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Forest Fires in the Boreal Zone: Climate Change and Carbon Implications

Introduction

The global boreal zone, situated generally between 45 and 70 degrees north latitude, stretches in two broad transcontinental bands across Eurasia and North America. Covering approximately 12 million square kilometres, two-thirds in Russia and Scandinavia and the remainder in Canada and Alaska, the boreal zone contains extensive tracts of coniferous forest which provide a vital natural and economic resource for northern circumpolar countries. Although terrestrial ecosystems found in the boreal zone cover less than17% of the earth's land surface, these ecosystems contain in excess of 30% of global terrestrial carbon. The export value of forest products from global boreal forests is ca. 47% of the world total (Kusela 1990, 1992).

Boreal forests are generally bounded immediately to the north by lichen-floored open forests or woodlands which in turn become progressively more open and tundra-dominated with increasing latitude. To the south the boreal forest zone is succeeded by temperate forests or grasslands. These closed-crown forests have a moist and deeply-shaded forest floor where mosses predominate, the result of a distinct seasonality in which a short growing season and low temperatures. The partially decomposed and compacted organic layer takes many years to accumulate and stores a large amount of carbon. The boreal forest is composed of hardy species of pine (*Pinus*), spruce (*Picea*), larch (*Larix*), and fir (*Abies*), mixed, usually after disturbance, with deciduous hardwoods such as birch (*Betula*), poplar (*Populus*), willow (*Salix*), and alder (*Alnus*), and interspersed with extensive lakes and organic terrain.

Forest fire has been the dominant disturbance regime in boreal forests since the last Ice Age, and is the primary process which organizes the physical and biological attributes of the boreal biome over most of its range, shaping landscape diversity and influencing energy flows and biogeochemical cycles, particularly the global carbon cycle (Weber and Flannigan 1997). The physiognomy of the boreal forest is therefore largely dependent, at any given time, on the frequency, size and severity of forest fires (Kasischke and Stocks 2000). The overwhelming impact of wildfires on ecosystem development and forest composition in the boreal forest is readily apparent and understandable. Large contiguous expanses of even-aged stands of spruce and pine dominate the landscape in an irregular patchwork mosaic, the result of periodic severe wildfire years and a testimony to the adaptation of boreal forest species to natural fire over millennia. The result is a classic example of a fire dependent ecosystem, capable, during periods of extreme fire weather, of sustaining the very large, high intensity wildfires which are responsible for its existence.

For a number of reasons, boreal forests and boreal fires have taken on an added significance in a wide range of global change science issues in recent years. Climate change is expected to be most significant at northern latitudes, and the distribution of ecosystems in this region will change dramatically in response to climate change. This will have serious economic implications for many northern countries relying on forest industries. In addition, forest fire activity is expected to increase significantly with climate change, acting as a catalyst to a wide range of ecosystem processes controlling carbon storage in boreal forests, and likely resulting in a loss of terrestrial carbon to the atmosphere.

Forest Fire Activity in the Boreal Zone

Over the past century, human settlement and exploitation of the resource-rich boreal zone has been accomplished in conjunction with the development of highly efficient forest fire management systems designed to detect and suppress unwanted fires quickly and efficiently. During this period people throughout northern forest ecosystems have coexisted, at times somewhat uneasily, with this important natural force, as fire management agencies attempted to balance public safety concerns

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and the industrial and recreational use of these forests, with costs, and the need for natural forest cycling through forest fires. Canadian, Russian, and American fire managers have always designated parts of the boreal zone, usually in northern regions, as "lower priority" zones that receive little or no fire protection, since fires occurring there generally have little or no significant detrimental impact on public safety and forest values. This policy has become more widely accepted with the realization that total fire exclusion is neither possible nor ecologically desirable, which initiated a gradual move toward the widespread adoption of fire management strategies that prioritize protection of high-value resources while permitting natural fire in more remote areas. This is particularly true in the boreal forest regions of Canada, Russia, and Alaska where lower population densities and forest use allow more flexible fire management strategies.

Even a cursory examination of forest fire statistics from northern circumpolar countries shows that, while humans have had an influence on the extent and impact of boreal fires, fire still dominates as a disturbance regime in the boreal biome, with an estimated 5-15 million hectares burning annually in this region (Stocks 1991; Kasischke and Stocks 2000; Conard et al. 2002). Canada and Alaska, despite progressive fire management programs, still regularly experience significant, resource-stretching fire problems. In contrast, Scandinavian countries do not seem to have major large fire problems, probably due to the easy access resulting from intensive forest management over virtually all of the forested area of these countries, and will not be considered here. Russian fire statistics are available over the past four decades but, until recent years, these statistics are considered very unreliable. In addition, the Russian fire management program has been severely crippled by a struggling economy over the past decade.

Alaska

In Alaska, forest fire statistics are available for the past half-century, and generally indicate that the area burned in this northernmost US state has decreased steadily while fire incidence has increased (Barney and Stocks 1984; Stocks 1991, Murphy et al. 2000)). During the 1940s Alaska recorded an annual average of 114 fires, which burned over an annual average area of ~500,000 hectares. By the 1980s the number of fires and area burned averaged 590 and ~200,000 hectares annually. During the 1990s the average annual number of fires increased to 625, averaging ~400,000 hectares burned annually (Kasischke and Stocks 2000). Increased accessibility has influenced both fire incidence and area burned. Road and rail access meant both an increase in forest use, which resulted in increased fire occurrence, but also a corresponding enhanced detection capability and a shortened response time. Faster initial attack, particularly using smoke jumpers, coupled with aerial detection, are the major contributors to the reduction in area burned. Lightning fires, generally occurring in areas where response intervals are longer, account for a large percentage of the area burned in Alaska (38% of Alaska fires are lightning-caused and these fires account for 80% of the area burned). In addition, many fires in Alaska are fought on a priority basis, with extensive zones of limited protection, resulting in recent area burned statistics being somewhat inflated as a result of selective fire suppression.

Canada

Forest fire statistics have been archived since 1920 in Canada and, within limits, this extensive record permits a general analysis of trends in this country. The Canadian fire record prior to the early 1970s (when satellite coverage began) is relatively incomplete, as various parts of the country were not consistently monitored during this period. This problem likely increases as one goes back in time, being more of a problem in the earlier part of the century than during the mid-1900s. Keeping this uncertainty in mind, annual fire occurrence in Canada, without fluctuating greatly on a year-to-year basis, has increased rather steadily from approximately 6,000 fires annually in the 1930-1960 period, to almost 9,000 fires during the 1980s and 1990s. This is a reflection of a growing population and increased forest use, but is also due to an expanded fire detection capability. The area burned by Canadian forest fires fluctuates tremendously on an annual basis, with the 1980-99 period significant in this regard, due to major fire years in 1981, 1989, 1994,1995 and 1998. While fire occurrence numbers were relatively constant over the 1920-1959 period, and have increased steadily since that time, area burned actually decreased over the first four decades of record only to increase over the last three decades. The most dramatic increase occurred during the 1980s, and 1990s, primarily due to periods of short-term extreme fire weather in western and central Canada. During the 1980-1999 period an average of ~9,000 fires annually burned over an average of 2.7 million hectares in Canada, with annual area burned fluctuating by more than an order of magnitude (0.62 million to 7.56 million hectares). Lightning accounts for 35% of Canada's fires, yet these fires result in 85% of the total area burned, due to the fact that lightning fires occur randomly and therefore present access problems usually not associated with human-caused fires, with the end result that lightning fires generally grow larger, as detection and subsequent initial attack is often delayed.

Recent analysis and evaluation of Canadian fire statistics (e.g. Stocks 1991; Stocks et al. 1996; Stocks et al. 2002) also identified some of the reasons why Canadian fire impact varies significantly. Sophisticated provincial and territorial fire management programs are largely successful at controlling the vast majority of forest fires at an early stage, such that only~2% of fires grow larger than 200 hectares in size, but these fires account for ~98% of the area burned across Canada. In addition, the practice of "modified" or "selective" protection in remote regions of Canada results in many large fires in low-priority areas being allowed to perform their natural function. Recent studies comparing fire sizes relative to levels of protection indicate that, on average, fires in the largely unprotected regions of the boreal zone are much larger than fires in intensively protected regions (Stocks 1991; Ward and Tithecotte 1993), accounting for ~50% of the annual area burned across Canada (Stocks et al. 2002). Examinations of the spatial distribution of all large (>200 hectares) Canadian fires (Stocks et al. 1996; Stocks et al. 2002) showed that by far the greatest area burned occurred in the boreal region of west-central Canada, and attributed this to a combination of fire-prone ecosystems, extreme fire weather, lightning activity, and reduced levels of protection in this region.

Russia

While northern Russia and Siberia have long been noted as areas where extensive forest fire activity is common (Lutz 1956), no documented statistics were ever published by the former Union of Soviet Socialist Republics (USSR) which would allow accurate quantification of the magnitude of the problem in that country. Documentary accounts from the early 1900s describe enormous forest fire losses covering thousands of square kilometres in Siberia, and giving the impression that it was difficult to find areas where evidence of recent fire was not present. In the particularly dry year of 1915, an estimated total of 14,000,000 hectares burned in Siberia (Shostakovitch 1925). Periodically some qualitative accounts of the role of fire in the Siberian forests were published, but these contained only partial statistics at best, which did not permit even rudimentary analysis. 1987 was a particularly severe fire year in Inner Mongolia and Siberia. The well-publicized Great China Fire burned in excess of one million hectares near the China-USSR border during the early spring of that year (Stocks and Jin 1988, Cahoon et al. 1991). NOAA AVHRR satellite imagery revealed that a much larger area was burning in central Siberia during the same period. Analysis of this low-resolution imagery revealed 40-50 fires, ranging in size from 20,000 to 2,000,000 hectares, had burned over a total of approximately 10,000,000 hectares in this part of the USSR (Cahoon et al. 1994). While the absolute accuracy of this estimate may be questionable due to the coarse resolution of the NOAA imagery, it still provides, in the absence of any official statistics from the USSR, a reasonable indication of the enormous forest fire problems that existed in this region in 1987, and is supported in a recent paper by Rylkov (1996). While fire activity in the USSR can be assumed to fluctuate dramatically from year to year, as is the case in other countries, the 1987 scenario is strong evidence that a major proportion of the earth's large boreal forest fires occur in Siberia. Korovin (1996) presented fire statistics for the 1956-1990 period, which indicated that, on average, 16,500 fires burned over ~650,000 hectares annually in the former USSR, with very little annual variation. Russian fire managers agree, however, that these numbers are a gross underestimation of the actual extent of boreal fire in Russia, primarily due to an incomplete reporting structure that emphasized under-reporting actual fire statistics. Recent satellite monitoring (e.g. Kasischke et al. 1999) and analysis (Conard and Ivanova 1997; Conard et al. 2002) has resulted in new estimates that show the annual area burned in Russia averaging close to 12,000,000 hectares, but more study is required before accuracy can be assured. The strongly continental climate of Russia, and in particular Siberia, produces fire weather and fire danger conditions that match ,or even exceed, those observed in Canada and Alaska (Stocks and Lynham 1996) over a much larger land base. It seems likely then that Russian fire statistics should show significant annual variation in area burned, with periodic major fire years, as is the case in both Canada and Alaska. Given the importance of Russia's boreal forests in a global context, it is critical that an accurate representation of fire activity in that major part of the boreal zone be obtained, and extensive satellite monitoring should provide that information in the near future.

Characteristics of Boreal Forest Fires

Boreal forest fires may be classified, based on their physical fire behavior characteristics, into three general categories (Van Wagner 1983): smoldering fires, surface fires , and crown fires. Crown fires can be either intermittent (trees torching individually) or active (with solid flame development in the crowns), with active crown fires being by far the most common. Crown fire development depends on a number of interacting factors: the height of the crown layer above he ground, the bulk density of crown foliage, the crown foliage moisture content, and the initial surface fire intensity. In general, surface fires must generate sufficient intensity to involve the crown layer, resulting in ready access to the ambient wind field which largely determines the rate of spread of the fire. The surface and crown phases of the fire advance as a linked unit dependent on each other. The fast-spreading active crown fires that dominate the boreal landscape are primarily the result of strong winds, and are aided by both short- and long-range spotting of firebrands ahead of the flame front.

The frequency of fires in a given area depends on both the climate and the rate at which potential fuels accumulate following each fire. The fire frequency must be in long-term equilibrium with the longevity of the primary tree species and their reproductive ages. The natural fire cycle averages 50-200 years in the boreal forest (Heinselman 1981). However, human use/protection of the boreal zone has created a much wider gap in fire return intervals than would be the case under natural conditions. Stocks et al (1996), based on 1980s data for Canada, showed mean fire return intervals ranging from <100 years in remote, modestly-protected regions of the northern boreal to >500 years in heavily protected boreal zones.

Fire-adapted forests can generally be divided into two categories (Van Wagner 1983): those species able to regenerate although all trees have been killed over a large area, and those species of which some individuals must remain alive to provide seed for the next generation. Species of the first type are either conifers that store seed in insulated serotinous cones that require heat to open, or hardwoods that regenerate through suckering from the root layer following fire. Species of the second type are conifers that release seed every year when the cones mature. Canadian and Alaskan boreal forests are dominated by species (e.g. *Pinus banksiana* [jack pine] and *Picea mariana* [black spruce]) that bear serotinous cones and require lethal fire to regenerate, and the boreal landscape in North America reflects this, consisting almost entirely of large tracts of pure, even-aged stands of fire-origin species resulting from high-intensity, active crown fires. Alternatively, Eurasian boreal forests are dominated by conifer species not generally considered serotinous. Many Eurasian species have adapted to periodic, lower-intensity surface fires (e.g. thicker basal bark), releasing seed annually and creating a much more heterogeneous, uneven-aged forest. It can be assumed then, that active crown fires are far less common in the Eurasian boreal forest, and this is borne out in the Russian fire literature (e.g. Artsybashev 1967) which shows that crown fires account for ~25% of the total area burned in Russia.

Fuel consumption and spread rates can vary considerably, both within and between boreal fires. In general, however, boreal crown fires consume 20-30 tonnes/ha of fuel (Stocks 1991, Stocks and Kauffman 1997) with roughly 2/3 of this total associated with consumption of forest floor (litter, moss, humus layer) and dead woody surface fuels. Crown fuels (needles and fine twigs) account for the remaining 1/3 of the total fuel consumed. Spread rates can vary between ~5 m/min in intermittent (torching) crown fires and >100 m/min in fully-developed crown fires (Stocks and Kauffman 1997). In a recent comparison of the dynamics of boreal and savanna fires, Stocks et al. 1997 showed that boreal fires consume, on average, an order of magnitude more fuel than savanna fires. Despite similar spread rates, this large difference in fuel consumption means boreal fires develop very high energy release rates, and produce towering convection columns that can reach the upper troposphere and lower stratosphere directly. Conversely, savanna fires usually develop less well-defined convection columns, usually only 3-4 kilometres in height. The differing convection column dynamics of boreal and savanna fires are important in terms of the long-range transport of smoke products from biomass burning. Although much larger areas burn in the savannas annually than in the boreal zone (Crutzen and Andreae 1990), smoke transport mechanisms are likely much different. Regionally-generated savanna fire emissions must be transported vertically at the Inter-tropical Convergence Zone (ITCZ) to have a more global impact, whereas boreal fire emissions are injected at much higher atmospheric heights, promoting the likelihood of wider-ranging transport and impacts.

Climate Change and Boreal Forest Fire Activity

Reconfirming earlier analyses (IPCC 1995), the Intergovernmental Panel on Climate Change (IPCC) has recently concluded (IPCC 2001) that "the global average surface temperature has increased over the 20th Century by 0.6°C, lower atmosphere temperatures are rising, snow cover and sea ice extent have decreased, sea levels are rising, atmospheric greenhouse gas concentrations continue to increase due to human activities, and that global temperatures and sea levels will continue to rise under all modelling scenarios". Extreme weather and climate events are also projected to continue to increase in frequency and severity. There is also evidence of an emerging pattern of climate response to forcings by greenhouse gases and sulphate aerosols, as evidenced by geographical, seasonal and vertical temperature patterns. In North America and Russia this pattern of observed changes has taken the form of major winter and spring warming in west-central and northwestern Canada, Alaska, and virtually all of Siberia over the past three decades, resulting in temperature increases of 2-3^{o}C over this period (Environment Canada 1995, Hansen et al. 1996).

Numerous General Circulation Models (GCMs) project a global mean temperature increase of 0.8-3.5^{o}C by 2100 AD (IPCC 2001) a change much more rapid than any experienced in the past 10,000 years. Most significant temperature changes are projected at higher latitudes and over land. In addition, greatest warming is expected to occur in winter and spring, similar to the trends measured recently, although warming is projected for all seasons. While GCM projections vary, in general winter temperatures are expected to rise 6-10^{0}C and summer temperatures 4-6^{o}C over much of Canada and Russia with a doubling of atmospheric carbon dioxide. Global precipitation forecasts under a 2xCO_2 climate are more variable among GCMs, but indications are that large increases in evaporation over land due to rising air temperatures will more than offset minor increases in precipitation amounts. In addition, changes in the regional and temporal patterns and intensity of precipitation are expected, increasing the tendency for extreme droughts and floods. Recent transient GCMs, which include ocean-atmosphere coupling and aerosols, and project climate continuously through the next century, support these earlier predictions.

Despite their coarse spatial and temporal resolution, GCMs provide the best means currently available to project future climate and forest fire danger on a broad scale. However, Regional Climate Models (RCMs) currently under development (e.g. Caya et al. 1995; Caya and Laprise 1999) and validation (Wotton et al. 1998), with much higher resolution, will permit more accurate regional-scale climate projections. In recent years GCM outputs have been used to estimate the magnitude of future fire problems. Flannigan and Van Wagner (1991) used results from three early GCMs to compare seasonal fire weather severity under a 2xCO_2 climate with historical climate records, and determined that fire danger would increase by nearly 50% across Canada with climate warming. Wotton and Flannigan (1993) used the Canadian GCM to predict that fire season length across Canada would increase by 30 days in a 2xCO_2 climate. An increase in lightning frequency across the northern hemisphere is also expected under a doubled CO_2 scenario (Fosberg et al 1990, 1996; Price and Rind 1994). In two recent studies, Fosberg et al.(1996) used the Canadian GCM, and Stocks et al.(1998) used four current GCMs, along with recent weather data, to evaluate the relative occurrence of extreme fire danger across Canada and Russia, and showed a significant increase in the geographical expanse of severe fire danger conditions in both countries under a warming climate. This increase does not appear to be universal across Canada though, as Flannigan et al. (1998) report results using the Canadian GCM that indicate increased precipitation over eastern Canada could result in a decrease in fire activity in that region. In addition, a dendrochronological analysis of fire scars from northern Quebec indicates a decrease in fire activity during the warming period since the end of the Little Ice Age (ca. 1850). However, most paleoecological studies of lake sediments in North America show fire frequency and intensity have increased in past warmer and drier climates (e.g. Clark 1988, 1990)

In addition to increased fire activity and severity, climate warming of the magnitude projected can be expected to have major impacts on boreal forest ecosystem structure and function in northern circumpolar countries (see Weber and Flannigan 1997). Based on GCM projections large-scale shifting of forest vegetation northward is expected (Solomon and Leemans 1989; Rizzo and Wilken 1992; Smith and Shugart 1993), at rates much faster than previously experienced during earlier climate fluctuations. Increased forest fire activity is expected to be an early and significant result of a trend toward warmer and drier conditions (Stocks 1993), resulting in shorter fire return intervals, a shift in age-class distribution towards younger forests, and a decrease in biospheric carbon storage (Kasischke et al. 1995; Stocks et al. 1996). This would likely result in a positive feedback loop between fires in boreal ecosystems and climate change, with more carbon being released from boreal ecosystems than is being stored (Kurz et al. 1995). Reinforcing this point, a retrospective analysis of carbon fluxes in the Canadian forest sector over the past 70 years (Kurz and Apps 1999) found that Canadian forests have been a net source of atmospheric carbon since 1980, primarily due to increasing disturbance regimes (fire and insects). It has been suggested that fire would be the likely agent for future vegetation shifting in response to climate change (Stocks 1993; Weber and Flannigan 1997).

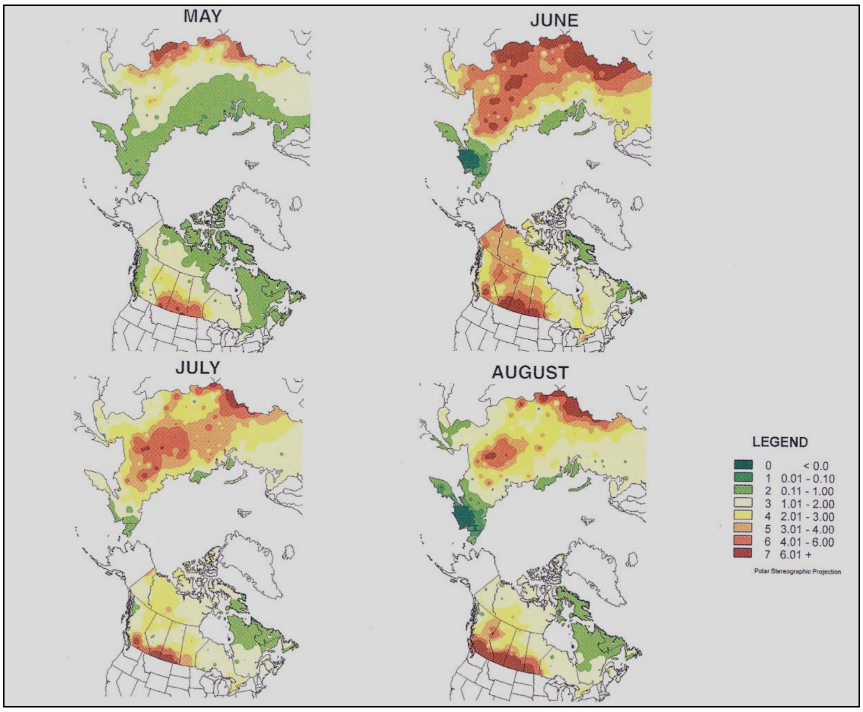

Figure 1. Average Monthly Severity Rating (MSR) maps for Canada and Russia, based on measured 1980-1989 daily weather.

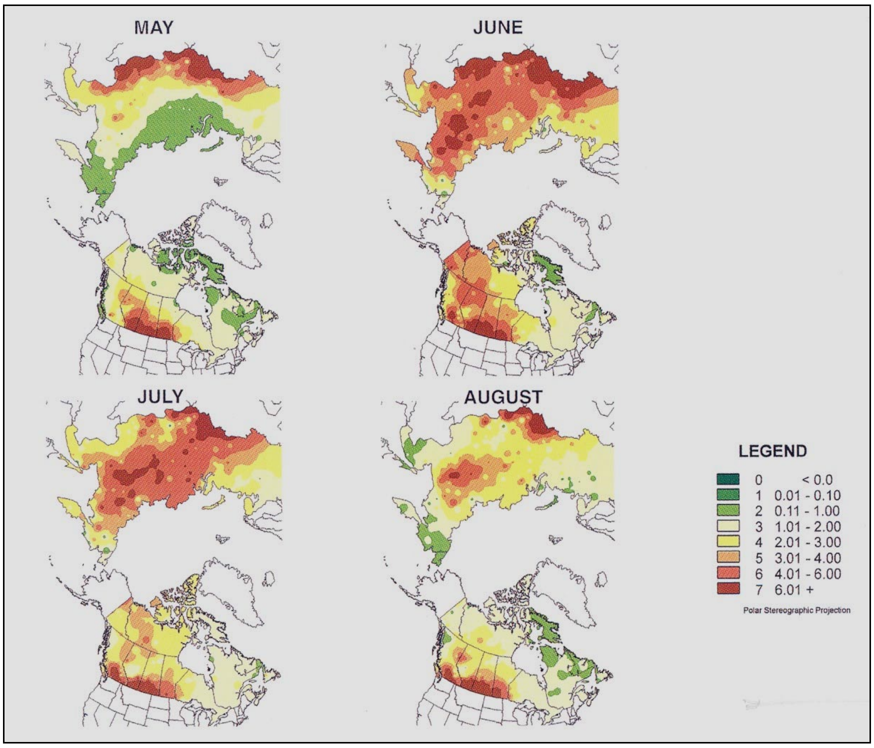

Figure 2. Average Monthly Severity Rating (MSR) maps for Canada and Russia under a 2xCO2 climate using the Canadian General Circulation Model.

While fossil fuel burning contributes most significantly to increasing atmospheric greenhouse gas concentrations, emissions from biomass burning of the world's vegetation (forests, savannas, and agricultural lands) has recently been recognized as an additional major source of greenhouse gas emissions (Crutzen and Andreae 1990). Recent cooperative international experiments (e.g. Andreae et al. 1994, FIRESCAN Science Team 1996) have confirmed that biomass burning produces up to 40% of gross carbon dioxide and 38% of tropospheric ozone, along with a suite of less common, but equally important greenhouse gases (Levine et al. 1995). While most biomass burning emissions originate from savanna and forest conversion burning in the tropics, there is a growing realization that boreal and temperate forest fire emissions are likely to play a much larger role under a warming climate. Cofer et al. (1996) recently outlined a number of reasons why the importance of atmospheric emissions from boreal fires may be underestimated: the tremendous fluctuations in annual area burned in the boreal zone, the fact that boreal fires are located at climatically sensitive northern latitudes, the potential for positive feedback between climate warming and boreal fire activity, and the high energy level of boreal fires which traditionally produce smoke columns reaching into the upper troposphere. A recent analysis of forest fires in Canada post-1959 determined that an average of 27 Tg of carbon was released to the atmosphere annually through direct combustion (Amiro et al. 2001).

The 1997 Kyoto Protocol to the United Nations Framework Convention on Climate Change calls for the "protection and enhancement of sinks and reservoirs of greenhouse gases", and will require all countries to monitor and understand the major factors influencing the exchange of carbon between the biosphere and the atmosphere. With a large amount (37%) (Kurz and Apps 1999) of the total global terrestrial carbon stored in boreal forests, boreal countries will be required to be in the forefront of these efforts. As discussed here, fire is the major disturbance regime affecting carbon cycling in the boreal zone and, with the likelihood of significant increases in forest fire activity in this region, predicting future boreal fire regimes is an urgent international research goal. Policy development and adaptation strategies require this information as soon as possible.

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