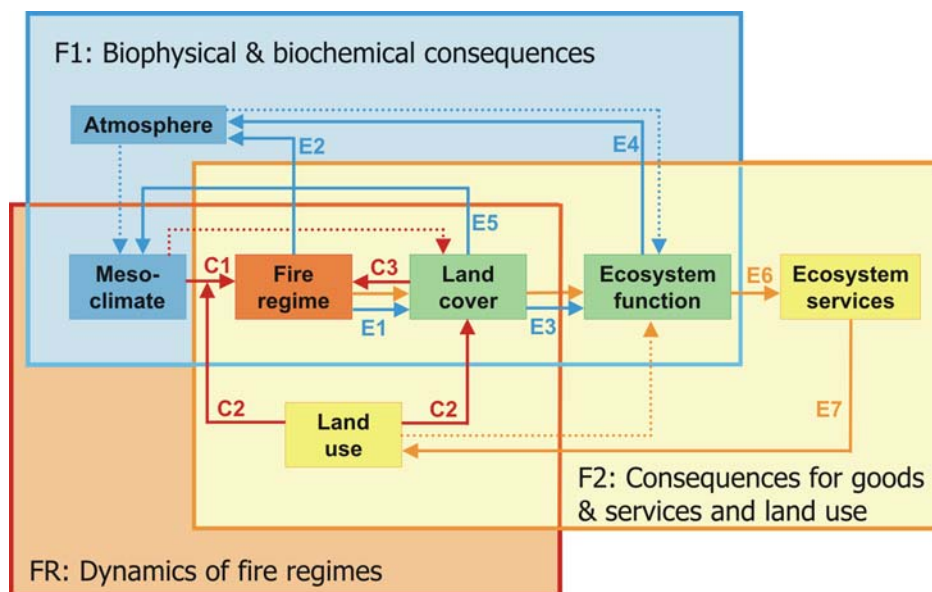


Figure 4. Integrated fire research framework. The framework presents relationships between different compartments of the human-environment system involved in fire causes and effects. These are organised into one control loop on fire regimes (FR, red box and arrows) and two feedback loops, the first one driving consequences of fire for biophysical and biochemical processes (F1, blue box and arrows), and the second one (F2, yellow box and arrows) consequences of fire for ecosystem services and land use. Full arrows indicate topics of direct concern to integrated fire research while dotted arrows represent other important, often indirect effects. Arrows representing different causes (C) and effects (E) are numbered (Lavorel et al. 2005).

fire and climate change issues. In addition to fire, other disturbances (e.g., insects, disease, wind and human activities) should be considered in a similar framework along with interactions between disturbances and there is the potential for synergies between disturbances. For example, fire is more likely during the first decade following a severe spruce budworm outbreak (Fleming et al. 2002). Additionally, there is an interaction with fire-generated smoke that may impact regional and probably even global radiation budgets (Simmonds et al. 2005). In the short term, smoke can have a positive feedback on weather and fire activity by promoting lightning ignitions (Lyons et al. 1998) and reducing local precipitation (Rosenfeld 1999). The feedbacks of carbon losses from global fire have the potential to be a major factor in our changing climate. There is the possibility of a positive feedback, whereby a warmer and drier climate will create conditions conducive to more fire. This in turn will increase carbon emissions from fires, which would feed the warming (Kurz et al. 1995). Although this scenario is possible, we believe that the boreal forests may present some limit to large fire occurrence and increasing area burned since very young forests tend to be less susceptible to fire and could create more landscape fragmentation. We do not yet have a quantitative estimate of these feedbacks, an area of needed research combining fire and climate science with landscape dynamics. A fundamental question is what is the ecological amplitude of our forests in their adjustment and adaptation to fire? We recognize that many of our forests have evolved with some level of fire, but we still need to ask how much fire do they need, and how much fire can they tolerate? If the analyses of Bergeron et al. (2004) are representative of the circumboreal forest as a whole, we may be entering a fire regime that is not catastrophically different from the historical situation but the ecological and economic impacts of a climate change altered fire regime may be severe.

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