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Transformation of a northern hardwood forest by aboriginal (Iroquois) fire: charcoal evidence from Crawford Lake, Ontario, Canada

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Abstract: Ecologists have long debated whether Indian burning had important impacts on presettlement forests. We obtained stratigraphic evidence for fire using charcoal analysis of southern Ontario lake sediments. The record spans a period of Iroquois occupation when cultivation coincides with pollen evidence for transition from northern hardwoods to white pine/oak forests. Charcoal data reveal that this transition was attended by increased charcoal accumulation, sufficiently high to suggest vegetation fires. Results support the notion that Indian burning is capable of producing dramatic changes in forest composition spanning centuries.

Key words: Emissions, fire, Iroquois, forest dynamics, human impact, charcoal, Canada.

Introduction

Estimates of presettlement burning affect how we manage for biodiversity (Wright, 1974; Kauffman *et al.*, 1993) and the way we interpret current massive emissions from fossil-fuel combustion and deforestation (Andreae, 1991). If fire has long been present in a given vegetation type, it is likely that burning is partly responsible for patterns in species composition. Maintenance of existing diversity or restoration of past composition might involve reintroduction of fire (Stottlemeyer, 1981; Abrams, 1992; Sharitz *et al.*, 1992). The implications of current burning emissions depend on the 'baseline' burning that occurred prior to rapid deforestation and fossil-fuel combustion of recent times. Atmospheric scientists call for reconstruction of burning rates from key periods in the recent past to serve as baselines for comparison with current rates (Crutzen and Andreae, 1992; Malingreau *et al.*, 1993). Past emissions could have been high if aboriginal people regularly burned the forest understorey (Kauffman *et al.*, 1993).

The prevalence and impacts of aboriginal burning in eastern North America have been the subject of continuing debate for several reasons: (1) interpretations are often based on second-hand observation, most from long after native populations were decimated by disease; (2) early settlers may have had ulterior motives for reporting frequent Indian burning; (3) little ethnographic evidence exists to support the concept of routine vegetation burns; and (4) problems resulting from burning may have outweighed benefits (Pyne, 1982; Russell, 1983; Williams, 1989). These questions regarding the prevalence of Indian burning bear on the debate of whether Indians may have had significant impacts on vegetation of the northeastern North America, by fire or other means (Bromley 1953; Day, 1953; Martin, 1973; Patterson and Sassaman, 1982; Russell, 1983; Whitney, 1990). The role of anthropogenic burning might be better understood from evidence of precolonial fire and forest composition spanning the initiation of Indian burning so that pre-and post-Indian fire and forest composition can be compared.

Close correspondence of dated fire-scarred red pine trees and stratigraphic charcoal data in Minnesota (Clark, 1988a, 1988b) led us to hypothesize that, if fire were used to burn forests near small lakes, then accumulations of charcoal significantly greater than background regional levels should be recorded in the varved sediments. Finding such charcoal accumulations would (1) provide direct evidence for increased importance of fire in the vicinity of Indian settlements, and (2) demonstrate that the method could be applied with pollen analysis over a broader region to determine the geographic importance of Indian burning in presettlement forests. If fire were found to increase in importance during occupation and forest change, then it is possible that Indian

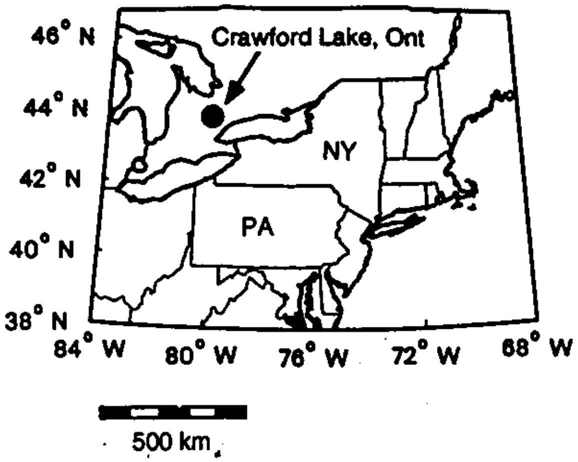

Figure 1 Location map showing Crawford Lake.

burning was capable of causing dramatic transitions in forest composition. We addressed this question through analysis of charcoal accumulation in the sediments during the last 2000 years. This time period was selected as one of sufficient duration to establish the rate of charcoal accumulation before evidence for Indian occupation in this region after AD 1400 (McAndrews, 1988). We chose to analyse Crawford Lake, Ontario, because previous pollen analysis contains well-dated evidence for pre-Columbian agriculture (McAndrews and Boyko-Diakonow, 1989). To determine potential changes in fire occurrence through the past, we used a method of stratigraphic charcoal analysis that has demonstrated the importance of fire during periods of cultural manipulation of forests in Europe (Clark *et al.*, 1989) and of natural fires in the midwestern US (Clark, 1988a).

Study area

Crawford Lake (44°N, 80°W; elevation 279 m; Figure 1), a 2.5 ha meromictic lake containing annually laminated (varved) sediments (Burden *et al.*, 1986), provided an opportunity to examine the relationship between forest vegetation and fire at a time of Indian occupation. The 28.5 m deep basin (24 m water above 4.5 m sediment) occupies Silurian dolomite west of the Niagara escarpment in southern Ontario, possibly a sink. Couplets consist of summer calcite layers alternate with dark organic-rich winter layers. Identification of cultural pollen indicators in the sediments confirm that laminations are annual (Boyko-Diakonow, 1979).

Previous studies show that modern forests underwent dramatic transition from the fourteenth to fifteenth centuries when first archaeological evidence for an Iroquois village is present in the lake catchment (Boyko-Diakonow, 1979; McAndrews and Boyko-Diakonow, 1987). Today the catchment is largely forested, dominated by mixed hardwoods. Fossil pollen data show that *Quercus* spp. and *Pinus strobus* recently replaced northern hardwoods taxa. There is evidence for cultivation of corn (*Zea mays*) during the transition in arboreal taxa from AD 1360 to 1650. Archaeological evidence of *Zea* cultivation is present in southern Ontario after AD 600, with numbers of sites increasing until AD 1600 (McAndrews, 1988). Small Iroquois villages were established within several kilometres of Crawford Lake *c.* AD 1280. Peak densities of perhaps 2400 individuals spanned AD 1360 to 1613, when settlements may have existed near the lake. Two other southern Ontario lakes in Awenda Provincial Park show evidence of Huron agriculture from AD 1450 until 1650, including *Zea* pollen (Burden *et al.*, 1986). There is no evidence of occupation near Crawford from 1650 until Eurocanadian settlement in AD 1840 (Dodd et al., 1990; McAndrews, pers. comm.). Today, the catchment includes a reconstruction of an Iroquois village.

Methods

The upper 1.3 m of sediment was obtained with a freeze corer (Swain, 1973) from the ice surface in winter. Petrographic thin sections of the sediments were prepared according to methods of Clark (1988a). Frozen sediments were cut into contiguous subsamples 5 cm long × 2 cm wide × 1 cm thick. Subsamples were dehydrated in acetone, embedded in epoxy resin (Spurr's medium), and sectioned by a modified petrographic technique. All charcoal fragments >50 μm long that occurred within each varve were counted at 63×. Charcoal indices reported here are calculated as the fraction of the sediment surface covered by charcoal fragments in each year (Clark, 1988a). They have units of mm^2 charcoal cm^{-2} sediment yr^{-1}. Fossil pollen was prepared and analysed by usual methods (Boyko-Diakonow, 1979) at five-year (sediments younger than AD 1800), 10-year (AD 1370–1800), or 20-year (pre AD 1370 sediments) intervals.

Changing abundances of arboreal taxa are represented in two ways. First, conventional pollen diagrams are presented with percentages of total upland pollen and spores excluding agricultural indicators such as *Ambrosia*. This sum is used to highlight composition changes that occur within forested areas, rather than for the landscape as a whole. Second, we also present rates of change in arboreal pollen percentages dp/dt, expressed as change in per cent pollen p divided by elapsed time dt, represented by median ages of stratigraphically adjacent samples. The resulting series is smoothed using a filter with a window of 20 years, the maximum interval between samples, in order that rates not be dominated by the changing sample interval. The magnitudes of dp/dt can be compared within and among pollen series to determine when rates of change are greatest. Also presented are chord distances between adjacent samples, the 'rate of change' index of Jacobson *et al.* (1987). In contrast to dp/dt, chord distances indicate changes in the entire spectrum. The two indices are complementary ways to analyse change in pollen profiles.

Interpretation of charcoal data and application to cultural activity

Comparisons of thin-section charcoal in annually laminated sediments from Minnesota with fire scars on nearby *Pinus resinosa* trees demonstrated that individual surface fires could be identified as departures from low 'background' levels (Clark, 1990). Burns were patchy, with individual catchments often supporting fires in years when nearby catchments did not. Charcoal profiles generally showed little response to burns that occurred more than 10^2 m from the lake. This observation is consistent with airborne measurements of particulate emissions that show atmospheric residence times of particles counted on thin sections (>50 μm diameter) to be low (e.g., Radke *et al.*, 1991). Background levels were taken as the accumulation rates of charcoal during years in which local fires do not occur. These background levels are interpreted as the combination of low atmospheric inputs that may arise from more distant fires (i.e., beyond 10^2 m) plus particulates borne by surface flow or redeposited within a lake during non-fire years. This notion of charcoal transport implies that landscapes support a certain spatially integrated charcoal accumulation that is related to the burning activity on a regional scale. Catchment fires produce individual 'peak' accumulation rates that add to this background flux. Background is approximated by integrating in time (averaging within a series) or by integrating in space (averaging among series; Clark and Royall, 1994a), whereas local fires are estimated from peak, short-lived (annual) events (Clark, 1990). We estimate background levels here by averaging charcoal accumulation rates within pollen-stratigraphic zones.

Subcontinental scale patterns in charcoal accumulation rate support the notion that background charcoal values reflect burning at regional scales. Average charcoal accumulation rates in lake sediments approximate trends in climate and vegetation across eastern North America (Clark and Royall, 1994a). The level of background charcoal declines in step with the frequency of charcoal peaks, suggesting that as the local frequency of fire declines so too does the regional importance of fire.

Results

Pollen

Pollen analysis has been discussed by McAndrews (1988). Here we highlight several aspects of the data relevant to interpretation of fire history. For purposes of comparison with fossil charcoal data, we define four pollen-stratigraphic zones on the basis of gross changes in herbaceous indicators of disturbance (Figure 2):

Zone I – pre-AD 1360: Cultural pollen indicators are in low abundance.

Zone II – AD 1360–1650: *Zea mays* pollen is present and Gramineae pollen, Tubuliflorae pollen, and *Pteridium* spores increase in abundance. Several pollen grains of *Portulaca* (not included in Figure 2) are also present during this interval (Byrne and McAndrews, 1975). This is the 'Iroquios' phase of McAndrews (1988).

Zone III – AD 1650–1850: All indicators of cultural disturbance decline. Gramineae, including *Zea mays*, Chenopodiaceae, Tubuliflorae and *Pteridium*, decline to minimum during the eighteenth century.

Zone IV – AD 1850 to present: Cultural or disturbance indicators of zone II increase, particularly Gramineae, attended by increases in Chenopodiaceae, *Ambrosia* and *Plantago*.

Several changes in forest pollen taxa are associated with changing herb pollen abundance. Northern hardwoods taxa, including *Fagus* and *Acer saccharum*, dominate before the zone II increases in herbaceous taxa (Figure 3). Arboreal percentages are rather constant throughout zone I, with the exception of an increase in *Betula* at AD 1000. Rates of change are near zero for all other taxa during the central portion of zone I (Figure 4).

Zone II is characterized by changing abundances of several arboreal taxa. From AD 1360 until the late seventeenth century increased *Pteridium* spores and Gramineae pollen (Figure 2) coincide with declines of northern hardwoods pollen types and increased *Pinus* and *Quercus* (Figure 3). Following their steep declines during the fifteenth century, *Fagus* and *Acer saccharum* remain constant, and then begin slight increases with the beginning of zone III. The *Fagus*

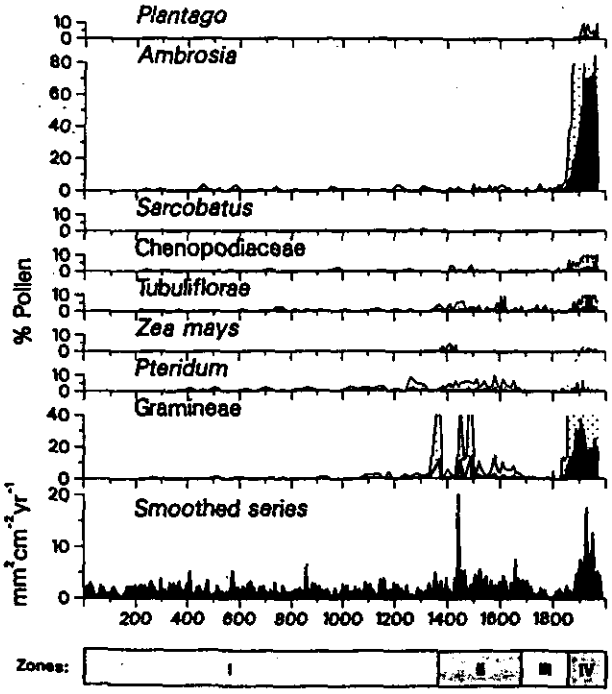

Figure 2 Some pollen and spore types indicative of fire and agriculture and charcoal. A Fourier transform is used for a low-pass filter of the charcoal data to emphasize general trends over the time of occupation. Pollen and spore profiles are expressed as percentages of the total arboreal pollen.

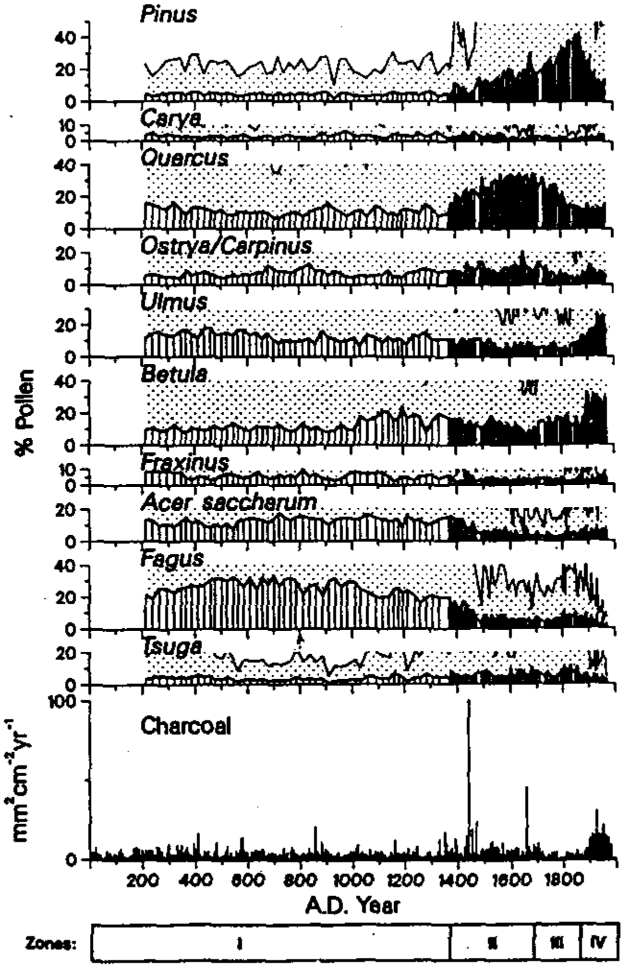

Figure 3 Stratigraphic pollen of dominant tree taxa and charcoal from Crawford Lake, southern Ontario. Pollen profiles are expressed as percentages of the total arboreal pollen.

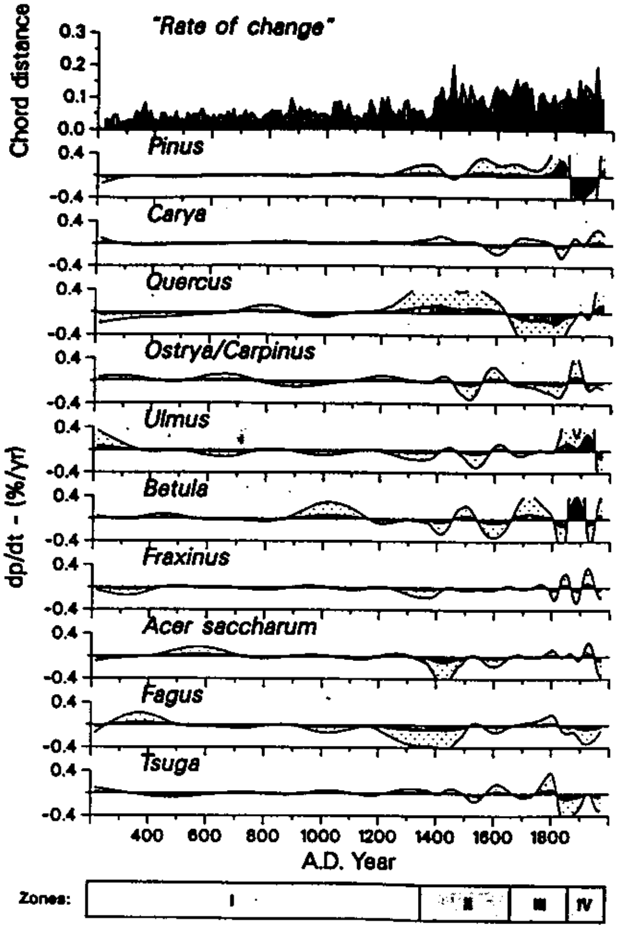

Figure 4 Rates of change in selected arboreal pollen types and chord distances.

decline begins earlier, as observed at many northeastern sites (e.g., Gajewski, 1988), but the rate of decline is greatest during the fifteenth century (Figure 4). The increases in *Quercus* and *Pinus* begin during the fourteenth century (Figure 3). Transient increases in *Populus* and *Acer rubrum* follow in the latter half of the fifteenth century, coincident with declines in *Acer saccharum* and *Fagus*. *Populus* and *Acer rubrum* decline with *Carya* at AD 1600. The *dp/dt* profiles emphasize zone II as a time of rapid change in many arboreal pollen types, with absolute values of all taxa except *Betula* exceeding any observed in zone I (Figure 4). Chord distances are high at the beginning and end of the zone.

The predominant features of arboreal profiles within zone III are minimal percentages for *Populus* and *Acer rubrum*, declining *Quercus* and *Ostrya/Carpinus*, and increasing *Betula* and *Pinus* (Figure 3). The *dp/dt* profiles for most arboreal taxa change sign within or near zone III (Figure 4). Chor distances decline from zone II.

The pace of stratigraphic change quickens during zon IV. European clearance, with dramatic increases in the ruderal *Ambrosia* and grazing indicators such as *Plantago* (Figure 2), coincides with changing abundances of most arborea taxa (Figure 4). *Quercus* continues to decline during th nineteenth century. Decreased *Pinus* and *Tsuga* from AD 185 to 1900 coincide with rising early successional *Populus*, *Betul* and *Ulmus* (Figure 3). Maximum chord distance in th nineteenth century reflect these changes in large numbers o arboreal pollen types.

Charcoal

Fossil charcoal of the pre-Iroquois zone I (before AD 1360 shows consistently low accumulation rates of 0.88 ± 0.6 (Table 1), no values above 30 mm^2 cm^{-2} yr^{-1} (Figure 3), and relatively few above 7 mm^2 cm^{-2} yr^{-1} (Figure 5a).

Higher values, including several large peaks, occur in zon II, from AD 1350 to 1650 (Figure 3). The largest peaks ar dated AD 1442 and 1658. Average accumulation rate for zon II, 1.15 ± 0.71, is significantly greater than for the previou zone, and values commonly reach 7–12 mm^2 cm^{-2} yr^{-1} (Figure 5b). A KS two-sample test was performed between distributions of transformed charcoal data from zones I and II (Table 1). The two large peak values >40 mm^2 cm^{-2} yr^{-1} during zone II were excluded from the analysis, because they might be viewed as anomalies and would increase the chances of finding a significant difference between distributions. Even with these large values excluded there was a highly significant difference between distributions. Thus, the higher background levels of zone II differ importantly from those of pre-occupation forests. The increased importance of charcoal is evident in the filtered series (Figure 2).

Values decline abruptly after AD 1650 and remain low until the rise toward the end of the nineteenth century (Figure 3). The average zone III accumulation falls to 0.79 ± 0.67, and no values reach above 10 mm^2 cm^{-2} yr^{-1}. The distributions of charcoal values of zones I and III (Figure 5a) do not significantly differ (Table 1).

The recent zone IV values are, on average, the highest in the core at 1.59 ± 0.89, due to an abundance of values from 10 to 17 mm^2 cm^{-2} yr^{-1} (Figure 5b). These moderately high values, together with a lack of large peaks, make this distribution significantly different from occupation zone II. The distribution of zone IV values differs from all previous zones (Table 1) in having a substantial range of values from 10 to 20 mm^2 cm^{-2} yr^{-1}.

Table 1 Comparisons of distributions of charcoal accumulation rates shown in Figure 5. The zones are labelled in Figures 2 and 3. Comparisons are Kolmogorov–Smirnov two-sample tests. Table entries are probabilities that two distributions differ. With the exception of zones I and III, all two-way comparisons were significantly different at a probability of <0.01. *N* is the number of years (data points) in a series. Mass flux calculations follow Clark and Royall (1994a) and are discussed in the text

Zone	Dates	*N*	mean ± SD (mm^2 cm^{-2} yr^{-1})	mass flux (g m^{-2} yr^{-1})	Zone II	Zone III	Zone IV
I	61 BC–AD 1360	1422	0.88 ± 0.62	22	<0.01	*NS*	<0.01
II	AD 1361–1650	290	1.15 ± 0.71	29		<0.01	<0.01
III	AD 1651–1850	200	0.79 ± 0.67	20			<0.01
IV	AD 1851–1987	137	1.59 ± 0.89	39			

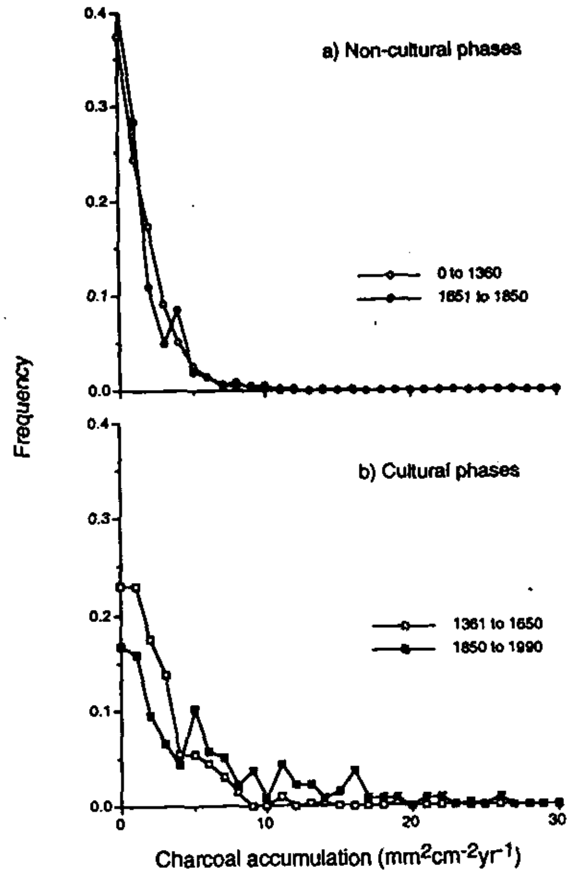

Figure 5 *Distributions of charcoal accumulation rates for the four zones. The zones without occupation (I and III) (a) are homogenous and similar to each other. The 'cultural' zones (b) are noisy and differ from each other and from both of the distributions in (a) (Table 1).*

Charcoal evidence in context

Charcoal values during zones II and III coincide rather closely with pollen and spore types of several cultural indicators. Smoothed charcoal data show how average charcoal abundances follow the general trends in *Pteridium* spores and Gramineae pollen (Figure 6). The series of charcoal 'peaks' from AD 1350 to 1500 attend the maximum values of Gramineae and *Pteridium*, and all but one of the pre-European *Zea mays* pollen grains occur here. Charcoal remains high up to the peak at AD 1658, after which both charcoal and cultural indicators decline.

Our charcoal accumulation rates are low relative to those observed prior to fire suppression in Minnesota. Frequent local fires in *Pinus resinosa* stands produced large individual peaks in charcoal series, and more distant fires and/or transport during non-fire years supported a high background supply of charcoal to the lake (Figure 7a). The charcoal series contrasts with the pre-occupation charcoal record from Crawford Lake (Figure 7c). Absence of any peak values suggests that local fires did not occur during zone I.

Zone II contains charcoal peaks of the magnitude observed in years of local fire at Minnesota lakes (compare Figure 7a and 7b). However, average values are substantially lower at Crawford, suggesting that fire was regionally far less important. Together, peaks and average levels suggest occurrence of fires nearby, but low importance of fire across the landscape as a whole.

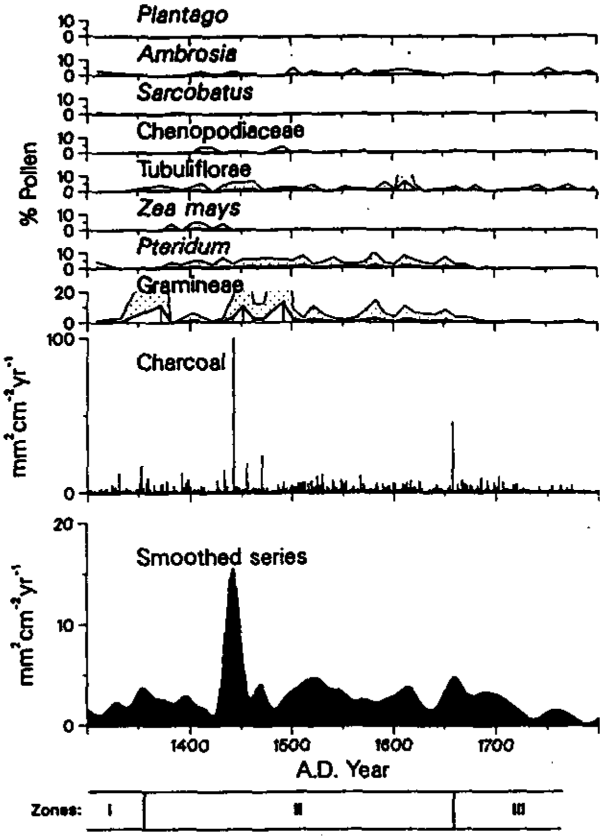

Figure 6 *Cultural indicators (above), charcoal, and filtered charcoal series highlighting correspondence of change among series during zone II.*

Discussion

Here we report stratigraphic charcoal data establishing that fire and forest transition coincided with Indian occupation near Crawford Lake. Our results show that (1) average charcoal accumulation rates were higher during Iroquois times (AD 1360–1650) than during any other interval over the last 2000 years, with the exception of post-European time, and (2) 'peak' charcoal values suggestive of local fire occurred only twice in the last 2000 years, both during the Iroquois occupation phase. Interpretation of these results raises two questions. First, do the large peaks really indicate vegetation fires, or could they reflect other sources, such as cook fires? Second, is the background charcoal simply due to some regional-scale process (e.g., climate change) and therefore potentially unrelated to Indian activities? We consider these questions in turn, followed by a consideration of Indian versus climate effects on changing forest composition.

Vegetation fires or cook fires?

Although previous work aids understanding of charcoal accumulation rates to be expected from different vegetation settings during years of local fire (Clark, 1990) and at regional scales (Clark and Royall, 1994a, 1994b), there are not yet data sets to calibrate charcoal accumulation in lakes against nearby cook fires and associated prehistoric cultural activities (e.g., Clark *et al.*, 1989; Bennett *et al.*, 1990). Some progress is possible using simple estimates of total charcoal fluxes observed at Crawford Lake. Clark and Royall (1994a) estimated mass fluxes of charcoal to lake sediments of eastern North America. They assumed charcoal density of 0.5 g cm^{-3} to transform counts obtained by optical microscopy (area char-

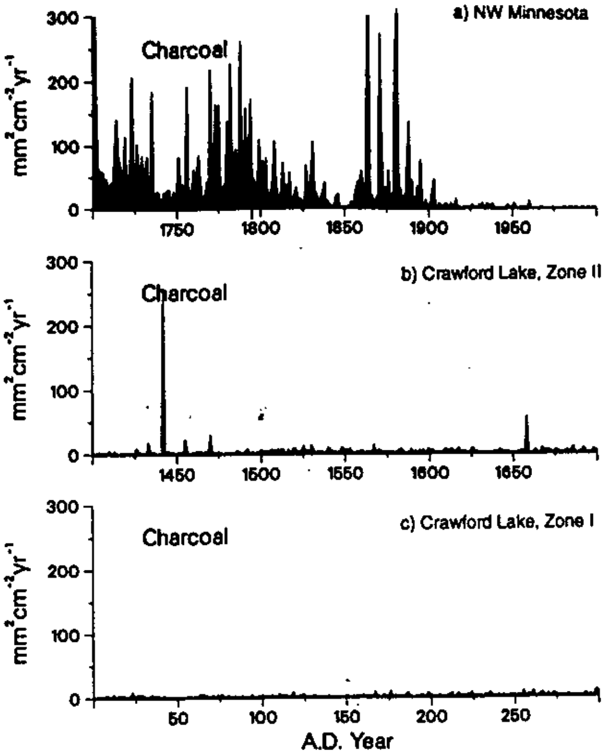

Figure 7 Comparisons of equally scaled charcoal series from a site with high background charcoal and frequent local fire (a) versus two periods at Crawford Lake. Charcoal peaks in (a) >100 mm^2 cm^{-2} yr^{-1} represent local fires (Clark, 1990). Zone II (b) has several 'peaks' comparable in magnitude to those indicating local fire in northwest Minnesota, but has much lower background charcoal. Zone I (a) also has low background levels but additionally lacks evidence of local fire. The low levels in (c) are comparable to those observed after fire suppression (AD 1910) in the northwest Minnesota series (a).

coal) : (area sediment), to accumulation (g charcoal) : (area sediment). Their estimates were broadly consistent with climate trends and reasonable given those that might be predicted on the basis of emissions estimates from modern wildfires (Clark and Royall, 1994a. Clark *et al.*, in prep.). That method can be useful here, provided we accommodate the broad error that might result from variability in accumulation across a lake bottom.

To allow for highly variable charcoal sedimentation we limit estimates to order-of-magnitude precision. The fact that charcoal is buoyant until pores are saturated (e.g., Schweingruber, 1976) leads us to believe that sediment charcoal in the deepest location of a lake (the core location) probably underestimates basin-wide accumulation rate; wind should tend to move particles to lake edges before saturation and sinking. Secondary deposition may supply particles initially deposited in the littoral zone to a lake centre, but it is unlikely that this process would more than compensate for the initial bias toward underrepresentation in a lake centre. However, in the event that accumulation is actually higher in the centre (e.g., due to focusing) we choose to err on the conservative side by assuming that accumulation in the lake centre is high and may only apply to a radius of the orders 10^1 to 10^2 m of the entire lake bottom. We obtain a range of charcoal accumulations representing the difference fluxes between zones I and II and of charcoal peaks (Table 2).

The production of charcoal from a series of point sources needed to account for observed accumulation rates are

Table 2 Calculated mass of charcoal over a given radius of lake bottom given estimates from Table 1

Radius of lake bottom over which flux is assumed to apply (m)	Increase in total accumulation from zone II to zone I[1] (kg yr^{-1})	Mass of charcoal[2] represented by peaks of 100 mm^2 cm^{-2} yr^{-1} (kg yr^{-1})
20	9	3000
100	220	80000
300	2000	700000

[1] The calculation uses the 7 g m^{-2} difference between zones I and II (Table 1).
[2] This flux is approximated as 2500 g m^{-2} yr^{-1} using estimates from Clark and Royall (1994a).

extremely high (Table 1). 'Char' can represent 5–20% of initial wood mass (Weidemann *et al.*, 1988). Clark in prep.). Emission factors (EF, the emission mass per mass of fuel consumed) for aerosol (μm) size particles are $<10^{-2}$ g g^{-1} and lower still for the larger particles (Sandberg *et al.*, 1979), e.g., those counted on thin sections. Depending on distance, wind and precipitation, only a small proportion of this fraction is expected to be deposited on or washed to the lake surface. Assuming char fraction = 10^{-1} g g^{-1}, EF = 10^{-3} g g^{-1}, fraction deposited on the lake surface of 10^{-2} g g^{-1}, and sediment radius of 10^1 to 10^2 m (Table 2), we calculate fuel consumption in the range of 10^4 to 10^6 Tyr^{-1}. For scale, this estimate represents the annual above-ground net primary production (ANPP = 10^0 to 10^1 T ha^{-1}yr^{-1} for this region) of 10^2 to 10^4 ha yr^{-1}, a level of consumption that is clearly not sustainable over a period of centuries. These calculations suggest that the amounts of charcoal added to a lake from point sources like cook fires would have to be enormous to produce significant increases in charcoal profiles.

We take a somewhat different tack to estimate contributions from non-point sources, e.g., vegetation fires. Assume a collecting basin embedded within a burning landscape where emissions everywhere balance accumulation. Then the 7 g m^{-2}yr^{-1} increase in charcoal accumulation from zone I to zone II (Table 2) represents an average increase of 70 kg ha^{-1} yr^{-1} or 10% of ANPP. This estimate is probably somewhat high for an undisturbed northern hardwood forest, but certainly possible, especially if burning rates were increased through human activities. These rates are well within values that could be produced by vegetation burning (Clark and Royall, 1994a), because the source area is larger. Differences in point-versus non-point-source strength implied by observed charcoal accumulation at Crawford Lake are so vast as to favour the interpretation that increases in zone II reflect vegetation fires rather than a series of point sources like cook fires. Indeed, the increased flux of 7 g m^{-2} from zone I to zone II is rather modest for vegetation fires, well within the geographic variability that probably exists for this region. (Clark *et al.*, in prep.).

Peak values of 50 to 100 mm^2 cm^{-2} yr^{-1}, such as those observed when local fires occurred in Minnesota (Figure 7a) and like those present in zone II (Figure 7b), imply much higher source strength, well beyond that readily explained by a series of point sources (e.g., cook fires). Even if the total charcoal production of cook fires (including ash) were dumped into a 100 m radius of the lake centre, we would require ~80 metric tonnes of charcoal to account for values of this magnitude (Table 2). Given inefficient combustion and restricted transport, huge point-source strengths would be required to explain this amount of charcoal. Although we cannot rule out the possibility that these peak values represent anomalous sedimentation, we have found consistent occurrence of peak values in separate cores from Schleinsee, Germany (Clark *et al.*, 1989) and good agreement of values of this magnitude with fire scars in Minnesota (Clark, 1990). The increase of several kg m^{-2} of charcoal is well within that expected by an increase in nearby vegetation fires.

Forest transition: Indians or climate change?

At least two interpretations might explain forest transition at Crawford Lake. McAndrews and Boyko-Diakonow (1989) noted coincident abrupt declines in northern hardwoods taxa, occurrence of cultural and disturbance indicators, and the beginning of *Pinus* and *Quercus* expansion at a time when archaeological evidence indicates Indian occupation; the coincidence points to Iroquois transformation of forests. More recently Campbell and McAndrews (1993) used a simulation model to argue that climate change is the cause of forest transition. Although we do not question that the effects of decreasing temperatures are evident in pollen data of the last millennium from throughout temperate eastern North America, we question the climate interpretation for rapid changes in forest composition that occurred during and immediately following Iroquois occupation at Crawford Lake, because the observed changes (1) are not well predicted by Campbell and McAndrews model results, (2) are not well supported by other pollen data from the region, and (3) are not supported by the charcoal evidence reported here. We also argue that models of this sort are hard to apply to questions of species transitions, because of the assumed responses to temperature.

Campbell and McAndrews (1993) used a 'FORET-derived' model to simulate forest composition over the last 1000 years with an assumed 2°C decrease in mean annual temperate from AD 1200 to 1850. The model predicted increasing *Acer, Fraxinus, Quercus* and *Pinus strobus*, decreasing *Fagus* and *Tsuga*, and no change for *Carya* and *Ulmus*. The authors used regression equations to transform predicted biomass to pollen per cent. They point out that declining *Fagus* and rising *Quercus* and *Pinus* predicted by this method are consistent with the actual data. They argue that canopy gaps would have been produced by mortality of canopy *Fagus* and those gaps would have been exploited by *Quercus, Fraxinus* and *Pinus strobus*. The predicted increase in *Acer saccharum* is interpreted as the consequence of declining temperatures.

Important aspects of the model predictions are inconsistent with pollen data. First, the decline in *Fagus* pollen percentages is abrupt and coincident with the rises in cultural indicators, early successional tree taxa (e.g., *Populus, Acer rubrum*), and charcoal, unlike the gradual and >100-year-delayed decline predicted by the model. The decline in *Fagus* pollen in the region begins at most sites by 1000 BP (e.g., Gajewski, 1988), a trend that is also evident at Crawford. The abrupt decline after AD 1400 (Figure 3) is not present at other sites, nor is it predicted by the model. An exception is Second Lake, Ontario, but, like at Crawford, the *Fagus* decline there is attended by increases in indicators of Indian agriculture (Burden *et al.*, 1986). Archaeological evidence indicates Indian farming at that site.

Acer saccharum decreases with *Fagus* in the pollen profile, while it is predicted to increase in the model. Although it could be argued that the *Acer saccharum* pollen per cent decline belies an actual increase that is masked by changing abundances of other pollen types, this and other sites in the region lacking signs of aboriginal activities all suggest rising *Acer saccharum* at this time. The influx diagrams from Hams Lake and Nutt Lake, Ontario (Bennett 1987), show no tendency for *Acer* to increase as *Fagus* declines during the last millennium, i.e., the cooling scenario. Both *Acer* and *Fagus* remain constant and tend to recover following Iroquois occupation (Figures 3 and 4), even in the face of increases in pollen production by *Quercus* and *Pinus*. A decline and subsequent increase is consistent with disturbance and recovery.

Other types are not consistent with the modelled climate scenario. *Fraxinus* pollen percentages decrease abruptly at AD 1400 and remain constant up to AD 1800. The model predicts *Fraxinus* increase, likely reflecting its low-temperature tolerance. Declining *Fraxinus* pollen at Crawford Lake is not consistent with declining temperatures. *Tsuga* goes extinct in the model as temperatures drop, while pollen percentages remain constant or increase until the twentieth century. If temperatures really do explain these forest transitions, *Tsuga* pollen should decline as rapidly as *Fagus*, as it does in the model.

The argument that *Quercus* and *Pinus strobus* would colonize canopy gaps requires some further explanation. These species are not gap colonizers in most northern hardwoods forests, certainly not in the moderately fertile sites that support *Fagus, Acer saccharum* and *Fraxinus* (Lorimer, 1977; Whitney, 1986; Crow, 1988; Abrams, 1992). Failing widespread and dramatic climate change that would be observable on a regional scale, the only conceivable way to produce rapid transformation from northern hardwoods to *Quercus* and *Pinus strobus* is through anthropogenic disturbance.

The increase in charcoal abundance during occupation times represents a relatively large increase and suggests that vegetation fires could have occurred during this interval. This observation is consistent with the changes in pollen abundance and archaeological data indicating forest disturbance, agriculture, and succession. Increased fire frequency is not consistent with the general cooling trend of the last millennium, unless humans were involved.

The timing and magnitude of climate change assumed by Campbell and McAndrews (1993), a 2°C decrease that begins in AD 1200, might best explain the transitions at Crawford Lake, but they are not evident at other sites. Although temperature decline of the last millennium is suggested by pollen data in eastern temperate forests (Gajewski, 1988), it is more gradual and appears to begin by AD 1000. The AD 1200 date may be the one that best matches pollen changes at Crawford, but that is not the case regionally. Sites near the prairie/forest border in Minnesota show abrupt transitions in fire regime (Clark, 1988, 1990) and forest composition (Grimm, 1983) after AD 1500, three centuries after that assumed here, and it is not evident at sites as far east as Crawford Lake.

For reasons outlined in Pacala and Hurtt (1993), the model is not well-suited for predicting species responses to climate change near range boundaries, like those presented here. The model assumes climate dependencies that are quadratic fits to modern temperate range limits. The quadratic control on growth rate assures that abundance falls precipitously near a modern range boundary, regardless of whether that range boundary is controlled by temperature, fire, competition, or other factors. It is well-known that many species can grow outside their existing range limits (e.g., if planted). The model used here prohibits that growth. Although it is likely that minimum winter temperatures set the northern range limit of several northern hardwoods species in eastern North America (Sakai and Weiser, 1973; Larcher and Bauer, 1981; Arris and Eagleson, 1989), the model exaggerates sensitivity to the growing degree days prevailing near modern limits. Even with this exaggerated response, the observed transitions in pollen abundance occur far more rapidly than those predicted by the model. The assumed temperature dependence in the model is probably more realistic near the centre of a species range than near the range limit. Obvious examples of this problem in Campbell and McAndrews (1993) are *Fagus* and *Tsuga*, which cannot survive in the simulation run, but are still present well north of these elevations (Fowells, 1965) and represented in pollen diagrams (e.g., Bennett, 1987).

Implications for presettlement fire in eastern North America

Historic records from early European colonists of eastern North America contain impressive evidence for Indian burning. So common are the references to burning and their effects on native vegetation that historians can argue convincingly that much of the region may have been maintained in a relatively open condition (reviews by Pyne, 1982; Williams, 1989). And these accounts come after demise of many native populations due to disease transmission at first contact. Indeed, the southeastern travels of William Bartram (1792, facsimile edition 1980) of the late eighteenth century took him to many 'ancient' Indian settlements and abandoned fields that suggest higher population densities in the recent past. Fire may have been used for slash-and-burn (swidden) agriculture, to drive game, to improve productivity of deer browse, or to communicate (Day, 1953; Pyne, 1982). Unfortunately, such documents may contain biases that make difficult estimates of the importance of Indian burning (Russell, 1983; Forman and Russell, 1983).

We selected Crawford Lake for analysis because it had an archaeological record of occupation. The 13 centuries before Iroquois occupation show little evidence for fire, and no significant changes in forest composition (Figure 3). We found evidence for increased burning at the times that coincide with predictions based on archaeology, including the right times of onset and decline. Results do not unequivocally demonstrate intentional burning by Indians, nor can we conclude that fire was necessarily the direct cause for altered forest composition at the time. They do demonstrate a striking coincidence in space and time of Indian occupation, fire occurrence, and dramatic vegetation change that is predicted by the argument that Indian burning may have been sufficient to significantly alter forest composition in pre-Columbian time. Increased importance of fire, together with transition from late-successional northern hardwoods to early-successional oaks and pines, is consistent with interpretations that Indians could have had profound effects on fire regimes and forest vegetation long before Europeans began to permanently colonize eastern North America (Pyne, 1982; Patterson and Sassaman, 1988). Dramatic transitions that occurred at our site may not be widespread, however, and further studies are needed to establish the geographic extent of Indian influences on fire regimes and vegetation. Support for the argument that Indian burning was extensive and that it resulted in changes in forest composition would require extensive use of the method. If the sediment record of burning in varved sediments is as reliable as this and previous studies suggest (Clark *et al.*, 1989; Clark, 1990) then records from a large number of lakes should help to establish the extent of prehistoric Indian burning.

Baseline emissions

The charcoal series from Crawford Lake can be viewed as an extended record of homogeneous charcoal accumulation rates interrupted by two cultural phases during which emissions increased on average and became more erratic. The two periods without known settlement (zones I and III) are remarkably homogeneous and similar to one another (e.g., Figure 5a). Following the intervening Iroquois phase emissions settled back down to a distribution no different from observed previously. The average accumulation rates of 0.88 and 0.79 $mm^2\ cm^{-2}\ yr^{-1}$ provide an estimate of the pre-industrial accumulation of charcoal. The increase to the zone IV mean of 1.59 represents a doubling of emissions during the twentieth century. It suggests that pre-twentieth century emissions of relatively large charcoal particles may have been substantially lower than observed today in some regions, despite a general decrease across eastern North America on average (Clark and Royall, 1994b).

Comparisons of peak values of zone II (Figure 7b) with those of Minnesota (Figure 7a) suggest an emerging consistency of in charcoal accumulation during fire years. Charcoal peaks in these sites fall within the range of 100–500 $mm^2\ cm^{-2}\ yr^{-1}$. Although these comparisons are not sufficient to establish a trend, they suggest that additional data might aid establishment of indices of fire occurrence that might apply across a range of sites. The 'background' values of zone I (Figure 7c) are also consistent with the post-fire-suppression (post-1910) values at Minnesota.

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