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Past, Current and Future Fire Frequency in the Canadian Boreal Forest: Implications for Sustainable Forest Management

Over the past decades, there has been an increasing interest in the development of forest management approaches that are based on an understanding of historical natural disturbance dynamics. The rationale for such an approach is that management to favor landscape compositions and stand structures similar to those of natural ecosystems should also maintain biological diversity and essential ecological functions. In fire-dominated landscapes, this approach is possible only if current and future fire frequencies are sufficiently low, comparing to pre-industrial fire frequency, that we can substitute fire by forest management. We address this question by comparing current and future fire frequency to historical reconstruction of fire frequency from studies realized in the Canadian boreal forest. Current and simulated future fire frequencies using 2 and 3 x CO_2 scenarios are lower than the historical fire frequency for many sites, suggesting that forest management could potentially be used to recreate the forest age structure of fire-controlled pre-industrial landscapes. There are however, important limitations to the current even-age management.

INTRODUCTION

Over the past decade, there has been an increasing interest in the development of forest management approaches that are based on an understanding of natural disturbance dynamics (1–3). The rationale is that management that favors the development of stand and landscape compositions and structures similar to those that characterize natural ecosystems should favor the maintenance of biological diversity and essential ecological functions (4–7). For the conservation of native flora and fauna, emulation of natural disturbance has been justified by the knowledge that boreal forest species are mostly generalists that are well adapted to the environmental forces that have been acting over thousands of years (8, 9).

Understanding of the fire regimes that characterize the boreal forest is still fragmentary, and it is inappropriate to generalize from regional studies to the entire boreal zone. This lack of understanding has often led to false generalizations. For example, clearcutting has been justified for use throughout the boreal forest based on the assumption that the fire regime is characterized by the presence of large, frequent and severe fires that produced even-aged stands. In fact, it has become increasingly evident that a short fire cycle applies only partially to the boreal forest and that the situation is regionally more complex (10).

In areas where current fire frequency is low, but which historically had more fire, clearcutting might be used as a means to emulate natural disturbance. As the fire cycle increases, extended rotations of even-age management (11) and/or uneven-age management (10) could be used to promote the structure of over-mature and old-growth stands (12). The proportion of even/uneven-age management could be determined by the natural fire cycle of a specific area (13).

However, in areas where fires are still frequent, logging activities are competing with fire for timber, and even-aged short rotation management systems might be unsustainable. Most productive areas in the North American boreal forest lie between these two extreme situations. In the context of climate change, however, situations might improve or degrade because model predictions for fire frequency vary significantly from region to region (14, 15).

In this article, we present historical, current, and projected future frequencies of stand-replacing fires for different regions of the North American boreal forest. We discuss the extent to which the use of conventional even-age management (clearcutting under short rotation) could potentially be used as a means to recreate the forest age structure of pre-industrial landscapes that were controlled mainly by fire regimes.

MATERIALS AND METHODS

Study Area

Fire history studies used in the analysis (Table 1) represent different ecozones of the Canadian boreal forests (Fig. 1). Descriptions of the ecozones can be found in Ecological Stratification Working Group (16). There are only a few studies for many

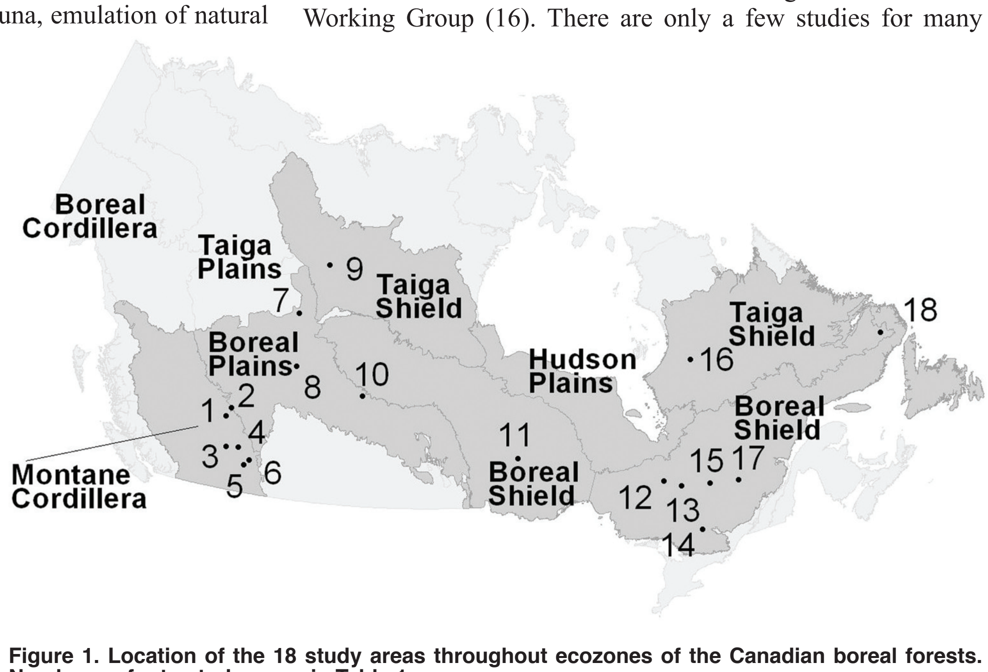

Figure 1. Location of the 18 study areas throughout ecozones of the Canadian boreal forests. Numbers refer to study areas in Table 1.

Table 1. Geographic location and burn rates for each study area.

Site No.	Study area	Reference	Latitude	Longitude	Study area (km^2)	Time period Historical	Past burn rate (%)	Current burn rate (%) (31 416 km^2)	2 x CO_2 burn rate	3 x CO_2 burn rate	2 x CO_2/ curent ratio	3 x CO_2/ current ratio
1	Jasper Park	Tande (43)	52.9	118,1	432	1714-1975	1.04	0.0271	0.0000	0.0000	0	0
2	W.Central Alberta	Van Wagner (37)	53.4	117.8	NA	NA	2.00	0.0194	0.0243	0.0275	1.25	1.42
3	Glacier Park	Johnson et al. (44)	51.3	117.6	1350	1760-1988	0.90	0.0628	0.0000	0.0000	0	0
4	Yoho Park	Johnson and Wowchuk (45)	51.4	116.5	20 500	1740-1988	0.67	0.0493	0.0000	0.0000	0	0
5	Kootenay	Masters (46)	50.5	115.8	1400	1788-1928	0.58	0.0650	0.0000	0.0000	0	0
6	Kananaskis	Johnson and Larsen (47)	50.8	115.4	1300	1730-1980	0.76	0.0503	0.0000	0.0000	0	0
7	Wood Buffalo Park	Larsen (48)	59.0	113.0	44 807	1750-1989	1.41	0.6603	0.8122	0.7726	1.23	1.17
8	Northern Alberta	Cumming (49) (in Armstrong (50))	56.2	112.5	86 000	NA	NA	0.2223	0.3512	0.4268	1.58	1.92
9	Rutledge Park	Johnson (17, 51)	61.7	110.5	105 000	~1760-1980	0.85	0.9033	1.2104	1.7343	1.34	1.92
10	Prince Albert	Weir et al. (24)	55.0	106.0	3461	< 1890	1.03	0.4697	0.4509	0.4838	0.96	1.03
11	Northern Ontario	Suffling et al. (52)	51.5	92.0	24 000	~1870-1974	1.92	0.4615	1.9983	2.6582	4.33	5.76
12	LAMF	Bergeron et al. (10)	49.0	80.0	8245	1740-1998	0.58	0.0456	0.0602	0.0643	1.32	1.41
13	Western Quebec	Bergeron et al. (10)	48.5	79.3	15 793	~1750-1998	0.72	0.0322	0.0328	0.0483	1.02	1.50
14	Algonquin Park	Cwynar (53)	45.9	77.9	186	1696-1920	1.40	0.0067	0.0066	0.0056	0.99	0.84
15	Abitibi east Quebec	Bergeron et al. (10)	48.5	76.0	3294	1760-1998	0.90	0.0323	0.0262	0.0204	0.81	0.63
16	Northern boreal Quebec	Payette et al. (54)	55.0	75.0	5670	1920-1984	1.00	0.2608	0.4147	0.8685	1.59	3.33
17	Central Quebec	Bergeron et al. (10)	48.0	74.0	3844	1720-1998	0.79	0.1109	0.0000	0.0000	0	0
18	Southeastern Labrador	Foster (29)	52.5	58.0	48 500	1870-1975	0.20	0.0379	0.0565	0.0682	1.49	1.80

NA: non applicable
Current burn rate were computed from 1959-1999.

of the ecozones, making it difficult to generalize to the entire ecozone. In most cases, however, fire history studies cover very large areas (Table 1).

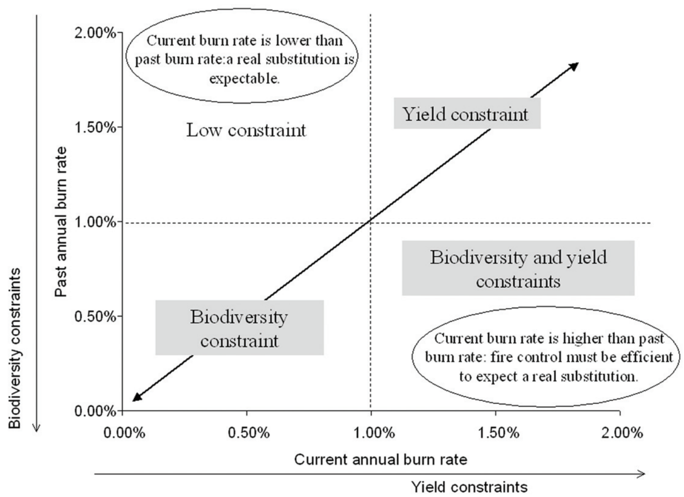

Figure 2. Simple model to assess biodiversity and yield constraints based on past and current annual burn rates.

Model

We developed a simple model based on the comparison of historical and current burn rates to evaluate whether even-age management (clearcutting under short rotation) might be an appropriate way to emulate forest age structures associated with natural fire regimes in different regions, given biodiversity and yield constraints (Fig. 2). The ability to maintain the full suite of native species is constrained when fires or harvests are so frequent that there is a low diversity of stand ages on the landscape. Biodiversity constraints upon even-age management are therefore potentially greater when current fire frequency is higher or equal to historical fire frequency. A higher fire frequency means that a lower proportion of overmature and old-growth stands will be observed on the landscape compared to the historical situation, meaning that stand and age-class diversity will be reduced. Constraints also emerge if historical fire cycle (whatever the current fire frequency) is greater than the usual even-age rotation length because, in this case, the proportion of old-growth stands that would have been present in the past are not maintained under even-age management (12). The area located below the 1-to-1 line (current burn rate = historical burn rate) in Figure 2 is characterized by current burn rates sufficiently high to reproduce historical burn rates, leaving no room for additional clearcutting as a means to emulate natural disturbances. On the other hand, in regions located above this line, a lower current burn rate in comparison with the historical burn rate would allow for the use of even-age management to make up the difference. The amount of even-age management that would be allowed increases according to the distance that regions are located above the line.

Yield constraints are high when current fire frequency is equal or higher to the desired annual harvest level. We fixed it at 1% (100 years rotation) as a general average for the high latitude boreal forest. This value assumes that fires occur randomly with respect to stand age, a characteristic generally attributed to boreal forests (17). It also assumes a regulated forest age structure, a feature that seldom applies to areas that were only recently opened to logging activities. The 1% threshold divides Figure 2 in four quadrants. Briefly, the lower right quadrant (biodiversity and yield constraints) is the worst scenario: a low historical fire frequency means that the pre-industrial landscape was composed mainly of overmature and old-growth forests while climate changes or land uses have increased the current burn rate, thus creating pressure on the system's biodiversity (Fig. 2). In addition, even-age management competes with forest fires, thus accelerating forest age structure changes. Conversely, the upper left quadrant (low constraint) is the best scenario; while historical fire frequency was high, climate changes, land uses or fire suppression has led to a decrease of current fire frequency. Even-age management may therefore be desirable to preserve the historical forest age struc-

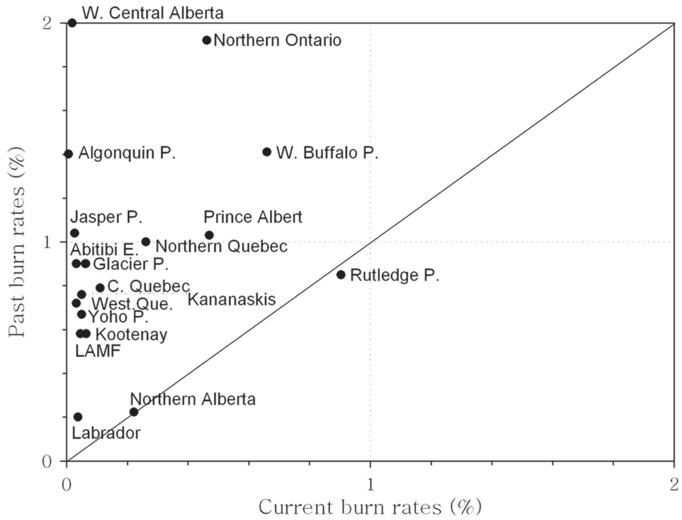

Figure 3. Past and current burn rates of the 18 study areas. Note: same value of Northern Alberta's recent burn rate has been assigned to the past burn rate missing value.

ture. The lower left quadrant means a biodiversity constraint, as historical and current burn rate are lower than the 1% desirable annual harvesting level. The upper right quadrant implies a yield constraint, as historical and current burn rates are higher than the desired 1% annual harvesting level; thus, even-age management would compete with forest fires.

Burn Rates

Historical burn rates were determined from a literature review using available forest fire history studies in the North American boreal forest (Table 1). Average age of the forest (time since-fire) or, if not available, fire cycle before large clearcutting activities began were used to estimate historic burn rates. The average age of the forest was preferred to the historic fire cycle because it integrates climatically induced changes in fire frequency over a long period, and because it is easier to evaluate than a specific fire cycle (10). The inverse of average age (or fire cycle) was used as an estimator of the annual historic burn rate.

Current burn rate was estimated from the Canadian large-fire database (18). The large-fire database includes all fires 200 ha and larger, and represents over 97% of the area burned. For each site, we used a 100 km radius and calculated the average annual area burned using the large fire database for the period 1959–1999 (Table 1).

Future burn rates were calculated using relations developed between observed annual area burned and observed weather and fire weather indexes (19). We then substituted weather and fire weather indexes from General Circulation Models (GCMs) into our calculations to obtain an estimate of the future area that would burn. The weather data included temperature, relative humidity, wind speed and 24-hr precipitation at 1200 Local Standard Time (LST) for the fire season and were obtained from Environment Canada. These weather variables are also input variables for the calculation of the Canadian Fire Weather Index System (FWI) that represents fuel moisture of three layers, rate of fire spread, total fuel available and the intensity of a spreading fire. Weather and FWI indexes were interpolated from weather stations or GCM gridpoints to each site in Table 1 using a thin-plate cubic spline (20). We used the Canadian first generation coupled GCM - (CGCM1, 21) for the 2 x CO_2 and 3 x CO_2 scenarios. This model included both greenhouse gas and sulphate aerosol forcing contributing to a 1% increase in CO_2 per year. At this rate, the time periods 2040–2060 and 2080–2100 roughly correspond to a 2 x CO_2 and 3 x CO_2 scenario, respectively. The grid spacing is approximately 3.75 longitude by 3.75 latitude. Additional details of this method can be found in Flannigan et al. (22)

RESULTS

Current *vs.* Past Burn Rates

Most of the fire history studies show current burn rates significantly lower than their associated historical burn rates (Fig. 3; Table 1). Studies located in Montane cordillera or eastern Canada lie well above the 1-to-1 line (current burn rate = historical burn rate) while several studies from western Canada are close to the 1-to-1 line. Rutledge Park in the taiga shield lies slightly below the line. Current burn rates are significant for most of the regions studied but only in Rutledge is it close to the 1% threshold.

Future Burn Rates

The 2 x CO_2 simulation (Table 1) shows a lot of variability between regions with large increases in burn rates for northern Ontario (4.33), northern boreal Quebec (1.59), Northern Alberta (1.58), Labrador (1.49), Rutledge Park (1.34), LAMF (1.32), Central Alberta (1.25) and Wood Buffalo Park (1.23). Except for central Quebec and Rocky Mountain sites, with a ratio of 0, all other regions show slight decreases or increases: Prince Albert (0.96), western Quebec (1.02), Algonquin Park (0.99) and Abitibi east Quebec (0.81). Despite strong increases in burn rate for the 2 x CO_2 and 3 x CO_2 simulation scenarios, most sites show a higher historical burn rate.

The changes observed in the 3 x CO_2 scenario are generally going in the same direction as for the 2 x CO_2 scenario (Fig. 4 a,b). Exceptions are Wood Buffalo Park and Prince Albert for which a 6 and 7% change in the opposite direction is observed, respectively.

Even in a 3 x CO_2 scenario (Fig. 4b) most of the regions still have future burn rates that are lower than their historical burn rates. In fact, several regions are located in an area with lower constraints than previously (compare Figs 3 and 4). Northern Quebec and Northern Ontario show the most significant changes as their location in a 3 x CO_2 scenario is close to the biodiversity (1-to-1 line) constraint line and the 1% yield constraint line as described in the conceptual model (Fig. 2).

DISCUSSION

Changes in Fire Frequency

The observed shift from short fire cycles in the past to longer cycles over the last 50 years is probably due to a combination of climate changes and better fire protection. Many studies from the Canadian boreal forest report a general decrease in fire frequency since the mid-19th century (10, 23, 24). As most of the forest was still unexploited at that time, it is very likely that the decrease in fire frequency was driven by changes in climate. In northwestern Quebec, the decrease in fire frequency was related to a reduction in the frequency of drought events since the end of the Little Ice Age (25). It is hypothesized that the warming that started at the end of the Little Ice Age is associated with an important change in the circulation of global air masses (26, 27).

While the firefighting tools available during the first part of the 20th century seem to have been insufficient to deal effectively with large fires (28), active fire suppression has increased during the last 50 years. Moreover, with the introduction of water bombers, firefighting methods have probably been improved continuously through enhanced fire detection and initial response systems. Fire suppression was very likely more efficient due to increased landscape fragmentation by land clearing and a well-developed road system which increases the number of firebreaks (29, 30) and improves firefighting capacity (31).

Simulation results suggest that the effects of climate change on fire activity are complex, and that they will vary from region

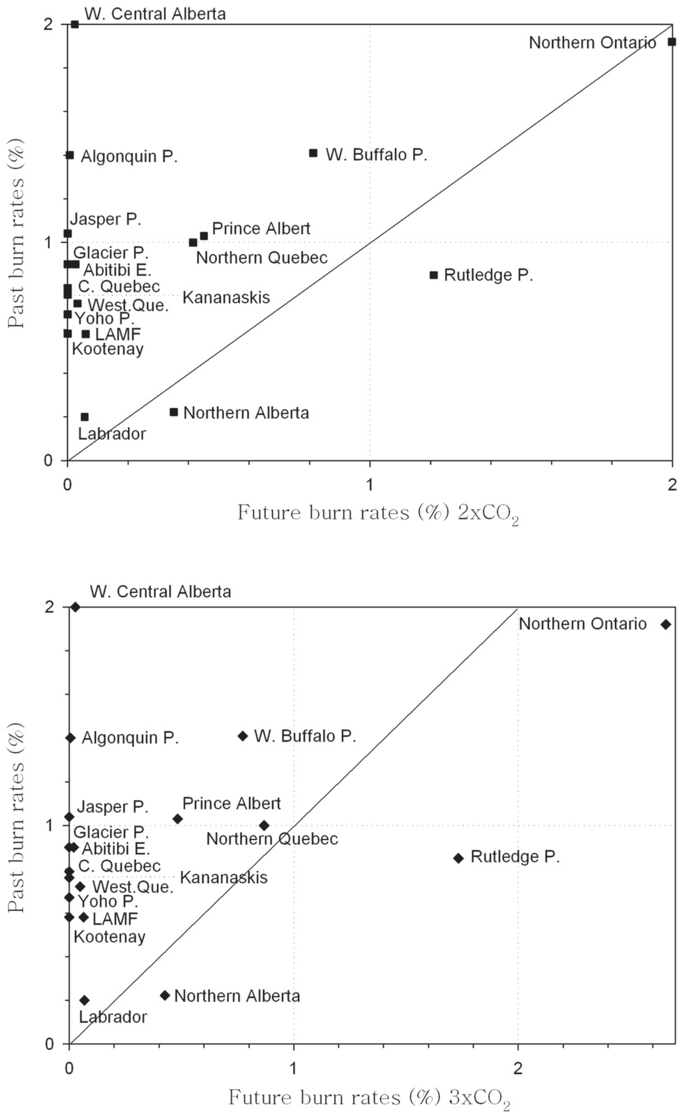

Figure 4. Past and 2 x CO_2 (a) and 3 x CO_2 (b) burn rates of the 18 study areas.

to region. Increasing temperature alone would lead to increasing fire activity, but in some parts of Canada increases in precipitation frequency and amount may more than compensate for the increase in temperature leading to no change or even a decrease in predicted fire activity especially for the first part of this century (14). This can also be seen in Table 1 where parts of eastern and western Canada show no change or a decrease in the burn rate for 2 x CO_2 and 3 x CO_2 scenarios. Absence of fire predicted for the 2 x CO_2 and 3 x CO_2 scenarios for the Montane cordillera might be partly due to difficulties of the GCM models to capture spatial changes in Montane areas.

Implications for Sustainability

The recent decrease in fire frequency favors management strategies that use even-age management on a proportion of the landscape to create forest age structures that would exist under shorter fire-return intervals. Moreover, simulation results presented in this paper and elsewhere (15) show that, even if this trend is reversed in the future, predicted increases in fire frequency would probably fall short of the shortest fire intervals observed in the past. Under these circumstances, the use of even-age management would still be allowable to make up differences between historical and predicted (2 x CO_2 and 3 x CO_2) burn rates (Fig. 2). However, our results have to be interpreted with caution. First simulations based on different GCM scenarios often give a range of results (32). Moreover it is dangerous to extrapolate from our study of specific locations to suggest that our results would be applicable over larger areas. On the one hand, regions in the same ecozone showed wide variability in the effects of climate change. On the other hand, large Nordic regions in the taiga and western boreal shield represented by only a few data points showed an enormous increase in predicted burn rates, suggesting that impact in the Nordic, mainly noncommercial portion of boreal forest, might be very important.

In those cases where current or future fire frequency is high, logging competes with forest fires for timber (Fig. 2). Thus, logging might not be sustainable without a large investment in fire suppression (active and passive), and extensive use of salvage logging. However, fire suppression has its limitations, and it is more and more recognized that it is not really efficient in large tracts of natural forest where access is limited, and when fire season conditions are particularly severe. The use of salvage logging is also limited by road access, especially in cases where the timber quality is affected by insects feeding on dead boles. Extensive use of salvage logging may also be detrimental to biodiversity because many plant and animal species depend upon or become periodically concentrated in recently burned stands (33–35). Brais et al. (36) also report, that in the case of poor soils, the additives effects of fire and logging might decrease nutrient pools affecting stand productivity.

Differences between past, current, and future fire frequencies may be used to justify the use of clearcutting to emulate the distribution of a proportion of post-fire stands in the landscape. However, the exclusive use of clearcutting cannot be justified by observed historical fire frequencies. Reported historical fire frequencies are in most cases less than 1% (implying a 100 year forest rotation) (Fig. 2), which means that a large proportion of the pre-industrial landscape was composed of forests older than the 100-year commercial forest rotation. This figure is even higher if you consider that fire is a random process while forest management is not: With 1% burn rates, 37% of the stands are in fact older than 100 years in a landscape subject only to fires, while no stands are older than 100 years in a fully regulated managed landscape (37). Alternative silvicultural systems that include extended rotations, and/or a variety of silvicultural treatments have been proposed to maintain a proportion of overmature and old growth forests in the managed landscape (10, 13).

CONCLUSIONS

Our results show that forest management could potentially be used to recreate pre-industrial, fire controlled landscapes over a large part of the Canadian boreal forest. There are, however, important limitations to the use of clearcut systems for this purpose. Clearcutting and fire are obviously not the same process (38) and a careful examination of their respective effects on pattern and processes should help define clearcutting guidelines (39, 40). Moreover, clearcutting is unable to emulate overmature and old growth forests that composed a large part of our natural forests. Development of alternative silvicultural systems for the boreal forests is an urgent task to accomplish.

The feasibility of our modelled solutions is based on a decrease in fire frequency from the pre-industrial era to the present. This situation might be different in other regions of the boreal forest. Natural fire frequencies in Eurasian boreal forests are difficult to reconstruct due to the long-term human influence. However, a similar decrease of fire frequency is reported for part of Scandinavia (41). In Russia, important fires recently reported (42) could lead us to completely different conclusions. Uncertainty about the effects of climate change should also force us to be prudent about forecasting our conclusions in the future (55).

References and Notes

1. Attiwill, P.M. 1994. The disturbance of forest ecosystems: the ecological basis for conservative management. *For. Ecol. Manage. 63*, 247-300.
2. Bergeron, Y. and Harvey, B. 1997. Basing silviculture on natural ecosystem dynamics: an approach applied to the southern boreal mixedwood forest of Quebec. *For. Ecol. Manage. 92*, 235-242.
3. Angelstam, P.K. 1998. Maintaining and restoring biodiversity in European boreal forests by developing natural disturbance regimes. *J. Veg. Sci. 9*, 593–602.
4. Franklin, J.F. 1993. Preserving biodiversity: species, ecosystems or landscapes? *Ecol. Appl. 3*, 202–205.
5. McKenney, D.W., Sims, R.A., Soulé, F.E., Mackey, B.G. and Campbell, K.L.(eds). 1994. Towards a Set of Biodiversity Indicators for Canadian Forests: *Proc. Forest Biodiversity Indicators Workshop*. Sault Ste. Marie, Ontario, Nov. 29-Dec.1, 1993, 133 pp.
6. Gauthier, S., Leduc, A. and Bergeron, Y. 1996. Forest dynamics modelling under natural fire cycles: a tool to define natural mosaic diversity for forest management. *Environ. Monit. Assess. 39*, 417-434.
7. Hunter, M.L. Jr. (ed.). 1999. *Maintaining Biodiversity in Forest Ecosystems*. Cambridge University Press, Cambridge, 698 pp.
8. Hunter, M.L. Jr., Jacobson, G.L. and T. Webb. III, 1988. Paleoecology and the coarse filter approach to maintaining biological diversity. *Conserv. Biol. 2*, 375-385.
9. Hunter, M.L., Jr. 1993. Natural fire regimes as spatial models for managing boreal forests. *Biol. Conserv. 65*, 115-120.
10. Bergeron, Y., Gauthier, S., Kafka, V., Lefort, P. and Lesieur, D. 2001. Natural fire frequency for the eastern Canadian boreal forest: consequences for sustainable forestry. *Can. J. For. Res. 31*, 384-391.
11. Burton, P., Kneeshaw, D. and Coates, D. 1999. Managing forest harvesting to maintain old growth in boreal and sub-boreal forests. *For. Chron. 75*, 623-631.
12. Kneeshaw, D. and Gauthier, S. 2003. Old growth in the boreal forest: A dynamic perspective at the stand and landscape level. *Environ. Rev. 11,* 99-114.
13. Bergeron, Y., Harvey, B., Leduc, A. and Gauthier, S. 1999. Forest management guidelines based on natural disturbance dynamics: Stand- and forest-level considerations. *For. Chron. 75*, 49-54.
14. Flannigan, M.D., Bergeron, Y., Engelmark, O. and Wotton, B.M. 1998. Future wildfire in circumboreal forests in relation to global warming. *J. Veg. Sci. 9*, 469-476.
15. Flannigan, M., Campbell, I., Wotton, M., Carcaillet, C., Richard, P. and Bergeron, Y. 2001. Future fire in Canada's boreal forest: paleoecology results and general circulation model – regional climate model simulations. *Can. J. For. Res. 31*, 854-864.
16. Ecological Stratification Working Group 1996. *A National Ecological Framework for Canada*. Agriculture and Agri-Food Canada and Environment Canada, Ottawa.
17. Johnson, E.A. 1992. *Fire and Vegetation Dynamics: Studies from the North American Boreal Forest*. Cambridge Studies in Ecology, Cambridge University Press, Cambridge.
18. Stocks, B.J., Mason, J.A., Todd, J.B., Bosch, E.M., Wotton, B.M., Amiro, B.D., Flannigan, M.D. and Hirsch, K.G., 2002. Large forest fires in Canada, 1959-1997. *J. Geophys. Res. – Atmospheres*, 107, 1-12
19. Van Wagner, C.E. 1987. *The Development and Structure of the Canadian Forest Fire Weather Index System*. Canadian Forest Service, Forest Tech. Report 35, Ottawa, 37 pp.
20. Flannigan, M.D. and Wotton, B.M. 1989. A study of interpolation methods for forest fire danger rating in Canada. *Can. J. For. Res. 19*, 1059-1066.
21. Flato, G.M., Boer, G.J., Lee, W.G., McFarlane, N.A., Ramsden, D., Reader, M.C. and Weaver, A.J. 2000. The Canadian Centre for Climate Modelling and Analysis Global Coupled Model and its Climate. *Climate Dynamics 16*, 451-467.
22. Flannigan, M.D., Stocks, B.J., Logan, K.A., Bosch, E.M., Wotton. B.M., Amiro, B.D. and Todd, J.B. 2002. Fire and climate change - where are we going. In: *Forest Fire Research & Wildland Fire Safety.* Viegas, D.X. (ed.). Proc. IV International Conference on Forest Fire Research/2002 Wildland Fire Safety Summit (Nov. 18-23, 2002, Luso-Coimbra, Portugal). Millpress Sci. Publ., Rotterdam, CD-ROM.
23. Larsen, C.P.S. 1996. Fire and climate dynamics in the boreal forest of northern Alberta, Canada, from AD 1850 to 1989. *Holocene 6*, 449-456.
24. Weir, J.M.H., Johnson, E.A. and Miyanishi, K. 2000. Fire frequency and the spatial age mosaic of the mixed-wood boreal forest in western Canada. *Ecol. Appl. 10*, 1162-1177.
25. Bergeron, Y. and Archambault, S. 1993. Decreasing frequency of forest fires in the southern boreal zone of Québec and its relation to global warming since the end of the 'Little Ice Age'. *Holocene 3*, 255-259.
26. Hofgaard, A., Tardif, J. and Bergeron, Y. 1999. Dendroclimatic response of *Picea mariana* and *Pinus banksiana* along a latitudinal gradient in the eastern Canadian boreal forest. *Can. J. For. Res. 29,* 1333-1346.
27. Girardin, M.P., Tardif, J., Flannigan, M.D. and Bergeron, Y. 2004. Multicentury reconstruction of the Canadian drought Code from eastern Canada and its relationships with paleoclimatic indexes of atmospheric circulation. *Climate Dynamics*. (In press).
28. Lefort, P., Gauthier, S. and Bergeron, Y. 2003. The influence of fire weather and land use on the fire activity of the Lake Abitibi area, eastern Canada. *For. Sci. 49*, 509-521.
29. Foster, D.R. 1983. The history and pattern of fire in the boreal forest of southeastern Labrador. *Can. J. Bot. 61*, 2459-2471.
30. Turner, M.G. and Romme, W.H. 1994. Landscape dynamics in crown fire ecosystems. *Landsc. Ecol. 9*, 59-77.
31. Lefebvre, P. 1972. Guide to Forest Fire fighting (Manuel de Lutte Contre les Feux de Forêt). Éditeur officiel du Québec, Québec. 437 pp. (In French).
32. Intergovernmental Panel on Climate Change 2001. *Climate Change 2001 The Scientific Basis*. Cambridge University Press, Cambridge, 881 pp.
33. Drapeau, P., Nappi, A., Giroux, J.F., Leduc, A. and Savard, J.P. 2002. Distribution patterns of birds associated with snags in natural and managed eastern boreal forests. In: *Ecology and Management of Dead Wood in Western Forests*. Laudenslayer, W.F., Shea, P.J., Valentine, B.E., Weatherspoon, C.P. and Lisle, T.E. (eds). USDA. For. Serv., Gen. Tech. Rep. PSW-GTR-18, pp. 193-205.
34. Nappi, A., Drapeau, P., Giroux, J.-F. and Savard, J.-P. 2003. Snag use by foraging Black-backed Woodpeckers (*Picoides arcticus*) in a recently burned eastern boreal forest. *The Auk 120*, 505-511.
35. Purdon, M., Brais, S. and Bergeron, Y. 2004 Response of understorey vegetation to fire severity and salvage-logging in the Québec southern boreal forest during the first two years after disturbance. *Appl. Veg. Sci*. (In press).
36. Brais, S., Paré, D. and Ouimet, R. 2000. Impacts of wild fire severity and salvage harvesting on the nutrient balance of jack pine and black spruce boreal stands. *For. Ecol. Manage. 137*, 231-243.
37. Van Wagner, C.E. 1978. Age-class distribution and the forest fire cycle. *Can. J. For. Res. 8*, 220-227.
38. McRae, D.J., Duchesne, L.C., Freedman, B., Lynham, T.J. and Woodley, S. 2001. Comparisons between wildfire and forest harvesting and their implications in forest management. *Environ. Rev. 9*, 223-260.
39. OMNR 2001. *Forest Management Guide for Natural Disturbance Pattern Emulation*, Version 3.1. Ont. Min. Nat. Res., Queen's Printer for Ontario, Toronto. 40 pp.
40. Bergeron, Y., Leduc, A., Harvey, B.D. and Gauthier, S. 2002. Natural fire regime: A guide for sustainable management of the Canadian boreal forest. *Silva Fenn. 36*, 81-95.
41. Engelmark, O., Kullman, L. and Bergeron, Y. 1994. Fire and age structure of Scots pine and Norway spruce in northern Sweden during the past 700 years. *New Phytol. 126*, 163-168.
42. Conard, S.G., Sukhinin, A.I., Stocks, B.J., Cahoon, D.R., Davidenko, E.P. and Ivanova, G.A. 2002. Determining effects of area burned and fire severity on carbon cycling and emissions in Siberia. *Climatic Change 55*, 197-211.
43. Tande, G.F. 1979. Fire history and vegetation pattern of coniferous forests in Jasper National Park, Alberta. *Can. J. Bot. 57*, 1912-1931.
44. Johnson, E.A., Fryer, G.I. and Heathcott, M.J. 1990. The influence of man and climate on frequency of fire in the interior wet belt forest, British Columbia. *J. Ecol. 78*, 403-412.
45. Johnson, E.A. and Wowchuk, D.R. 1993. Wildfires in the southern Canadian Rocky Mountains and their relationship to mid-tropospheric anomalies. *Can. J. For. Res. 23*, 1213-1222.
46. Masters, A.M. 1990. Changes in forest fire frequency in Kootenay National Park, Canadian Rockies*. Can. J. Bot. 68*, 1763-1767.
47. Johnson, E.A. and Larsen, C.P.S. 1991. Climatically induced change in fire frequency in the southern Canadian Rockies. *Ecology 72*, 194-201.
48. Larsen, C.P.S. 1997. Spatial and temporal variations in boreal forest fire frequency in northern Alberta. *J. Biogeogr. 24*, 663-673.
49. Cumming, S.G. 1997. *Landscape Dynamics of the Boreal Mixedwood Forest.* PhD Thesis, Department of Forest Sciences. University of British Columbia, Vancouver, Canada.
50. Armstrong, G.W. 1999. A stochastic characterisation of the natural disturbance regime of the boreal mixedwood forest with implications for sustainable forest management. *Can. J. For. Res. 29*, 424-433
51. Johnson, E.A. 1979. Fire recurrence in the subarctic and its implications for vegetation composition. *Can. J. Bot. 57*, 1374-1379.
52. Suffling, R., Smith, B. and Dal Molin, J. 1982. Estimating past forest age distributions and disturbance rates in North-western Ontario: a demographic approach. *J. Environ. Manage. 14*, 45-56.
53. Cwynar, L.C. 1977. The recent fire history of Barron Township, Algonquin Park. *Can. J. Bot. 55*, 1524-1538.
54. Payette, S., Morneau, C., Sirois, L. and Desponts, M. 1989. Recent fire history of the northern Québec biomes. *Ecology 70*, 656-673.

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