



Presettlement analogs for Quaternary fire regimes in eastern North America *

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Abstract

We present a method for identifying analogs for past fire regimes and use it to assess similarity between late Quaternary fire regimes in northern Wisconsin and central New York and a reference set of charcoal series from just prior to presettlement time. The analog method is based on comparisons of distributions of charcoal accumulation rates from annually laminated sediments using a Kolmogorov-Smirnov two-sample D statistic (D). D is a non-parametric statistic expressing the difference between distributions that does not require assumptions concerning the shape of the distributions (e.g. normality, homoscedasticity) and it summarizes differences in a single index. Our study consists of (i) mapping D values obtained by comparisons between pairs of 'reference' charcoal series from the immediate presettlement (calibration) and (ii) identifying possible presettlement analogs from this reference set for Late Quaternary charcoal distributions. Our calibration analysis identified geographic transitions in charcoal transition that were much steeper than apparent from pollen data. Otherwise, geographic patterns in presettlement charcoal and pollen are comparable, including a group of oak/hardwood forest sites in Wisconsin, central Ontario, and New York having similar values, and another group of mostly northern hardwood/hemlock sites in Pennsylvania and Maine. Application to charcoal series dated after 11 000 yr BP at Wisconsin and New York suggests that fire regimes may have been different from those occurring at any of our reference sites. Differences in seasonality of climates and different fuel structures are a possible explanation.

Introduction

Analysis of charcoal particles in lake sediments is used to interpret past importance of fire at several spatial and temporal scales. Stratigraphic change in the abundance of sediment charcoal gives evidence for broad-scale changes in climate (Winkler *et al.*, 1986; Clark, 1988a), vegetation (Tsukada *et al.*, 1981; Cwynar, 1987), and/or land use (Iversen, 1941; R. L. Clark, 1983; Clark *et al.*, 1989; Almquist-Jacobson, 1994; Davis *et al.*, 1994). Close sample intervals in well-stratified sediments can identify individual fires (e.g.

Swain, 1973; Cwynar, 1978; Green, 1981; Anderson *et al.*, 1992) making possible the estimation of fire frequencies (Clark, 1990; MacDonald *et al.*, 1991). Comparisons among sites reveal geographic patterns of fire importance that can be linked to fire frequency, land use, and/or vegetation (Patterson & Backman, 1988; Clark & Royall, 1994, 1995b).

Despite some progress toward understanding temporal and geographic changes in average charcoal abundance, the use of charcoal series to compare fire regimes within and among sites remains problematic. Fire regimes consist of a distribution of waiting times between fires, spatial pattern of burns, and behavior of individual fires (heat release, fuel consumption, and so on). Profiles of annual charcoal accumulation produced by thinsection analyses of varved sediments include clear 'peak' values for years when fires occur with a

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lake catchment (Clark, 1990; Clark *et al.*, in review). The peak values can be calibrated against independent records of fire and used to construct distributions of fire intervals that can change with changing climate (Clark, 1990). These charcoal series also contain a low, 'background' accumulation during years in which local fires do not occur. This background likely includes contributions from long-distance transport in the atmosphere (Andreae, 1983) as well as transport and deposition processes within a lake and its catchment (Patterson *et al.*, 1987; Clark, 1988b).

'Peak' and 'background' components of charcoal series each contain information that might be exploited to better understand past fire regimes. Comparison of fire regimes within and among sites using, say, mean accumulation rate (e.g. Tolonen, 1983; Patterson & Backman, 1988; Clark & Royall, 1994, 1995a, b), does not utilize the different kinds of information contained in the full distribution of values that come from a charcoal series. A series of low background values separated by large peaks during fire years could have a mean accumulation similar to a second series of uniformly intermediate values. The mean misses much of the information contained in charcoal series and so makes for only coarse comparison. It is possible, however, that the full distribution of accumulation rates could better characterize a fire regime than does a single parameter, such as a mean.

We tested a method for characterizing series of charcoal accumulation rates in lakes and applied that method to the problem of finding analogs for Quaternary fire regimes within a data set of 'presettlement' analogs. The presettlement analogs are distributions of charcoal accumulation rates from lake sediments deposited before A.D. 1800 in eastern North America, when effects of colonial land use became widespread. Comparisons are made between pairs of presettlement charcoal and other series using a Kolmogorov-Smirnov 2-sample D statistic. We begin with a 'calibration' step, an analysis of the presettlement data themselves, to determine D values that indicate when two charcoal series are 'similar'. These criteria are then applied to late Quaternary charcoal series from the upper Midwestern and the Northeastern United States. The method allows us to assess closest 'presettlement analogs' for settings in the more remote past, for which our understanding of climate and vegetation is much more limited. As a complement to the search for charcoal analogs we analyze pollen analogs (Overpeck *et al.*, 1985) for the same sites and time periods to establish the extent to which the two indicators (pollen

vs charcoal) may differ in their representation of past vegetation.

The analog method

Application of the Kolmogorov-Smirnov 2-sample D statistic

The Kolmogorov-Smirnov (KS) 2-sample D statistic is one of several possible measures of the difference between two distributions of, in our case, charcoal accumulation rates. It is a convenient statistic for comparison of charcoal series, because (i) it is simple, (ii) it is nonparametric (it does not assume any underlying distribution of values), and (iii) its own distribution for the null hypothesis of no difference between distributions is readily approximated and thus can be used to determine probabilities (e.g. Press *et al.*, 1986). We refer to our application of D for comparison of charcoal series as an 'analog approach', because it entails pairwise comparisons followed by selection of 'closest' pairs (defined by smallest D), in the manner similar to that used to compare pollen spectra (Overpeck *et al.*, 1985).

Although D does not accommodate autocorrelation, waiting times between 'peaks', or temporal scales of variation, we use it for this application because it is based on a single index, and it does not require assumptions concerning when a particular value indicates a local fire. Autocorrelation functions and power spectra are used to analyze variance within series (Green, 1981; Clark *et al.*, 1989; Clark & Royall, 1996), but are not themselves indices of similarity. These methods cannot be used to define a single index; both express variance as a function, either in the time or frequency domain. Distributions of waiting times between 'peak' values that occur during individual, local fires can be compared among sites (Clark, 1989), but they require an assumption that peaks of a particular magnitude represents fires. Thus, although the D statistic is limited by its failure to accommodate temporal relationships within series, the advantage of a one-dimensional index of the difference between any pair of distributions makes it a logical choice for identification of analogs. An example from Crawford Lake, Ontario is presented first as a demonstration of the method.

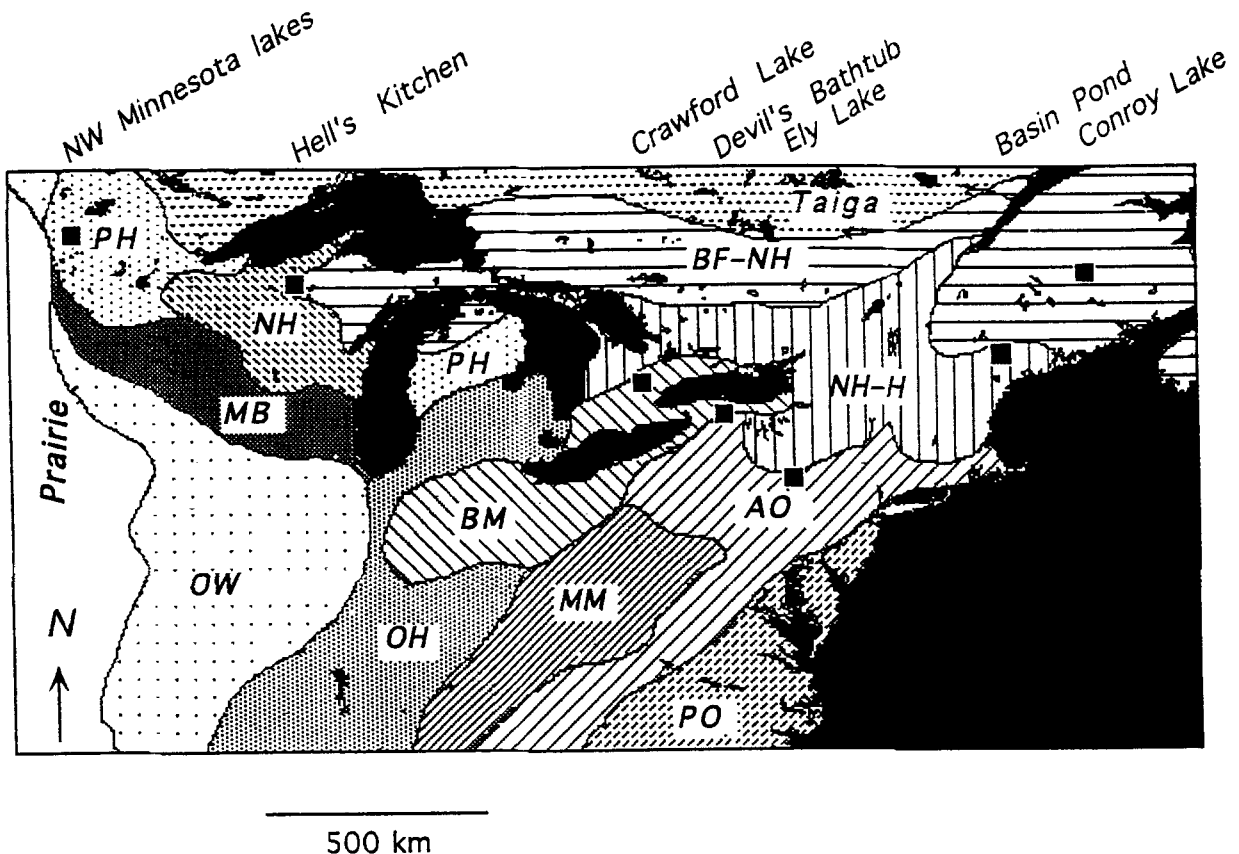


Fig. 1. Location map showing lakes analyzed in this study. Vegetation type abbreviations are OW – Oak Woodland, OH – Oak Hickory, PH – Pine Hardwood, MB – Maple Basswood, NH – Northern Hardwood, BF – NH – Balsam Fir – Northern Hardwood, BM – Beech Maple, MM – Mixed Mesophytic, AO – Appalachian Oak, PO – Pine Oak.

Comparisons within a series

Crawford Lake, Ontario (Fig. 1) has experienced four cultural periods that influence fire regimes during the last 2000 yr (Clark & Royall, 1995a). Fossil pollen data and archaeological evidence indicate Iroquois settlements were established around the lake by A.D. 1360 and remained active until roughly 1650 (McAndrews, 1988). The site apparently was not strongly impacted again until 1850, when European settlement expanded to include surrounding forests. Fossil charcoal data (Clark & Royall 1995a) showed clear differences for different occupation phases of the past. A 'pre-Iroquois' phase included consistently low charcoal

accumulation, followed by an increase and occurrence of several peaks during an 'Iroquois' phase (Fig. 2a). Charcoal subsequently declined until the high values of the late 19th and early 20th century, when wood-burning is likely to have increased with forest clearance and domestic activities. During this 'European' phase, values were consistently high (relative to previous phases), but extreme high values, such as those observed during the Iroquois phase, did not occur. A smoothed series (Fig. 2b) aids identification of these differences, because low values are obscured and difficult to see in the raw data of Fig. 2a.

Distributions for each of the four intervals show differences in frequency of low and high accumula-

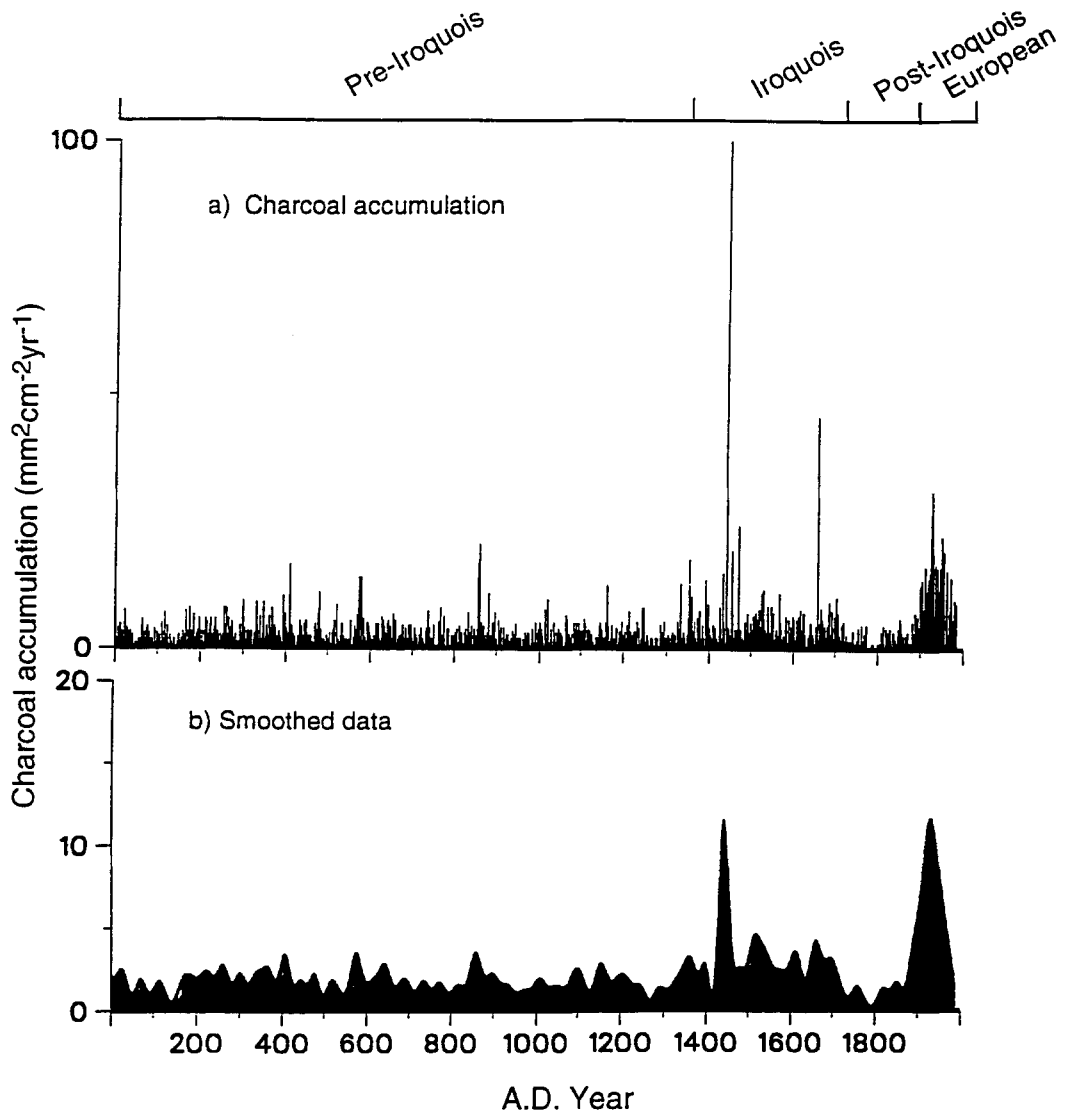


Fig. 2. Charcoal accumulation over the last 2000 yr at Crawford Lake, Ontario with cultural intervals. a) Annual accumulation rates. b) The same data smoothed with a 30-yr window to emphasize low-frequency variability. (Redrawn from Clark & Royall (1995a)).

tion rates (Fig. 3a). The Pre- and Post-Iroquois series are both dominated by low accumulation rates, with distributions tending to zero by $10 \text{ mm}^2 \text{ cm}^{-2} \text{ yr}^{-1}$. Iroquois and especially European phases have greater abundance of high ($>10 \text{ mm}^2 \text{ cm}^{-2} \text{ yr}^{-1}$) accumulation rates at the expense of low values. The Iroquois phase contains only a few values in this range, but it also has the highest values, two exceeding $40 \text{ mm}^2 \text{ cm}^{-2} \text{ yr}^{-1}$. Thus, the high average charcoal accumulation for occupation zones are influenced, on the one hand, by a few extreme values (Iroquois phase), and, on the other hand, by consistently high, but less extreme,

values (European phase). Comparison of means is one way to summarize these differences (a t test is one example of such a comparison), but it assumes dispersion is described by a normal distribution, which it clearly is not. The observed strong positive skewness describes distributions of all lakes we have analyzed (see below).

The KS test accounts for the full shape of the distribution. First, we construct cumulative distributions for each series from the densities in Fig. 3a. A pairwise comparison consists of subtracting these cumulative distributions at each accumulation rate. Figure

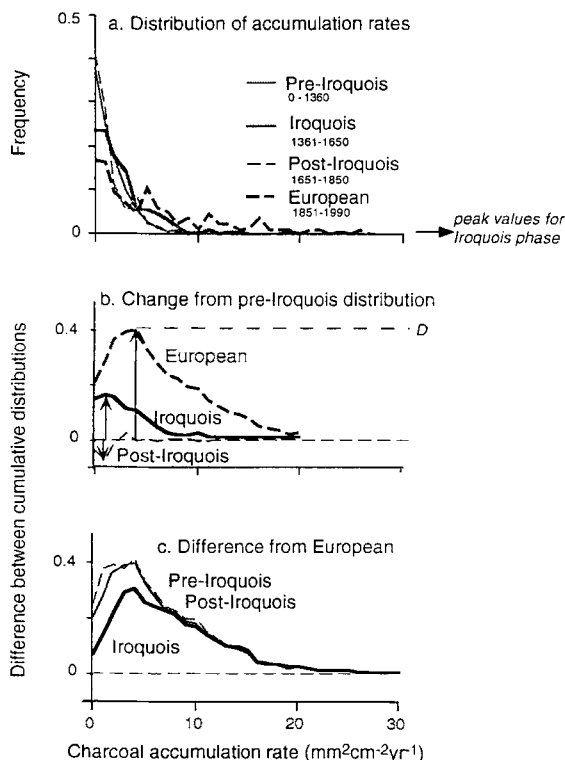


Fig. 3. Example D statistic calculation for the Crawford Lake charcoal distributions in Fig. 2. The four frequency distributions in a) are constructed from charcoal data for each of the four cultural intervals in Fig. 2 b) and c) are differences between maximum for each curve in b) and c) is a D statistic (indicated in b).

3b shows the differences between cumulative distributions for three pairwise comparisons with the Pre-Iroquois phase, that expected to be closest to a 'natural' fire regime. In each case D is taken as the largest absolute value attained by this difference. Those differences are large for Iroquois and European phases, but small for the post-Iroquois phase; following Iroquois occupation, the distribution returns to one nearly identical to that prevailing before Iroquois arrived.

A second set of comparisons is presented in Fig. 3c. Here are rather large differences between the European phase and each of the other phases. D for the comparison with the only other occupation series (Iroquois) is the lowest, but it is still nearly as large as that for comparisons with non-occupation series. Thus, the European series is not much like any of the foregoing series. It differs from the other distributions in having large numbers of values in the 5 to 20 $\text{mm}^2 \text{cm}^{-2} \text{yr}^{-1}$ range at the expense of values in the 0 to 5 $\text{mm}^2 \text{cm}^{-2} \text{yr}^{-1}$ range (Fig. 3a, c). Although Iroquois and

European series have similar mean accumulation rates the D statistic quantifies the difference in the distributions without imposing any assumption concerning the distribution of those values (Table 2).

Calibration: geographic trends in presettlement series

Use of an analog approach based on the KS D requires calibration in order to judge the magnitude of D to be expected between charcoal distributions that are importantly dissimilar. The magnitude of D ranges from zero (identical densities) to unity (no overlap in densities). The probability of obtaining a given D value depends on sample size. With sufficient data points, it will nearly always be possible to reject the null hypothesis that distributions are the same, despite broad overlap.

For purposes of calibration, we adopt a method similar to that used by Overpeck *et al.* (1985) for pollen data. They calculated chord distances for modern (i.e. pre-settlement) pollen spectra from within and among vegetation types that might be usefully differentiated in fossil assemblages. On the basis of these comparisons they concluded that chord distances < 0.15 generally represented spectra from the same vegetation type. We use a similar approach. We constructed charcoal series for immediate presettlement times from sites across eastern North America to serve as the 'modern' data set. We completed all pairwise comparisons between series and examined the geographic distribution of D values. These comparisons were used to assess whether a particular value of D might be used to say when two series are similar. Because fire regimes depend on vegetation rather directly (fuels) and indirectly (both depend on regional climate), we completed chord distance comparisons between pairs of surface pollen spectra across the same region to determine the extent to which pollen vs charcoal reflect similar patterns at a broad geographic scale. Those spectra came from the North American Pollen Database (NOAA Paleoclimate Program). Chord distances were calculated from pollen percentages of the following taxa: *Picea*, *Abies*, *Pinus*, *Betula*, *Populus*, *Fraxinus*, *Quercus*, *Ulmus*, *Ostrya/Carpinus*, *Acer saccharum*, *Acer rubrum*, *Carya*, *Tsyga*, *Fagus*, *Corylus*, and Gramineae.

Table 1. Site information for reference series used in this analysis

Site name	Latitude	Longitude	Elevation (m)	Time interval for reference set	Dominant tree taxa
Deming Lake, MN	47.2	95.2	464	A.D. 1651 to 1800	<i>Pinus resinosa</i> , <i>P. strobus</i> <i>Betula papyrifera</i> , <i>Populus</i> spp.
Arco Lake, MN	47.2	95.2	470	A.D. 1651 to 1800	"
Budd Lake, MN	47.2	95.2	470	A.D. 1651 to 1800	"
Hell's Kitchen, WI	46.2	89.6	500		<i>Betula papyrifera</i> , <i>Populus</i> spp., <i>Acer</i> <i>saccharum</i> , <i>Betula alleghaniensis</i> <i>Abies balsamifera</i> , <i>Tsuga canadensis</i> , <i>Pinus</i> <i>strobus</i> , <i>P. resinosa</i>
HK Pine				A.D. 221 to 720	
HK Hardwood / hemlock				A.D. 1651 to 1800	
Hardwood /hemlock					
Devil's Bathtub, NY	43.0	77.6	198	2500 to 2000 B.C.	<i>Quercus</i> spp., <i>Tsuga</i>
Crawford Lake, Ont	44.0	80.0	279		
Pre-Iroquois				A.D. 1 to 500	<i>Fagus grandifolia</i> , <i>Acer saccharum</i>
Post-Iroquois				A.D. 1650 to 1850	<i>Pinus strobus</i> , <i>Quercus</i>
Ely Lake, PA	41.7	75.8	384	A.D. 1651 to 1800	<i>Tsuga canadensis</i> , <i>Quercus</i> spp., <i>Fagus grandifolia</i> <i>Acer saccharum</i>
Basin Pond, ME	44.4	70.5	125	A.D. 1651 to 1800	<i>Fagus grandifolia</i> , <i>B.</i> <i>papyrifera</i> , <i>B. alleghaniensis</i> , <i>saccharum</i> , <i>Tsuga</i> <i>canadensis</i> , <i>Pinus strobus</i>
Conroy Lake, ME	46.3	67.7	140	A.D. 1651 to 1800	<i>Betula papyrifera</i> , <i>P.</i> <i>glauca</i> , <i>P. rubens</i> , <i>Abies</i> <i>balsamea</i>

Table 2. Values of KS *D* for pairwise comparisons of series in Figure 2. *D* values are accompanied by significance levels, ** - $P < 0.01$, NS - $P > 0.05$

	Mean log(C+1)	S.D. log(C+1)	Iroquois	Post-Iroquois	European
Pre-Iroquois	0.88	0.62	0.157**	0.0771 (NS)	0.409**
Iroquois	1.15	0.71		0.233**	0.302**
Post-Iroquois	0.79	0.67			0.414**
European	1.59	0.89			

The modern charcoal data set

Our set of presettlement analogs consists of 11 charcoal series from nine sites (Table 1) constructed by thin-section analysis of varved sediments from small (most-

ly <10 ha) lakes (Fig. 1). We selected this suite of sites, because they are all analyzed by a consistent method (Clark, 1988b; Clark & Royall, 1994, 1995b). The sites represent gradients in climate, vegetation, and fire importance. The western portion of the study region

Table 3. ^{14}C dates for Hell's Kitchen and Devil's Bathtub cores

Lab number	Depth(cm)	^{14}C age	$^{13}\text{C}\text{‰}$	^{13}C Corrected age	Calendar Years ^a
Devil's Bathtub, NY					
Beta-38681	1500–1510	1950±70	–37.1	1760±70	AD 256,296,319(221-390)
Beta-36236	1540–1550	2990±120	–	–	977,964,936 (1126-827) BC ^b
Beta-38682	1605–1615	3290±50	–35.5	3130±50	1405 (1430-1320) BC
Beta-38683	1670–1680	4620±60	–33.8	4480±60	3260,3244,3101 (3336-3036) BC
Beta-38684	1710–1720	5390±90	–35.5	5220±50	4030,3994 (4210-3973) BC
Beta-38685	1740–1750	6290±60	–35.9	6110±60	5040,5017,5005,(5194-4937) BC
Beta-36237	1770–1780	7010±90	–	–	5681 (5747-5598) ^c
Beta-38686	1795–1805	8430±50	–34.8	8280±50	7303 (7423-7108) BC
Beta-38687	1830–840	10160±110	–32.5	10040±110	9468,9447,9422,9420,9384,9338, 9306,9293,9272,(9932-9057) BC
Beta-3X688	1860–1869	11330±80	–31.0	11230±80	11188 (11288-11095) BC
Hell's Kitchen, WI					
Beta-75547/ CAMS-15562	1960–1964	1430±60	–31.1	1330±60	AD 680 (660-770)
Beta-72831	2115–2125	3810±70	–29.7	3740±70	2140 (2210-2030) BC
Beta-75548	2213–2223	5370±80	–32.2	5260±80	4045 (4220-3975)
Beta-72832	2313–2320	6800±80	–32.1	6690±80	5580 (5610-5500) BC
Beta-75549	2464–2472	9790±100	–29.6	9710±100	9000 (9040-8925, 8765-8720) BC

^a Calibrated dates were determined using CALIB (Stuiver and Reimer 1993). Calibrated dates are intercepts of the mean BP estimate followed by 1sd intercepts.

^b The ^{13}C was not obtained for this date. An estimated ^{13}C of –35.5‰ was used for calibration.

^c The ^{13}C was not obtained for this date. An estimated ^{13}C of –35.4‰ was used for calibration.

is relatively dry, approaching a net balance between annual precipitation and evapotranspirative demand. Vegetation spans mixed Pine-Hardwood forests near the prairie/forest boundary in northwestern Minnesota and stretches eastward across mixed conifer/deciduous forests of the Northeast (Fig. 1, Table 1). Fire is clearly most important near the western end of the study region, both in the presettlement (Grimm, 1984; Whitney, 1986; Clark, 1990) and today (Haines *et al.*, 1975), and declines in importance eastward (Lorimer, 1977; Patterson & Backman, 1988; Whitney, 1990; Clark & Royall, 1995b). Fire may have been least important in hemlock and northern hardwoods stands of the eastern portion of our study region (Whitney, 1986; Abrams, 1992; Clark & Royall, 1996). Fire seasons occur in spring (after snowmelt and before greenup) and autumn (after fuels cure and before snowfall) (Haines *et al.*, 1975).

Charcoal series are dated by varve counts and confirmed by dated increases in agricultural pollen indicators (Clark & Royall, 1994). For comparisons here we use portions of these series dated to the last several centuries before European settlement. This inter-

val was selected, because (i) it precedes widespread deforestation that altered fire regimes over most of the region, (ii) it is restricted to relatively recent time to minimize effects of climate change, and (iii) it is of sufficient duration to provide a homogeneous distribution of charcoal accumulation rates.

Although reference series come principally from the last 2000 yr, we did not use precisely the same interval at all sites (Table 1). We used an interval of 150 yr immediately preceding European settlement for sites having uninterrupted sequences (Deming, Arco, Budd, Hell's Kitchen, Ely, Basin, Conroy). Varves could not be confidently identified near the surface of the Devil's Bathtub, NY core, so we used counts from 2500 to 2000 B.C. (Clark *et al.*, 1996) as the best estimate of the distribution there. The dating of the varves is controlled at that site by ten ^{14}C dates and the so-called 'hemlock decline' at 4634 ± 304 ^{14}C yr BP (Webb, 1982). Although pollen assemblages of forest taxa do not change from that time to the presettlement, it is possible that fire importance may have changed (Clark *et al.*, 1996). Because of recent changes in fire regime, we used two parts of series in our comparisons

for Hell's Kitchen, WI and Crawford Lake, Ontario. Charcoal accumulation declined since A.D. 1000 at Hell's Kitchen, at a time when *Tsuga* and *Betula* pollen increased and *Pinus* pollen declined. We compared charcoal series from A.D. 221 to 720 and from 1651 to 1800 to capture both of these recent vegetation types. The former is termed 'HK pine' and the latter, 'HK hemlock/hardwood', reflecting the prevailing pollen assemblages. The transitions in fire importance that attended Iroquois occupation at Crawford Lake (Fig. 2) are likely unrepresentative of those observed at other sites. Here we used two intervals, A.D. 1 to 500 ('Pre-Iroquois') and 1651 to 1800 ('Post-Iroquois').

Results of charcoal comparisons

D statistics for pairwise comparisons of charcoal series show (i) geographic continuity among charcoal series, (ii) transitions (changes in D) that are, in some cases, similar to transitions in pollen, and (iii) the magnitude of D values that might suggest similar charcoal series. To permit comparison of pollen and charcoal analogs, both data types are presented as a series of maps (Fig. 4). To avoid confusion of data types, pollen analogs (chord distances) are indicated by symbols, and charcoal analogs (KS D statistics) are indicated by lines indicating magnitude of difference. For pollen analogs, only surface spectra having chord distance <0.25 from the focal site are mapped. Two symbol types distinguished different levels of dissimilarity. For charcoal analogs lines separate sites having D values greater than indicated. The lines are not to be viewed as contours, as we do not believe all sites falling between two lines would have the same D value. Site-to-site differences in soils, vegetation, climate, and basin characteristics produce much fine-scale variability among sites (Clark, 1990). Given the objective of comparing pollen and charcoal analogs, however, we preferred this presentation over separate maps and/or plots of each data type. Figure 4 includes seven plots, beginning with western sites at top left (Fig. 4a) through eastern sites at bottom right (Fig. 4g). Charcoal comparisons are summarized in Table 3.

The sites most different from all others come from the western extreme of the transect. The Deming Lake example (Fig. 4a) is similar to the other two northwestern Minnesota lakes ($D < 0.28$, Table 3), but D rises to >0.8 for remaining comparisons. We term these northwestern Minnesota sites 'Group A'. The series from hardwood/hemlock and mixed oak at Hell's Kitchen, Devil's Bathtub, and Crawford Lake repre-

sent a 'Group B' set of sites, similar to one another ($D < 0.25$), but different from most other sites ($D > 0.25$) (Fig. 4b, c, d), including the earlier distribution from Hell's Kitchen 'HK pine' (Table 3). An exception is the Crawford Lake comparison, for which low D values are also calculated with Basin Pond and Conroy Lake (Fig. 4g), all having $D < 0.25$. In addition to these three groups might be added a 'Group A1', the HK Pine series at Hell's Kitchen, which is intermediate between the northwestern Minnesota sites and the mixed hardwood sites represented by HK Hardwood/hemlock, Crawford, and Devil's Bathtub (Table 3). The two Crawford series are more similar to one another than they are to other series, but they are most like Group C.

On the basis of geographic comparisons among charcoal series across the vegetation types represented in our study, it appears that values of $D < 0.25$ represent charcoal series from relatively similar vegetation and climate settings. Group A sites represent one end of the continuum, where pines and early successional hardwoods are tolerant of and/or require fire for reproduction. Group C includes sites where fire may have been rare. The intermediate B sites are from mixed forest, where fires may have occurred on occasion, although not as frequently as in the Group A sites.

Geographic patterns in charcoal and pollen compared

Maps of chord distances between pollen samples from our sites vs those contained in the North American Pollen Data Base shows clusters of points where pollen spectra are similar (Fig. 4). As pointed out by Overpeck *et al.* (1985), such maps reflect broad geographic pattern in forest composition. Closest analogs for the northwestern Minnesota sites (Fig. 4a) are clustered primarily in northern Wisconsin and northern Michigan. Hell's Kitchen (Fig. 4b) finds close pollen analogs in the same region, with a larger number of sites from the eastern part of the study region. The areas of close pollen analogs for remaining sites shift eastward in step with the focal site.

If both pollen and charcoal data reflected similar controls at this scale, then (i) low D values would come from regions where map points indicate similar pollen spectra, and (ii) steep changes in D would correspond to the disappearance of map points indicating transition in pollen spectra. We find cases where this pattern holds and others where it does not. Sediment pollen and charcoal define rather consistent regions of

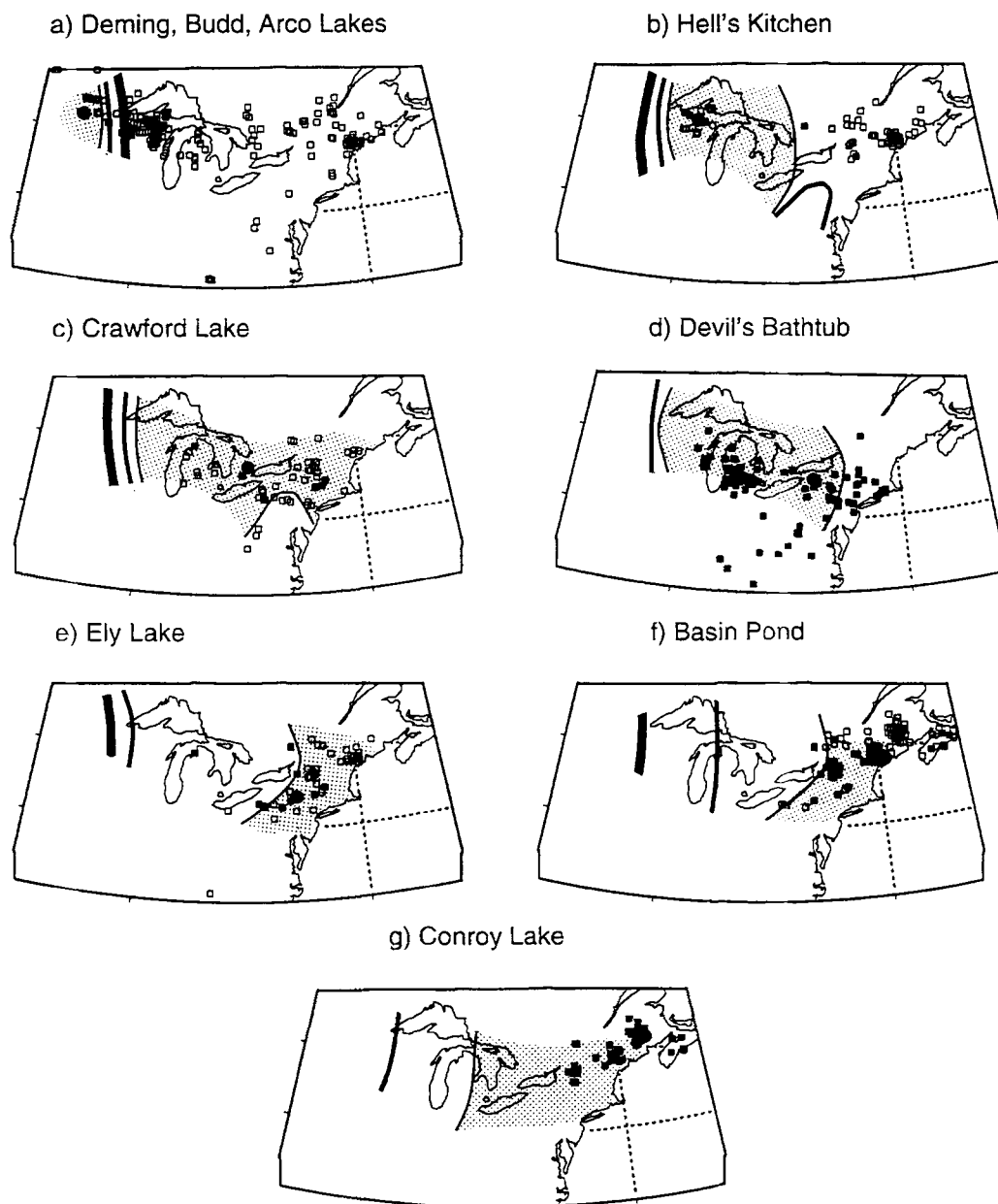


Fig. 4. Comparison of trends in D statistics and pollen analogs across the study region. Each comparison consists of map of symbols, for pollen analogs, and lines, for charcoal analogs. The lines separate different values of D calculated between the site that is labeled and each of the other sites along the transect (Fig. 1). Lines representing D values are of three thicknesses, <0.25 (thinnest line), <0.50 , and <0.75 (thickest line). The maps show all surface pollen spectra having chord distances <0.25 from the site labeled on the histogram. Chord distances <0.15 are shaded symbols, and chord distances from 0.15 to 0.25 are unshaded.

similarity in the Northeast and Lake States and different regions as climate becomes increasingly xeric near the prairie/forest boundary. Just as charcoal analogs provide only approximate differences between regions grouped as B and C, pollen analogs also show over-

lap in these regions. Group B charcoal sites tend to fall within a region of similar pollen assemblages (Fig. 4b, c, d). Hell's Kitchen, Crawford, and Devil's Bathtub all find pollen analogs from the Lake States, spanning the range of Group B charcoal sites, and

extend into the Northeast. The Group C charcoal sites of the Northeast are broadly consistent with pollen comparisons, close charcoal analogs following a trend similar to pollen analogs (Fig. 4e, f, g).

The largest contrast between charcoal and pollen trends lies at the western end of our study region. In the Midwest, the transition in charcoal is more dramatic than is observed in pollen data. Between Wisconsin and the prairie/forest border is the principal change in charcoal contained in our modern data set (Fig. 4a). Charcoal comparisons define the transition between Group A and B (the northwestern Minnesota sites, such as Deming Lake, and Hell's Kitchen), a transition that is not clearly defined on the basis of pollen (Fig. 4). Charcoal series change markedly east of northwestern Minnesota sites. In contrast, pollen analogs for northwestern Minnesota stretch across northern Wisconsin and into Michigan (Fig. 4a).

Although the pollen data are dense and provide for far greater geographic resolution than do current charcoal data, the rough agreement between methods and differences that are explainable on the basis of perceived trends in past fire importance (see '*The modern charcoal data set*') suggest approximate values of D that can be used to compare charcoal series within in this region. In the next section we use values of D derived from this comparison as the basis for interpretation of charcoal data from the more remote past.

Presettlement analogs for late Quaternary fire regimes

Charcoal and pollen data

Comparisons among charcoal distributions from forest types in our study region suggest that D values <0.25 come from similar fire regimes (Fig. 4). This value serves as a simple index that might permit identification of 'presettlement analogs' for late Quaternary fire regimes. We analyzed sediment charcoal of late Glacial and Holocene age from varved sediments of Hell's Kitchen, WI and Devil's Bathtub, NY (Fig. 1). We compared distributions of annual charcoal accumulation rates in these cores with those contained in our reference set (Fig. 4) in order to determine similarity among them. D statistics calculated between pairs of fossil charcoal vs presettlement distributions suggest regions where recent climate and fuels probably supported fire regimes most similar to those of the distant past.

Long cores were analyzed by methods identical to those used for the presettlement data set. Chronologies were determined by varves and verified by ^{14}C chronologies (Table 4). Pollen diagrams were prepared for each site and used to define pollen assemblage zones (Fig. 5). Because of great cost of thin-section preparation, we were unable to complete full profiles for charcoal data. We completed representative sections from each pollen assemblage zone. Locations of gaps in charcoal series are readily determined from Fig. 5. Distributions of charcoal values were constructed for each of the pollen assemblage zones. D statistics were calculated between each of these charcoal distributions from the two long cores vs each of the reference distributions. Chord distances were calculated between pollen spectra from the presettlement reference set and the average pollen spectrum for each pollen zone. Thus, there is a best charcoal analog (lowest D) and a best pollen analog (lowest chord distance) for each pollen assemblage zone from the long cores.

Results

Comparisons were completed between each of four pollen assemblage zones at Devil's Bathtub (Fig. 5a) and each distribution from the reference data set. The oldest 'DB Spruce' assemblage represents a pollen assemblage most like that prevailing today south of James Bay (Fig. 6d), containing *Picea* and *Pinus*. With the expansion of *Pinus* comes an assemblage, DB Spruce/pine (Fig. 5a), that finds close presettlement analogs throughout much of the eastern boreal forest (Fig. 6c). A subsequent increase in *Pinus* and decline of *Picea* by 900 yr BP, DB Pine, sees a transition to closest analogs in the western Great Lakes of northern Michigan, Wisconsin, and NE Minnesota (Fig. 6b). The rise of hardwood taxa by 7750 yr B.P., especially *Quercus* and *Fagus*, DB Hardwood, produces a shift in the region of a close analogs to the eastern Great Lakes region and southern New England (Fig. 6a).

Charcoal comparisons for the Devil's Bathtub pollen assemblage zones show an eastward shift in the location of closest analogs since the late Glacial. Charcoal from the conifer dominated pollen assemblage zones of the late Glacial and early Holocene (Fig. 5a) find closest charcoal analogs at Hell's Kitchen, WI. HK Pine is the best match for DB Spruce (Fig. 6d) and DB Spruce/pine (Fig. 6c) zones, with D values sufficiently low (<0.25) to suggest similar charcoal distributions. The similarities among charcoal distributions for DB Spruce, DB Spruce/pine, and HK Pine, lie in the rel-

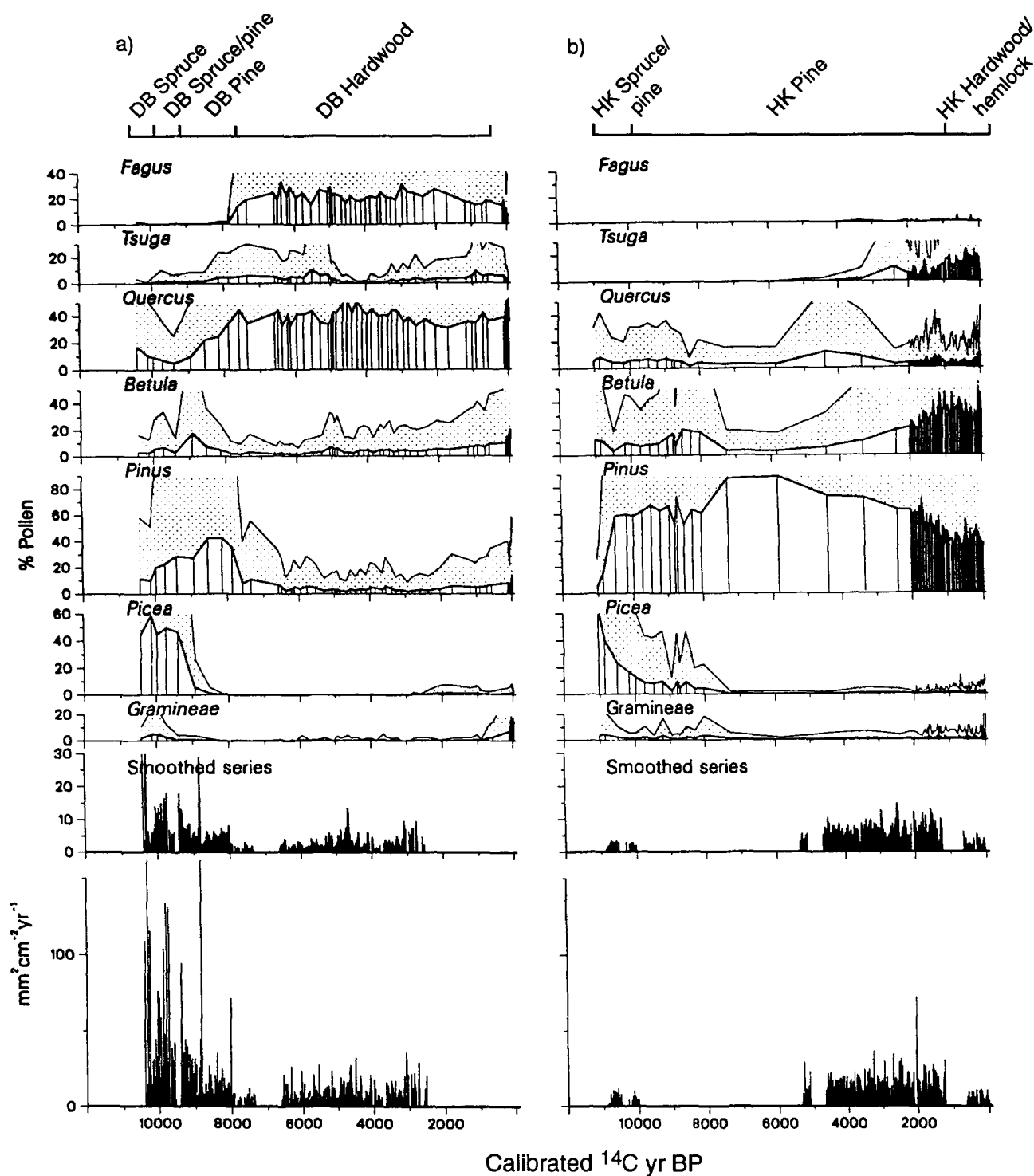


Fig. 5. Pollen and charcoal diagrams for Devil's Bathtub, NY (left) and Hell's Kitchen, WI (right). Pollen assemblage zones are labeled above. Charcoal accumulation rates are represented by raw data and smoothed series. ^{14}C dates are included in Table 4.

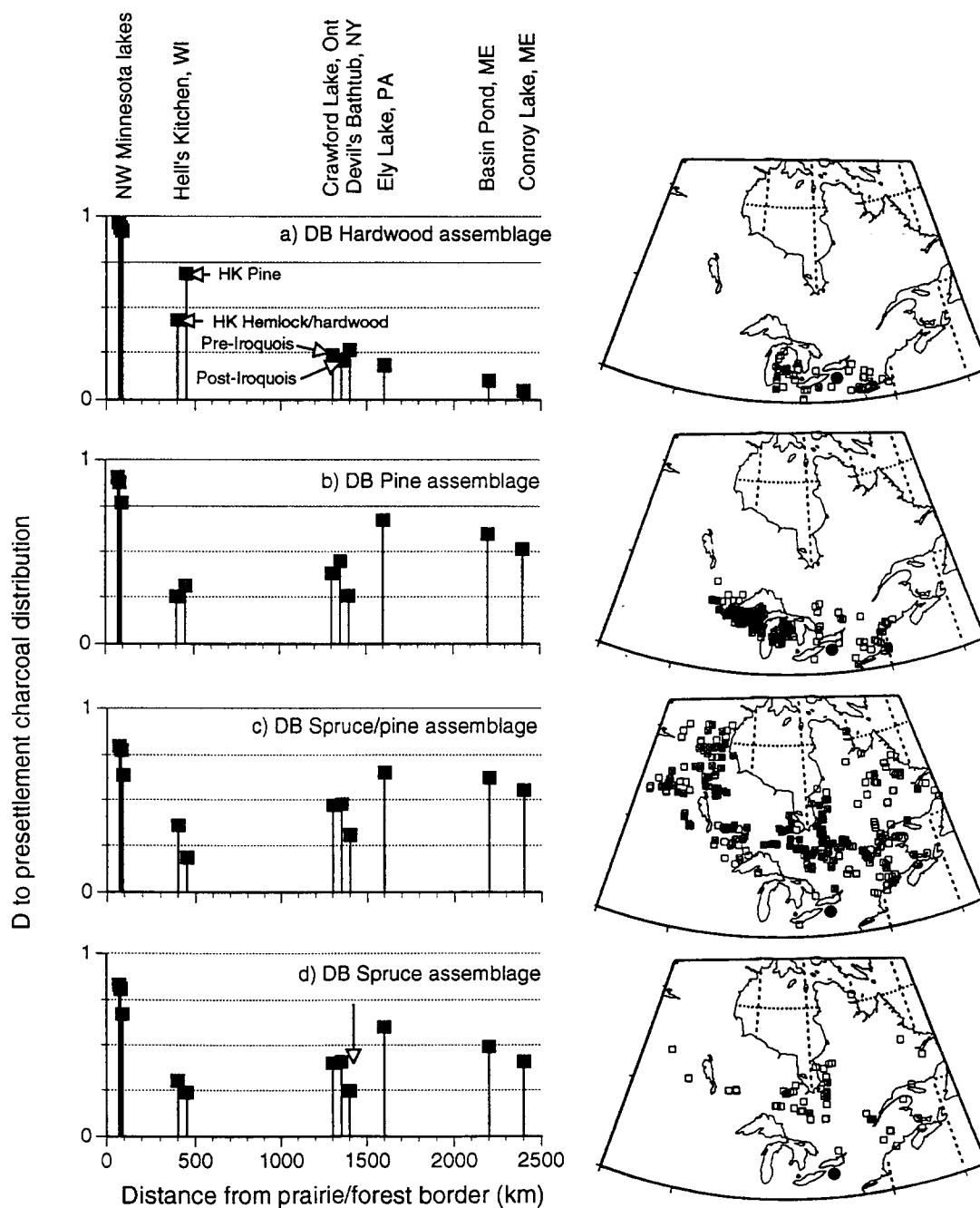


Fig. 6. Charcoal (left) and pollen (right) analogs for four pollen assemblage zones at Devil's Bathtub, NY (Fig. 1). Charcoal analogs are represented by D statistics, calculated for charcoal data in each pollen zone (Fig. 5a) and each of the reference charcoal distributions from sites listed in Fig. 1. Maps of closest modern pollen analogs for pollen spectra of these same zones follow symbolism of Fig. 4.

atively high mean values, that can be best seen in the smoothed series of Figs 5a and 5b. The DB distributions differ from HK Pine in the occurrence of large peak values that are absent from the unsmoothed HK

Pine (Fig. 5). HK Hardwood and Crawford Lake are the next closest matches for these zones, but $D > 0.25$ indicates substantially different charcoal distributions (Fig. 6b, c). None of the other reference distributions

are similar, including the northwestern Minnesota sites that showed especially high charcoal accumulation just prior to fire suppression (Clark, 1990). The closest charcoal analog shifts to HK hardwood during the DB Pine zone, but HK pine is almost as good a match (Fig. 6b). A shift to close analogs in the Group C sites of the Northeast occurs with the transition to the DB Hardwood assemblage (Fig. 6a). Each of the Group C sites shows *D* values sufficiently low (<0.25) to suggest good analogs.

The Spruce/pine pollen assemblage zone of Hell's Kitchen (Fig. 5b) finds best pollen analogs in the eastern boreal region (Fig. 7c) similar to those for the Spruce/pine assemblage of Devil's Bathtub (Fig. 6c). Following decline of *Picea* is a HK Pine assemblage (Fig. 7b), with close analogs in the western Great Lakes region, much the same as observed for the DB Pine zone (Fig. 6b). The expansion of hardwoods and hemlock is reflected in a shift to best analogs throughout the Great Lakes and Northeast (Fig. 7a).

The geographic distribution of *D* values and their magnitudes for the HK Spruce/pine zone (Fig. 7c) is similar to that for DB Spruce/pine (Fig. 6c). The closest matches come from Group B sites, but all of these *D* values exceed 0.25; no close analogs exist for HK Pine (Fig. 7b), although Group B sites are still closer than others. The HK Hardwood/hemlock distribution finds closest analogs in the Group B sites (Fig. 7a).

Taken together, the changes in closest charcoal analogs through the Holocene show some important differences between Hell's Kitchen and Devil's Bathtub (Fig. 8). Since the early Holocene dominance by *Picea*, Devil's Bathtub witnessed a transition from a Great Lakes Pine distribution to the modern northern hardwood/oak/hemlock distribution (Fig. 8a). Hell's Kitchen saw its greatest similarity to presettlement distributions during the Hardwood/hemlock assemblage, when it was closest to Group B. The recent Holocene distribution there is closest to Group B sites.

Discussion

The characterization of fire regimes for presettlement landscapes has remained an elusive goal (Russell, 1983; Patterson & Sassaman, 1988; Abrams, 1992). Fire regimes prevailing before widespread land clearance in eastern North America were likely more 'natural' than those of all but the most remote regions today, and they could provide a baseline for understanding consequences of post-settlement land use. If

the consequences of climate change are mediated by impacts on fire regime, then the many examples of changing climate in the past represent a large reservoir of case studies that might be further exploited. The interpretation of these examples depends on the quality of fire records and on the amount of information that can be extracted from them. The timing and distribution of ignition in presettlement vegetation might be inferred from modern lightning data (e.g. Stocks & Street, 1983), provided there have not been large changes in the distribution of lightning over the last several centuries. But the behavior of fire in fuels that can be neither observed nor measured is unknown. Modeling efforts remain the sole basis for speculation on changes in fire regimes that might attend cultural activities or climate change.

Stratigraphic charcoal data represent a legacy that could aid the characterization of past fire regimes, provided records can be interpreted. Although such data have been used to interpret fire before, we explore here a method that considers more of the information contained in those data than has been applied in the past. Our method involves the assembly of a reference set of charcoal accumulation distributions for a range of vegetation types. Distribution of accumulation rates from the distant past can be compared to distributions in the reference set. Comparisons among distributions of accumulation rates represent one of several potential ways in which to draw inferences concerning past fire regimes. Although it is possible that vastly different fire regimes might produce similar distributions, we see this approach as the next logical step beyond simple comparison of means (e.g. Tolonen, 1983; Patterson & Backman, 1988; Clark & Royall, 1994) as a basis for interpretation. A finding of close similarity to distributions from recent forests does not in itself reveal a fire regime. It does allow us to say that a fire regime of the distant past may have been similar to ones that characterize climates and vegetation types we see today or about which we can obtain some information from historic documents.

Similarities and differences in charcoal and pollen distributions

The geographic agreement between KS *D*'s across charcoal series and chord distances for pollen spectra reflects a relationship between charcoal particle emissions and vegetation type at regional scales. Pollen and charcoal both reflect regional climate, vegetation through climate controls on plant recruitment, growth

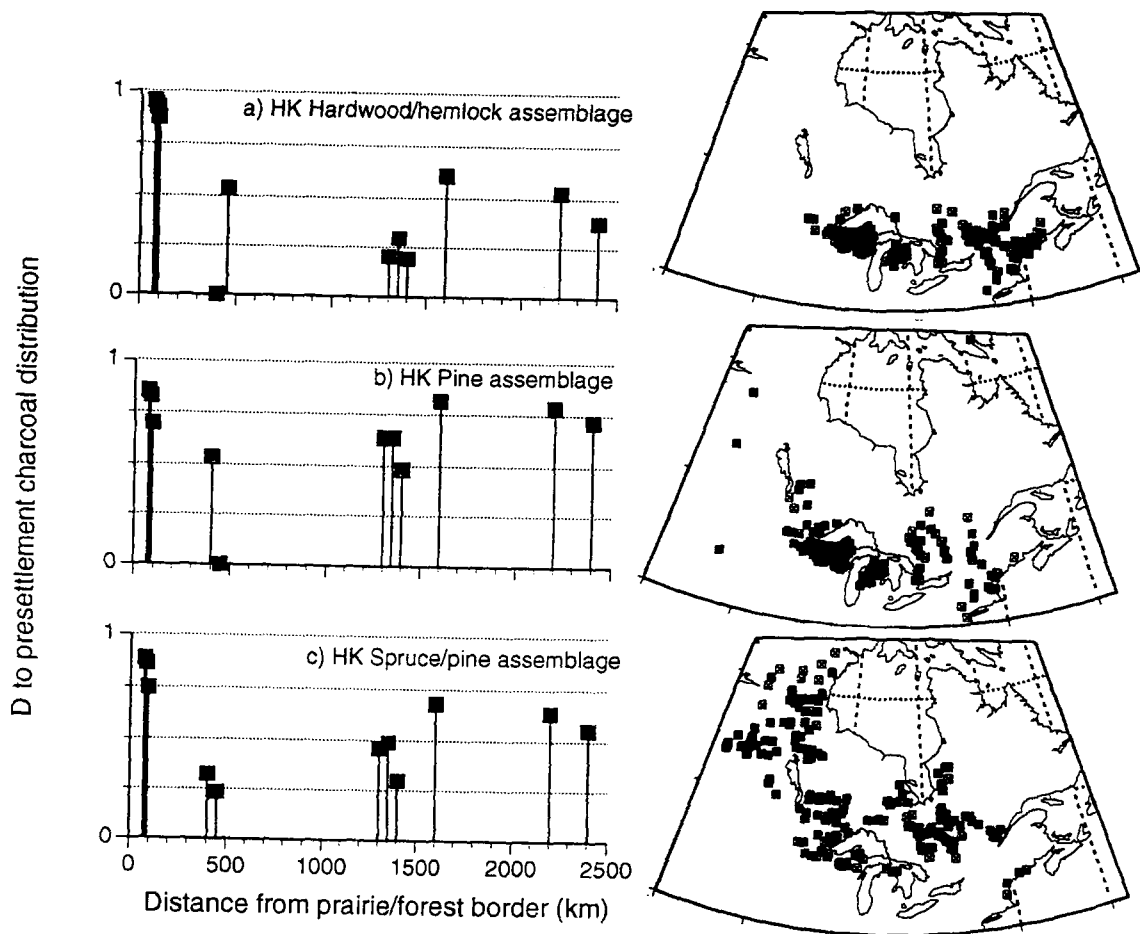


Fig. 7. Charcoal and pollen analogs for Hell's Kitchen. Symbolism follows Fig. 6.

and survival, and fire through climate effects on fuels, moisture, and ignition. The two also affect one another through fire effects on vegetation and fuel effects on fire probability and intensity. There is clearly some overlap in the environmental signal provided by sediment charcoal and pollen. Using $D = 0.25$ as an approximate index of dissimilarity among charcoal distributions, we identify three groups in our presettlement data set, (i) a northwestern Minnesota Group A, having high mean and variance, (ii) an intermediate mid-continent Group B, including Hell's Kitchen, Crawford Lake, and Devil's Bathtub, and (iii) the remaining Northeast sites, Group C, having low mean charcoal (Fig. 4). The transition between Groups B and C corresponds to a transition in vegetation composition, reflected in surface pollen data. Group C contains a larger amount of *Tsuga* pollen, whereas Group B tends to have larger amounts of *Pinus*. The difference between these char-

coal groups appears to simply reflect greater fire importance in stands having more *Pinus* and less *Tsuga*.

Together with *Pinus*, species of the genus *Quercus* are thought to have required periodic fire to remain abundant in temperate forests (e.g. Abrams, 1992). We were surprised to find that the site containing the largest amount of *Quercus* pollen, Devil's Bathtub, did not show greater dissimilarity from other sites. Despite this result, it is possible that *Quercus*-dominated stands burn more frequently than do northern hardwoods (e.g. Fahey & Reinert, 1981; Crow, 1988; Abrams, 1992) and that Devil's Bathtub was in fact immediately surrounded by northern hardwoods in presettlement time. Although oaks dominate the overstory today, the understory contains large amounts of *Acer saccharum* and *Fagus grandifolia* seedlings. The pollen diagram from this site (Fig. 5a) shows large amounts of *Fagus* and *Quercus*. Complex topography of the glacio-fluvial

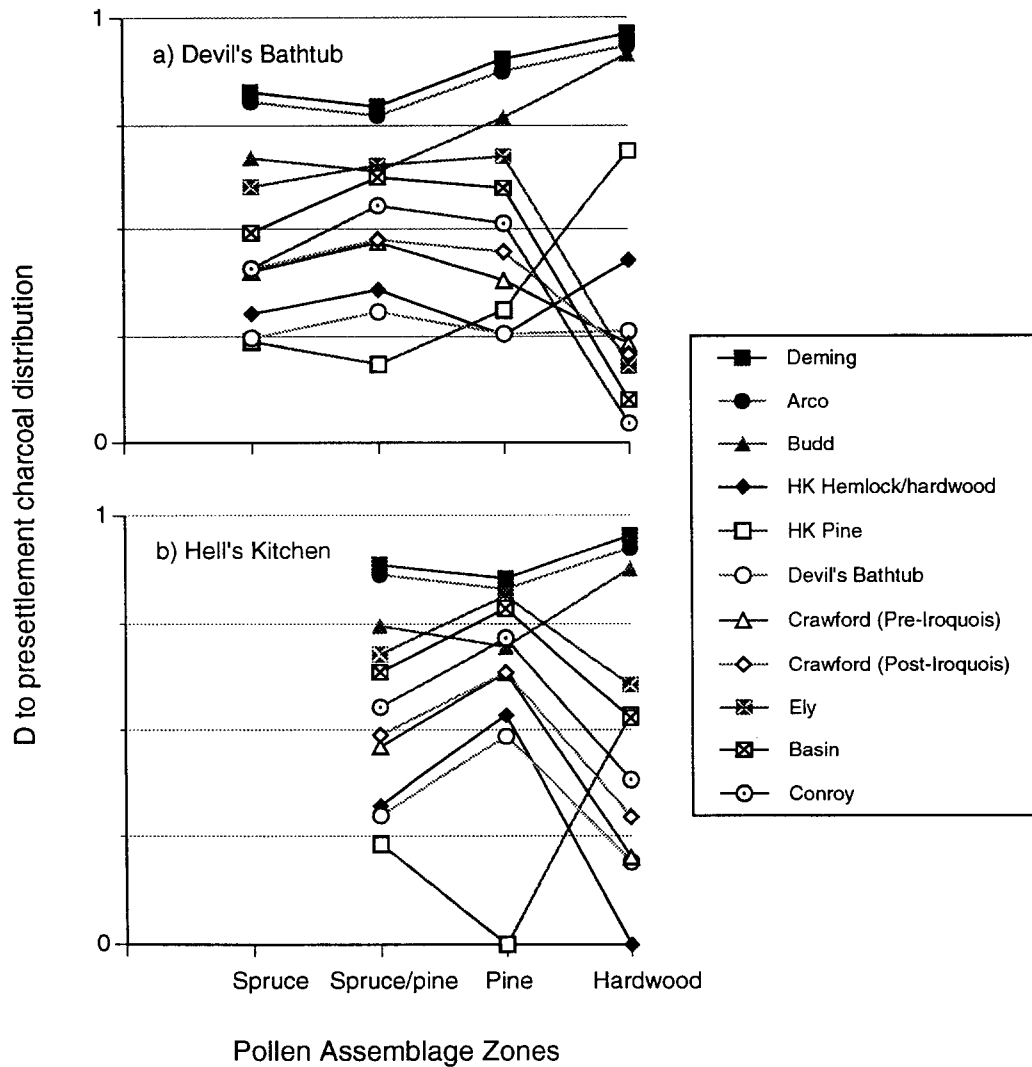


Fig. 8. Changes in D values between each pair of charcoal distributions for the pollen assemblage zones in Fig. 5 and each of the reference distributions (Fig. 1).

landscape today supports a mix of forest types, so pollen may reflect a mixture of vegetation types at the landscape scale, whereas charcoal reflects the more local fire regime of a northern hardwoods-dominated catchment.

The principal difference between the geographic patterns in presettlement charcoal and pollen spectra lies in the large increase in charcoal abundance that occurs at the western edge of the region, an increase that is not attended by large changes in pollen abundance. The frequent (10 to 20 yr intervals) surface fires of northwestern Minnesota correspond with pine-dominated stands that may have been rather open in

presettlement time (Clark, 1990). Pollen may not be as sensitive to climate gradients that cause fire importance to rise with decreasing moisture availability. Pines are important forest dominants from near the prairie forest border at the western edge of our study region eastward into the center of the study region (Fig. 1). Although substantially more mesic than northwestern Minnesota, Hell's Kitchen still supports large amounts of *Pinus resinosa*. The dominant pines at the northwestern Minnesota sites, *P. strobus* and *P. resinosa*, are abundant throughout the Lake States in areas where fire intervals are likely to have been much longer. This result is an important one, because it means that a range of fire

regimes may be discernible in charcoal data, depending on climate, that will not be evident in pollen data. *D* values may range as high as 0.8 between charcoal distributions within pollen assemblages that are essentially the same (Fig. 4). Charcoal data may be far more sensitive to climate variability in xeric regions such as northwestern Minnesota than are pollen data.

The large differences in charcoal distributions across the western end of our study region suggest that similar pollen assemblages could support different fire regimes, because dominant pollen taxa may not reflect important underlying changes in ecosystem function. Close pollen analogs may not be indicative of comparable ecosystems. For purposes of environmental reconstruction, pollen and charcoal data could be highly complementary, especially in these settings of relatively dry forests dominated by pines.

Analogues from the more distant past: fuels and climate

There are some striking similarities in the time course of pollen analog maps for the two sites since the end of the Pleistocene. Pollen assemblages at both sites shift from the central/eastern boreal (Fig. 6c, 7c), to the Lake States (Fig. 6b, 7b), and then depart somewhat, with Hell's Kitchen analogs remaining in the western Lake States (Fig. 7a), while those for Devil's Bathtub shift further east (Fig. 6a). Although pollen analogs for Devil's Bathtub are consistently shifted somewhat east of those at Hell's Kitchen, there is broad overlap.

Charcoal comparisons suggest past fire regimes may not have recent analogs within our study region. Early Holocene conifer assemblages from both sites have charcoal distributions closest to those from the central Group B (Fig. 6, 7). Fire was more important in these conifer assemblages (Fig. 6b, c, d; Fig. 7b, c) than in the northern hardwood stands of presettlement time, but the level of burning never approached that of the presettlement northwestern Minnesota. The extreme high charcoal accumulations from Group A do not characterize any of the climates and vegetation types observed at these two sites since the end of the Pleistocene. Although the trend in *D* values between pairs of charcoal series shift in a geographically similar pattern during the Holocene, the magnitudes of all *D* values remain sufficiently high throughout this period to suggest fire regimes rather different from anything present in our presettlement data set. It was difficult to identify good analogs within the presettlement data set suggesting that different fuel structures and/or

climates may have prevailed. Different seasonality in the past is likely to be critical for understanding fire regimes. Modern fire seasons across our study region depend on the timing of snow accumulation, snow melt, and fuel phenology. Much of the Lake States and northeastern US have a spring fire season that follows snowmelt and precedes greenup and an autumn fire season that follows leaf fall and precedes snow accumulation. Large seasonality of the early Holocene might shorten these transitions, depending on precipitation patterns and vegetation composition. The importance of seasonality for fire occurrence, together with the fact that circulation patterns and temperature distributions of the early Holocene may have been quite different from today (Wright, 1992), makes it possible that early Holocene fire regimes do not find close analogs to any fire regimes present in eastern North America during the last several centuries.

Conclusions

Comparisons of distributions of charcoal accumulation rates within pollen assemblage zones show that charcoal may reflect somewhat different geographic transitions than are interpreted from fossil pollen. In the mixed pine forests of the Upper Midwest KS *D* comparisons show a sharp transition in fire occurrence that attends the sharp rise in fire importance approaching the prairie/forest border. Pollen data do not show this transition, because dominant pollen taxa do not change.

Comparisons of charcoal distributions from the more distant past show the degree of similarity to more recent distributions, for which some information on fire regimes may be available. For our study region in eastern North America, we did not find close charcoal analogs for early Holocene charcoal data, despite the fact that reasonably close pollen analogs could be found for same locations. Because the discrepancies between pollen and charcoal involve comparisons within relatively xeric conifer-dominated vegetation, we believe that charcoal may resolve moisture-controlled differences in fire importance that are not reflected in pollen data.

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