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Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies

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Abstract: Stratigraphic records of macroscopic charcoal particles (>125 μm in diameter) are widely used as a means of reconstructing past fire events, yet fire-history studies rest on assumptions about the processes by which charcoal is transported and deposited in lake sediments. In order to clarify the interpretation of charcoal data, charcoal abundance in sediment cores was examined from 36 lakes within and near the 1996 Charlton Burn, a large stand-replacing fire in the central Cascade Range of Oregon. Stratigraphic variations in charcoal abundance provided strong evidence that macroscopic charcoal recorded a signal of local fire and that prevailing winds affected charcoal transportation, increasing charcoal abundance in lakes downwind of the fire. Charcoal abundance in the uppermost sediments (0–2 cm depth) was related primarily to whether or not a site had burned and secondarily to the surface area of the lake. At the Charlton Burn area, other variables that may influence the transportation of charcoal after a fire, such as relative position of unburned lakes, distance of the lake from the centre of the fire, maximum adjacent slope, and width of riparian vegetation, were not statistically significant. These results support the assumption in charcoal analysis that there is a relationship between the occurrence of local fire and peaks in macroscopic charcoal. Confirming this relationship strengthens the interpretation of long-term fire-history records.

Key words: Charcoal records, fire history, macroscopic charcoal analysis, lake sediments, Cascade Range, Oregon.

Introduction

Our ability to reconstruct prehistoric fires on the basis of charcoal records from lake sediments rests on understanding the processes that control charcoal accumulation in lakes following modern fires, including charcoal production, transportation and deposition. Charcoal production is related to the fire and vegetation characteristics, including the rate of fuel consumption and combustion efficiency (Cofer *et al*., 1997; Stocks and Kauffman, 1997). Transport is influenced by weather conditions (i.e., wind direction and speed), stream and surficial processes, and the relationship between charcoal particle size and particle settling velocity (Clark, 1988; Patterson *et al*., 1987). Characteristics of the watershed and lake influence the patterns of charcoal deposition (Larsen and MacDonald, 1993; Whitlock and Millspaugh, 1996; Whitlock *et al*., 1997).

Two studies have examined the accumulation of charcoal in lakes following modern fires: one in Yellowstone National Park after the 1988 fires (Whitlock and Millspaugh, 1996) and the other in Siberia after a prescribed burn in 1996 (Clark *et al*., 1998). The findings of these studies are used widely to interpret charcoal records in other regions. This paper builds on those investigations by presenting a comprehensive analysis of charcoal deposition following a large stand-replacing fire in the Oregon Cascade Range. This study addresses three questions that help clarify the interpretation of charcoal data: (1) is a fire event registered by a peak in charcoal abundance; (2) does transport of charcoal by prevailing winds during a fire distort recognition of the source area; and (3) how does the abundance of macroscopic charcoal in lakes relate to variables that influence the production, transportation and deposition of charcoal?

The study area lies in the *Tsuga mertensiana* zone (1700–2000 m elevation in Central Oregon) of the Cascade Range (Franklin and Dyrness, 1988). During 23–27 August 1996, an area of 37.7 km^2 was burned by a lightning-caused fire at the north end of Waldo Lake (Figure 1). The heat of the fire created a strong convectional plume reaching approximately 9000 m above the ground, and local winds were from the southwest during and

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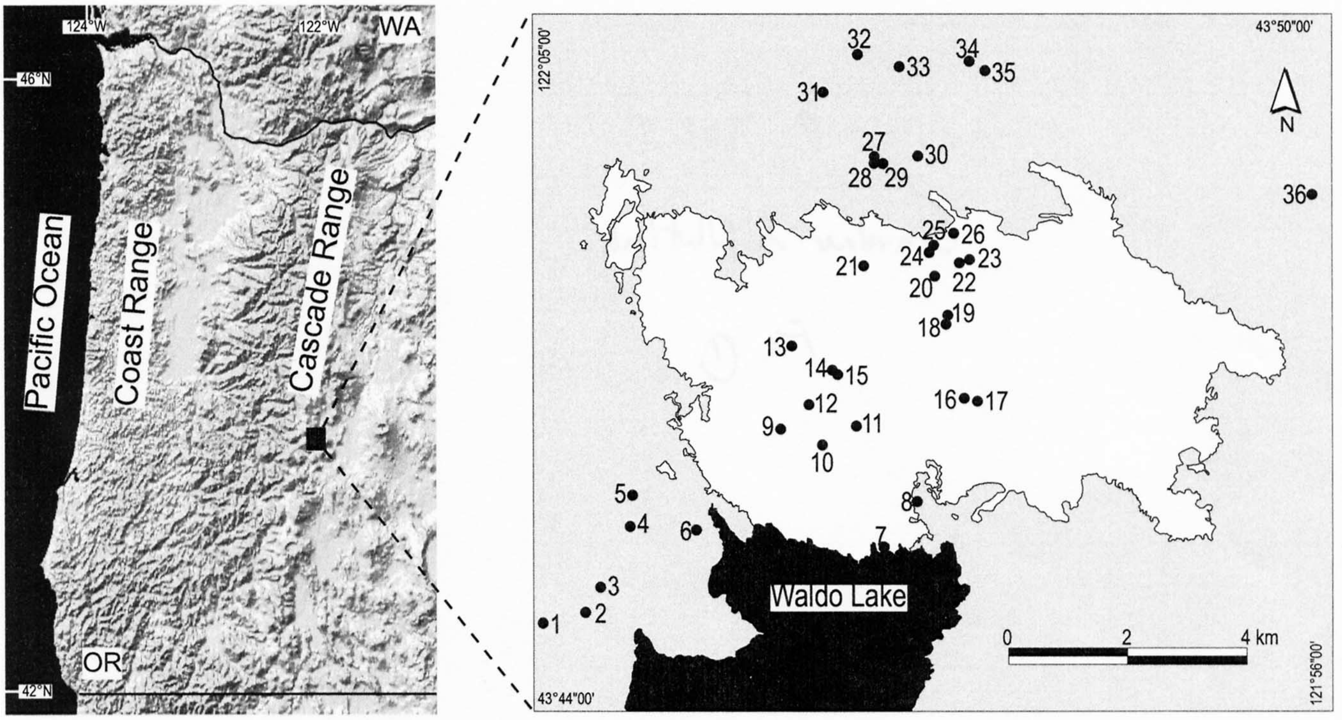

Figure 1 Location of study area (OR = Oregon; WA = Washington). White area shows location of Charlton Burn in 1996 and numbers are the study sites. See Tables 1 and 3 for site information.

immediately after the fire. Approximately 73% (26.3 km^2) of the area experienced >95% tree mortality (J. Kertis, USDA Forest Service, unpublished data, 1997). Historical records and dendrochronological data indicate that the Charlton Burn area is characterized by a variable fire frequency, ranging from 100 to 300 years, and variable fire severity, and that no fires had occurred there in the last 100 years (Williamette and Deschutes National Forests, 1996). The vegetation of the study area was dominated by late-successional stands of *Tsuga mertensiana*, and an understorey of *Vaccinium membranaceum* and *Xerophyllum tenax*. The severity of the fire and the presence of numerous lakes in and adjacent to the burned area offered an excellent opportunity to study how the abundance of charcoal in lake sediments related to fire and weather characteristics, physical characteristics of the lakes, and topographic features of the region.

Methods

Twenty-nine lakes sampled in 1997 were randomly selected from populations of lakes that met two sets of criteria: (1) burn status (located either in a burned watershed with >95% tree mortality or in an unburned watershed); and (2) surface area (four classes: <0.250 ha, 0.251–0.500 ha, 0.501–0.750 ha, and 0.751–1.500 ha) (R.E. Gresswell, unpublished data, 1997). Seven additional lakes were sampled in 1998 in order to include deeper lakes more comparable to those analysed in palaeoecological studies (Table 1). In all, 19 lakes were located within the burned area and 17 were located in unburned watersheds (Figure 1). Of the burned sites, two lakes were from areas with 51–95% mortality, seven lakes were located in areas with >95% mortality and crown scorch, and 10 lakes were in areas with >95% mortality and crown consumption. Seven of the unburned sites were located upwind and 10 were downwind of the fire. The topography of the study area was homogenous and most lakes (24 out of 36) were located in flat terrain. Ten lakes had moderate hillslopes adjacent to their shores, and two had steep slopes. Fourteen lakes lacked significant riparian vegetation, 15 lakes had a riparian margin of 0–3 m width, and seven lakes had a riparian margin >3 m wide.

Cores, 12 cm long, were collected from the deepest part of each lake (with the exception of 8 cm long cores at sites 2 and 24) by use of a gravity corer that preserved the mud-water interface intact. The cores were extruded vertically in the field at 2 cm intervals, and samples were stored in plastic bags. The maximum water depth of each lake was measured, and the width of riparian vegetation and maximum slope adjacent to the lakeshore were estimated in the field.

In the laboratory, 5 cm^3 samples were taken from contiguous, 2 cm thick slices of core (i.e., samples at 0–2 cm, 2–4 cm, 4–6 cm depth, etc.). Samples were soaked in a 1% solution of sodium hexametaphosphate for 24 hours and gently wet-sieved through a 63 μm mesh screen. They were treated in 5% sodium hypochlorite (bleach) and heated at low temperature for five minutes to remove excessive invertebrate faeces. Finally, they were gently washed through nested 250 μm and 125 μm mesh screens.

Charcoal particles >125 μm in diameter were tallied for each

Table 1 Description of study lakes

Year sampled	No. of lakes sampled	No. of lakes in burned watersheds	No. of lakes in unburned watersheds	Range of maximum water depth (m)	Range of surface area (ha)	Inflow or outflow streams
1997	29	15	14	0.30–4.35	0.04–1.46	none
1998	7	4	3	3.00–13.00	1.58–7.75	3 outflow
Total	36	19	17	0.30–13.00	0.04–7.75	3 outflow

sample using a binocular microscope. This size range was chosen on the basis of the observations of Clark (1990) and Whitlock and Millspaugh (1996) who found that large macroscopic charcoal particles provided a good record of local fires. The dry weight for each sample was obtained by heating a 1 cm^3 subsample at 90°C for 24 hours. Charcoal abundance (number of charcoal pieces per gram of dry sediment = char/g) was calculated by dividing charcoal concentration (char/cm^3) by dry weight (g/cm^3).

Eight variables were considered as possible controls of charcoal abundance: (1) burn status; (2) fire severity; (3) position of lakes in unburned watersheds relative to the fire (upwind or downwind); (4) surface area; (5) maximum water depth; (6) maximum adjacent slope; (7) width of the post-fire riparian-vegetation margin; and (8) distance of the lake from the centre of the fire. The variables were derived from multiple sources (Table 2). Table 3 describes the characteristics for all of the sites.

Stratigraphic and spatial variations in charcoal abundance were examined with paired and two-sample *t*-tests to compare the means of sets of observations grouped by burn status or by sample depth. We also examined the assumptions of normality and homogeneity of group variance that underlie such difference-of-means tests. Normality was evaluated using histograms and normal probability plots, and by the Ryan-Joiner test for normality, as implemented in Minitab, version 12.1. Homogeneity of group variance was evaluated using an *F*-test for this purpose, also implemented in Minitab. (This test considers the null hypothesis of no difference among groups, and failure to reject that hypothesis can be considered evidence for the homogeneity of group variance). Preliminary analyses of the data revealed that these assumptions would be satisfied if the charcoal data were logarithmically transformed. This transformation also reduced the influence of outlying observations. Hereafter, the term ‘charcoal abundance’ refers to logarithmically transformed data, but the group means discussed below are implicitly the geometric means of untransformed observations.

The stratigraphic variations of charcoal abundance within each burn-status group were examined by comparing the mean charcoal abundance between the top (0–2 cm depth) and second (2–4 cm depth) samples using a paired *t*-test of the null hypothesis that there was no enrichment of charcoal in the top samples (i.e., that there was no difference between the mean abundance in the top and second samples). Spatial variations of charcoal abundance were examined by comparing the groups of the top samples from burned and unburned sites using a two-sample *t*-test. Within the group of unburned sites, the stratigraphic and spatial variations of charcoal abundance were examined in a similar fashion.

The relationships between charcoal abundance in the top sample (0–2 cm depth) and the potential control variables listed in Table 2 were examined with regression analysis. Categorical variables (i.e., burn status, severity, relative position, slope and margin) were coded as binary indicator ‘dummy variables’. For each qualitative variable having (*p*) possible states, (*p*-1) dummy variables were included in the regression models to represent the variable. Histograms, normal probability plots and scatter diagrams for the continuous variables (i.e., area, depth and distance) were examined. They indicated that area, depth and distance were log-normally distributed and featured curvilinear relationships with charcoal abundance. Consequently, these data were logarithmically transformed, which served to linearize the relationships between some of the control variables and charcoal abundance.

Two of the potential control variables – burn status and severity – were highly correlated and nearly redundant. Consequently, we fit two series of models, each consisting of a full and a reduced model. For each series, the full model incorporated either burn status or severity in addition to the remaining six variables in Table 2. Best subsets regression was used to determine a logical order for the removal of variables from each full model in order to simplify it to a reduced model. Each reduced model maximized the explanatory ability of the model while minimizing the number of variables to only those that significantly contributed to the

Table 2 Variables examined as potential controls of charcoal abundance

Variable name	Description (units or classes)	Source
Burn status	Lake located in burned or unburned watershed (burned, unburned)	Geographic Information System (GIS) fire severity coverage,[a] field observations
Severity	Percentage of tree mortality surrounding each lake (0%, 5–50%, 51–95%, >95% crown scorch, >95% crown consumption)	GIS fire severity coverage[a]
Relative position	Position of lake in unburned watersheds relative to the fire (upwind, downwind)	Average wind direction calculated from Remote Automated Weather (RAW) Station data[b]
Area	Surface area of lake (ha)	Calculated from GIS lake coverages of the Willamette[c] and Deschutes[d] national forests
Depth	Maximum water depth (m)	Measured in the field with a seiche disk
Slope	Maximum slope adjacent to lakeshore (flat, moderate, steep)	Determined from field observations and a Digital Elevation Model (DEM)[e]
Margin	Extent (width) of post-fire riparian vegetation (0 m, 0–3 m, >3 m)	Field observations
Distance	Distance of lake from the centre of the fire (m)	Calculated from GIS lake coverages of the Willamette[c] and Deschutes[d] national forests

[a] GIS fire severity coverage provided in 1997 by J. Kertis, Siuslaw National Forest.

[b] The RAW stations are: Black Rock (T24s-R07e-S29) in the Deschutes National Forest, and Pebbles (T24s-R07e-S29) and Fields (T22s-R04e-S11) in the Willamette National Forest. The Black Rock and Pebbles RAW stations are located approximately 32 km southeast and 24 km south-southeast, respectively, of the Charlton Burn. The Fields RAW station is located approximately 24 km southwest of the burned area.

[c] Willamette National Forest GIS lake coverage provided in 1998 by the Willamette National Forest to the University of Oregon: obtained in 1999 from C. Leue, Social Sciences Instructional Lab (SSIL), University of Oregon.

[d] Deschutes National Forest GIS lake coverage provided in 1999 by D. Rawson, Deschutes National Forest.

[e] 10 m resolution DEM provided in 1998 by the Willamette National Forest to the University of Oregon: obtained in 1999 from C. Leue, Social Sciences Instructional Lab (SSIL), University of Oregon.

Table 3 Site characteristics

Site no.[a]	Char/g[b]	Burn status[c]	Severity (%)[d]	Relative position	Area (ha)	Depth (m)	Slope[e]	Margin (m)	Distance (m)	Year sampled
1	128	U	0	upwing	0.95	2.80	mod.	0	6792	1997
2	221	U	0	upwind	0.47	1.00	mod.	0	6135	1997
3	84	U	0	upwind	7.75	6.00	mod.	0	5723	1998
4	708	U	0	upwind	0.09	0.30	flat	0–3	4819	1997
5	216	U	0	upwind	0.26	1.00	flat	0–3	4545	1997
6	165	U	0	upwind	0.90	3.00	flat	0	4026	1997
7	570	B	>95-C	*	0.38	1.75	flat	0–3	2870	1997
8	85	U	0	upwind	0.20	1.50	flat	0–3	2199	1997
9	659	B	51–95	*	6.92	9.00	mod.	0	2058	1998
10	1211	B	>95-C	*	0.38	1.75	flat	0–3	1722	1997
11	1146	B	>95-C	*	0.29	2.50	flat	0	1184	1997
12	310	B	>95-C	*	1.58	13.00	steep	0–3	1494	1998
13	314	B	51–96	*	6.77	6.00	steep	0	1590	1998
14	413	B	>95-C	*	0.44	2.50	flat	0	975	1997
15	1002	B	>95-C	*	1.17	3.00	flat	0	907	1997
16	357	B	>95-S	*	0.44	0.50	flat	>3	1232	1997
17	560	B	>95-S	*	0.58	1.10	flat	0–3	1440	1997
18	1621	B	>95-C	*	0.09	1.30	flat	0–3	954	1997
19	1503	B	>95-C	*	0.16	2.50	flat	0–3	1056	1997
20	588	B	>95-S	*	0.16	1.30	flat	>3	1413	1997
21	269	B	>95-S	*	5.24	3.00	mod.	0	1499	1998
22	433	B	>95-C	*	0.22	1.00	flat	>3	1774	1997
23	1234	B	>95-C	*	0.06	1.50	flat	0–3	1905	1997
24	979	B	>95-S	*	0.04	0.50	flat	>3	1716	1997
25	226	B	>95-S	*	0.21	1.20	flat	0–3	1840	1997
26	909	B	>95-S	*	0.06	0.75	flat	>3	2127	1997
27	308	U	0	downwind	0.42	1.20	mod.	0–3	3010	1997
28	315	U	0	downwind	0.03	1.00	flat	0–3	3084	1997
29	288	U	0	downwind	2.53	4.00	mod.	0–3	2994	1998
30	488	U	0	downwind	0.34	1.50	flat	>3	3117	1997
31	421	U	0	downwind	0.07	1.00	flat	0	4215	1997
32	768	U	0	downwind	0.10	0.40	flat	>3	4673	1997
33	92	U	0	downwind	0.49	2.50	flat	0–3	4462	1997
34	515	U	0	downwind	0.26	4.25	mod.	0	4686	1997
35	598	U	0	downwind	0.24	2.50	mod.	0	4616	1997
36	190	U	0	downwind	2.44	3.00	mod.	0	6870	1998

[a] Location of site is shown on Figure 1.

[b] Charcoal abundance, top-sample interval (0–2 cm depth).

[c] U = unburned site; B = burned site.

[d] >95-C = >95% tree mortality – crown consumption. >95-S = >95% tree mortality – crown scorch.

[e] mod. = moderate.

explanation of the variation of charcoal abundance. We used Mallow's *Cp* statistic to guide the selection of the variable in the reduced model (Weisberg, 1985).

In addition to the regression coefficients and their *t*-statistics and *p*-values, the *F*-ratio for the model and its *p*-value, R^2, and R^2_{adj} were reported for each model. The adjusted coefficient of determination (R^2_{adj}) corrected for the automatic increase in R^2 resulting from the inclusion of a greater number of variables. The *t*-statistic for each regression coefficient and its associated *p*-value indicated whether or not the variable significantly contributed to explaining the variation of charcoal abundance, given the effects of the other independent variables in the model. Finally, the residuals and fits of the reduced models were examined to evaluate the assumptions of independent, normally distributed residuals.

Results

Stratigraphy and spatial variations

Examination of histograms, normal probability plots and the *r*-values of the Ryan-Joiner test of normality for all observations, and for stratigraphic (top and second) and spatial (burned and unburned) subsets of observations confirmed that the logarithmic transformation of charcoal abundance was warranted and effective in satisfying the assumption of normality required by the *t*-test (Gardner, 1999). *F*-tests for homogeneity of variance among groups of transformed charcoal-abundance observations failed to reject the null hypothesis of equal variances among groups for: (1) the top and second samples from burned sites ($F = 1.876$); (2) the top and second samples from unburned sites ($F = 1.125$, $p = 0.817$); and (3) the top samples from burned and unburned sites ($F = 0.415$, $p = 0.493$).

Figure 2 summarizes the important stratigraphic and spatial results, including four general patterns. First, charcoal abundance in cores from most of the sites was greater in the top sample (0–2 cm depth) than in the second sample (2–4 cm depth). Second, charcoal abundance in the top sample was highest in burned sites. Third, the uppermost sample in cores from unburned sites located upwind of the Charlton Burn area had less charcoal than did unburned sites downwind of the burn. Fourth, lakes as far as 3 km downwind of the fire had charcoal peaks in the upper sediments that were of similar magnitude to those from burned sites. These results and their significance are discussed below.

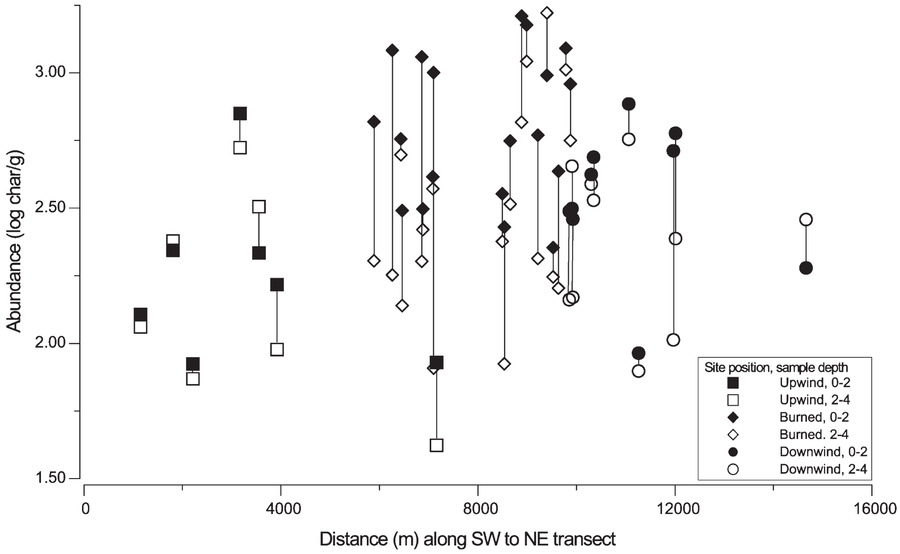

Figure 2 Comparison of charcoal abundance in the top and second samples from cores collected from upwind (unburned), burned and downwind (unburned) sites.

The stratigraphic trends of charcoal abundance in cores indicated significant decreases in charcoal abundance with depth (i.e., between the top and second groups of observations) for *both* burned and unburned sites (burned sites $t = 4.41$, $p < 0.001$; unburned sites $t = 2.50$, $p = 0.024$) (Figure 3). The means of the top samples from burned and unburned sites were statistically different ($t = 3.92$, $p < 0.001$) (Table 4). Thus, burned sites received more charcoal from the 1996 fire than did unburned sites, and they also had better defined peaks of charcoal abundance in the uppermost sediments.

Comparison was also made of the charcoal abundance variations between two subsets of the unburned sites, those upwind from the burned area and those downwind. Stratigraphic trends in cores from these two subsets show decreases in charcoal abundance with core depth (Figure 3), significantly so in downwind sites ($t = 2.11$, $p = 0.032$), but not in upwind sites ($t = 1.33$,

Table 4 Mean charcoal abundance for top two core samples

Site type	Core depth (cm)	Charcoal abundance (mean ± SD)
Total burned	0–2	2.80 ± 0.13
	2–4	2.47 ± 0.18
Total unburned	0–2	2.51 ± 0.15
	2–4	2.38 ± 0.16
Upwind, unburned	0–2	2.24 ± 0.29
	2–4	2.16 ± 0.36
Downwind, unburned	0–2	2.54 ± 0.19
	2–4	2.36 ± 0.21

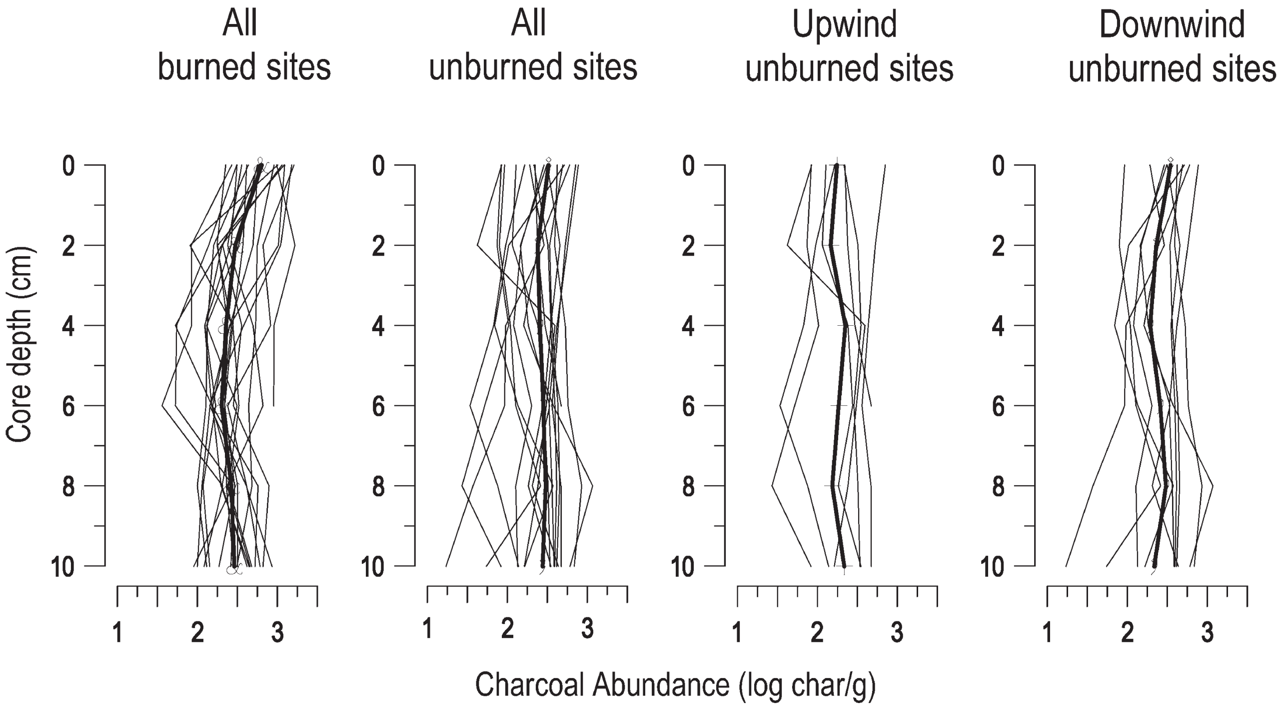

Figure 3 Stratigraphic variations of charcoal abundance plotted for all cores and grouped by burned status.

$p = 0.115$). The variances of charcoal abundance between the top and second samples were not significantly different in either of the subsets (upwind $F = 1.485$, $p = 0.643$; downwind $F = 1.153$, $p = 0.836$). The variances of charcoal abundance in the top samples of upwind and downwind sites also were not significantly different ($F = 1.410$, $p = 0.617$). The mean charcoal abundance in the top samples of the downwind sites was slightly greater than in the upwind sites ($t = 2.06$, $p = 0.034$) (Table 4). The results indicate that the downwind sites received more charcoal from the 1996 fire than the upwind sites and that peaks in charcoal abundance in cores from downwind sites were better defined than in upwind sites.

Analysis of variables controlling charcoal abundance

For the regression analysis, charcoal abundance in the top sample (0–2 cm depth) was used as the dependent variable to maximize the inclusion of charcoal from the 1996 event while minimizing that from previous fire events. The decision to use the top sample is supported by the slow sedimentation rates of lakes in the Charlton Burn area (*c*. 0.04 cm/yr; C. Whitlock, unpublished data, 1999), which suggests that the top 2 cm is likely to span the last 50 years. The dendrochronological record contains no fires in the last 100 years, which makes it also reasonable to assume that charcoal particles in the top core sample were indeed from the 1996 Charlton Burn. We were surprised to see so much charcoal in deeper levels of the core, and the source of that material is difficult to determine. It may be charcoal from the 1996 fire, which has moved into deeper sediments through bioturbation; it may be particles transported long distance from other fires in the Cascade Range; or it may be reworked secondary material from older fire events. To choose among these possibilities requires a research scheme that would allow the age of specific charcoal particles to be determined apart from the age of the encasing sediment. Ideally, the scheme would also provide a means of tracing the incorporation of recent particles into the sedimentary record over time.

Two controlling variables provide similar information about fire characteristics: burn status and fire severity (Table 2). Burn status divides the sites into burned and unburned categories. Severity describes the percentage of tree mortality and whether the canopy of forest at the site was scorched or consumed by the fire. Regression models considered either burn status or severity but not both. Series I models incorporated the burn-status variable, and Series II models considered fire severity as a variable. All regression models used the logarithm of charcoal abundance as the dependent variable.

Histograms and normal probability plots for the continuous variables (charcoal abundance, area, depth and distance from the centre of the fire) indicated that logarithmically transformed data were approximately normally distributed (Gardner, 1999), and so the transformed variables were used in the analysis below. Scatter diagrams constructed between charcoal abundance and the control variables revealed that the transformation also linearized the relationships among these variables. Lake area and depth, which describe bathymetric characteristics, were highly correlated ($r = 0.75$). Best subsets regression indicated that area had a slightly greater ability to explain the variation in charcoal abundance than depth. Therefore, area was chosen as a variable for the reduced models, instead of depth.

In the full models, the relative position of unburned sites, water depth, distance from the fire, hillslope gradient and width of the riparian margin were not important variables in explaining the variability in charcoal abundance (Table 5). For Full Model I (with burn status as a predictor), a significant relationship exists between at least one independent variable and charcoal abundance ($F = 4.40$, $p = 0.002$). However, only burn status and area had significant relationships ($p = 0.017$ and $p = 0.024$, respectively)

Table 5 Regression coefficients and their significance in full and reduced regression models

Full Model I (log charcoal abundance)

Predictor (X)	Coefficient (B)	*t*	*p*
Constant	3.7390	2.57	0.016
Burn status	0.5278	2.55	0.017
Relative position	0.2271	1.62	0.017
Log of area	–0.2881	–2.40	0.024
Log of depth	–0.0692	–0.31	0.736
Log of distance	–0.1548	–0.43	0.668
Slope (flat	0.0144	–0.06	0.953
Slope (moderate)	0.1392	0.61	0.546
Margin (0 m)	0.1376	0.82	0.417
Margin (0–3 m)	0.0368	0.27	0.788

$R^2 = 60.6\%$ $R^2_{\text{adj}} = 46.9\%$; F-ratio = 4.44, $p = 0.001$.

Full model II (log charcoal abundance)

Predictor (X)	Coefficient B	*t*	*p*
Constant	3.7740	2.90	0.008
Relative position	0.2106	1.69	0.105
Severity (50–95%)	0.7857	3.12	0.005
Severity (>95%, scorch)	0.2876	1.43	0.164
Severity (>95%, consumption	0.6661	3.35	0.003
Log of area	–0.2564	–2.29	0.031
Log of depth	0.2629	–1.22	0.235
Log of distance	–0.1807	–0.57	0.575
Slope (flat)	0.0642	0.29	0.778
Slope (moderate)	0.2868	1.32	0.198
Margin (0 m)	0.0107	0.07	0.945
Margin (0–3 m)	–0.0579	–0.46	0.647

$R^2 = 71.4\%$ $R^2_{\text{adj}} = 58.3\%$; F-ratio = 5.45; $p = 0.000$.

Reduced Model I (log charcoal abundance)

Predictor (X)	Coefficient (B)	*t*	*p*
Constant	3.29250	13.50	0.000
Burn status	0.39143	4.70	0.000
Log of area	–0.24459	–3.71	0.001

$R^2 = 51.6\%$ $R^2_{\text{adj}} = 48.7\%$; f-ratio = 17.61, $p = 0.00$.

Reduced Model II (log charcoal abundance)

Predictor (X)	Coefficient (B)	*t*	*p*
Constant	3.45280	13.10	0.000
Severity (50–95%)	0.60420	3.04	0.005
Severity (>95%, scorch)	0.22530	2.11	0.043
Severity (>95%, consumption)	0.46726	4.94	0.000
Log of area	–0.28934	–4.03	0.000

$R^2 = 59.0\%$ $R^2_{\text{adj}} = 53.7\%$; F-ratio = 11.16, $p = 0.00$.

with charcoal abundance when all variables were included in the model. A significant relationship also exists in Full Model II (with severity as a predictor) between at least one independent variable and charcoal abundance ($F = 5.45$, $p < 0.001$). As in Full Model I, most of the variables were not significant. Only area and two classes of fire severity had significant relationships ($p = 0.006$, $p = 0.005$ and $p = 0.003$, respectively) with charcoal abundance when all variables were included in the model.

In best subsets regression, many individual models with subsets of predictors were examined, and a final model was selected by trading off goodness-of-fit against the number of predictors. In the resulting reduced models, the variables of burn status (or severity) and area were retained and significantly explained the variation in charcoal abundance. Residuals were normally distributed and no pattern was evident in the plot of residuals versus fits for either of the models. Reduced Model II, which incorporated severity and area, had an R^2_{adj} value ($R^2_{adj} = 53.7\%$) that was 5% higher than Reduced Model I ($R^2_{adj} = 48.7\%$), which simply accounted for whether a lake was in a burned or unburned watershed and surface area. The difference in the R^2_{adj} values suggests that the additional information provided by knowing the severity of the fire surrounding a lake improved the explanation of variation in charcoal abundance. When the relationship between charcoal abundance and burn status alone was examined, R^2_{adj} was 29.5%. For charcoal abundance and severity, R^2_{adj} was 31.7%. Finally, for charcoal abundance and area, R^2_{adj} was 16.8%. Therefore, charcoal abundance in the upper sediments was related primarily to whether or not the site burned and secondarily to the surface area of the lake.

In summary, the results indicate the following: (1) All cores, including those from burned and unburned sites, received charcoal from the Charlton Burn. Although burned and unburned sites both tended to have peaks in charcoal abundance, peaks in burned sites were significantly better defined than in unburned sites. In addition, lakes from burned sites had significantly more charcoal in the top 2 cm of sediment than unburned sites. (2) Downwind sites had significantly better-defined charcoal peaks than upwind sites. Downwind sites had more charcoal in the top sample (0–2 cm depth) than upwind sites. These results suggest that the prevailing winds during the fire increased the amount of charcoal deposited downwind. (3) Charcoal abundance in the upper sediments was related primarily to whether or not the site burned or characteristics of fire severity, and secondarily to the surface area of the lake. Other variables examined, such as relative position of unburned lakes, distance of the lake from the centre of the fire, maximum adjacent slope and width of riparian vegetation, were not important controls of charcoal abundance at these sites.

Discussion

Use of charcoal to identify local fire events

Assumptions concerning the source area of the charcoal in lake sediments influence the interpretation of the charcoal data. The results of the Charlton Burn study suggest that a macroscopic-charcoal peak occurs when the watershed of a lake burns. This result validates a basic assumption of charcoal analysis: a relationship exists between charcoal abundance and fire events, enabling the reconstruction of a local fire history from charcoal data. Although the average trends of charcoal abundance in both burned and unburned sites had statistically significant charcoal peaks, the peak in burned sites was better defined than the one from unburned sites. In addition, the average amount of charcoal in the top 2 cm of sediment from burned sites was statistically greater than that from unburned sites.

These results are consistent with theoretical models (Clark, 1988; Patterson *et al*., 1987) and empirical studies (Whitlock and Millspaugh, 1996; Clark *et al*., 1988; Ohlson and Tryterud, 2000) that suggest macroscopic particles are not transported far from the fire. Whitlock and Millspaugh (1996) sampled macroscopic charcoal (125–250 μm particle diameter) in five lakes in burned watersheds and three lakes in unburned watersheds for five years after the 1988 Yellowstone fires. They found that all lakes received some charcoal during the fire, but the charcoal peak in lakes within the burned region was larger than in lakes outside the fire perimeter (Whitlock and Millspaugh, 1996). Clark *et al.* (1998) quantified charcoal particles deposited in 21 traps located along three transects extending away from a prescribed burn in Siberia. The burn consumed 50 ha and was severe, but there was little wind at the time of the fire. They found that charcoal abundance was high in traps within the burn and extremely low in traps outside of the burn, further supporting the idea that macroscopic charcoal does not travel far from source. Ohlson and Tryterud (2000) collected charcoal particles in traps inside and outside areas burned in three experimental forest fires in Scandinavia. Like this study, they found that large particles constituted most of the charcoal mass in the inside traps, and little charcoal was found beyond the burned perimeter.

Factors that influence charcoal accumulation

To reconstruct past fire events based on charcoal accumulation data requires an understanding of all the variables that contribute to the accrual of charcoal in lake sediments. The use of charcoal as a fire proxy rests on the assumption that stratigraphic intervals with abundant charcoal, the so-called charcoal peaks, represent a primary contribution that is deposited through aerial fallout or other fire-related processes during or shortly after the fire. Moreover, secondary charcoal introduced or reworked in the watershed or lake as a result of non-fire variables should be negligible so that spurious peaks are not formed.

Dendrochronological and historical data have been used in a number of studies to calibrate charcoal peaks with fire age, size and proximity (Swain, 1973; 1978; Cwynar, 1978; Clark, 1990; MacDonald *et al.*, 1991; Millspaugh and Whitlock, 1995; Larsen and MacDonald, 1998a; 1998b; Tinner *et al*., 1998). In principle, a threshold value is defined to identify the amount of charcoal that signifies a fire event. The threshold value is based on modern calibration studies that match years of known fires with the age of charcoal peaks in the core. This approach has worked well in several studies; however, others have shown that local fires located downwind of lakes are often not recorded as charcoal peaks, and some charcoal peaks correspond with extralocal events (Millspaugh and Whitlock, 1995). The results from the Charlton Burn area indicate that winds during the fire do transport macroscopic charcoal beyond the fire perimeter. Charcoal accumulation in downwind sites was significantly above background levels, i.e., charcoal abundance in the uppermost sample was greater than in deeper levels in the core. In addition, more charcoal was received in downwind sites than in upwind sites.

Whitlock and Millspaugh (1996) noted more charcoal in the two Yellowstone lakes located 7 km downwind of the fires than in a lake located 13 km downwind, suggesting decreased transport of charcoal beyond the fire border. In the Charlton Burn study, some lakes downwind of the fire had charcoal peaks in the upper sediments that were of similar magnitude to those from burned sites. Unfortunately, lakes were not available to sample beyond 3 km to determine at what distance this peak would attenuate. The finding suggests that wind transport of charcoal blurs the distinction between burned and downwind sites by enlarging the area over which macroscopic charcoal is deposited. Depending on fire and weather conditions, a peak in charcoal abundance in the palaeoecological record could mean anything from a fire at the edge of a lake to a fire within a few kilometres. This distortion between source area and signal registration might be critical when reconstructing fire events at a very small spatial scale, but less important when the objective is watershed-level reconstructions.

The Charlton Burn results indicate that charcoal abundance in the uppermost sediments was related primarily to whether or not the site had burned and secondarily to the surface area of the lake. Other variables, such as distance of the lake from the centre of the fire, maximum adjacent slope and the width of riparian vegetation were statistically shown to be unimportant. Despite the differences in charcoal abundance between downwind and upwind unburned sites, the relative position of unburned lakes was also shown to be statistically unimportant when other variables in the models were considered. Information about the patterns of fire severity slightly increased the explanation of variations in charcoal abundance, suggesting that charcoal abundance in lake sediments is partially related to the amount of charcoal produced by a fire but that other factors were also important. For example, lakes in areas with $>95\%$ tree mortality and crown consumption tended to have greater amounts of charcoal in the uppermost sediments than lakes in areas with $>95\%$ tree mortality and crown scorch.

In the modern Siberian study, Clark *et al.* (1998) calculated an emission factor (i.e., the percentage of biomass consumed by a fire deposited as macroscopic charcoal) for charcoal deposited in the traps within and near the fire. The emission factor was 2% within the burn and 0.005% for traps that were >20 m away, a value that is similar to emission factors for smoke particles. Clark *et al.* (1998) further suggested that a range of emission factors could be established from additional studies of charcoal accumulation from modern fires. These estimates would enable the mass of fuels consumed by the fire over a specified time period to be calculated from the mass of charcoal in sedimentary records.

Calculation of biomass consumed based on charcoal abundance in lake sediments requires a clear and consistent relationship between fuel consumed, charcoal produced and charcoal abundance in lake sediments. It implies that the magnitude of a charcoal peak is related solely to the amount of fuel consumed, i.e., a larger peak indicates either more fuel per unit area was consumed or that a greater area was burned. In the Charlton Burn area, the pattern of fire severity was relatively homogeneous, with much of the area burned experiencing $>95\%$ tree mortality. In that circumstance, the abundance of macroscopic charcoal was partly related to charcoal production, as evidenced by the peak in burned and downwind unburned sites. Charcoal abundance was also weakly related to fire severity. This relation between production and charcoal abundance may be less straightforward when fire conditions are more heterogeneous.

The relationship between the amount of charcoal produced and charcoal abundance in lake sediments is further complicated by charcoal transportation and deposition after a fire event. Sources of secondary charcoal include: (1) charcoal carried by surficial processes; (2) charcoal from burned trees near the lakeshore; and (3) charcoal redeposited within a lake, from the littoral zone to deep water (Whitlock *et al.*, 1997). If any of these processes is significant, calculating biomass from charcoal abundance may not be possible.

Surficial processes may move significant amounts of macroscopic charcoal after a fire. Macroscopic particles are, in theory, easy to lift off the ground and move short distances by winds (Clark, 1998). However, overland flow has been considered to be unimportant except at sites with steep hillslopes, impermeable soils and frequent severe rainstorms. In the Charlton Burn study, two variables related to overland flow were specifically examined as potential controls of charcoal abundance: the extent of the riparian vegetation margin and the maximum slope adjacent to each lakeshore. Greater widths of riparian vegetation could have trapped particles moving by surficial processes before they reached the lake. Steeper slopes could have encouraged greater amounts of overland flow during the spring and summer precipitation events. Neither variable proved significant in this study; however, the region is not characterized by steep slopes, and areas of riparian vegetation were not extensive. To assess the importance of secondary transportation processes, additional studies in more heterogeneous areas are necessary.

Bathymetric characteristics can also influence amounts of charcoal deposited in deepwater areas of a lake. In the Charlton Burn study, surface area and maximum water depth were highly correlated, and area was inversely related to charcoal abundance in the deepwater sediments. The results corroborate the relationships between bathymetric characteristics (i.e., surface area and maximum water depth) and the likelihood of processes influencing sediment mixing (i.e., thermal stratification, wind-driven currents and depth of wave action) suggested by Larsen and MacDonald (1983). Small, shallow lakes (i.e., <5 ha and <5 m deep) rarely are thermally stratified, and sediments within such sites are continually disturbed by wave action and wind-driven currents. In contrast, larger, deeper lakes may be thermally stratified, and sediments in the littoral zone are more disturbed by wave action and wind-driven currents than sediments in the deepest part of the lake (Larsen and MacDonald, 1993). The redistribution of charcoal from the littoral zone to deepwater sediments in such lakes occurs gradually and charcoal abundance in deepwater sediments is generally less than in the littoral zone.

Secondary deposition within lakes has been shown to be important in other studies. In a large lake in northwestern Minnesota, Bradbury (1996) found that lake circulation and seasonal mixing influenced the spatial distribution of charcoal and diatoms. Charcoal and diatom abundances were concentrated in the littoral zone at the downwind end of the lake by wind-induced currents in spring. Charcoal was transported to deep water during spring and fall by redeposition of material from the littoral zone. Whitlock and Millspaugh (1996) provide evidence of secondary remobilization of charcoal in Yellowstone National Park following the 1988 fires. In deep lakes there, charcoal abundance was initially highest in the shallow zones of the lake, but it increased over time at all depths in the years after the fire. The increase was more gradual at deepwater sampling locations than at shallow ones. In shallow lakes, charcoal abundance varied irregularly across the basin and no trend, either spatial or temporal, was evident to suggest focusing of charcoal. The charcoal increase in deepwater sediments was greater in lakes in burned watersheds than in unburned watersheds.

In the Charlton Burn study, differences in charcoal abundance were apparent in cores from burned and unburned sites two years after the fire. This result contrasts with that of Whitlock and Millspaugh (1996), where it took five years to clearly distinguish between burned and unburned sites. The difference in timespan may have several explanations. First, the two studies were in different vegetation types, and this may have influenced the fuel levels or the amount of charcoal produced (Cofer *et al.*, 1997; Stocks and Kauffman, 1997). Second, charcoal abundance in the Charlton Burn study was quantified as the number of charcoal particles per dry weight gram of sediment (char/g) in order to correct for the abundance of water in the upper sediments, whereas in Yellowstone charcoal abundance was the number of charcoal particles per cm^2 of sediment (char/cm^2). Third, the charcoal signal from the Charlton Burn may have been strengthened by the small, shallow nature of most lakes. Sites in the Yellowstone study were relatively large, with surface areas of 8.2 to 46.5 ha and depths from 8.0 to 19.0 m (Whitlock and Millspaugh, 1996). In this study, 29 lakes had a surface area of $\leqslant 1.5$ ha and depths ranging from 0.30 to 4.35 m. It is possible that charcoal in shallow lakes is deposited evenly across the lake bottom in a relatively short period, whereas charcoal introduced to larger lakes may be initially concentrated in the littoral zone and then reworked to deepwater sediments over time. Similar reasoning may be used to explain the significance of surface area in explaining the variation of charcoal abundance in the top sample interval (0–2 cm).

Conclusions

The Charlton Burn study provides additional evidence that macroscopic charcoal studies offer an opportunity to reconstruct the history of local fire events. Prevailing winds affect the transportation of macroscopic charcoal and increased charcoal abundance in lakes that were downwind of the fire. Charcoal abundance in lake sediments after the Charlton Burn was controlled primarily by whether or not a site had burned and secondarily by surface area. The relationship between fire severity and charcoal abundance suggests that the magnitude of the charcoal peaks, in part, reflects the amount of charcoal produced near a site. At the Charlton Burn, other variables that may influence the transportation of charcoal after a fire were not statistically significant.

Thus, surface area and maximum water depth are probably the most important variables in the selection of fire-history study sites because they determine the likelihood of sediment mixing. Other site characteristics, such as steepness of the surrounding hillslopes and the extent of riparian vegetation, may not be important in predicting whether a site will consistently record a clear signal of local fire. Additional studies are needed to verify that secondary charcoal transportation does not significantly influence the magnitude of the charcoal peak. Confirmation that charcoal production does not fluctuate widely in fires that have a more heterogeneous pattern of fire severity is also necessary. Addressing these issues will clarify the relationship between fuel consumption, charcoal production and charcoal accumulation in lake sediments. Understanding how these factors influence one another is necessary to determine if the calculation of biomass consumed from the mass of charcoal in lake sediments is possible.

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