PROJECT REPORT
1999-7

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Palaeoecological Reconstruction of Holocene Fire Chronology and Associated Changes in Forest Composition in Northern Alberta and Saskatchewan

I.D. Campbell

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Sustainable Forest Management Network
G208 Biological Sciences Building
University of Alberta
Edmonton, Alberta, T6G 2E9
Ph: (780) 492 6659
Fax: (780) 492 8160
http://www.biology.ualberta.ca/sfm

ISBN 1-55261-.021-7

Palaeoecological Reconstruction of Holocene Fire Chronology and Associated Changes in Forest Composition in Northern Alberta and Saskatchewan

by

I.D. Campbell
Canadian Forest Service
and
Adjunct Professor
Earth and Atmospheric Sciences
University of Alberta

June 1999

EXECUTIVE SUMMARY

Fire is the major natural disturbance in the westeiiirn boreal forest. Emulating fire requires understanding its relationship with vegetation and with climate. While "modern" fire studies can yield much valuable information and understanding, it is difficult for such studies to inform us about the impact of climate change or vegetation change through time. This study uses charcoal-rich horizons in lake sediments to examine changes in fire regimes over the last several centuries at various locations in Alberta and Saskatchewan.

Now entering its final year of funding, this study at this time offers preliminary results only. Much of the work to date has focused on the development of appropriate methods of study. There are three major conclusions to date:

1. Active fire suppression has been effective in the Christina Lake area, but there is as yet little evidence for its effectiveness at a regional scale.
2. Fire regimes have varied strongly through time, but not always in the simplistic way of reduced fire during periods of wetter climate. Controls on fire are still poorly understood, but are now known to be more complex than generally recognized.
3. While in some areas the current level of fire activity may be less than in the past, at most sites it is within the range of natural variability. This is particularly so in the montane forest of Jasper national park, where prehistoric fire activity was as low as it is now; the generally held belief that prehistoric fire activity was higher appears to be mistaken and based on the occurrence of a high level of fire activity coincident with the construction of the railroad through the park.

Management implications are:

1. In general, it would dangerous to assume that active fire suppression saves timber which can therefore be harvested without affecting the natural disturbance regime; until a larger network of sites has been analyzed, harvesting must be viewed as a disturbance at least in part supplementing fire.
2. Fire activity is expected to generally increase in the prairie provinces in response to global warming. This increase will not however be evenly distributed on the landscape, and may not be gradual through time. The mechanisms by which climate controls fore frequency include vegetation change, which may cause non-linear and unexpected responses.

3. There is no single “natural” level of fire activity in any given location. Instead, there is a range of fire activity levels which naturally occur. In emulating natural disturbance, it will not be possible to select a single “natural” level of fire activity. Rather, a disturbance rate will need to be selected that falls within the natural range of variability and which achieves explicit management objectives. This choice of disturbance rate will need to be justified on grounds other than purely emulation of natural fire regimes.

ACKNOWLEDGMENTS

I thank the students who have been involved in this project: Lana Laird, Arlene Collins, Jacqueline O’Connell, Karen Peronnet, Farrah Gilchrist, and Robert Field. Thanks also to Dave Schindler, Mike Flannigan, Yves Bergeron, Christopher Carcaillet, Pierre Richard, and other participants in other projects from whose work this project has benefitted.

INTRODUCTION

Fire is the major disturbance in the boreal forest, particularly in the western boreal (Johnson, 1992). The Sustainable Forest Management Network of Centres of Excellence has focused research efforts on a paradigm of "sustainable management by emulation of natural disturbances". In order to emulate natural disturbances, however, these disturbances must be known and understood. In particular, natural controls on the frequency, magnitude, severity, seasonality, and other aspects of natural disturbances must be well understood if we are to replace them by harvesting regimes.

While much information can be and has been derived about the characteristics of fire as a disturbance through the study of modern fire records, this provides only a snapshot of fire. Not only does this snapshot suffer from representing a very brief period of time, it also suffers from that period of time being known to be atypical of natural fire regimes. The western boreal forest has been heavily affected by human activity in the last few decades. Thus the study of current fire regimes cannot unequivocally inform us about natural fire regimes - the disturbances we wish to emulate.

To study natural fire regimes in the western boreal forest, it is necessary to obtain information on fires that occurred more than 100 years ago, prior to any observation network and to formal fire records. This can be done partly through stand origin mapping and fire scars (Johnson, 1992). While these methods have the great advantage of providing precise dates and detailed spatial extents of fires, they are unsatisfactory in several ways. Firstly, they can only inform us about fires that occurred withing the life-span of individual trees, which in the western boreal, is in many areas limited to less than 100 years. Secondly, they can only inform us about the age of the last stand-replacing fire - since by definition the trees on which these methods depend originated in that fire.

To understand the response of natural fire regimes to climate change, we need to develop fire records spanning several centuries or even millennia. This can only be achieved through palaeoecological techniques. In this Project, lake sediments from several sites in Alberta and Saskatchewan are being examined for charcoal-rich horizons indicating past forest fires in the watersheds of the lakes. At the same time, these sediments are being examined for their fossil pollen content to provide indications of the vegetation in which these fires occurred, and of the post-fire revegetation sequences. Data are also being collected to provide estimates of past climate changes at these sites, in order to relate changes in fire regime to changes in the climate and/or the vegetation.

This Project is being carried out largely through the efforts of graduate students, resulting in the development of highly qualified personnel. There has however been one upset related to this emphasis: Arlene Collins, who joined the Project as a probationary PhD student, has re-registered as a MSc student following unsatisfactory candidacy exams. In combination with funding reductions, this has forced the realignment of parts of the study. Research facilities and additional support are provided by the Canadian Forest Service and the Department of Earth and Atmospheric Science sat the University of Alberta. This Project is also strongly coordinated with that of Yves Bergeron et al in eastern Canada.

PREVIOUS PALAEOECOLOGICAL RESEARCH

The prairie provinces have in general been less well investigated by palaeoecologists than have the eastern provinces or British Columbia. One area which is an exception is the "ice-free corridor", a narrow region extending mainly along the foothills in western Alberta. The ice-free corridor has attracted much palaeoecological interest due to its hypothesized use as a migration corridor into the Americas for humans, animals and plants during and immediately following the last glacial maximum. The boreal forest region has in contrast attracted relatively little interest from palaeoecologists (Beaudoin, 1993). This Project is accordingly focused mainly on the plains.

The known palaeoclimate history of the western interior is summarized in Campbell (1998) and Campbell and Campbell (1997). In essence, there was a period of unknown duration prior to 10,000 years ago during which Laurentide ice was retreating towards the northeast and Cordilleran ice was retreating towards the west. This was followed in the early Holocene[1] by the Hypsithermal (also known as Altithermal Xerithermal, or mid-Holocene Warm Period), lasting several thousand years, during which summer temperatures were warmer, while winter temperatures were likely colder, and precipitation was generally lower than at present. This period is often used as an analogue for future warming. The Hypsithermal was followed by a general cooling trend, leading to the Medieval Warm Period (MWP, approximately AD 800-1200), the Little Ice Age (LIA, approximately AD 1450-1900), and the recent warming (since AD 1900).

[1] The Holocene is the last 10,000 years.

These climate periods are well-recognized in the palaeoecological record. The Lofty Lake pollen diagram (Lichti-Federovich, 1970) shows a clear Hypsithermal signal, which takes the form of a decrease in conifer abundance to the benefit of deciduous trees (mainly birch) and non-tree vegetation. The Lofty Lake record has also been interpreted as recording, during the Hypsithermal, a vegetation community for which there is no known present analogue (MacDonald and Reid, 1989). It has also been shown that sites in the southern boreal forest, including Lofty Lake, experienced a decline in water table of as much as 15 m during the Hypsithermal (Schweger and Hickman, 1989). The MWP does not show clearly in most boreal pollen records, perhaps in part because it was of insufficient duration to substantially affect the vegetation; the same is true of the LIA. There are however clear indications that both substantially affected the hydrology of the grasslands regions (Vance et al, 1992; Campbell, 1998).

The vegetation of the prairie provinces is not believed to have changed significantly in the last 3000 years (Vance et al., 1983). There are however indications that the fire regime has changed over this time, particularly in the last hundred or so years (Schindler, unpubl. data). There are also indications of significant, if as yet poorly understood, changes at the southern margin of the boreal forest in the historic period (Campbell et al., 1994; Strong, 1977).

STUDY SITES

Site Selection

Sites for palaeoecological research can be selected to provide various types of information. In general, it is desirable to obtain lake sediments with minimal disturbance through bioturbation, as this leads to the best-resolved signals. Such lakes will typically be deep and flat-bottomed. When the lake depth : ln(area) ratio is high enough, the lake may be meromictic, that is, may not turn over completely, such that the bottom water is permanently anoxic. This excludes benthos capable of disturbing the sediments and allows the develop of annual laminations in the sediments, termed varves. These varves can be counted like tree-rings, providing a high degree of temporal control as well as assurances of the most highly resolved signal.

A second consideration in site selection is the size of the lake. Larger lakes are believed to integrate their pollen and charcoal signals form larger area (Clark, 1988). Thus, while small lakes provide a reasonable degree of spatial precision, larger lakes provide a more regional record, which may thus be of greater interest in areas where little previous work has been done.

With a few key exceptions, there has generally been little palaeoecological research has been done in Alberta north of Slave Lake or east of 112° west (Beaudoin, 1993). This project has therefore chosen to focus mainly on larger lakes in eastern and northern Alberta and Saskatchewan. Specific sites were selected during the course of two summers of testing, to find sites with varved sediments. Of approximately 12 likely sites identified from fishing maps, two in Alberta were identified and cored: Christina Lake, at Conklin, and Flemming Lake in the Caribou Mountains, Alberta. The Flemming Lake core has been deselected for further analysis due to final year funding cuts. Additional sites previously known to be varved included in this Project are Amisk Lake, Alberta, and Opal lake, Saskatchewan. Further, in this final year of funding, three sites in Jasper National Park have been added; though not varved, much of the work required has already been done on these lakes by Schindler, and further work is being partly funded through Jasper National Park, making them and inexpensive replacement for the remote and as yet unstudied Flemming Lake. All sites are shown in Figure 1.

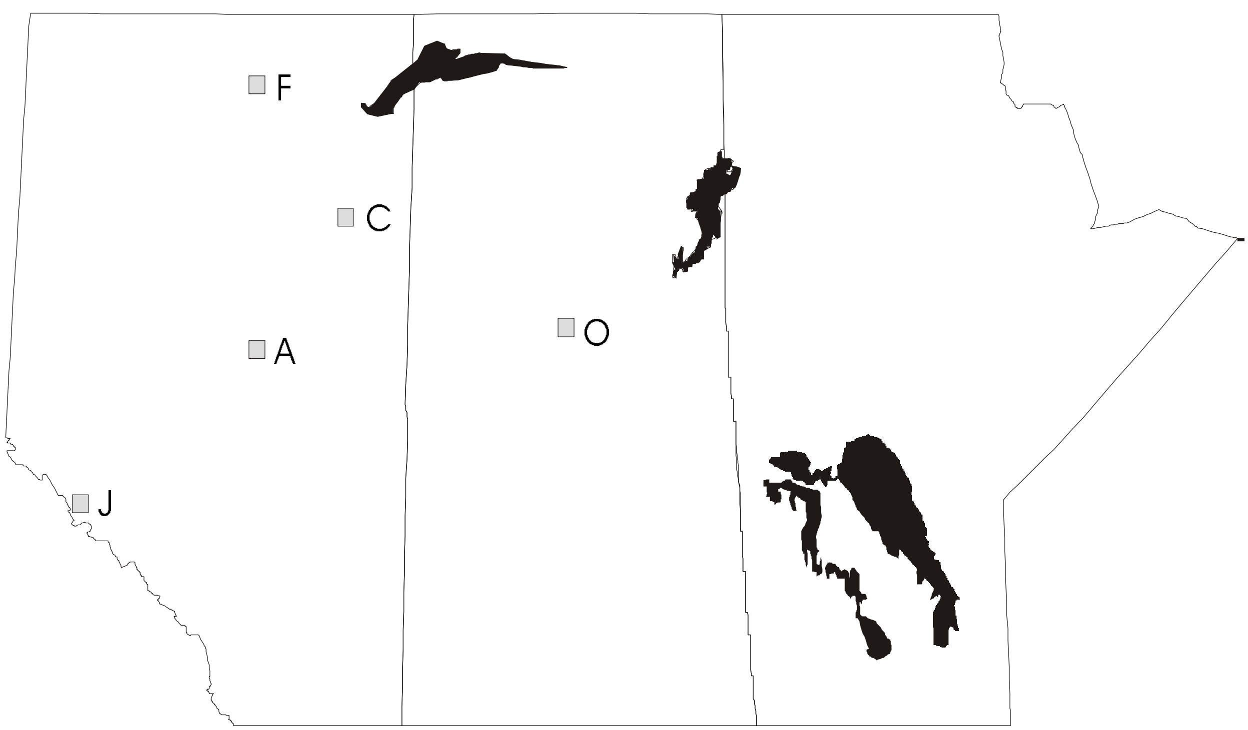


Figure 2: site locations. A = Amisk lake; O = Opal Lake; C = Christina Lake; F = Flemming Lake; J = Jasper Park lakes.

Site Descriptions

Amisk Lake

Amisk lies in the southern boreal forest of Alberta, in the mixedwood region. It is a long, narrow, deep (>50 m) lake, with cottages and other recreational activities. Its sediments are known to be varved (Prepas, pers. comm.).

Christina Lake

Christina Lake is a long narrow deep (>30 m) lake in the mid boreal of eastern Alberta. The surrounding terrain is relatively flat, with abundant black spruce. Gas and oil exploration and development are active in the area, with tar sands development proposed in the area immediately south of the lake.

Flemming Lake

Flemming Lake is a large lake on the Caribou mountains of northern Alberta, in the high boreal ecoregion. A large forest fire in 1994 burned most of the watershed.

Opal Lake

Opal Lake is part of the Jewel lakes system in central Saskatchewan, at the north end of Nipawin Park. The lake is a small kettle depression. The surrounding vegetation varies strongly with drainage, with the gravelly hills dominated by aspen and jack pine.

Jasper Park lakes

Three sites are being examined in the Montane ecozone of Jasper National Park. As these sites have only recently been added to this project, they will not be discussed at length here.

METHODS

Lake sediment cores were extracted using freezing samplers, complemented in most cases by Reasoner cores (Reasoner, 1986). Dating is by 210Pb, 14C, and where applicable, varve count. Where varves are available, the varve count is taken as definitive with the radiometric dates as supporting evidence for the annual nature of the laminations.

Known fires are useful to validate the charcoal peaks as identifiers of earlier, unknown fires. At Flemming Lake and Christina Lake, undergraduate students were involved to conduct fire scar surveys of the watersheds to determine historic fire dates. These surveys used disks cut from dead trees or increment cores from live trees to date fire scars, using DendroScan (Varem-Sanders and Campbell, 1996). Further historic fire dates and extents were determined from published fire maps and unpublished data available from the Canadian Forest Service or Alberta Lands and Forests.

Further field work at Christina Lake involved sampling surface sediments at 43 different points in the lake to determine the homogeneity of charcoal distribution. These analyses are in progress.

Charcoal analysis methods varied, as part of the Project involved determining the source areas and characteristics for the signals provided by different analytical techniques. Opal Lake was analyzed by modified Winkler (1985) method chemical assay; the modification consisted solely in prolonging the nitric acid digestion until no further reaction could be observed, and by multiplying the distilled water washes until no further crystals formed on drying. This method may exaggerate the charcoal content of the sediments, but in the absence of changes in lithology, should yield useful trends and peaks (Laird, unpublished data). As it quantifies all size fractions of charcoal, including the very finest dust, it is expected to provide the most regional signal; this should patly compensate for the small area of the lake. The same modified Winkler method was applied to Amisk Lake.

A further modification of the Winkler method was used at Christina Lake. In this modification, the loss on ignition measurement of the final charcoal content was replaced with analysis on a carbon analyzer, to remove any possible clay-bound water losses being counted as charcoal. Christina Lake was also analyzed by the Oregon sieving method (Whitlock and Millspaugh 1996). The Jasper Park lakes are also being analyzed by the sieving method.

Pollen analysis at Christina Lake is in progress, using standard methods (Faegri et al., 1989). Bulk authigenic geochemistry at Christina Lake uses a mild hydrochloric acid extraction analyzed by ICP-AES (Malo, 1977).

The Christina Lake core contains the mineral vivianite (a hydrous iron phosphate). To determine if the abundance of this mineral is in any way related to climate or fire activity ion the watershed (as might be expected if P and Fe concentrations in the lake water limit vivianite formation), vivianite abundances in the core have been quantified using image analysis techniques developed specifically for this purpose.

In order to determine the fire and vegetation responses to climate change, the climate changes must be know in some detail. Pore-water stable isotope analyses have been carried out on a portion of the Amisk Lake record to determine past climate changes. This technique has not been previously used, and the results must be considered tentative.

RESULTS TO DATE

Flemming Lake

Fire scar work has identified several fires in the watershed of Flemming Lake. This work is still in progress, with completion anticipated in summer 1999.

Sediment work at Flemming Lake has been discontinued due to the combination of funding reductions and student status change.

Opal Lake

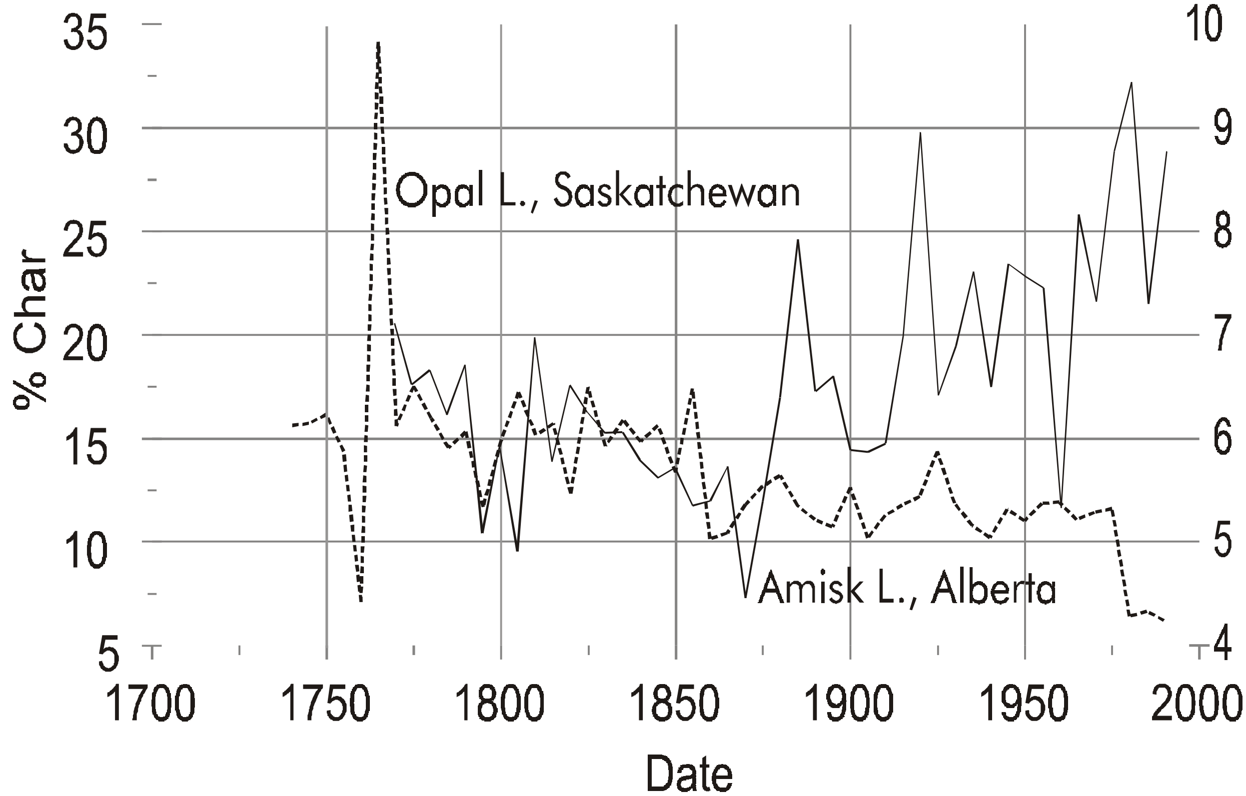
Nitric acid assay of Opal Lake sediments (Figure 2) shows two stepwise reductions in regional fire activity. While the most recent of these reductions, in the 1970s, can be reasonably attributed to either active or passive fire suppression, the earlier prehistoric step cannot be attributed to this. Pollen analyses are required to determine the associated vegetation changes, but preliminary results suggest the reduction in fire activity in both cases may be at least in part due to changes in the local vegetation from pine-dominated to greater aspen abundance.

Further work at Opal Lake is presently on hold due to funding reductions and change in student's status.

Amisk Lake

Amisk Lake charcoal by nitric acid assay (Figure 2) shows a fire activity minimum ca. 1850, followed by increasing fire activity through the present. This increase may be in part from anthropogenic fires, but may also reflect the recent climate warming.

The stable isotope results from Amisk Lake suggest that (1) the sediment pore water is in fact segregated lake water rather than percolating groundwater, and (2) the pore water isotopes do reflect climate changes. The apparent attenuation of signal variability with depth, however, suggests the pore water may be subject to increasing contamination with depth (age) due in all probability to diffusion of pore water within the sediment column. We are currently evaluating the usefulness of this technique for palaeoclimate reconstruction.



The charcoal record also shows a period of distinctly reduced fire activity from AD 1100 to 1550. This corresponds with the early half of the LIA. The fire maximum ca. AD 1800 reflected in the assayed charcoal curve may be an artefact of increased stream flow bringing more charcoal to the lake, rather than of an actual fire activity maximum. The recent minimum in both curves (since AD 1950) may reflect active fire suppression, which is intense in this area due to the presence of a twon, a road, a railroad, and intensive oil and gas activity.

Christina Lake

The Christina Lake site was the first cored and is most advanced. The large (sieved) charcoal record (Figure 3) shows several peaks corresponding with fires in the watershed identified from either fire maps or the fire scar survey. The nitric acid assay results show much the same peaks, but with additional peaks not represented in the coarse charcoal record (Figure 3).

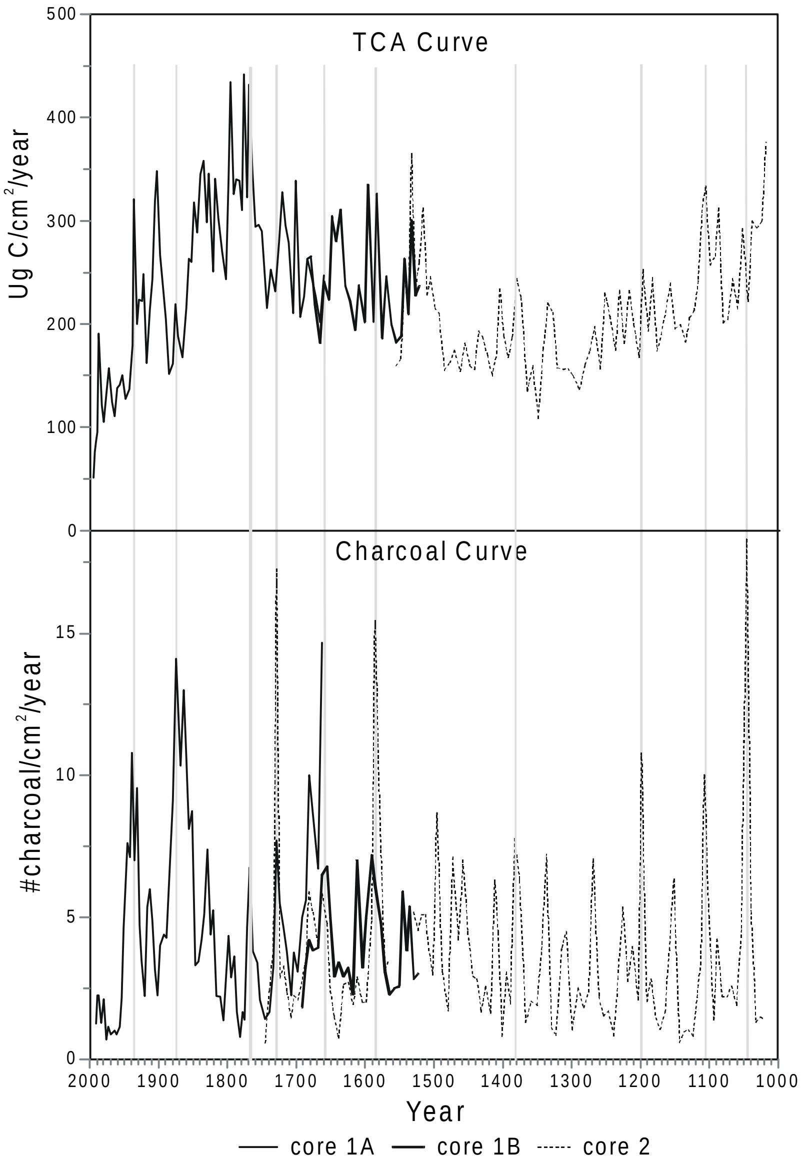


Figure 3. Christina Lake charcoal results. Upper panel: assayed charcoal; bottom panel: sieved charcoal. Vertical lines for comparison purposes only, marking selected fires. Line styles reflect changes in core segments.

It appears that both the coarse charcoal and the nitric acid assay charcoal reflect fire in the watershed. Interestingly, large fires which did not reach the watershed (including the Mariana Lakes fire) are not represented, while relatively small fires in the watershed are represented. The representation of a fire by a charcoal peak appears to be strongly related to the proximity of the fire to the lakeshore or to and inflowing stream. This suggests that much of the present theory of charcoal dispersal (e.g. Clark 1988), developed for small lakes, is inappropriate for larger lakes. The current theory suggests that most charcoal reaches the lake by airborne transport, and that therefore the size of the charcoal fragments is in proportion to the distance of the fire from the lake. The Christina Lake results, on the other hand, suggest that most charcoal reaches the lake by stream runoff, and that the size of the fragments is therefore related not to the distance form the fire to the lake, but to the distance from the fire to the stream.

Pollen results from Christina Lake are expected in the summer of 1999. Preliminary pollen results suggest no major changes in the vegetation around the lake, although many of the charcoal peaks are reflected by temporary changes in the pollen spectra. There is a weak peak in spruce pollen abundance ca. 1800, which may be related to the increased streamflow hypothesized for the assayed charcoal peak at the same time.

The vivianite record suggests there is no particular relationship between vivianite formation and either fire activity or climate at short time scales, although there may be a weak relationship at longer timescales..

Jasper Park lakes

Work on the Jasper Park Lakes started under a another project under D. Schindler; as this Project's involvement in these lakes is only just beginning, only a general outline of the results will be given here.

The charcoal records of two of the Jasper lakes suggest that fire activity reached a maximum in the late 1800s, coincident with the construction of the railroad through the Park. The low level of fire activity experienced since then, rather than being unnatural, seems to constitute a return to natural conditions of low fire activity in the montane region.

There is some evidence in the pollen records of slight changes in vegetation composition, principally an opening of the forest coincident with the fires of the late 1800s. The forest seems to be regenerating towards the pre-historic composition.

DISCUSSION

The results to date in this project are most intriguing. Only one site (Christina Lake) shows a signal which most readily attributed to active fire suppression. Amisk Lake, at which a strong active fire suppression signal might be expected given the concentration of values-at-risk in the area, instead shows and increase in charcoal influx. Opal Lake, which shows a decrease, also shows a prehistoric decrease, such that both are most readily attributed to changes in the vegetation or unintentional fire suppression (as from logging or highway construction) rather than to human influences. The Jasper Park lakes show that natural fire activity in the montane is very low.

The methods of charcoal analysis clearly are not as developed as the literature might seem to indicate. In fact, the dispersal of charcoal from fire to lake sediment is as yet poorly understood. The Christina Lake results suggest that stream-borne charcoal may be critical to the formation of the eventual charcoal deposit. If this is so, then the charcoal method may be more powerful than previously thought: rather than reflecting fires that are in some poorly defined way "close" to the lake, charcoal peaks may reflect fires which are definitely in the watershed of the lake. This would allow the method to gain a great deal of spatial precision.

The response of fire to climate change is complex, and appears, as at Opal Lake, to be mediated by change in the vegetation -which is itself undoubtedly mediated by change in the fire regime. Thus we must envisage a more complex system than is usually recognized.

The stable isotope results, which suggest limited applicability of the method for palaeoclimatic reconstruction, are nevertheless intriguing in their implications for water flow in boreal systems. If it is generally true that lake sediment pore water is segregated lake water, rather than percolating groundwater, this suggests that groundwater flow into lakes must be largely confined to spatially limited flow zones.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

While final recommendations must await the completion of the project, some preliminary observations may be made. Firstly, in reference to the montane vegetation of Jasper Park, natural fire is very rare. This implies that a management by emulation of natural disturbances paradigm must either focus on disturbances other than fire, or accept a very low rate of disturbance, and therefore a very long rotation.

Secondly, with reference to active fire suppression, it is unclear to what degree we are able to suppress fire in the long term. There can be no doubt that we are able to prevent a given area form burning in a given year, but we may not be able to substantially affect the overall area burned over a period of decades. This is reflected in the Yellowstone Park experience, in which long-term fire suppression resulted in fuel buildup, bringing about a very large fire in which all the area saved from burning in the preceding years burned at once in a catastrophic fire. While these data cannot answer they question, they do raise the question of the long-term effectiveness of fire suppression in saving fiber as opposed to spot values-at-risk. The major management implication is that until better evidence of the long-term effectiveness of active fire suppression is available, harvest should be viewed as at least partly in addition to fire, rather than replacing fire.

Thirdly, with reference to the natural variability of fire activity, there is clearly a range of fire activity levels that have been experienced at a given site. Changes in fire activity result from climate and/or vegetation change; vegetation changes in response to fire and/or climate change (Campbell and Flannigan In Press, and Flannigan et al. 1999). Thus human activities which change the vegetation can be expected to affect the fire regime directly. Further, fire response to climate change is mediated by vegetation change; while western Canada can in general expect increased fire activity with climate warming, there will be a great deal of spatial heterogeneity in the response. The management implication of this is that it will not be possible to independently and objectively determine a single "natural" rate of disturbance for any given area. A range of such natural disturbance rates have occurred in the past, providing some guidance, but ultimately, the disturbance rate selected will have to be defended as much in terms of management objectives as in terms of emulating natural disturbances.

This Project is still in progress; more definite and quantitative conclusions are expected in the near future.

REFERENCES

Beaudoin, A.B. 1993. A compendium and evaluation of postglacial pollen records in Alberta. Canadian Journal of Archaeology 17: 92-112.

Campbell, C. 1998. Late Holocene lake sedimentology and climate chnage in southern Alberta, Canada. Quaternary Research 49: 96-101.

Campbell, C., Campbell, I.D., Blyth, C.B., and McAndrews, J.H. 1994. Bison extirpation may have caused aspen expansion in western Canada. Ecography 17: 360-362.

Campbell, C. and Campbell, I.A. 1997. Calibration, review and geomorphic implications of postglacial radiocarbon ages in southeastern Alberta, Canada. Quaternary Research 47: 37-44.

Campbell, I.D. and Flannigan, M.D. In Press. Long-term perspectives on fire-climate-vegetation relationships in the North American boreal forest.

Clark, J.S. 1988. Particle motion and the theory of charcoal analysis: source area, transport, deposition, and sampling. Quaternary Research 30: 67-80.

Faegri, K., Kaland, P.E., and Krzywinski, K. 1989. Faegri and Iversen's Textbook of Pollen Analysis. IV edition. Wiley, New York.

Flannigan, M.D., Wotton, M., Carcaillet, C., Richard, P.J.H., Campbell, I.D., and Bergeron, Y. In Press. Fire weather: past, present and future. Proceedings of the second international conference on biomass burning, Portugal, 1998.

Johnson, E.A., 1992. Fire and Vegetation Dynamics. Studies from the North American Boreal Forest. Cambridge Studies in Ecology. Cambridge University Press. 129 pp.

Lichti-Federovich, S. 1970. The pollen stratigraphy of a dated section of late Pleistocene lake sediment from central Alberta. Canadian Journal of Earth Sciences 7: 938-945.

MacDonald, G.M. and Reid, R.T. 1989. Pollen-climate distance surfaces and the interpretation of fossil pollen assemblages from the western interior of Canada. Journal of Biogeography 16: 403-412.

Malo, B.A. 1977. Partial extraction of metals from aquatic sediments. Environmental Science and Technology 11: 277-282.

Reasoner, M.A.1986. An inexpensive, lightweight percussion core sampling system. Geographie physique et Quaternaire 40: 217-219.

Schweger, C.E. and Hickman, M. 1989. Holocene paleohydrology of central Alberta: testing the general circulation model simulations. Canadian Journal of Earth Sciences 26: 1826-1833.

Strong, W.L 1977. Pre- and post-settlement palynology of southern Alberta. Review of Palaeobotany and Palynology 23: 373-387.

Vance, R.E., Emerson, D., and Habgood, T. 1983. A mid-Holocene record of vegetative change in central Alberta. Canadian Journal of Earth Sciences 20: 364-376.

Vance, R.E., Mathewes, R.W., and Clague, J.J. 1992. 7000 year record of lake-level change on the northern Great Plains: a high-resolution proxy of past climate. Geology 20: 879-882.

Varem-Sanders, T.M.L. and Campbell, I.D. 1996. DendroScan. A tree-ring width and density measurement system. Special report 10, Canadian Forest Service, Northern Forestry Centre, Edmonton. 131 pp + diskette and calibration wedge.

Whitlock, C. and Millspaugh, S.H. 1996. Testing the assumptions of fire history studies: and examination of modern charcoal accumulation in Yellowstone National park, USA. The Holocene 6: 7-15.

Winkler, M.G. 1985. Charcoal analysis for paleoenvironmental interpretation: a chemical assay. Quaternary Research 23: 313-326.