THE ROLE OF FIRE IN LAND/WATER INTERACTIONS[1/]

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ABSTRACT

Forest fires cause a temporary increase in runoff to streams and lakes, in part because of decreased evapotranspiration, according to studies in Washington (Entiat Fire), Minnesota (Little Sioux Fire), and Ontario (Experimental Lakes Area). Mass transport of nutrients and cations also increases, but no algal blooms were detected. Extent of fires is commonly limited by natural firebreaks provided by lakes and streams. The charcoal and pollen stratigraphy of annually laminated lake sediments provides a record of past fire frequency. Lake-sediment studies also document forest history over thousands of years, showing the shift from fire-adapted forests to fire-resistant forests, or the reverse.

KEYWORDS: forest fire, nutrients, firebreaks, charcoal, pollen

INTRODUCTION

A major forest fire may be a catastrophic disturbance to a landscape, and one can well suppose that any stream or lake in the area will be seriously affected. It is well established that many of the physical, chemical, and biological characteristics of a lake, for example, directly or indirectly reflect the nature of the vegetation cover in the watershed, and a major perturbation in the vegetation such as fire can be expected to alter the flow of energy and nutrients from one ecosystem to the other (Likens and Bormann 1974). The objective of this paper is to examine various interactions of terrestrial and aquatic ecosystems insofar as they are affected by fire.

The subject can include at least three aspects: (1) effects of fire on the morphology, hydrology, water chemistry, and biological productivity of streams and lakes, (2) the role of streams and lakes in the distribution and severity of fires, and (3) the record of fires contained in lake sediments, both for the historic period

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and for the distant past. The last aspect will be considered in particular, to describe methods by which fire frequency can be determined for the time range beyond the tree-ring record, and to speculate on the nature and magnitude of vegetation changes that may reflect past changes in fire frequency.

EFFECTS ON STREAMS AND LAKES

General

Many mature forests are characterized by (1) a closed canopy that intercepts much of the rain and snow, (2) a deep forest floor that absorbs the moisture and stabilizes the slopes, and (3) a regime of internal cycling that releases only modest quantities of nutrients to streams and lakes, which in turn are adjusted in their chemistry and biology to the stable conditions within the drainage basin. A severe fire in such an ecosystem might be expected to remove much of the canopy, convert the accumulated fuel on the forest floor to readily soluble ash, reduce the infiltration capacity of the mineral soil by developing a water repellency, increase runoff and erosion, and cause algal blooms in streams and lakes by the addition of nutrient-rich water. Several recent studies have been designed to test the various hypotheses involved in these suppositions. A few of these studies will be reviewed, and some generalizations on these and other aspects of the effects of fires on streams and lakes will then be added.

Entiat Fire, Washington

The Entiat Fire in August 1970 in the eastern Cascade Mountains of north-central Washington burned an area of ponderosa pine and Douglas-fir where fire had not occurred for 200 years, and where streamflow had been monitored in connection with another project by the USDA Forest Service for 9 years and water chemistry for 4 months (Helvey 1972, Helvey and others 1976). The immediate effect of the fire was to reduce streamflow for 12 hours, presumably because of direct vaporization of water. Subsequently the diurnal flow variations decreased, as daily evapotranspiration by riverine vegetation was reduced. Water temperature increased as much as 12°C because of the loss of shade. Water yield increased 50 percent during the first year (fig. 1, 2), and the maximum discharge occurred earlier in the spring than usual, as the reduced shade and the blackened surface resulted in faster snowmelt, and as the decreased infiltration of snowmelt into the burned-over forest floor caused increased runoff. In the second year streamflows were even greater (fig. 3), although this increase may be attributed in part to heavy snowpack and very heavy summer rains; severe erosion, landsliding, and siltation occurred, especially in areas where salvage logging had followed fire.

Chemical changes in the streams following the fire have recently been summarized by Tiedemann and others (1978). Three watersheds were burned, but two of them were fertilized with nitrogen compounds and seeded to stabilize slopes and encourage regeneration. Although chemical changes in the three streams were generally similar, the summary that follows concerns only Fox Creek, which was not affected by the fertilizer treatment. The nearby Lake Creek watershed was not touched by the fire and serves as a control.

Alkalinity and conductivity of Fox Creek in one of the burned watersheds were higher immediately after the fire, apparently because of ash washed into the stream, but they returned to prefire levels the next year (Tiedemann and others 1978).

Nitrate-nitrogen concentrations in Fox Creek increased after the fire, and in the second year they were about 6 times that of the control (Lake Creek). The higher values are attributed by Tiedemann and others (1978) first to interruptions of the soil-plant

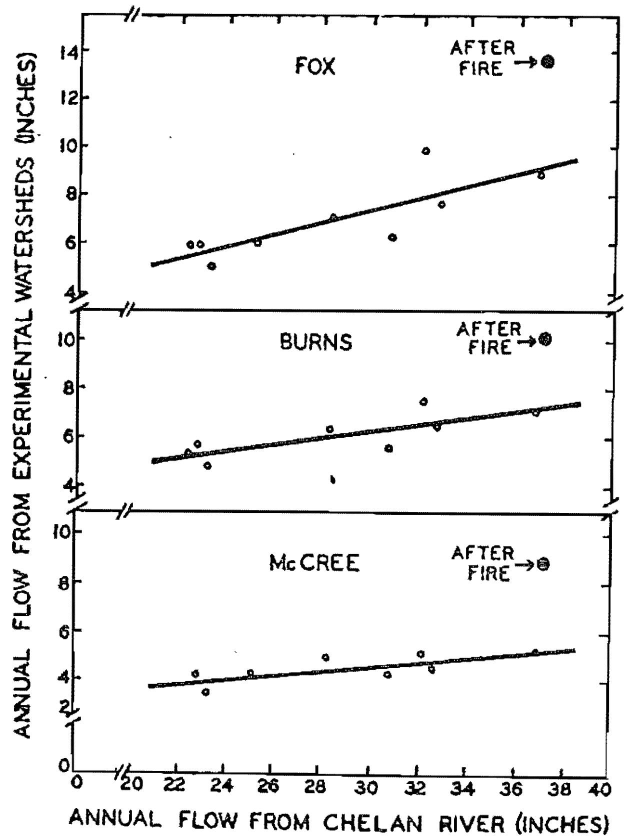


Figure 1.--Annual discharge of three burned watersheds in the Entiat Experimental Forest, Washington, plotted against the discharge of the nearby Chelan River, for the year after the fire as compared to the 9 years of monitoring before the fire. From Helvey (1973, fig. 5).

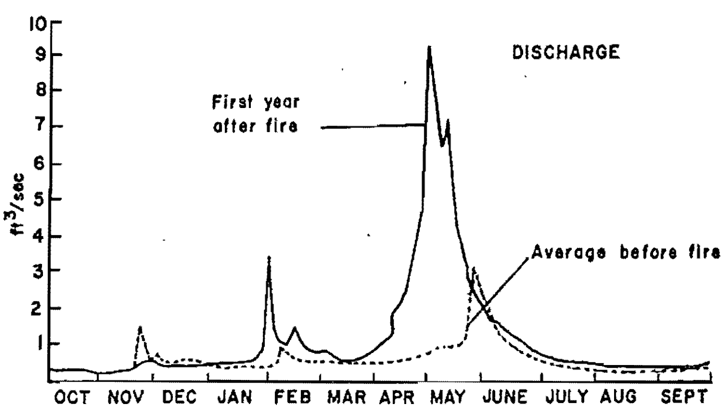


Figure 2.--Discharge of McCree Creek in Entiat Experimental Forest, Washington, for an average year (1962-1963) during the period of calibration, and the discharge for the first year after the fire, which occurred in August 1970 and covered the entire watershed. Extracted from Helvey (1972, fig. 3).

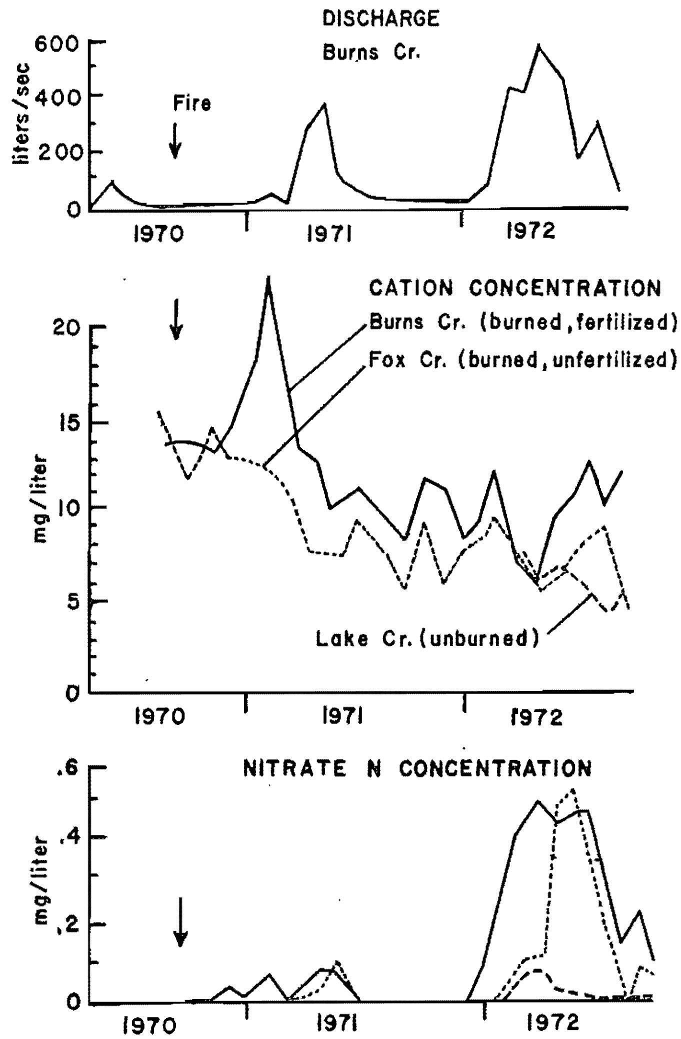


Figure 3.--Discharge for Burns Creek in the Entiat Experimental Forest, Washington, following the fire of 1970, compared with the cation and nitrate-nitrogen concentrations on Burns Creek and Fox Creek for 1971 and 1972 and Lake Creek for 1972. The Burns Creek watershed was fertilized with ammonium sulfate after the fire to encourage the growth of grasses and legumes, but the Fox Creek watershed was untreated; the two streams showed similar patterns of cation and nitrogen concentration. Extracted from Helvey and others (1976, fig. 4-5).

nutrient cycle caused by the reduction of plant growth, and then to increased nitrification caused by higher soil pH. Organic nitrogen concentrations also increased after the fire, as greater surface runoff brought more organic detritus to streams.

Phosphorus was not measured initially, but 2 to 4 years after the fire the concentration of total phosphorus in Fox Creek was 2 to 3 times higher than that in Lake Creek in the unburned watershed. Major cations (Ca, Mg, Na, K) did not increase in concentration after the fire; in fact they decreased, as a reflection of dilution by higher streamflow. Values for Ca were below prefire levels even after 5 years, although the other cations were back to normal.

Concentrations of dissolved nutrients and cations tell only part of the story, however, for stream transport of the solution mass depends as well on stream discharge. Thus the modest increase in nitrate-nitrogen concentrations when coupled with increased discharge in the second year after the fire resulted in a 240-fold increase in solution transport in Fox Creek compared to prefire levels, and a doubling of cation transport (Helvey and others 1976). The loss in total nitrogen during the first 4 years after the fire, however, amounted to only 0.5 percent of the nitrogen capital of the ash and soil. The loss for phosphorus, which is less mobile, was only 0.01 percent, and for calcium 17 percent. Part of the nitrogen loss is made up by precipitation, and much more by nitrogen fixation by *Ceanothus* shrub, alder, and lupine (Tiedemann and others 1978). Losses of phosphorus and cations must be made up primarily by rock weathering.

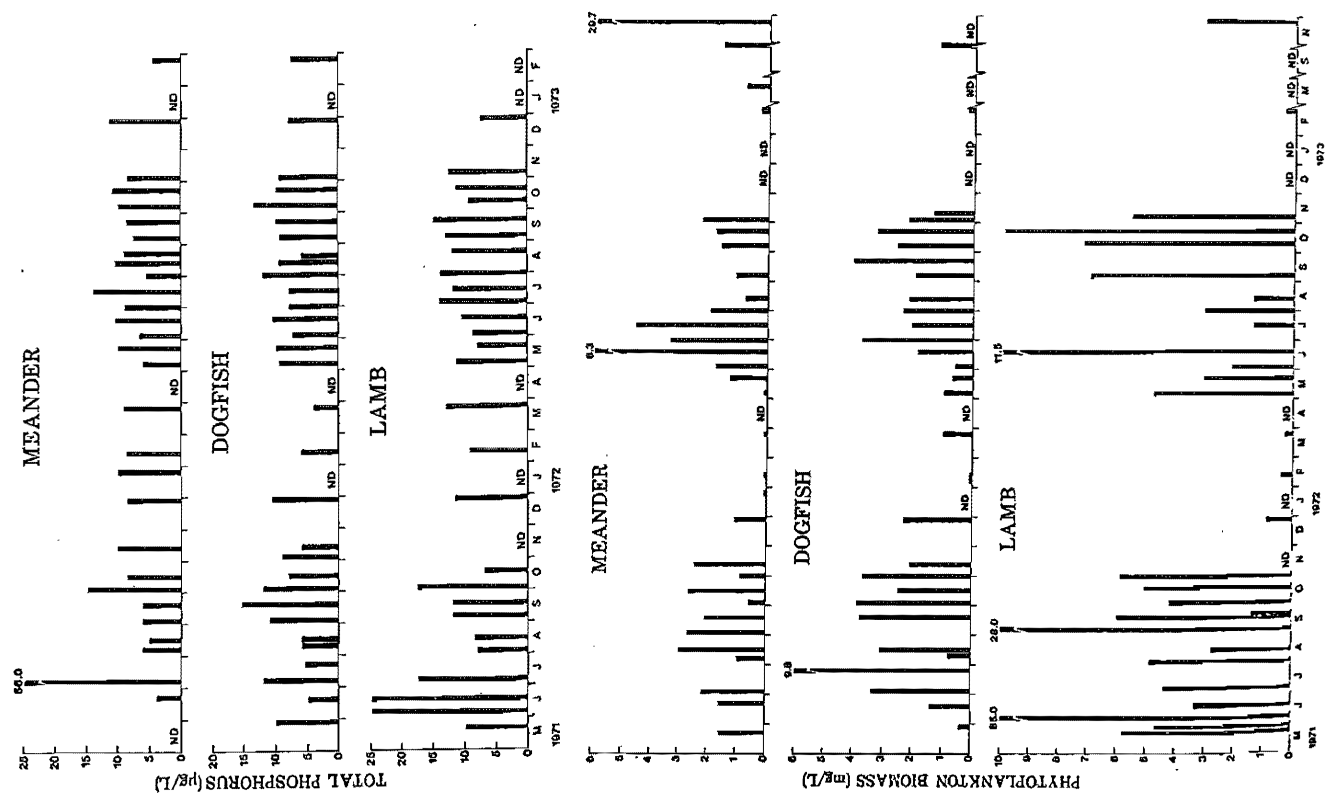
Nitrogen and cation concentrations in streams after the fire were well below limits established by the U.S. Environmental Protection Agency. No measurements of biological activity in the streams were made.

Little Sioux Fire, Minnesota

The Little Sioux Fire in May 1971 in the largely virgin conifer forest of the Boundary Waters Canoe Area of northeastern Minnesota provided the opportunity to examine impacts of wildfire on oligotrophic lakes as well as on the forest itself. Because the fire was unanticipated, the watersheds had not been monitored, so the impacts were assessed by comparing a burned with an unburned watershed of similar size on the same kind of granitic terrain.

Phosphorus released by the burning of living and dead biomass was largely absorbed on the clay components of the soil and then taken up by vigorous vegetative regrowth, which started immediately after the fire (Grigal and McColl 1975, McColl and Grigal 1976). Stream inflow to the lake in the burned area increased by 60 percent compared to that of the unburned area, and this increase accounted for about two-thirds of the 93 percent increase in phosphorus input to the lake from the burned watershed (R. F. Wright 1976) when expressed as phosphorus loading to the lake surface (mg/m^2). This increase is 38 percent, probably within the yearly variation for this forest/lake ecosystem, in which most of the phosphorus input comes ultimately from precipitation rather than from rock weathering. As was the case with the Entiat Fire in Washington, the loss of phosphorus from the watershed was small compared to the phosphorus capital of the forest/soil system. Analysis of the total phosphorus, phytoplankton biomass, and chlorophyll *a* concentrations (fig. 4) made at generally biweekly intervals for 2 years after the fire showed no significant increase attributable to the fire, nor any differences in the composition of the phytoplankton (Bradbury and others 1975, Tarapchak and others 1979).

Of the cations, calcium export from the burned watershed increased 26 percent compared to the unburned, magnesium 29 percent, sodium 65 percent, and potassium 265 percent. Most of the cations were flushed out the lake outlet. Only potassium is important biologically in the lake, but it is already present in such a large quantity that it does not effect algal growth, and its increase after fire had no impact on the lake ecosystem.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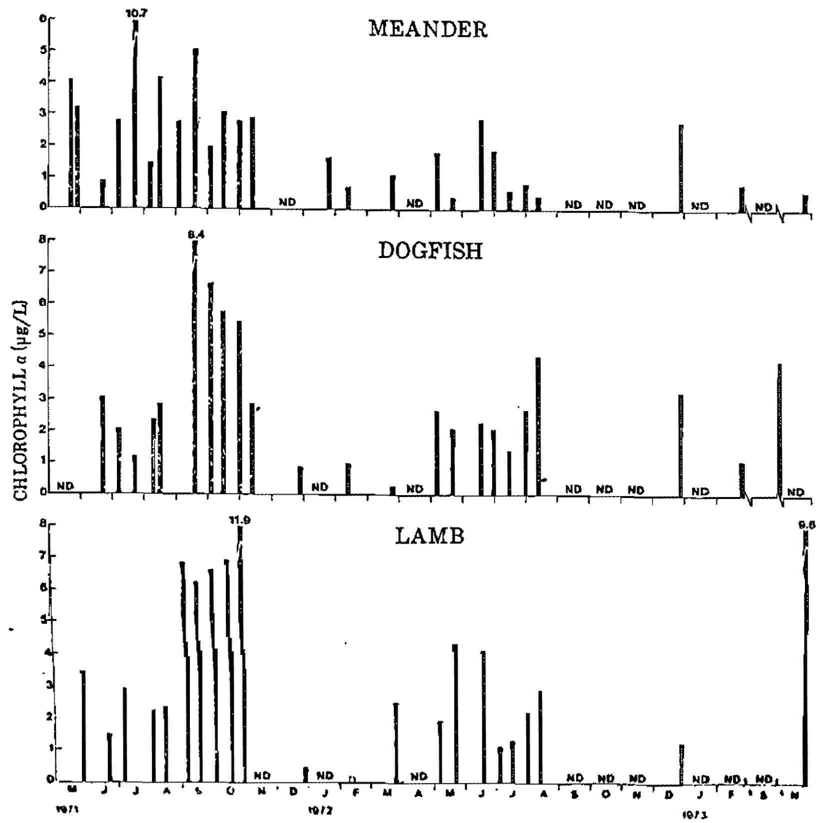

Figure 4.--Total phosphorus, phytoplankton biomass, and chlorophyll a for generally biweekly water samples from Meander and Lamb Lakes (burned watersheds) and Dogfish Lake (unburned control), Minnesota. The fire occurred in May 1971. ND means no data. From Tarapchak and others (1979).

ELA Fire, Ontario

An even better test of the effects of forest fire on lakes was made possible by events in the Experimental Lakes Area in northwestern Ontario (Schindler and others 1979). Here two watersheds monitored for 4 years were subject to a violent windstorm in 1973 and then a year later in 1974 by a summer wildfire, followed by drought with little vegetative regrowth and then by two major rainstorms. An adjacent monitored watershed was untouched by winds or fire, providing exceptional circumstances for assessing nutrient release after fire.

Water yields from the blowdown (both during storms and during base flow) increased immediately, and they further increased after the fire, but in the third year the vigorous vegetative regrowth renewed the evapotranspiration losses from the forest, and the runoff decreased to normal levels.

Nitrogen concentrations increased only slightly after both windstorm and fire. Because of the greater runoff, the total nitrogen loss from these watersheds about doubled. Phosphorus concentrations were not affected by the windstorm but increased after the fire; total loss was greater in all years. For potassium, both concentrations and yields were increased in all cases.

Because precipitation accounts for most of the nutrient input to this forest ecosystem, the perturbations brought by windstorm and fire have little effect on the long-range nutrient supply to the forest nor to the runoff streams. No increases in nutrient or phytoplankton concentrations were noted in a lake into which the monitored streams drained.

Miscellaneous Studies

A variety of physical and geological effects of fire on different time scales are covered in a companion paper in this volume by Swanson and some additional biological aspects by Tiedemann. Quantitative analysis of stream discharge and sediment production during 7 years of recovery in the burned watersheds of the Entiat Fire, newly discussed by Helvey (1979), show that peak discharges during snowmelt have decreased in successive years as leaf litter builds up and improves soil infiltration, and as evapotranspiration from the developing canopy takes up some of the excess. Concomitantly sediment production has lessened as the supply of eroded material from revegetated hillslope diminishes and as the stream channels themselves become stabilized. But it is anticipated that stream discharge and sediment production will not return to prefire levels for several decades.

All of these studies show that mountainous regions are much more susceptible to various kinds of erosion after fire than are the interior plains. Degradational processes such as particle creep, slump, washouts, earthflows, and mudflows are all enhanced by steep slopes and thin soils. These in turn may result in local sedimentation along streams, destroying certain habitats for aquatic organisms but creating others. Between fires, dead trees on the lower slopes fall into streams, producing debris dams that may eventually get flushed out by occasional torrents, or burned out in the next fire (Swanson and Lienkaemper 1978). Thus the macrobiology of mountain streams may be indirectly controlled by fire frequency. But the wildfire studies reviewed above indicate that nutrient supply to streams and lakes apparently does not change enough to affect the microflora.

FIRE AT THE PRAIRIE/FOREST BORDER

A different interrelation of fire and water can be seen in the transition from prairie to forest--but here it is not the fires that affect the water bodies but the reverse.

Since the work of Daubenmire (1936) in the "Big Woods" of south-central Minnesota, it has been recognized that the natural position and composition of the prairie/forest border was determined in part by the incidence of fires that originated in the prairie and swept into the forest margin, killing or preventing the establishment of the fire-intolerant trees and favoring the thick-barked bur oak and certain trees that sprout readily if damaged. Tree relations today are not easy to see in the field, however, not only because agricultural clearance has opened the forest extensively in the transitional area, but also because fire protection has permitted the forest to advance into the prairie.

Examination of the land-survey records that were made before significant agricultural development in the area reveals the natural distribution of forest and prairie, as well as the species composition of the forest. The records contain the identification of two or four "witness trees" at every half mile along the surveyed section lines, thus as many as 288 trees for each township (36 square miles). A compilation of the data in a current study by Grimm (1979) for the entire Big Woods area, which measures about 160 x 100 km, shows not only that the position of the prairie/forest border is controlled in detail by such firebreaks as streams and lakes, but that the composition of the forest can also be related to this factor (fig. 5). Thus bur oak and aspen were dominant at the prairie border in the more exposed areas where fire frequently invaded the forest, for bur oak has thick bark, and aspen readily sprouts after fires. Elm, basswood, ironwood, red oak, and particularly sugar maple, on the other hand, are susceptible to fire and were confined to areas in the lee of firebreaks or in morainic topography where the spread of fire is interrupted by valleys.

Stratigraphic pollen analysis by Grimm of lake sediments in the area implies that the forest moved slowly westward for several thousand years to its present position, although enclaves of forest occupied areas in the lee of lakes and in rugged topography during earlier times when the climate was drier and prairie was more extensive. Oak and possibly aspen invaded prairie and dominated the arboreal vegetation until only a few hundred years ago, when the populations of the fire-intolerant trees characteristic of the Big Woods greatly increased, probably because of climatic cooling correlated with the "Little Ice Age." The forest invasion of prairie occurred at different times in different places depending on location--first in areas protected by firebreaks ans in strongly rolling topography, and later in flatter land and in areas farther west. There is some indication that the migration and expansion took place in steps, from one firebreak to another. In any case it seems clear that water bodies have played a significant role in the composition of the forest.

The effectiveness of lakes as firebreaks in the northern conifer forest can be seen in the Boundary Waters Canoe Area in northeastern Minnesota, where more than 1,000 lakes dot the million-acre wilderness area. The relations are apparent on the stand-origin maps of Heinselman (1973), which reflect the ages of fire-adapted units in the forest mosaic and thus serve to show the areal extent of past fires. Many of the units terminate on the south or west shores of large lakes and streams, and it is clear that although fires occasionally jump ahead over water bodies their limits are commonly determined by such firebreaks, and the oldest stands of trees are commonly found on islands or peninsulas that have escaped fire for several centuries. The relations could be quantified by plotting the ratio of lakeside or streamside perimeter of a fire to total perimeter. Orientation of firebreaks could then be examined and inferences made about wind directions at the time of fires.

In the western mountains, stream valleys also serve as firebreaks, especially broad valleys with wet meadows on the valley floor. In steeper mountain topography, however, a fire can often spot from one side of a valley to another; here ridge crests are more commonly firebreaks than valley bottoms, because air convection usually accentuates the upslope progress of fire when aided by the wind. If maps of past fires are prepared, directions of fire winds might be worked out from the orientation of the ridge crests that served as firebreaks.

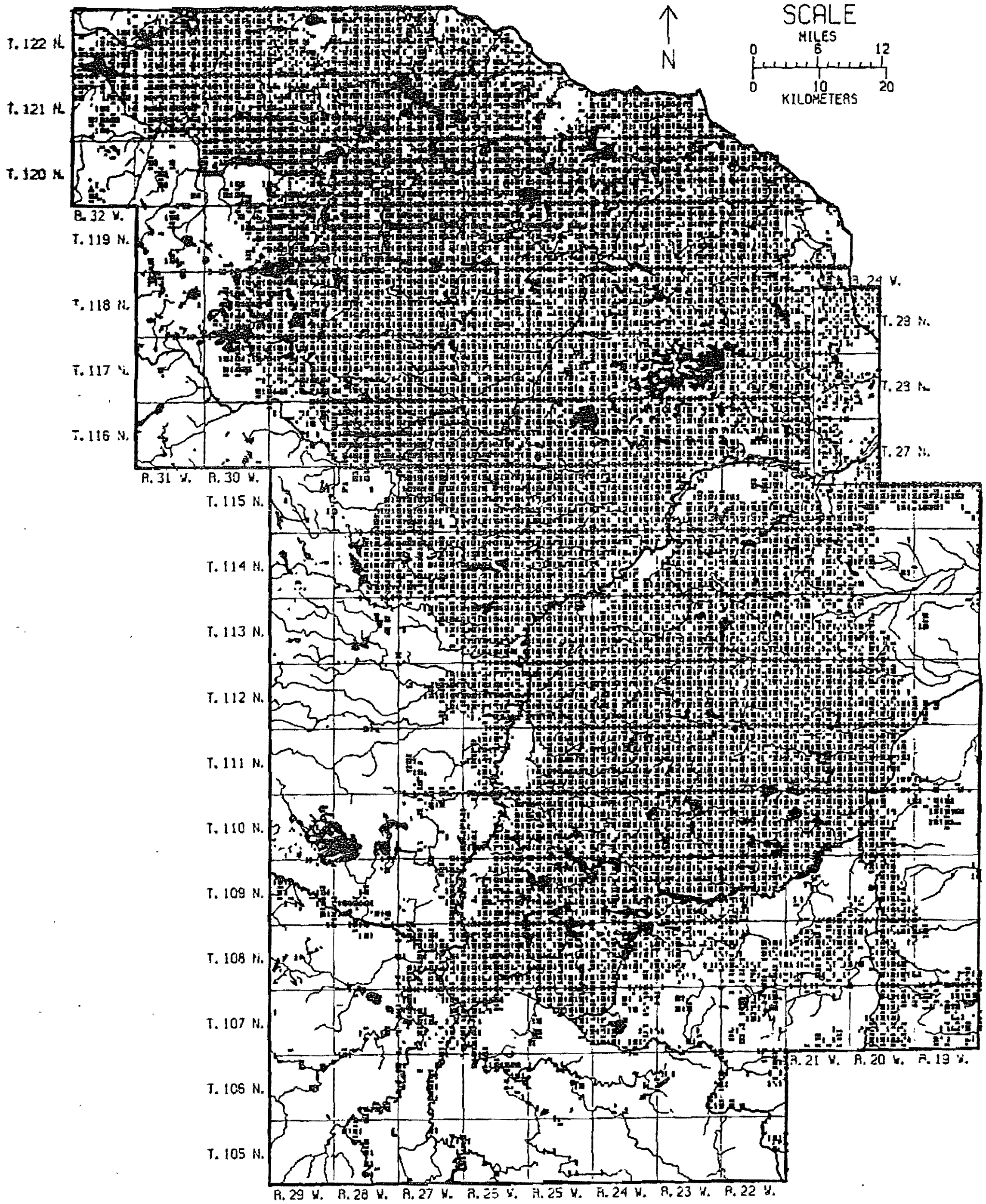

Figure 5.--Distribution of trees in the Big Woods of south-central Minnesota, plotted from the land-survey records prior to agricultural land clearance. Note that the prairie/forest border coincides in many areas with streams and lakes. From Grimm (1979).

The third approach to fire/water interactions involves the fact that lake sediments offer the opportunity to study the incidence of fire in the distant past, to cover the time range before the period accessible by tree-ring analysis in extant forests. In certain respects a lake can be viewed as a passive recorder of events in a forest/lake ecosystem, for much of the sediment it receives from its drainage basin or generates by its own productivity settles to the bottom and is progressively buried. The sedimentary record is particularly useful if it features annual laminations, for these provide the means for a precise chronology as well as the indication that the bottom deposits are absolutely undisturbed by burrowing organisms or by deep water currents.

The most direct evidence for fire that can be determined from lake-sediment study is the stratigraphy of charcoal fragments, which are deposited as airborne ash or are washed into a lake from burned hill slopes. The first such detailed study made was that of Swain (1973) at Lake of the Clouds in the conifer forest of northeastern Minnesota, where the importance of fire as a major factor in forest composition is documented for the last 350 years by the tree-ring and fire-scar studies of Heinselman (1973). Lake of the Clouds contains annually laminated sediments (Anthony 1976), which provide the opportunity for precise dating of stratigraphic changes in charcoal and other sedimentary components, as well as the determination of the sedimentation rate as it might be affected by postfire events. The charcoal and pollen content were analyzed at 2-year intervals for sediment deposited from 1890 to 1970 (Swain 1979) and at 10 to 20 year intervals for the last 1,000 years (Swain 1973). Results reveal variations that can be correlated with the tree-ring fire chronology for the past 300 years, and additional variations during earlier centuries suggest an average fire-recurrence interval for the area of about 65 years for the past 1,000 years (fig. 6). Stratigraphic changes of significance include a maximum in charcoal abundance and particularly in the ratio of charcoal to pollen grains, a decrease in the pollen ratio of conifers to "sprouters," and a slight increase in thickness of annual laminations. The charcoal stratigraphy is not so sharp as one might hope, probably because of continued inwash of charcoal fragments from hillslopes for several years after a fire, or because of redeposition from shallow to deep water at times of lake turnover. The increase in pollen percentage of "sprouters" (birch, aspen, alder, hazel, braken, and grasses) is attributed to the growth of these plants in the sunlight after removal of the canopy by fire, as well as to the delay in the maturation of pine seedlings (usually at least 10 years in the case of jack pine, longer for red and white pine). The increase in thickness of laminae after inferred fires is attributed to algal productivity resulting from nutrient influx, although other factors may be more important, such as increase in sediment focusing in the deep part of the lake after the forest canopy is removed by fire, allowing winds to generate stronger water currents.

A similar stratigraphic study of annually laminated lake sediments was made by Swain (1978) at Hell's Kitchen Lake in northern Wisconsin. In this case fire frequency is best reflected by maxima in birch pollen, averaging about 120 years apart for the interval 200 to 300 years ago. White pine pollen increased 40 to 80 years after most of the birch pollen maxima, and hemlock increased 80 to 170 years after birch, as these conifers succeeded birch and aspen during intervals between fires. Average return interval between fires is estimated as about 140 years through the last 1,150 years, and 100 years before that. Relatively moist climatic intervals are inferred from higher pollen percentages of white pine and/or hemlock relative to oak and aspen, and from greater ratios of yellow birch to paper birch seeds. During these moist intervals the charcoal abundance is less than during the inferred dry intervals.

LAKE OF THE CLOUDS, MINNESOTA
A. M. Swain 1973

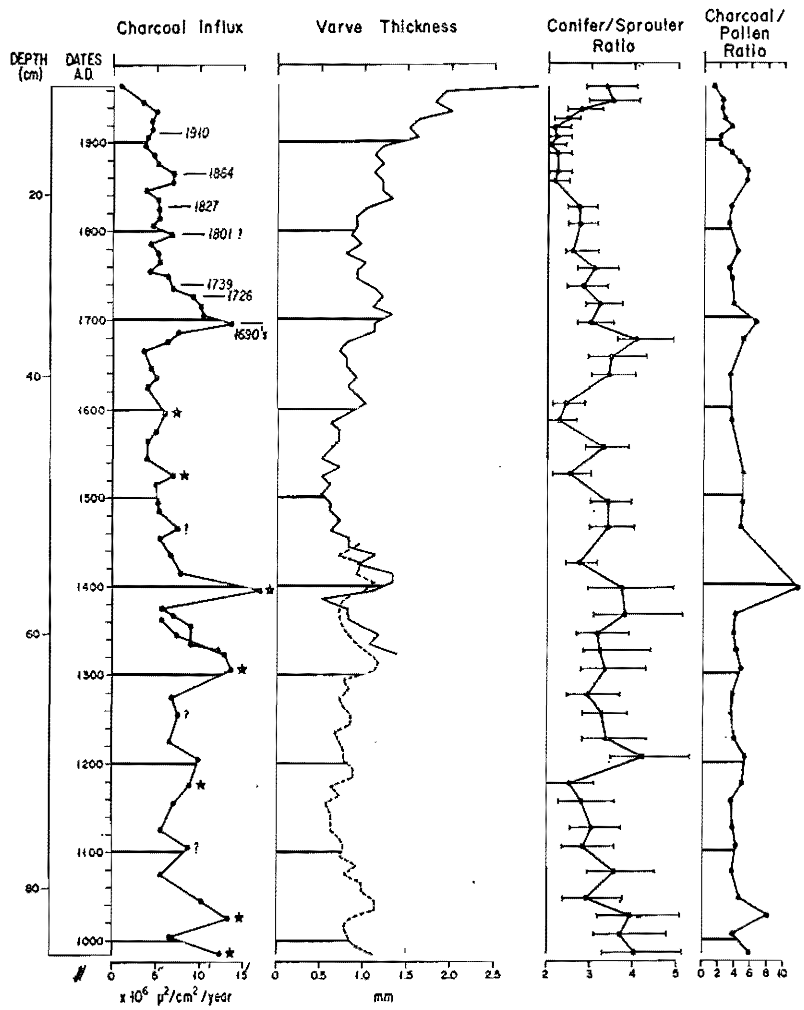

Figure 6.--Stratigraphic profiles from a short core of annually laminated (varved) sediments from Lake of the Clouds, northeastern Minnesota, showing how several maxima in the influx of charcoal match the dates of fires as known from tree-ring studies back to the 1690's. Before that, important charcoal maxima (starred) match the maxima in varve thickness and charcoal/pollen ratio of trees and shrubs that sprout after fires. Extracted from Swain (1973, fig. 3).

The only other area in the western Great Lakes region where a sizable stand of old-growth pines permits the technique of charcoal stratigraphy to be checked against a tree-ring chronology is in Itasca State Park in northwestern Minnesota (Frisell 1973). The advisability of close-interval sampling of annually laminated sediments is seen from a study by Foster (1976) at Lower LaSalle Lake in this area. The pronounced charcoal stratigraphy can be correlated easily with the incidence of known fires (fig. 7). The most prominent fires in the area, as well as in the rest of Minnesota and perhaps western North America as well (Heinselman 1979), were in 1863-1864, and this shows as a major maximum on the profiles. Another big year for fires in the Itasca area was 1874. The highest peak on the curve for total charcoal, at 1895-1900, reflects slash burning in the area associated with the period of most extensive logging. The peak at about 1935 registers fires during the drought years of the 1930's.

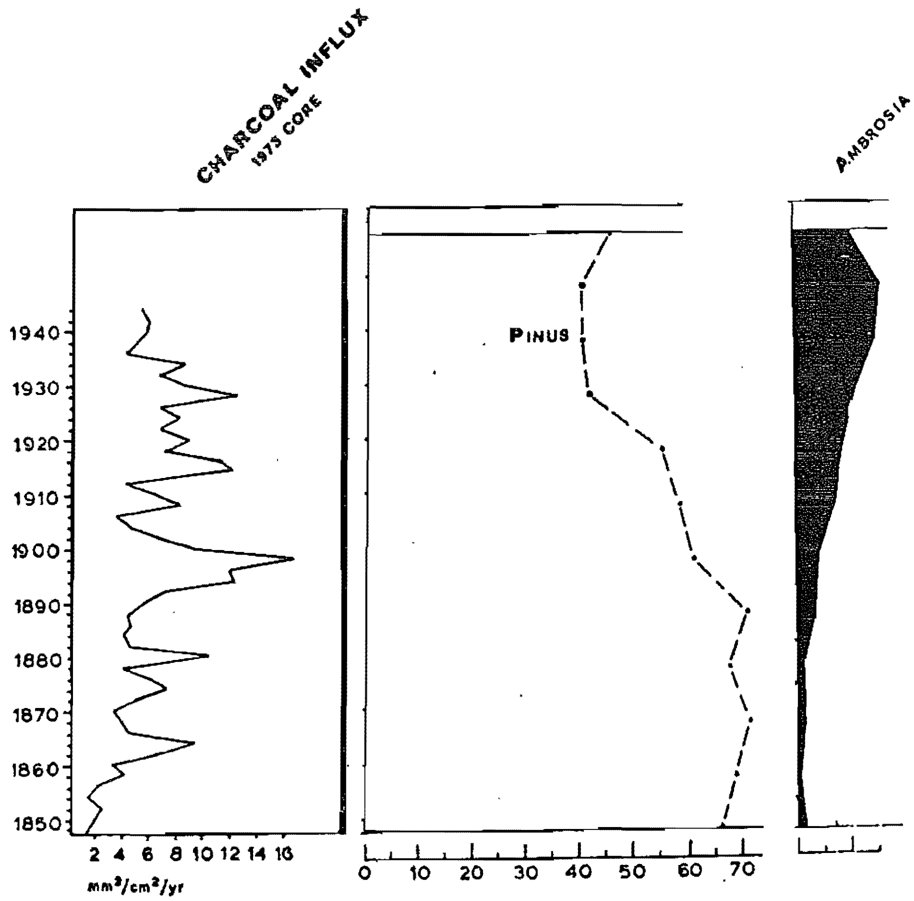

Figure 7.--Charcoal stratigraphy for the interval 1844-1944 from annually laminated sediments at Lower LaSalle Lake near Itasca State Park, northwestern Minnesota, compared with the decrease in pine pollen related to timber cutting and the increase in pollen of Ambrosia (ragweed) attributable to agricultural and land clearance. The charcoal maxima correlate with fires known from the tree-ring record. From Foster (1976).

This and the other stratigraphic studies of laminated lake sediments so far described were made on frozen cores, acquired by dropping a weighted metal tube filled with dry ice and butanol into the sediment. If left in position for about 30 minutes a crust of sediment a centimeter or so thick will freeze to the outside of the tube. When withdrawn to the surface the crust can be closely sampled, with careful avoidance of the thin distorted portion immediately next to the tube.

Another stratigraphic project in the Itasca area was undertaken at Squaw Lake by Patterson (1978), who combined this stratigraphic approach with a 2-year study of the hydrology and water chemistry of the lake and its influent streams. The watershed consisted primarily of birch and aspen regrown after largely clearcut logging of pines, followed by slash fires. During the period of observation a very heavy rainfall resulted in conspicuous stream erosion and inflow of mineral sediment to the lake, producing a thin layer of white silt in the otherwise organic sediments. A core of sediments from the deepest part of the lake showed several such silt layers, many of which occur just below maxima in the charcoal profile (fig. 8). Patterson concludes that periodic deforestation by fire resulted in erosion of the forest floor at the time of the next heavy rain, with the mineral sediment settling out in the lake more rapidly than the more buoyant charcoal particles. Although the lake sediment is not annually laminated, the sedimentation rate could be determined by identification of the level of the rise of ragweed pollen and the decrease in pine pollen, marking the time of farming in areas to the west and logging in the Itasca area itself. A radiocarbon date near the base of the section provides an additional datum. The extremely low sedimentation rate--only about 6 cm per century, unusually slow for a Minnesota lake--as well as the irregularities introduced by the silt bands, make it difficult to correlate closely the charcoal stratigraphy with the tree-ring record of past fires.

Another study in which fire-induced erosion is inferred from the stratigraphy of annually laminated lake sediments is that of Cwynar (1978) at Greenleaf Lake in Algonquin Provincial Park west of Ottawa in forest of dominantly white pine. He found that maxima in charcoal profiles (fig. 9) correlate with thick annual layers and with high influx of pollen, aluminum, and vanadium, presumably because of enhanced erosion following fire: the pollen was washed into the lake from the forest floor, and the mineral ions were contributed by soil erosion. Analysis of 10-year samples through a 500-year section of sediment dating from 770 to 1270 A.D. yielded a fire frequency of about 80 years. Pollen analysis indicates that regional forest composition did not change during this period or in subsequent time.

A different sedimentary approach to fire history was applied by Griffin and Goldberg (1975) to the annually laminated sediments of the Santa Barbara basin off the coast of southern California and Saanich Inlet in British Columbia. Here the technique involved the determination of elemental carbon, which ranged from 0.01 to .09 percent of dry weight. Results show a slight increase over the last 120 to 135 years, although the scatter of points is very large. The authors believe that the carbon is derived from fires in chaparral or forest, either by smoke or by subsequent erosion of burned landscape by streams, even though they list several other possible factors (burning of fossil fuels, microbial decomposition of organic matter, variations in winds and streams). Although they show by scanning electron micrographs that the carbon particles resemble those derived from burned wood, they state that fossil fuels could produce similar particles. Their conclusion that "management practices in the control of forest and brush fires of California and British Columbia appear to have had little effect on the fluxes of elemental carbon in the marine environment" would seem to be unwarranted, in view of the uncertainties in the source of carbon and in the mode of transport of the site.

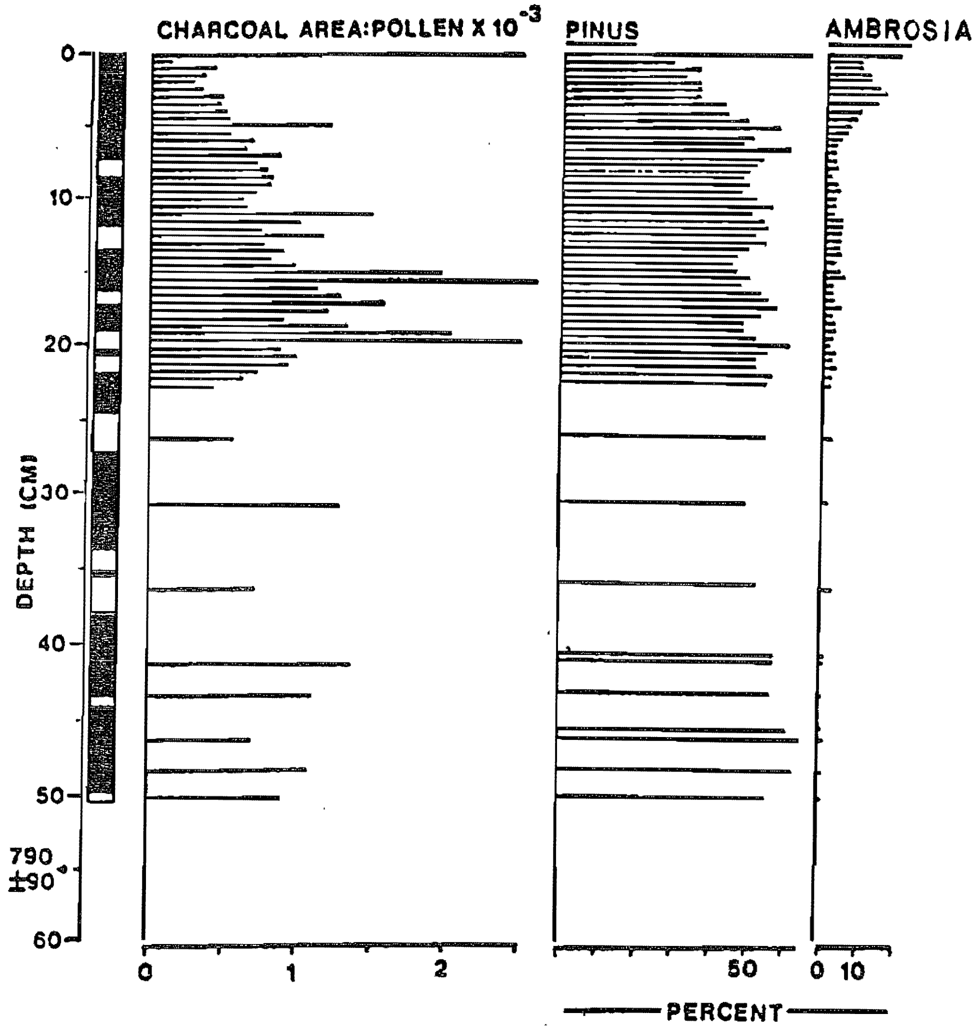

Figure 8.--Charcoal stratigraphy for a short core from Squaw Lake in Itasca State Park, northwestern Minnesota. Time scale is provided by a radiocarbon date at 55 cm and by the rise in ragweed pollen and fall of pine pollen, dated to about 1895 on historical evidence. Maxima in the charcoal curve down to a depth of 16 cm correlate with fires from the region as known from the tree-ring record. Several charcoal maxima occur just above the bands of silt (white on sediment column), which may represent erosion after fire. From Patterson (1978).

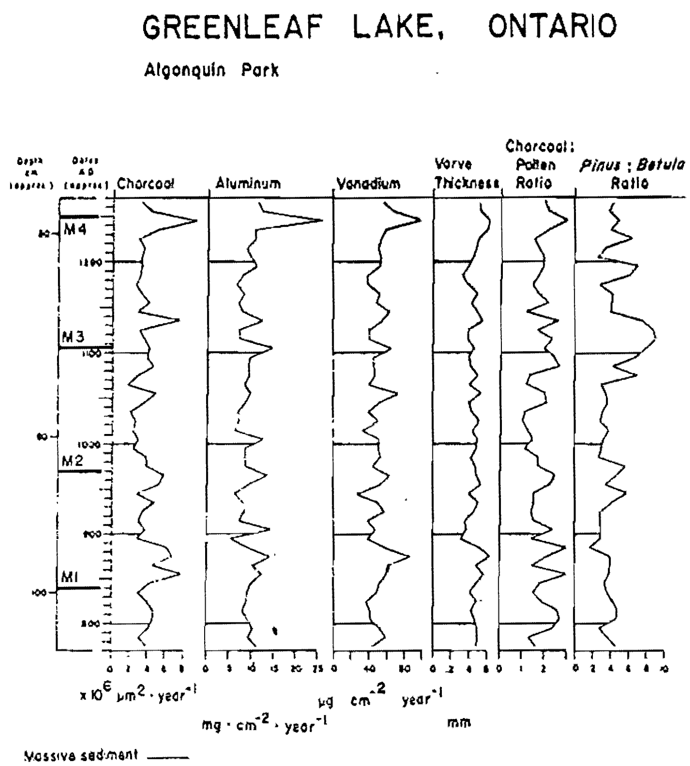

Figure 9.--Stratigraphic profiles for charcoal and other components in the annually laminated sediment from Greenleaf Lake, Adirondack Park, Ontario, for the time interval 770-1270 A.D. Massive layers M-1 to M-4 are interpreted as turbidities. Charcoal maxima correlate with maxima of Al, Va, and lamina thickness, implying hillslope erosion after fire. Extracted from Cwynar (1978).

A more realistic analysis of the Santa Barbara varved sediment was made by Byrne and others (1977), who were able to correlate the influx of charcoal particles in core segment 1931-1970 with the known years of wildfires in the Los Padres National Forest on the mainland only 25 km away. Similar charcoal counts at a greater depth covering an interval of about 150 years imply a frequency of 20 to 40 years for major fires--a frequency not unlike that of the modern period of attempted fire suppression.

THE RECORD OF FIRE IN THE DISTANT PAST PROVIDED BY LAKE SEDIMENTS

The tree-ring record of fire history in the pine forests of northern Minnesota leaves little doubt that fire has been a major factor in determining forest composition, and the charcoal record in short cores of lake sediment, as described above, indicates that the mosaic of forest types controlled by periodic fires has maintained a relatively uniform overall composition for many centuries, at least as far as can be detected by stratigraphic pollen analysis. And in some areas the record of regional stability is documented for several millennia, so that one can think of the mosaic as a fire climax that has persisted through many generations of trees (H. E. Wright 1974). But what of the longer term record through the 10,000-15,000 years of postglacial time, or even longer in unglaciated areas?

Pollen analysis of long cores of lake sediment show that in most areas vegetation has changed substantially in this time range. In central Minnesota, for example, the dominant vegetation changed from spruce forest to pine forest about 10,000 years ago, then to oak forest and even prairie, culminating about 7,000 years ago, followed by a reversal to the modern pine forest. These changes almost certainly are a result of a trend to warmer, drier climate, followed by a reversal. It would be possible to determine fire frequency for different vegetation types on a semiquantitative basis by stratigraphic charcoal analysis of representative segments of lake-sediment cores in this area, as Cwynar did at Greenleaf Lake for the interval 770-1270 A.D. (fig. 9). This was attempted for the transformation from spruce forest to pine forest 10,000 years ago, with the hypothesis that spruce is less well adapted to fire than pine and thus might show a lower fire frequency (Amundson and Wright 1979). The sample interval was not sufficiently small to establish an interpretable stratigraphy, however. It could be concluded only that fires occurred in both forest formations (fig. 10).

In the pine forests of the Atlantic Coastal Plain and the Appalachian Piedmont in southeastern United States, fire is an important ecological factor (Christensen this volume). Pollen diagrams from this region (fig. 11) indicate that before 5,000 years ago pine was much less common than today, and that the dominant pollen type was oak (Watts 1979). Several explanations can be offered for this transformation, ranging from climatic change to delayed migration of southern pines from earlier refugia. Whether or not fire frequency played a role in this transformation is uncertain.

In the hardwood forests of the Appalachian Mountains fire is not important, and regeneration of forest stands is abetted by windstorms instead. No studies of charcoal stratigraphy have been made in this region, however. The climate there is warm and humid enough and the microbial activity is sufficient so that detritus does not accumulate on the forest floor to an extent great enough to fuel extensive fires.

Another area with low fire frequency is southeastern Labrador, where the climate is cool and humid. Although the forest consists dominantly of black spruce, which regenerates readily after fire, the forests of all of Labrador completely lack jack pine (the fire tree *par excellence*), in contrast to the rest of the boreal forest farther west. Except for the lowland near Hamilton Inlet and Goose Bay, where the climate is milder and tree growth is sufficient to sustain logging operations, the black spruce forest of southeastern Labrador is depauperate, pockmarked with openings, and commonly marked by a thick mat of mosses and other ground plants that show little

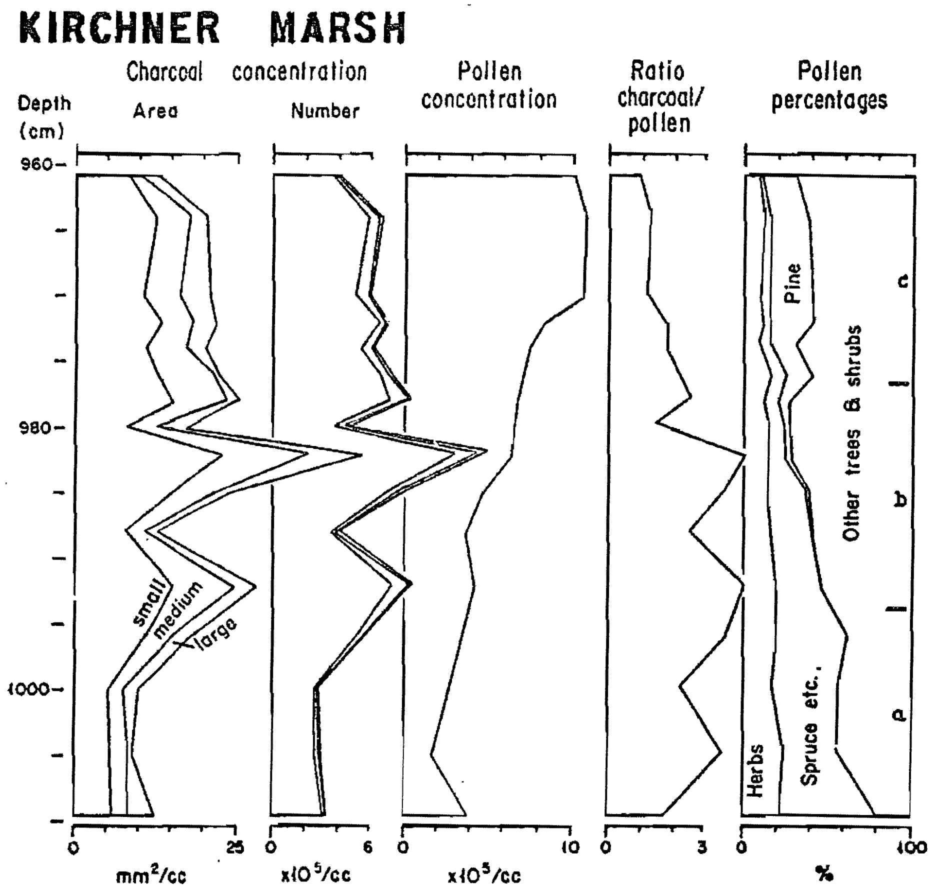

Figure 10.--Charcoal stratigraphy for an interval of 50 cm (representing about 200 years) at Kirchner Marsh, southeastern Minnesota, expressed as area and as number of small, medium, and large particles per cc of sediment. The summary pollen percentages show that the change from dominant spruce to dominant pine was not accompanied by a change in charcoal abundance. From Amundson and Wright (1979).

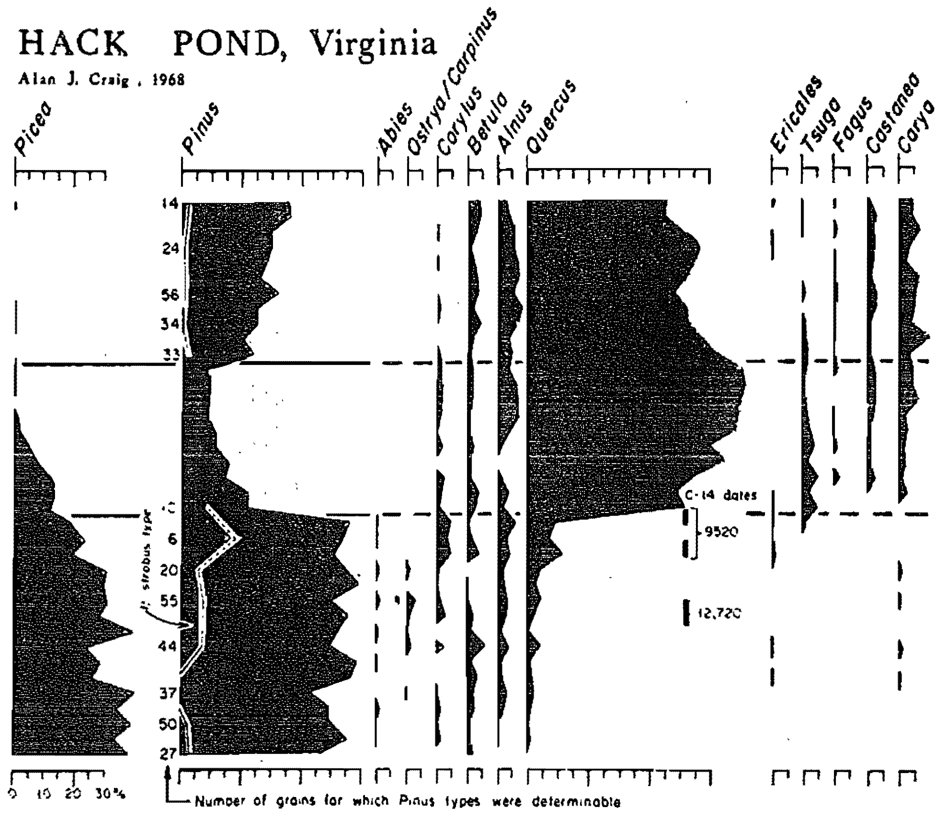

Figure 11.--Pollen diagram for Hack Pond, Shenandoah Valley, Va., showing transformation from dominant oak to dominant pine, as characteristic for much of the southeastern United States. Many species of southeastern pines are adapted to fire, but it is not known whether the vegetation change recorded here resulted from a greater frequency of fire. Redrawn from Craig (1969).

sign of recent fire. Poorly drained areas are covered with sedge marshes and string bogs, which climb up gentle slopes and invade the forest. Much of the landscape seems destined for take over by wetlands.

The lakes in southeastern Labrador are brown-water lakes, being affected by drainage of dissolved humic materials from the wetlands, and the sediment currently being deposited is "dy"--the very-fine-grained organic substance characteristic of such dystrophic lakes. The historical development of these lakes and landscapes has been worked out in a preliminary way by Lamb (1979) from stratigraphic studies of lake sediment (fig. 12).

It appears that white spruce invaded a shrub tundra of alder and dwarf birch in southeastern Labrador as early as about 9,000 years ago, soon after deglaciation, according to the pollen record and radiocarbon dating, and that an open spruce park tundra prevailed for several thousand years. The hill slopes became stabilized early in this phase as frost disturbance decreased, and normal organic sediment (gyttja) composed largely of algal detritus was deposited in the lakes. About 6,000 years ago balsam fir increased at the expense of white spruce, and a closed forest of fir, white and black spruce, and paper birch then probably developed, lasting for several hundred years. This type of forest is found today in southern Labrador on the best sites, i.e., those neither excessively wet nor dry (Wilton 1965), but not in areas close to the northern forest limit. About 5,000 years ago fir and birch decreased sharply, and spruce attained the almost sole dominance it has since exerted.

It was just at this time that the lake sediments studied changed from gyttja to dy, reflecting inflow of dissolved organics from the hill slopes. It is likely that the forest change involved a shift from mesic conifers to black spruce, as the carpet of mosses, ericaceous shrubs, and conifer needles built up on the forest floor in the more poorly drained areas and created acid conditions favorable for black spruce. Lowland bogs probably were widespread by this time, as suggested by the fact that the carbon dates from basal peats in southern Labrador are almost all in the range of 6,500 to 5,000 years ago--not older. The growth of bogs up gentle slopes may have begun at this time, aided locally near lake shores by progressive development of ice-push ridges, which impede the drainage from hill slopes. This process has led to the progressive paludification so apparent today in the landscape of southeastern Labrador. Radiocarbon dates indicate that the deposition rate of the sediment decreased in the last few thousand years, reflecting reduced lake productivity. The influx of spruce pollen also decreased, presumably the result of decreased abundance or productivity of the spruce trees as paludification proceeded.

These paleoecological relations imply that fire has been relatively unimportant in the last few thousand years in the boreal forest of southeastern Labrador, for frequent fires tend to consume the forest floor and inhibit the buildup of peat. In this situation the nutrients derived from rock weathering are not recycled within the mineral soil and biomass but are stored in the undecomposed forest floor and the growing peatlands. As the peat thickens the living plants lose contact with the nutrient supply from mineral soils, and the plants that succeed are those that can tolerate the low nutrient status. The depauperate black spruce forest, with undergrowth of mosses and ericaceous shrubs and with reproduction almost entirely by layering, is moist enough to escape severe burns, and it is this vegetation type that is the most extensive in southeastern Labrador today.

The postulated progressive paludification of the boreal forest of southeastern Labrador may reflect higher levels of precipitation and lack of summer drought there compared to central and western Canada, which have a continental climate, frequent fires, and abundance of jack pine adjusted to a fire regime. Only in the vast Hudson Bay Lowlands or in the great Red Lake peatland in northern Minnesota can similar

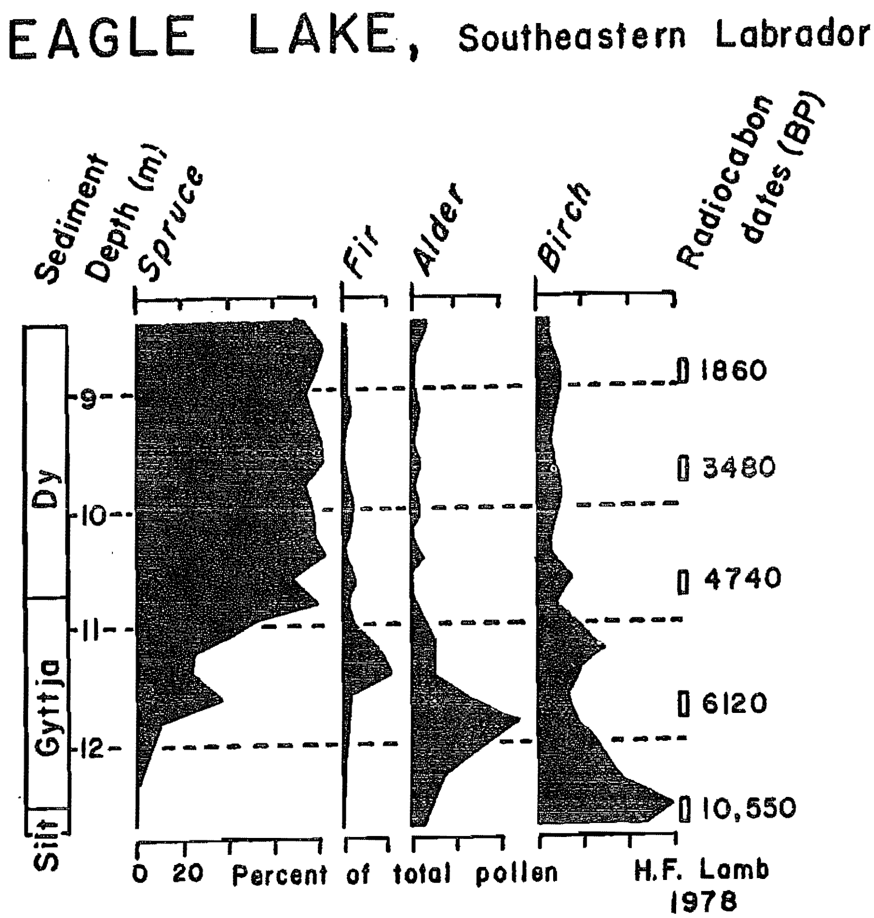

Figure 12.--Summary pollen diagram for the sediments of Eagle Lake southeastern Labrador, showing some of the evidence for the succession from shrub tundra and spruce parkland to a forest of white spruce, fir, and paper birch (about 6,000 years ago) and then to black spruce forest (about 5,000 years ago), as the lake sediment changed from predominantly algal detritus (gyttja) to a sediment charged with humic substances (dy) resulting from the development of peat in the drainage basin. Redrawn from Lamb (1979).

broad-scale paludification be demonstrated. In the latter area the poor drainage on the floor of Glacial Lake Agassiz reduces the fire frequency compared to that of the surrounding upland; the climatic change of about 4,000 years ago facilitated the western expansion of conifer forest and the accumulation of peat.

CONCLUSIONS

This review of some of the interactions of fire and water started with comments on the low potential of forest fire to produce flooding and eutrophication of streams and lakes, considered the role of streams and lakes in controlling the spread of fires at the prairie/forest border, and terminated with accounts of the sedimentary record of past fires and with speculations on the importance of fire in holding down the paludification of humid northern landscapes, a gradual process whose history is revealed by the stratigraphic study of lake sediments. Many other interactions could be discussed, for an aquatic ecosystem relies heavily on the terrestrial ecosystem in its drainage basin to supply water, nutrients, and sedimentary particles. Not the least important is the role that lakes play in preserving the sedimentary record of past events, so that our speculations on the long-range role of fire in the development and stability of forest ecosystems can be tested by careful analysis of this record. Forests do change over time for a variety of reasons, and fire may play a direct or indirect role in forest history. The elucidation of this role in the past is a challenge for the paleoecologist, working from fragmentary data, but in the absence of any such historical test the speculations of the neoecologist must remain quite hypothetical.

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