Article

Michael G. Weber and Brian J. Stocks

Forest Fires and Sustainability in the Boreal Forests of Canada

The boreal forest is the largest forest region in Canada, occupying approximately 315 mill. ha. Within this forest region long-term average annual area burned is 1.3 mill. ha, with extreme fire years being common, covering up to 7 million ha in a single fire season. Only 2% to 3% of those fires that cover more than 200 ha eventually contribute about 98% of the total area burned annually. Careful examination of fire statistics seems to indicate that fire occurrence is increasing in the boreal forest. Boreal forest tree species and ecosystems are adapted to the periodic passage of fire and some would disappear as natural components of the landscape in the absence of fire. Use of fire as a management tool recognizes the natural role of fire and is applied judiciously for ecosystem maintenance and restoration in selected areas. Implications of possible anthropogenically generated climate change are examined within the context of sustainability of the boreal forest biome and the anticipated impact on fire regime and fire management.

Thermokarst development on permafrost terrain as a result of fire line construction for protection of the town of Inuvik, N.W.T., 1968. Photo: M.G. Weber.

INTRODUCTION

The boreal forest constitutes the largest forest region of Canada. It forms an uninterrupted, transcontinental band from Newfoundland in the east to the Yukon Territory in the west and continues into the State of Alaska (Fig. 1.). In Canada, 75% of all wooded land and 67% of exploitable closed forest are located in the boreal forest (1).

The boreal forest is of variable latitudinal width and species composition, but its overall character across latitudinal and longitudinal dimensions imparts a distinctiveness which sets it apart from other Canadian forest regions. What delineates the boreal forest more than anything else is its climate, locally and regionally. Short, warm summers and long, extremely cold winters are the norm, with fire as the critical ecosystem process which organizes forest plant communities, successional patterns and ecosystem structure and function across landscapes.

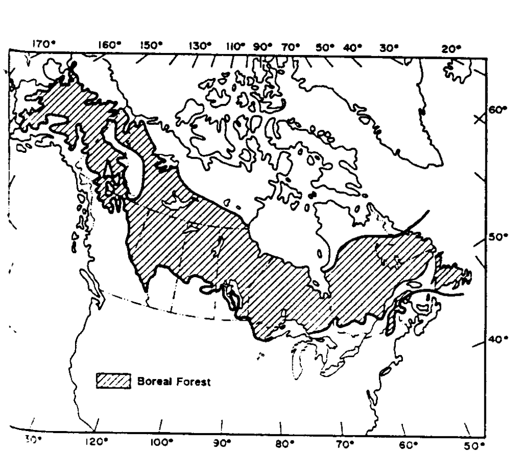

Figure 1. Geographical extent of the boreal forest biome in North America.

In the following we position fire within the wider context of Canadian boreal forest ecosystems and their sustainability. In Canada, the boreal forest biome occupies approximately 315 mill. ha (2). Occupation of such a large continental area by a single, unbroken forest biome will exert influence over global patterns of transformation and circulation of energy and matter. This, in turn, dictates that prudent stewardship be practiced in the management of this resource.

Socioeconomic concerns related to fire and the boreal resource must be an integral part of any ecosystem management plan addressing the utilization of Canada's boreal forests. In-depth socioeconomic considerations, however, beyond selected national fire statistics, would be outside the scope of this paper and will have to be addressed elsewhere. Therefore, after brief examination of relevant fire statistics, we emphasize the ecological role of fire in the boreal forest, including potential impacts of projected anthropogenic climate change on fire regimes in this keystone forest region.

FOREST FIRES IN CANADA

In Canada, records of the national burned area extend back in time, inconsistently, only as far as 1918. In fact, the Yukon and Northwest Territories, which contain large areas of boreal forest within their boundaries, only reported burned areas since 1946, and the provinces of Newfoundland and Prince Edward Island since 1949 and 1971, respectively. The average annual area burned during this period was estimated at 1.3 mill. ha yr^{-1} with variations between 14% to 412% around the mean (3). Extreme fire years are common, with recent examples of large areas burned covering 7.4 mill. ha in 1989, 6.4 mill. ha in 1994, and 7.3 mill. ha during the 1995 fire season (4). These statistics apply to all of Canada's forested lands, but the boreal forest susnorthern parts of the boreal forest where terrain may be underlain by permafrost. As can be seen from Figure 5, vast stretches of the boreal forest in Canada and Alaska are underlain by discontinuous, and smaller areas by continuous, permafrost. When a forest fire burns over permafrost-dominated terrain, the active layer (that which thaws out in the summer) tends to deepen for a few years in response to the improved thermal regime. Increased substrate temperatures are generated by removal of insulating vegetation cover and surface organic layers, reduced heat loss from evapotranspiration, and lowering of the albedo from the burned surface. In time, the active layers depth decreases and reverts to pre-fire thickness as vegetation redevelops (7). Conventional fire suppression on this type of terrain may result in undesirable landscape degradation such as thermokarst initiation from fire-line production. Protection considerations under these circumstances have to be carefully weighed against the long-term impacts on sensitive terrain.

Presumably, the annual fire load before European contact, i.e. pre-European times, would have included lightning fires in addition to aboriginal fires, all burning without control (8). This scenario probably resulted in average annual areas burned, much in excess of what is experienced today (3). A true measure of pre-European forest fire occurrence and coverage will never be known. Quantitative uncertainty, however, in no way reflects the level of our understanding regarding the ecological role of fire in the boreal forests of Canada.

FIRE AND BOREAL FOREST ECOLOGY

Boreal forest ecology is shaped by fire. Boreal forest species, communities, ecosystems, landscapes and the processes at work therein are all affected by the periodic passage of fire. Judging by the adaptations exhibited by major forest species to fire, indications are that fire must have been an integral component of vegetation dynamics as long ago as the Miocene (30M years BP) or early Pliocene (12M years BP) when members of modern forest assemblages evolved (9). That means that by the end of the last glaciation (15K years BP), species' adaptations, including successional pathways after disturbance and forest ecosystems' interaction with fire, were fully developed. Therefore, when boreal forest ecosystem initiation commenced on recently exposed surfaces from propagules originating south of the ice sheet or from unglaciated refugia, fire had already been incorporated as an ecosystem process into the development of the post-glacial landscape.

Forest succession, for the purpose of this discussion, is defined as " the directional change with time of the species composition and vegetation physiognomy of a single site where the climate remains effectively constant" (10). Intimately tied to succession is the concept of climax. Theoretically, at least, this is the last sere in the succession sequence, characterized by self perpetuating vegetation types which are in steady state equilibrium with their environment. Strict application of these concepts to boreal forest ecology has been difficult. The major reason for this is the ubiquity of fire and the adaptation of the species to the more or less regular recurrence of this disturbance. For example, in boreal forests of jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill.) B.S.P.), paper birch (*Betula papyrifera* Marsh.), and aspen (*Populus tremuloides* Michx.), post-fire recolonization is immediate, and overwhelmingly by the same species present before the disturbance. In these cases, there is no large-scale species displacement and gradual recovery over time through various plant community stages to the pre-fire forest cover type. Thus, the terms succession and climax, used in the classical sense, seem inappropriate when applied to boreal forest ecosystem dynamics after fire.

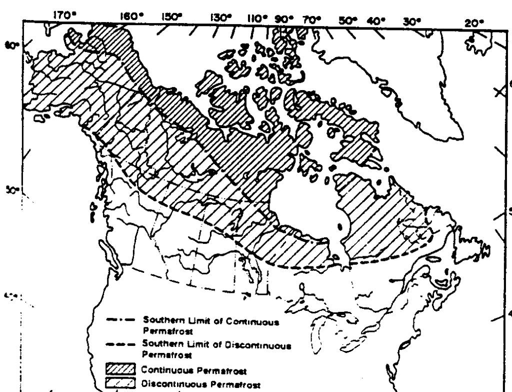

Figure 5. Distribution of permafrost in Canada (46).

The pre-fire area occupied by jack pine, for example, is retained after fire as a jack pine mosaic within the landscape. The case of jack pine provides the strongest example for adaptations of tree species to the periodic passage of fire. This tree species would actually disappear as a natural component of the boreal forest landscape in the absence of fire. The major reason for this is the serotinous nature of the cones. Without the heat from fire to melt the resins which bond the cone scales, the seed crop cannot be released. Besides providing heat to open serotinous cones, fire fulfils two more important requirements for successful regeneration of this species. The first is the creation of a mineral soil seedbed necessary for germination and survival of the young seedling and the second is the temporary elimination of overstorey shade and other competition to allow early growth in full sunlight. Black spruce has similar, if not as exacting, regeneration requirements and pre-fire birch and aspen stands recolonize disturbed areas vegetatively from stem sprouts or root suckers, respectively.

The other important role of fire in the boreal forest, besides its vital association with individual tree species, is the maintenance of the vegetation mosaic in the landscape. The boreal forest landscape mosaic, in turn, constitutes the underlying basis for plant and animal biodiversity within this biome. The landscape mosaic, and hence biodiversity, are safeguarded by the dynamic nature of fire. Fire is more than a straightforward binary event, i.e. it does more than simply occur or not occur. Once a forest fuel complex has been ignited and fire starts spreading, it does so in nonuniform fashion across the landscape. The resultant patchwork of vegetation types and age classes in the landscape is therefore much more than a function of fire return interval or fire frequency only. Even a single fire does not provide uniform burned area coverage. Each of the patches, differentially affected by fire, will take a different pathway to preburn recovery with respect to vegetation dynamics, ecosystem processes, and immigration and emigration of animal species. There are infinite possible landscape diversity scenarios when superimposing various fire return intervals, fire intensities, phenological state of the vegetation (time of year of the fire), postfire local climatic conditions, etc. over the occurrence of a single fire. Only fire can provide the resource mix required by various wildlife populations or the habitat requirements for a single species at different times during the year and for different stages in its life cycle.

THE USE OF FIRE IN ECOSYSTEM MANAGEMENT

Having thus identified fire as a crucial boreal forest ecosystem process, it follows that interference with its natural role or alteration of its long-term regulatory function can be expected to have pronounced effects on the local level or even biome-wide.

tains by far the largest amount of burned area, other forest regions accounting for only a small fraction in both the proportional and absolute sense (5). It is interesting to note that the greatest annual areas burned since records have been kept, are restricted to the 1980s and 1990s (with the exception of 1961 when almost 4 mill. ha burned). Also, when examining these statistics, it must be recognized that the reliability of the information decreases with increasing distance into the recent past. It can be safely assumed that in remote regions of the boreal forest, fires burned large areas undetectedly and therefore were never included into early fire statistics. This problem was eliminated in the early 1970s with the advent of satellite technology dedicated to natural-resource management issues.

The national burned area recorded annually is a complex statistic in the sense that its distribution across the country is very uneven. During the extreme fire years mentioned above, for example, a greater proportion of the area burned was located to the west of the Ontario-Manitoba boundary than to the east. This seems to be a pattern with some degree of consistency. Additional complexity is introduced by the disparity in value of a given unit area burned. Thus, accessible, commercial forests burning anywhere in the southern part of the boreal forest are more likely to represent great financial losses compared to those forest ecosystems located in the northern, inaccessible and noncommercial portions of the biome (3).

Careful analysis of the national forest fire statistics reveals some interesting trends and realities of the Canadian forest fire situation. For example, annual fire occurrence in Canada has increased steadily from approximately 6000 fires annually in the 1930 to 1960 period to almost 10 000 in the 1980s. This trend has continued to date with the number of wildfire starts from all causes averaging just under 10 000 for the first half of the 1990s (4). The observed increase in fire occurrence has been ascribed to a growing population coupled with more intensive forest use and an expanded and more sophisticated fire detection capability across the country. As mentioned above, concomitant with the increase in fire occurrence there was an increase in the annual area burned over the last three decades, with the most dramatic increase observed in the 1980s and early 1990s (Fig. 2.), primarily due to periods of short-term extreme fire weather in western and central Canada (5).

Lightning is the cause of 35% of Canada's fires. This proportion, however, is responsible for 85% of the total area burned. The reason for this has to do with the remoteness of much of Canada's boreal forests. Thus, lightning fires, ignited randomly across the landscape, may grow large, and frequently do, if occurring in remote areas where detection and initial attack is often delayed. Human caused fires, on the other hand, representing the bulk of ignition sources, more often occur in areas with improved access for both fire starters and suppression crews, improving the chances of early and successful detection and initial attack. This point may be illustrated by examining the trends in forest fire size class distribution in Canada during the last two decades (Fig. 3.). Figure 3 shows that most of the fires today are detected and controlled early. However, 2% to 3% of the fires that do grow larger than 200 ha will eventually contribute about 98% of the total area burned in the country (6).

Hidden in the national fire statistics are provincial and territorial fire management decisions regarding the level of suppression accorded a given detected fire. Most operational fire management agencies in the country now prioritize fires according to perceived values-at-risk. This practice is a function of economic realities and ecological considerations, resulting in numerous fires in low-priority areas being observed and allowed to run their course rather than being actively suppressed. A consequence of this policy is reflected in the fire size-class distribution of actioned compared to nonactioned fires in parts of the province of Ontario (Fig. 4.). Modified or selective fire suppression of this sort results in a negative exponential distributio which favors smaller fire size classes. Not actioning fires will result in a fire size-class distribution approaching normality, with large to very large fires being common (6).

Evaluation of economic feasibility or necessity *vs.* ecologica desirability of fire suppression assumes added importance in

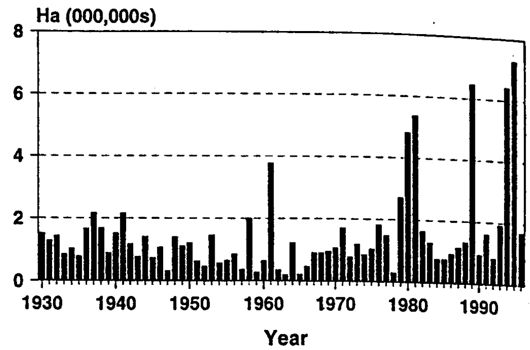

Figure 2. Annual area burned by forest fires in Canada. 1930 to 1989.

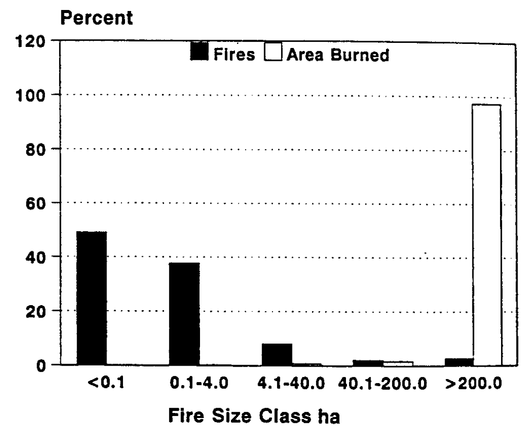

Figure 3. Forest fire size class distribution in Canada. 1970 to 1985 (6).

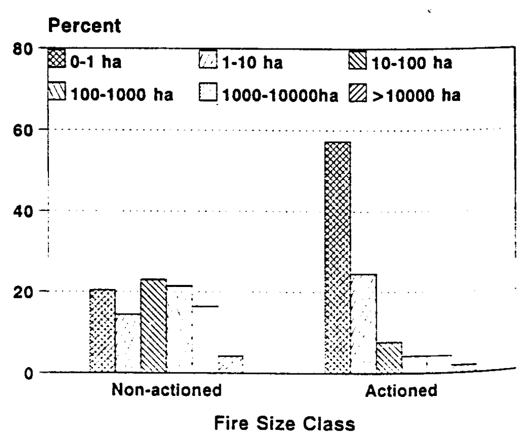

Figure 4. Forest fire size class distribution for actioned and non-actioned fires in northwestern Ontario. 1976 to 1988. (6).

Conversely, acknowledgement of fire as a natural agent validates its use as a management tool in contemporary forest ecosystem management practice. An instructive example of the effects of altering local fire regimes can be found in some of Canada's national parks. As elsewhere, national parks are set aside, presumably in perpetuity, to preserve a certain aspect of the natural environment. Until fairly recently, fire was not recognized as an ecosystem process in any of Canada's national parks and therefore suppressed as an undesirable influence whenever it occurred within park boundaries. This lack of recognition of fire as an integral part of boreal forest ecosystem structure (e.g. vegetation patterns) and function (e.g. biogeo-chemical cycling) resulted in vegetation changes which altered the appearance of some of the parks. The vegetation characteristics and landscape mosaics which had served as the rationale for designating these areas as parks in the first place, were rapidly disappearing . Even after fire was recognized as a key organizing factor in forest ecosystem dynamics, it took some time to provide the policy framework which allowed restoration of fire to those plant communities which required it for their perpetuation (11, 12). The Canadian Parks Service had three options to manage large parks containing fire dependent vegetation: use fire as a management tool; permit artificial means of vegetation renewal; or accept drastic changes in park vegetation and wildlife with time (13). Parks Canada policy makers chose the first option and initiated an ambitious fire-management program for several of their parks, particularly in the west (14).

With a new directive produced in 1986 and a comprehensive fire policy review, Parks Canada embarked on a new relationship with fire and restored it to it's natural role by active management. Unregulated wildfire was considered an unacceptable alternative in most parks because of the implied lack of control over fire effects and values at risk, such as public safety, property, and protection of rare species or delicate habitats (15). The many years of fire exclusion in parks had resulted in fuel accumulations and changes in fuel complexes which would have resulted in fire behavior completely different from pre-suppression conditions. The only acceptable course of action to deal with the modern fuel realities was deemed to be through planned-ignition prescribed fires. Thus, in 1988 and 1989, for example, Parks Canada personnel burned a total of 2000 ha and 1937 ha, respectively, under prescription to maintain the natural age-class distribution in lodgepole pine/Douglas-fir (*Pinus contorta* Dougl. ex. Loud./ *Pseudotsuga menziesii* (Mirb.) Franco) ecosystems in Banff and Jasper National Parks (12).

Modern ecosystem management using fire appears to be the re-invention of an activity practiced for millennia by aboriginal peoples since their original occupation of the boreal forest environment, approximately 12 000 yrs BP. Widespread evidence suggests that settlement of land to the east of the Bering land bridge began around 12 000 yrs BP, at the end of the Pleistocene. Human colonization is thought to have occurred in response to environmental change which took place at that time. The critical environmental variable responsible has been proposed to be the reappearance of trees in river valleys and other protected areas. This provided adequate sources of fuel on deglaciated terrain for the first time since 25 000 yrs BP or earlier. Palynological data indicate that the earliest colonizers among the tree species were aspen and balsam poplar (*Populus balsamifera* L.) (16).

Anthropologists and archaeologists have made a convincing case for early and very sophisticated approaches to and understanding of the dynamics of fire by aboriginals for the management of plant and animal resources in a boreal environment (17, 18). Various lines of evidence suggest that the anthropogenic impact of late Pleistocene North American aboriginal peoples using fire, may have been locally significant and continued until the time of European contact (8, 17–20). One type of evidence for manipulation of vegetation types is derived from the pollen record, where major shifts in over- and understorey vegetation have been linked to human invasion or abandonment of an area. Another line of evidence is provided through recording of oral histories of modern aboriginal boreal forest dwellers. The picture that emerges from that study is one of regular and, at times, large-scale use of fire on an annual basis (17). The overall objective of aboriginal use of fire then was the maintenance of a particular seral state in vegetation development, or to set a certain successional stage back to some desired point. The most often-described conditions which were considered desirable were open, meadow-like seral stages used for grazing by large ungulates and later horses. Open areas, created and maintained by fire also facilitated travel, hunting, visibility and reduction of uncontrolled fire hazard. In addition, the value of fire for maintaining landscape and hence biodiversity was clearly recognized by the early hunter-gatherers of the boreal forest (17).

The rise and maintenance of the grassland biome in North America, for example, has been hypothesized to be due to widespread aboriginal burning and that reinvasion of woody plants occurred in the absence of this practice (21). Boreal forest aboriginals of northern Alberta maintained that this is exactly what happened after their annual burning activities were curtailed by Europeans (17, 22).

CLIMATE CHANGE AND BOREAL FORESTS

Prevailing climate is the critical state factor controlling ecosystem structure and function. On world maps, boundaries of natural vegetation zones, soil types, and climatic regions roughly overlap. Primary productivity (and hence fuel production), soil formation, and soil organic matter content, decomposition processes, etc. are all related to climate (23). This strong linkage between climate and terrestrial biota, both locally and globally, is the basis for anticipating substantial alterations to ecosystem structure and function in response to climate change.

The earth's climate varies at time scales ranging from very short (severe weather events, < 1 hour) to extremely long (warming or cooling trends due to tectonic forcing, 10 mill. yrs). Theories of underlying causes for climate change in the earth's recent or distant history are well developed and subject to ongoing revision or refinement (24, 25). What seems to set ongoing climate change apart from previous episodes is the cause of its onset, thought to be anthropogenic, and the accelerated rate at which it is proceeding. Regardless of acceptance or rejection of contemporary theories of climate change related to the accumulation of "greenhouse gases", prudence commands that the evidence be carefully examined and possible scenarios considered. Implications are serious for ecosystem integrity on a planetary scale if global warming is indeed to occur or already underway.

Boreal forest ecosystems assume added importance under current climate change scenarios because of the vast carbon stores they hold in conjunction with the ubiquity of wildfire. Scientists, studying global carbon sources and sinks, proposed that northern circumpolar forests, of which the boreal is the main component, represent the carbon sink necessary to balance anthropogenic emissions with observed atmospheric increases (26–28). The presence of continuous and discontinuous permafrost over vast tracts of boreal forest substrate (Fig. 5) represents an unknown, but potentially significant, source of carbon, should all or part of this storage compartment become unlocked by climatic warming.

If the boreal forest is indeed the "missing" global carbon sink, then elimination of any part of it would liberate added carbon, thereby increasing its content in the atmosphere, and further contribute to global warming through a positive feedback loop to the greenhouse effect (29, 30). Reduction in North American are several reasons cited for a reduction in boreal forest size, namely the area climatically suitable for boreal forest would advance northward by an area much less than eliminated by its retreat from the southern edge (33). The northward retraction of the southern limit of the boreal forest has been proposed to be mainly due to a reduction in summer soil wetness (34).

Stand replacing wildfire in mature, even-aged jack pine near Chibougamau, Quebec. Note opened serotinous cones on fire-killed trees. Photo: M.G. Weber.

CLIMATE CHANGE AND FOREST FIRES

Perturbations at the landscape level are a reflection of stresses at the ecosystem level. Ecosystem structure and function can be expected to be affected to the point where processes can no longer proceed at the rates to which organisms have become adapted over time. The major processes projected to be dramatically changed in the boreal forest are the frequency and intensity of disturbances such as insect and disease outbreaks, convective windstorms, and particularly fire. The historical role of fire in maintaining the present structure and functions of the boreal forest has been made abundantly clear above. However, in a shifting climate fire may become the means by which ecosystems are rapidly and permanently altered (35). Notable recent contributors to our understanding of the impacts of potential climate change on boreal forest ecology in relation to fire are numerous (36–42). The picture emerging from this research is one of disruptions to boreal forest integrity and loss of landscapes to cool and temperate grasslands and semideserts, fragmenting the Canadian boreal forest into eastern and western parts (32).

Three important aspects of fire regime which must be considered when projecting climate change impacts on the boreal forest are: *i)* climate change mediated transformations in vegetation and hence fuels; *ii)* changed potential for fire occurrence, either from lightning or human-caused; *iii)* modification of fire severity as a result of changes in fire weather (38).

Regarding the first aspect of fire and climate change in the boreal forest, indications are that organisms will be affected earliest and most drastically at the southern edge of the biome (43). Overstorey trees may persist for four of five decades, but seedlings would not. The latter are more sensitive to climate change and may disappear within a few decades, setting the stage for local extinctions of tree populations and associated understorey plants. Shifting of geographical ranges of plant communities due to warming cannot occur at the rate at which warming seems to proceed. The inevitable consequences are reduced geographical ranges and widespread replacement of present-day ecosystems with other vegetation types. The resultant vegetation, characterized by an increased proportion of deciduous species, represents fuel types which would generally burn at double the fire intensity experienced today (38). We must remember, however, that regional variability in altered fire regimes is likely to be large. For example, climate change simulations at 2 x CO_2 indicate reduced fire intensity for the southeastern part of the boreal forest (but not the west) which is corroborated by empirical data generated from local fire history studies (35).

The second aspect of the fire regime expected to change in a warming climate is ignition probability based on natural (lightning) as well as human-caused origin. Human-caused increase in fire occurrence was assumed to increase simply on the basis of increased human occupation and use of the boreal forest and its resources. Lightning frequency scenarios in a changed climate suggest an increase from 30 to 40% between latitude 50°N and 70°N. According to the modelling exercise reported here, the change in frequency is based on total lightning discharge in the boreal zone worldwide and does not distinguish between cloud to cloud and cloud to ground lightning (38). Studies modelling the impact of a 2 x CO_2 climate on lightning-caused fires in the United States suggested an increase of 44% in lightning-ignited wildfires with a resultant increase of 78% in area burned (44).

The third aspect to be considered is changed fire severity due to altered fire weather patterns. Examination of the relationship between seasonal fire severity (a measure of the work needed to suppress a fire) and annual area burned by wildfire in a 2 x CO_2 environment indicated a 46% increase in seasonal severity rating, with a possible similar increase in area burned (37). Extension of this work using the Canadian Climate Centre's general circulation model showed that an average increase in fire season length across Canada of 22% or 30 days can be expected, given the 2 x CO_2 scenario (42). The predicted increase in fire season length was most pronounced in British Columbia where fire season could increase by 51 days (39%).

Besides the obvious impacts of a modified fire regime on boreal forest structure and function under climate change, there are socioeconomic implications as well. Thus, strategic planning for fire management in the boreal forests of Canada will have to take the new fire regime into account. Anticipated increases in fire severity must take into consideration the financial requirements necessary to maintain existing or possibly expanded levels of resource protection. Should the prediction of a prolonged fire season come to pass (42), serious attention will have to be given to the size of the seasonal suppression staff and the tools and equipment needed to carry out the job during a longer and conceivably more severe fire season. Under this scenario personnel and equipment resource requirements for fire suppression must include provisions for deployment to small fires in order to limit damage and containment of large fires, which traditionally cause the majority of social and environmental damage (38). A simulation study (41), dealing with the impact of global warming on wildland fire, supports this concern. This particular analysis showed that in a 2 x CO_2 climate, area burned and frequency of escaped fires were consistently higher than what is observed under present conditions. Policy makers can be expected to be increasingly called upon to prioritize values at risk and allocate public expenditures accordingly. A reasonable set of fire management guidelines may include increased protection of high value areas, while expanding the area under limited protection (45).

SUMMARY

Fire is, and always has been, an integral part of the boreal forest landscape of Canada. Examination of recent fire statistics reveals that an average of nearly 10 000 wildland fires occur each year, burning over an average of 2.5 mill. ha annually (6). In spite of Canada's sophisticated fire-management capability, it is neither economically feasible nor ecologically desirable to eliminate all fires from the boreal forest. On the contrary, realization of the natural role of fire in the boreal forest has led to the reintroduction of fire into those national parks from which it had been excluded in the past. Restoration of fire to its original role as an organizing factor in ecosystem structure and function is an ongoing process in designated Canadian parks and conservation areas.

Projected climate change scenarios for the boreal forest generally predict warmer and somewhat drier conditions during a longer fire season. Increased fire severity would not only strain current levels of fire suppression resources, but may also adversely affect boreal forest distribution with a concomitant reduction in plant and animal biodiversity. Much uncertainty remains in unravelling the effects of rapid climate change on boreal forest ecosystems. If degradations are to occur they will involve complex and poorly understood changes in soil-plant relations unlikely to be reversed by quick fixes. It is therefore essential that degradation is prevented rather than be permitted to occur, because reversals of ecosystem degradation are very costly and extremely time consuming (35).

In addition to the local effects of climate change on boreal forest ecosystems, there are implications for global carbon storage and fluxes. Altered boreal forest fire regimes, especially frequency, size and severity of fire, may liberate carbon from vegetation and substrates at rates exceeding accumulation. The consequences of such a scenario may well include positive biospheric feedback to ongoing climate change, resulting in accelerated global warming (30, 40). Canada's responsibilities regarding the maintenance of boreal forest ecosystem integrity therefore extend beyond its national boundaries. Stewardship of this natural resource requires informed decision making based on the best available research.

References and Notes

1. Kuusela, K. 1992. The boreal forests: an overview. *Unasylva 43*, 3–13.
2. Canadian Council of Forest Ministers. 1995. *Compendium of Canadian Forest Statistics. 1994.* Natural Resources Canada. Ottawa, Canada.
3. Van Wagner, C.E. 1988. The historical pattern of annual burned area in Canada. *For. Chron. 64*, 182–185.
4. CIFFC. 1995. *Canada Report.* Canadian Interagency Forest Fire Centre, Winnipeg, Manitoba, Canada.
5. Van Wagner, C.E. 1991.Forest fire statistics and the timber supply. In: *Canada's Timber Resources.* Brand, D.G. (ed.). Forestry Canada Inf. Rep. PI-X-101, pp. 111–118.
6. Stocks, B.J. 1991. The extent and impact of forest fires in northern circumpolar countries. In: *Global Biomass Burning: Atmospheric, Climatic, and Biospheric Implications.* Levine, J.S. (ed.). MIT Press, Cambridge, Mass., USA, pp. 197–202.
7. Mackay, J.R. 1995. Active layer changes (1968 to 1993) following the forest-tundra fire near Inuvik N.W.T., Canada. *Arctic Alpine Res. 27*, 323–336.
8. Lewis, H.T. 1982. Fire technology and resource management in aboriginal north America and Australia. In: *Resource Managers: NorthAmerican and Australian Hunter-gatherers.* Williams, N.M. and Hunn, E.S. (eds). Am. Ass. Adv. Sci. Selected Symp. No. 67, pp. 45–67.
9. Hopkins, D.M. 1967. *The Bering Land Bridge.* Stanford University Press. Stanford, California, USA.
10. Finegan, B. 1984. Forest succession. *Nature 312*, 109–114.
11. Alexander, M.E. and Dubé, D.E. 1983. Fire management in wilderness areas, parks, and other natural reserves. In: *The Role of Fire in Northern Circumpolar Ecosystems. SCOPE 18.* Wein, R.W. and MacLean, D.A. (eds). John Wiley & Sons Ltd., New York, USA, pp. 273–297.
12. Weber, M.G. and Taylor, S.W. 1992. The use of prescribed fire in the management of Canada's forested lands. *For. Chron. 68*, 324–334.
13. Van Wagner, C.E. and Methven, I.R. 1980. Fire in the management of Canada's National Parks: philosophy and strategy. Parks Canada. *National Parks Occasional Paper No. 1.*
14. Lopoukhine, N. 1983. Parks Canada in the boreal forest ecosystem (A pilgrims progress). In: Resources and Dynamics of the Boreal Zone. Wein, R.W., Riewe, R.R. and Methven, I.R. (eds). Conf. Proc. Thunder Bay, Ontario, August 1982. Ass. of Canadian Universities for Northern Studies, pp. 167–179.
15. Woodley, S. 1995. Fire in protected areas. Parks Canada, Alberta and Pacific-Yukon Region. *Res. Links 3*, 1–10.
16. Hoffecker, J.F., Powers, W.R. and Goebel, T. 1993. The colonization of Beringia and the peopling of the New World. *Science 259*, 46–53.
17. Lewis, H.T. 1977. Maskuta: The ecology of Indian fires in northern Alberta. *West. Can. J. Anthrop. 8*, 15–52.
18. Russel, E.W.B. and Forman, R.T.T. 1984. Indian burning. The unlikely hypothesis. *Bull. Ecol. Soc. Am. 65*, 281–282.
19. Day, G.M. 1953. The Indian as an ecological factor in the northeastern forest. *Ecology 34*, 329–346.
20. Myers, R.L. and Peroni, P.A. 1983. Approaches to determining Aboriginal fire use and its impact on vegetation. *Bull. Ecol. Soc. Am. 64*, 217–218.
21. Axelrod, D.I. 1985. Rise of the grassland biome, central North America. *Bot. Rev. 51*, 163–201.
22. Sauer, C.O. 1950. Grassland climax, fire, and man. *J. Range Mgmt 3*, 16–21.
23. Jenny, H. 123.980. *The Soil Resource.* Springer-Verlag, New York, USA.
24. Farley, K.A. and Patterson, D.B. 1995. A 100-kyr periodicity in the flux of extraterrestrial 'He to the sea floor. *Nature 378*, 600–603.
25. McDowell, P.F., Webb, T., III, and Bartlein, P.J. 1991. Long-term environmental change. p. 143-162. In: *The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Past 300 Years.* Turner, B.L. et al. (eds). Cambridge University Press, Cambridge, UK or USA???
26. Tans, P.P., Fung, I.Y. and Takahishi, T. 1990. Observational constraints on the global CO_2 budget. *Science 247*, 1431–1438.
27. Broecker, W.S. and Peng, T.-H. 1992. Interhemispheric transport of carbon dioxide by ocean circulation. *Nature 356*, 587–589.
28. Sarmiento, J.L. and Lundquist, E.T. 1992. Revised budget for the oceanic uptake of anthropogenic carbon dioxide. *Nature 356*, 589–593.
29. Kasischke, E.S., Christensen, N.L., Jr. and B.J. Stocks. 1995. Fire, global warming, and the carbon balance of boreal forests. *Ecol. Appl. 5*, 437–451.
30. Kurz, W.A., Apps, M.J., Stocks, B.J. and Volney, W.J.A. 1995. Global climate change: disturbance regimes and biospheric feedbacks of temperate and boreal forests. In: *Biotic Feedbacks in the Global Climate System: Will the Warming Speed the Warming?* Woodwell, G. (ed.). Oxford Univ. Press, Oxford, UK. pp. 119–133.
31. Emanuel, W.R., Shugart, H.H. and Stevenson, M.P. 1985. Climate change and the broad-scale distribution of terrestrial ecosystem complexes. *Climatic Change 7*, 29–43.
32. Rizzo, B. and Wiken, E. 1992. Assessing the sensitivity of Canada's ecosystems to climate change. *Climatic Change 21*, 37–55.
33. Sargent, N.E. 1988. Redistribution of the Canadian Boreal Forest under a warmed climate. *Climatol. Bull. 22*, 23–34.
34. Manabe, S. and Wetherald, R.T. 1986. Reduction in summer soil wetness induced by an increase in atmospheric carbon dioxide. *Science 232*, 626–628.
35. Bergeron, Y. and Flannigan, M.D. 1995. Predicting the effects of climate change on fire frequency in the southeastern Canadian boreal forest. *Water Air Soil Pollut. 82*, 427–444.
36. Clark, J.S. 1988. Effect of climate change on fire regimes in northwestern Minnesota. *Nature 334*, 233–235.
37. Flannigan, M.D. and Van Wagner, C.E. 1991. Climate change and wildfire in Canada. *Can. J. For. Res. 21*, 66–72.
38. Fosberg, M.A., Stocks, B.J. and Lynham, T.J. 1998. Risk analysis in strategic planning: fire and climate change in the boreal forest. In: *Fire in Ecosystems of Boreal Eurasia.* Goldammer, J.G. and Furyaev, V.V. (eds). Oxford University Press, Oxford, UK. (In press). (AUTHOR CHECK!!)
39. Lenihan, J.M. and Neilson, R.P. 1995. Canadian vegetation sensitivity to projected climatic change at three organizational levels. *Climatic Change 30*, 27–56.
40. Stocks, B.J., Lee, B.S. and Martell, D.L. 1996. Some potential carbon budget implications of fire management in the boreal forest. In: *Forest Ecosystems, Forest Management and the Global Carbon Cycle.* Apps, M.J. and Price, D.T. (eds.). NATO ASI Series, Subseries 1, Vol. 40. Global Environmental Change, Springer-Verlag, Berlin, Germany, pp. 89–96.
41. Torn, M.S. and Fried, J.S. 1992. Predicting the impact of global warming on wildland fire. *Climatic Change 21*, 257–274.
42. Wotton, B.M. and Flannigan, M.D. 1993. Length of fire season in a changing climate. *For. Chron. 69*, 187–192.
43. Davis, M.B. and Zbinski, C. 1992. Changes in geographical range resulting from greenhouse warming: effects on biodiversity in forests. In: *Global Warming and Biological Diversity.* Peters, R.L. and Lovejoy, T.E. (eds). Yale Univ. Press, Cambridge, Mass., USA, pp. 297–308.
44. Price, C. and Rind, D. 1994. The impact of a 2 x CO_2 climate on lightning-caused fires. *J. Climate 7*, 1484–1494.
45. Stocks, B.J. 1993. Global warming and forest fires in Canada. *For. Chron. 69*, 290–293.
46. Brown, R.J.E. 1970. *Permafrost in Canada.* University of Toronto Press, Toronto, Canada, 234 pp.

47. Drs. M.D. Flannigan and E.D. Wells provided valuable reviews for an earlier draft of the manuscript.
48. First submitted 18 October 1996. Accepted for publication after revision 27 January 1997.

Michael G. Weber is a research scientist with the Canadian Forest Service. His research interests and publications are in the area of ecosystem processes and their recovery after disturbances such as fire and prescribed burning. His address: Canadian Forest Service, Northern Forestry Centre, 5320 122nd Street, Edmonton, Alberta, Canada T6H 4S5.
e-mail: mweber@nvcan.gc.ca

Brian J. Stocks is a Canadian Forest Service senior research scientist with an extensive research background in forest fire behavior and potential impacts of climate change on circumpolar fire regimes. His address: Canadian Forest Service, Great Lakes Forestry Centre, Box 490, Sault Ste. Marie, Ontario, Canada P6A 5M7.
e-mail: bstocks@nvcan.gc.ca