

CHARCOAL ACCUMULATION IN LAKE SEDIMENTS  
FOLLOWING A MODERN FIRE IN THE CENTRAL  
CASCADE RANGE, OREGON

by

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## CHAPTER I

### INTRODUCTION

Fire is a major form of natural disturbance in the forests of the Cascade Range in the Pacific Northwest (Agee, 1993; Weisberg, 1998). Natural disturbances, including fire, vary in their frequency, predictability through time, spatial extent, and magnitude (i.e., severity and intensity) (Agee, 1993; White and Pickett, 1985). The "fire regime" of an area broadly describes the role of fire in an ecosystem and may be defined by fire characteristics, such as frequency (the average number of fire events during a specified period of time) and severity (the effect of fire on vegetation or the ecosystem) (Agee, 1993). Fire characteristics are controlled by the climate and vegetation of an ecosystem and vary as climate and vegetation change through time. To critically examine the role of fire as an ecosystem process, it is necessary to consider the modern fire regime in the context of the frequency and severity of fires in the past. Reconstruction of prehistoric fire regimes is critical in assessing present-day forest "health" and in estimating the natural range of variability of fire in a particular ecosystem (Morgan, 1994; Swanson *et al.*, 1994). Long-term records are necessary to guide the development of sound land-management policy.

Fire-history information comes from three sources, which vary in the length of record they provide. Historic fire regimes are reconstructed on the basis of personal writings (i.e., journals and letters), government documents, and other archival materials (Burke, 1980). On longer time scales, prehistoric fire regimes are often reconstructed by analyzing tree-rings and stand-age structure of living trees (Agee, 1993). Tree-ring analysis reconstructs past fire events by dating fire scars on trees. Stand-age analysis determines the minimum date of establishment of early successional or dominant tree species following fire or other disturbances. In the Cascade Range of Oregon, dendrochronologic analysis has provided information on fire history in the last 500-800 years (see Heyerdahl *et al.*, 1995; Teensma, 1987; Weisberg, 1998). Such records have high temporal and spatial resolution. The chronology is established by counting the annual growth rings of trees to determine the year of a fire scar or of stand establishment (Agee, 1993). A fire scar or a uniform-age stand, determined to have originated from fire, provides evidence that a fire occurred at a specific geographic location.

Tree-ring and stand-age structure records have limitations in their ability to discern fire patterns in the past (Weisberg, 1998). First, the record becomes obscured with increasing time since the event. This "erasure problem" (Agee, 1993) occurs as (1) subsequent disturbances destroy evidence of previous fires, and (2) the trees bearing evidence of fire events eventually die (Agee, 1993; Weisberg, 1998). Further complications arise from the tendency for scars to heal

with time and the high mortality rate of young scarred trees (Morrison and Swanson, 1990). Erasure limits the length of fire record in areas with stand-replacing fires by reducing the maximum age of trees available for sampling (Weisberg, 1998). It also may reduce the fire evidence from areas with low-severity fires (Weisberg, 1998). Second, the selection of a study area and the sampling strategy are subject to bias; sites must be comparable in area and in the intensity of sampling effort (Weisberg, 1998). The sampling density must also be great enough to reflect the heterogeneity of the fire regime (Agee, 1993). Third, methods of scar detection and dating may further obscure the actual fire patterns. Sources of scars (i.e., fire, insect, wind damage etc.) must be correctly identified and dated by accurately counting the rings. Additional complications include: identifying missing or false rings, determining the date of sampling or the death of the tree, and determining the season the tree was scarred (Agee, 1993; Morrison and Swanson, 1990; Weisberg, 1998). Finally, different methods of summarizing the chronology of fires in an area to describe the frequency, severity, and size of fires within a fire regime often make it difficult to compare data sets.

Records of fire history that span several millennia come from the analysis of charcoal deposited in lake sediments (Clark *et al.*, 1998; Long *et al.*, 1998). Charcoal data provide records of fire frequency that span 1000s of years and enable the examination of the interactions between fire, climate, and vegetation

over long time scales (Clark, 1990; Long *et al.*, 1998; Millspaugh and Whitlock, 1995). Charcoal data from lake sediments record changes in fire frequency over time but cannot precisely describe the size of area that was burned. The temporal resolution of charcoal records is annual only for varved sediments (Clark, 1988b; Clark, 1990). In sediment that are not varved, a chronology is established by developing an age vs. depth curve from a series of  $^{210}\text{Pb}$  and  $^{14}\text{C}$  age determinations and is limited by the resolution of those methods (Saarnisto, 1988).

Our ability to reconstruct prehistoric fires from charcoal data rests on understanding the processes that control charcoal accumulation in lakes following modern fires, including production, transportation, and deposition. Fire behavior (i.e., whether the fire is smoldering or flaming), rates of fuel consumption, and emission production are highly variable within and between ecosystems (Cofer *et al.*, 1997; Patterson *et al.*, 1987; Stocks and Kauffman, 1997). Complete combustion converts organic fuels into heat, carbon dioxide, and water vapor. Incomplete combustion results in the production of emissions, including charcoal (Cofer *et al.*, 1997). Therefore, the amount of charcoal produced by a fire is related to the fire's behavior, rate of fuel consumption, and combustion efficiency. Weather conditions (i.e., wind direction and speed), in addition to the relationship between charcoal particle size and particle settling velocity, determine the distance that charcoal particles are transported from a fire (Clark,

1988a; Patterson *et al.*, 1987). Theoretical models (Clark, 1988a; Patterson *et al.*, 1987), empirical studies of charcoal deposited after modern fires (Clark *et al.*, 1998; Whitlock and Millspaugh, 1996), and charcoal studies that incorporate dendrochronological data (Clark, 1988b; Clark, 1990; MacDonald *et al.*, 1991; Millspaugh and Whitlock, 1995) suggest that macroscopic particles record signals from local fires and microscopic particles may record regional signals. Finally, characteristics of the watershed and lake influence the patterns of charcoal deposition within the lake and the remobilization of charcoal after the fire event (Larsen and MacDonald, 1993; Whitlock *et al.*, 1997). All of these processes, from charcoal production to deposition, influence the amount of charcoal in lake sediments and must be understood in order to accurately interpret fossil charcoal data in terms of past fire events.

Despite the fact that our ability to interpret prehistoric fires rests on understanding the charcoal taphonomic processes, only two studies have examined the accumulation of charcoal in lakes following modern fires (Clark *et al.*, 1998; Whitlock and Millspaugh, 1996). This study builds on previous information by examining the charcoal record of 36 lakes following a large stand-replacing fire in the central Cascade Range of Oregon. The Charlton Burn covered 37.7 km<sup>2</sup> from August 23-27 in 1996. Approximately 73% (26.3 km<sup>2</sup>) of the burned area had >95% tree mortality (J.Kertis, unpublished data, 1997). The fire burned old-growth stands (>300 years in age) of *Tsuga mertensiana*. Because

the burn contained several lakes, it provided an excellent opportunity to study how the abundance of charcoal in lakes related to fire and weather characteristics, the bathymetric characteristics of lakes, and topographic features of the region.

This study addresses three questions to clarify the interpretation of charcoal data: (1) do macroscopic charcoal particles ( $>125\ \mu\text{m}$ ) record a signal of a local fire, (2) do the prevailing winds during a fire affect the source area of macroscopic charcoal, and (3) is the abundance of macroscopic charcoal controlled by variables that influence the production, transportation, and deposition of charcoal? To address the first two questions, the stratigraphic variations of charcoal abundance in cores from burned sites and unburned sites were examined in order to determine if the charcoal signal recorded in lake sediments differed between different groups of sites. To address the third question, the relationship between the charcoal abundance in the top sample interval (0-2 cm depth) and variables that influence the production, transportation and deposition of charcoal in lake sediments was examined with regression analysis. Understanding the patterns of modern charcoal accumulation in lakes within and surrounding the Charlton Burn provides important information to assist in the interpretation of charcoal data.

## CHAPTER II

### STUDY AREA DESCRIPTION

The 1996 Charlton Burn is located primarily in the Waldo Lake Wilderness Area of the Willamette National Forest, in the central Cascade Range of Oregon (Figure 1)(J.Kertis, unpublished data, 1997). The burn abuts the northern shore of Waldo Lake. The abundance of lakes both within and outside of the burn perimeter and the relatively uniform topography and vegetation made the area north of Waldo Lake is ideal for this study.

The study area is located in the High Cascades physiographic province, a relatively young area having formed within the last nine million years (Priest *et al.*, 1983). Volcanism and glaciation are the primary processes that have shaped the landscape (Crandell, 1965; Porter, 1983; Woller, 1986). The High Cascades consists of a plateau, ranging in elevation from 1500-1800 m, punctuated by composite volcanic peaks, reaching elevations >3000 m (Franklin and Dyrness, 1988). The plateau is formed by overlapping shield volcanoes (Taylor, 1990), that produced flows ranging in composition from olivine basalt to basaltic andesite (Luedke and Smith, 1991; Taylor, 1990; Woller and Black, 1983). Most of the composite volcanoes that typify the modern landscape in the High Cascades

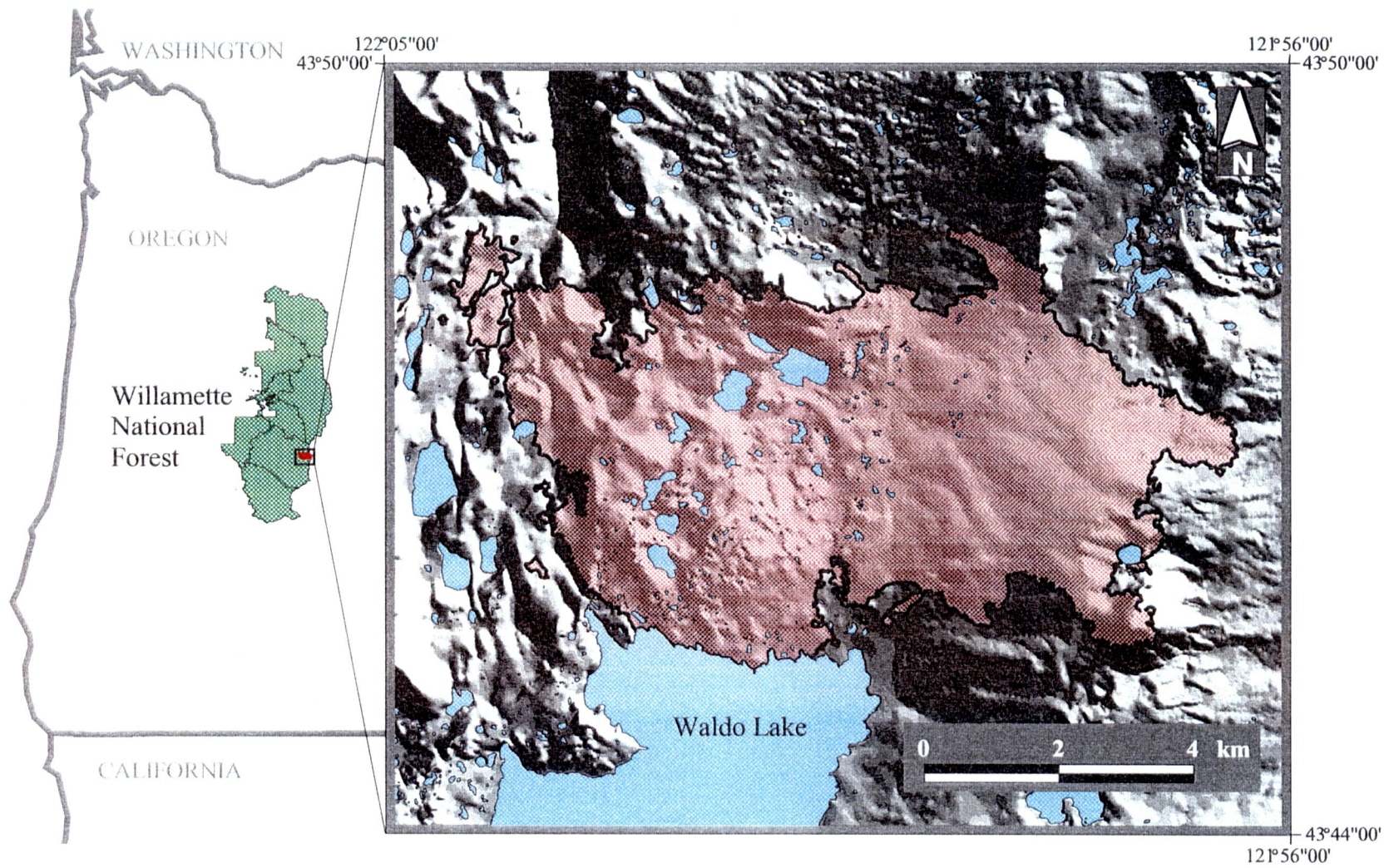


Figure 1. Location of study area. The 1996 Charlton Burn is highlighted in red.

developed since the beginning of the Quaternary (Orr *et al.*, 1992). During the Pleistocene, extensive glaciers developed along the crest of the Cascades and flowed into the surrounding valleys (Crandell, 1965; Porter, 1983).

The study area is located within the *Tsuga mertensiana* vegetation zone which is found in central Oregon at elevations ranging from 1700-2000 m (Franklin and Dyrness, 1988). *Tsuga mertensiana* dominates old-growth forests but also present are *Pinus monticola*, *Pinus contorta*, *Pseudotsuga menziesii*, and *Picea engelmannii* (Franklin and Dyrness, 1988). In the area north of Waldo Lake, the understory consists primarily of *Vaccinium membranaceum* and *Xerophyllum tenax*. *Pinus contorta* and *Abies lasiocarpa* dominate in seral stands (Franklin and Dyrness, 1988).

Annual precipitation based upon 31 years of data from the Round Mountain remote automated station (1950 m elevation), located approximately 27 km northeast of Waldo Lake, is 1067 mm (Willamette and Deschutes national forests, 1996). Most of the precipitation falls in the winter as snow (Franklin and Dyrness, 1988). Winter low temperatures average -6°C and summer high temperatures average 30°C (Willamette and Deschutes national forests, 1996).

Land-use activities have been limited in the area surrounding Waldo Lake. The area was never logged because of the availability of more productive forests elsewhere in the Cascades and also efforts to protect Waldo Lake (Burns,

1973; Rakestraw and Rakestraw, 1991). Land-uses have included recreational activities, such as fishing and hunting, and sheep grazing from the late 1800s to 1940s (Rakestraw and Rakestraw, 1991). Forest Service records and dendrochronological data indicate that the area directly north of Waldo Lake is characterized by a variable fire frequency, ranging from 100 to 300 years, and variable fire severity (Willamette and Deschutes national forests, 1996). In the absence of fire in the last 100 years and logging, the vegetation of the study area supported late-successional stands of *Tsuga mertensiana* (Burns, 1973).

The Charlton Burn covered 37.7 km<sup>2</sup> from August 23-27 1996. The fire was severe, with 73% (26.3 km<sup>2</sup>) of the area within the burn (excluding lakes and scree slopes) experiencing >95% tree mortality (Figure 2)(J. Kertis, unpublished data, 1997). The heat of the fire created a strong convectional plume reaching approximately 9000 m above the ground (D. Sullivan, personal communication, 1999). During the fire and the days immediately afterwards, local winds were from the southwest. The fire was actively fought from its ignition; however, it was not brought under control until the weather changed significantly on August 27, 1996 (D. Sullivan, personal communication, 1999).

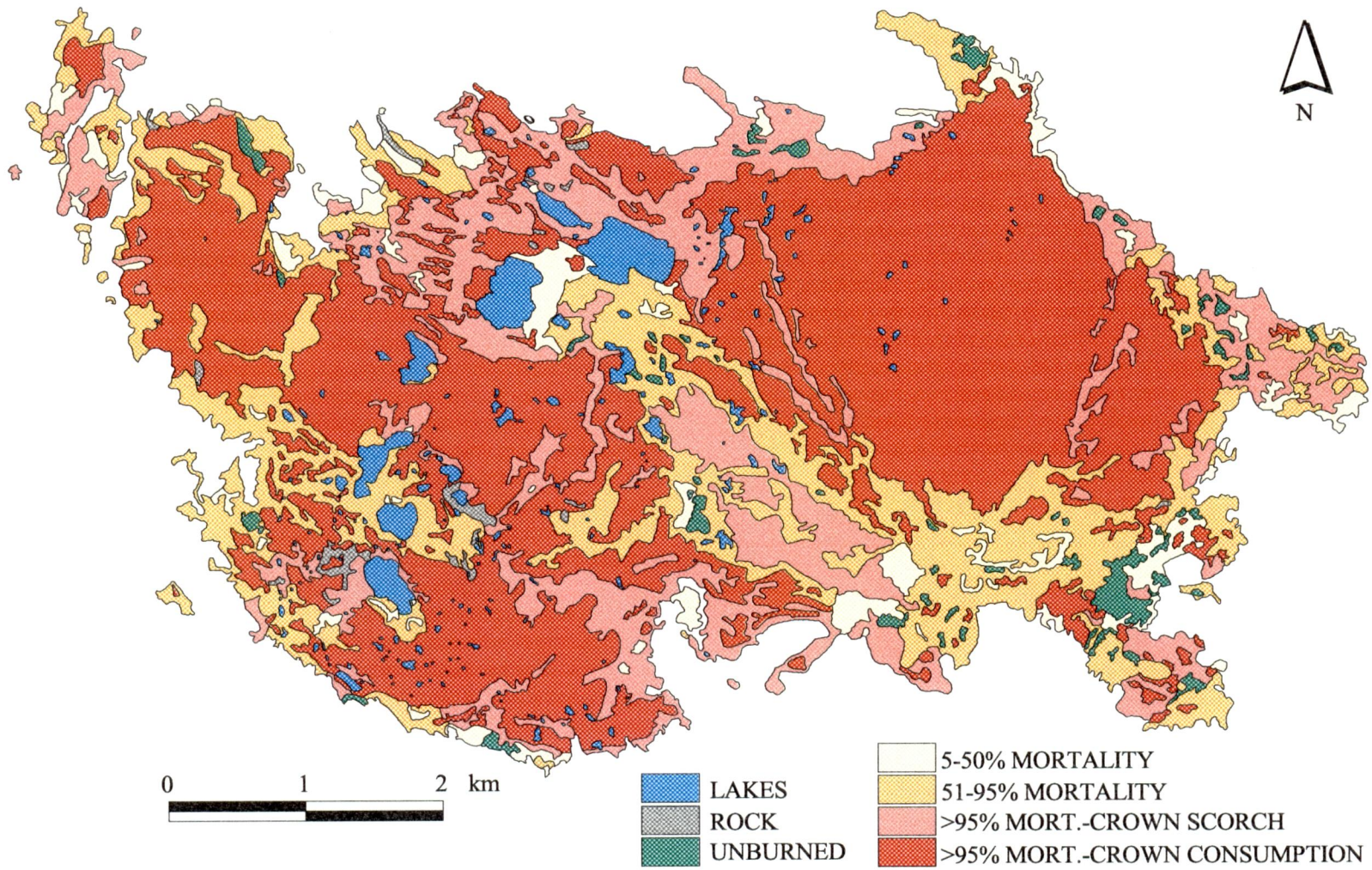


Figure 2. Patterns of fire severity in the Charlton Burn. See Figure 1 for geographic location.

## CHAPTER III

### METHODS

#### Introduction

Sediment cores were collected from lakes within and near the 1996 Charlton Burn. The number of charcoal particles per gram of sediment was quantified for each stratigraphic level of each core. Charcoal abundance within each core and among groups of cores (from burned, unburned, upwind, and downwind sites) was examined statistically. Finally, the relationship between charcoal abundance and variables that may control the production, transportation, or deposition of charcoal particles were analyzed. Field and laboratory procedures, the specific variables examined, and the methods of data analysis are described below.

#### Field and Laboratory Procedures

Sediment cores were collected in 1997 and 1998 from 36 lakes within and near the Charlton Burn (Figure 3; Table 1). Of the 36 lakes sampled, 19 were located within the burned area and 17 were located in unburned watersheds. Seven unburned sites lay upwind of the fire (to the southwest) and ten were

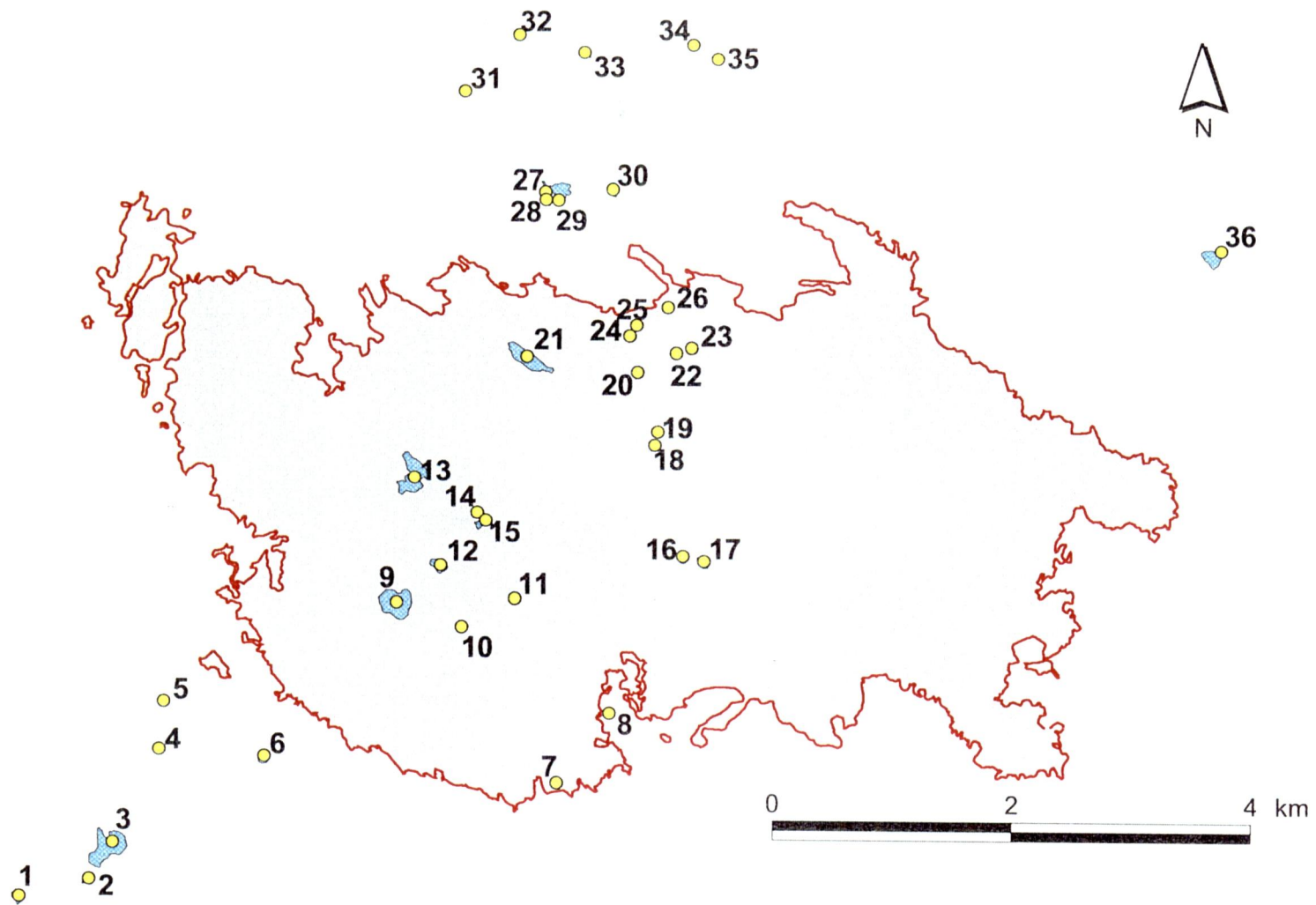


Figure 3. Location of study sites. See Figure 1 for geographic location and Tables 1 and 3 for site information.

located downwind (to the north and northeast) (Figure 3).

The 29 lakes sampled in 1997 were selected from those used in a study already in progress to monitor the effects of the 1996 Charlton Burn on lake ecosystems (Gresswell *et al.*, 1998, unpublished report)(Table 1). Gresswell *et al.* (1998, unpublished report) randomly selected 32 lakes 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). For a detailed description of the experimental design and sampling strategy of the lake study see appendix A. Seven additional lakes were sampled in 1998, solely for this study, in order to represent lakes that had bathymetric characteristics that were more similar to those used for paleoecological studies (Table 1). They were selected on the basis of burn status (located in either a burned or an unburned watershed, without regard to the severity of the burned watersheds), surface area ( $\geq 1.50$  ha), maximum depth ( $\geq 3.00$  m), and even-spatial distribution across

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

the study area.

Sediment cores, 12 cm long, were collected from the deepest part of each lake with a gravity corer that preserves the mud-water interface undisturbed. The cores were extruded vertically in the field at 2-cm intervals. Samples were stored in plastic bags and transported back to the laboratory for analysis. The maximum water depth of each lake was measured, and the width of riparian vegetation and maximum slope adjacent to the lakeshore was estimated in the field.

In the laboratory, a 5 cm<sup>3</sup> subsample from each 2-cm sample interval was soaked in a dilute (1:100) solution of sodium hexametaphosphate for 24 hrs and gently wet-sieved through a 63 µm mesh screen. Subsamples were treated in a dilute (1:20) solution of common household bleach (5% sodium hypochlorite) and heated below boiling for five minutes. Subsamples were then gently washed through nested 250 µm and 125 µm mesh screens.

Charcoal particles greater than 125 µm were tallied for each subsample using a binocular microscope (Appendix B). This size range was chosen on the basis of Whitlock and Millspaugh (1996) who found that larger macroscopic charcoal particles (>125 µm) showed the same trends as smaller size classes (63-125 µm) and provided a good record of local fires. Also, the larger particles are easier to positively identify and less tedious to quantify.

The dry weight for each sample was obtained by heating a 1-cm<sup>3</sup> subsample at 90° C for 24 hours. Charcoal abundance, the number of charcoal particles per gram (char/g), was calculated by dividing charcoal concentration, the number of charcoal particles per cubic centimeter (char/cm<sup>3</sup>), by dry weight (g/cm<sup>3</sup>) (Appendix B).

#### Variables Examined as Potential Controls of Charcoal Abundance

Eight variables were considered as possible controls of charcoal abundance. They include: (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 center of the fire. The variables were derived from multiple sources (Table 2). Table 3 describes all of the characteristics for all of the sites. Additional information about the derivation of average wind direction, slope, riparian margin, and distance from the center of the fire is provided below.

The prevailing wind direction was calculated by averaging the daily wind directions recorded by three USDA Forest Service Remote Automated Weather (RAW) Stations for the days during and immediately following the fire. The RAW stations are: Black Rock (T24s-R07e-S29) in the Deschutes National Forest, and Pebbles (T24s-R07e-S29) and Fields (T22-R04e-S11) in the Willamette

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 <sup>a</sup> , 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 <sup>a</sup>
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 <sup>b</sup>
Area	Surface area of lake (ha)	Calculated from GIS lake coverages of the Willamette <sup>c</sup> & Deschutes <sup>d</sup> 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) <sup>e</sup>
Margin	Extent (width) of post-fire riparian vegetation (0 m, 0-3 m, >3 m)	Field observations
Distance	Distance of lake from the center of the fire (m)	Calculated from GIS lake coverages of the Willamette <sup>c</sup> & Deschutes <sup>d</sup> national forests

<sup>a</sup> GIS fire severity coverage provided in 1997 by J. Kertis, Siuslaw National Forest

<sup>b</sup> RAW Station data provided in 1997 by P. McCulley, Willamette National Forest

<sup>c</sup> 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

<sup>d</sup> Deschutes National Forest GIS lake coverage provided in 1999 by D. Rawson, Deschutes National Forest

<sup>e</sup> 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. <sup>a</sup>	Char/g <sup>b</sup>	Burn status <sup>c</sup>	Severity (%) <sup>d</sup>	Relative position	Area (ha)	Depth (m)	Slope <sup>e</sup>	Margin (m)	Distance (m)	Year sampled
1	128	U	0	upwind	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

<sup>a</sup> Location of site is shown on Figure 3

<sup>b</sup> Charcoal abundance, top-sample interval (0-2 cm depth)

<sup>c</sup> U = unburned site; B = burned site

<sup>d</sup> >95-C = >95 % tree mortality -- crown consumption

>95-S = >95 % tree mortality -- crown scorch

<sup>e</sup> mod. = moderate

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. Maximum slope values were calculated from a 10-m-resolution digital elevation model for the Charlton Burn area and checked against U.S. Geological Survey 7.5' topographic maps and my field notes. Three slope classes were defined: (1) flat, (2) moderate, and (3) steep. The width of post-fire riparian vegetation margin was established from field photographs and notes. Three riparian-margin classes were defined as: (1) no riparian vegetation, (2) a riparian margin ranging from 0-3 m wide, and (3) a riparian margin >3 m wide. Distances from the geographic center of the fire to the center of each lake were computed based upon Geographic Information System (GIS) coverages of the Charlton Burn and lakes of the Willamette and Deschutes national forests.

### Data Analysis

The stratigraphic variation of charcoal abundance in each lake was examined. Charcoal abundance was plotted against depth (ranging from 0-12 cm) for each lake. Stratigraphic variations in cores from burned and unburned sites were compared to determine if the charcoal signal varied between the different groups of sites. The samples from unburned sites were also grouped according to the site's location with respect to the fire, either upwind or

downwind. The stratigraphic trend for each group (burned, unburned, upwind, and downwind) was determined by calculating the average charcoal abundance, i.e., the geometric mean, at each sample interval.

Minitab<sup>®</sup> 12.1 software was used to statistically analyze the data. To determine the presence or absence of a charcoal "peak" in the upper sediments of the cores, charcoal abundance of the top (0-2 cm depth) and second (2-4 cm depth) samples from each lake were paired. These paired values were grouped by burn status. For both groups, burned and unburned, a paired t-test was used to determine whether the mean of the sample differences between pairs of values was significantly different from zero, the hypothetical mean of differences. In addition, the mean of the top samples of cores from burned sites was compared to that of cores from unburned sites with a two-sample t-test to determine if they were statistically different.

Prior to these tests, the underlying assumptions of paired and two-sample t-tests were evaluated. For these tests to be valid, the groups of variates must be normally distributed and also the variances of the groups must be homoscedastic. Distribution of charcoal abundance for each group was evaluated by examining histograms and normal probability plots and also with the Ryan-Joiner test for normality, a correlation-based test. Homogeneity of variance was tested by comparing the variances of the two groups with an F-test. In order to satisfy the assumptions of normally distributed data for each group

and homogeneity of variances between groups, the charcoal abundance data were logarithmically transformed. The transformation changed the structure of the data and reduced the influence of outlying variates. In addition, the presence or absence of a charcoal peak in the cores from unburned sites, grouped by upwind and downwind position, was determined by repeating the analytic steps described above for the top and second samples from those sites.

The relationships between the charcoal abundance in the top sample (0-2 cm depth) and the 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 "dummy variables." For each qualitative variable having ( $X$ ) possible states, ( $X-1$ ) dummy variables were used in the regression model to represent the variable. Each dummy variable was assigned a value of one or zero, so that the term either dropped out or had a value of one in the regression equation. Histograms and normal probability plots of the distributions of numeric variables (i.e., charcoal abundance, area, depth, and distance) were examined. They indicated that charcoal abundance, area, depth and distance were log-normally distributed. Consequently, these data were logarithmically transformed.

Two series of models were created, 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 (Table 2). Best sub-sets 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 explanation of the variation of charcoal abundance.

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. Comparison of the calculated F-ratio ( $F\text{-ratio} = MS_{\text{regress.}}/MS_{\text{error}}$ ) with the critical F-ratio (i.e., the value of F where  $p=0.05$ ) indicated whether the regression model was significant (i.e., where at least one of the independent variables of the model improved the prediction of the dependent variable, charcoal abundance). The coefficient of determination ( $R^2 = MS_{\text{regress.}}/MS_{\text{total}}$ ) measured the quality of fit of the regression.  $R^2$  indicated the level of correlation between observed and predicted values of charcoal abundance. 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. The p-value was the probability of obtaining a specific t-statistic by chance alone. Finally, the

residuals and fits of the reduced models were examined to evaluate the assumptions of independent, normally-distributed residuals.

## CHAPTER IV

### RESULTS

#### Summary of Site Characteristics

Of the 36 lakes sampled, 19 were located within the burned area and 17 were located in unburned watersheds (Figure 3). Twelve-cm-long cores were collected from 34 of the lakes. Eight-cm-long cores were recovered from two lakes, sites 2 and 24 (Figure 3; Table 3). Of the burned sites, no lakes came from areas that experienced 5-50% tree mortality, two lakes were from areas with 51-95% mortality, seven lakes were located in areas with >95% mortality and crown scorch, and ten lakes were in areas with >95% mortality and crown consumption. Seven of the unburned sites were located upwind and ten were downwind of the fire (Figure 3). The topography of the study area was homogenous and most lakes (24) were located in flat terrain. Ten lakes had moderate slopes adjacent to their shores and two had steep slopes adjacent to their shores. Fourteen lakes lacked significant riparian vegetation, 15 lakes had a riparian margin of 0-3 m, and seven lakes had a riparian margin >3 m.

### Examination of Stratigraphic Variations of Charcoal in Lake Sediments

The assumptions of paired and two-sample t-tests, which include (1) normally-distributed data within each group and (2) equal variances between groups, were evaluated for charcoal abundance from the top (0-2 cm depth) and second (2-4 cm depth) samples of cores from burned and unburned sites. The histograms and normal probability plots for each of the four groups (Figures 4-7) indicated that (1) logarithmic transformation produced a normal distribution for the group whose raw charcoal abundance was not normally distributed and (2) logarithmic transformation slightly improved the normal distributions of the other three groups (Table 4). The variances of charcoal abundance in the top and second samples from burned sites were equal for both the raw ( $F=1.083$ ,  $p=0.868$ ) and transformed data ( $F=1.876$ ,  $p=0.192$ ) (Figure 8). Similarly, the variances of charcoal abundance in the top and second samples of cores from unburned

Table 4. Description of Charcoal Data from Burned and Unburned Sites

Data	Site group	Sample depth (cm)	Ryan-Joiner Normality Test		Normal distribution
			r	p	
Raw	Burned	0-2	0.96	>0.10	Yes
		2-4	0.86	<0.01	No
	Unburned	0-2	0.96	>0.10	Yes
		2-4	0.96	>0.10	Yes
Transformed	Burned	0-2	0.98	>0.10	Yes
		2-4	0.98	>0.10	Yes
	Unburned	0-2	0.98	>0.10	Yes
		2-4	0.98	>0.10	Yes

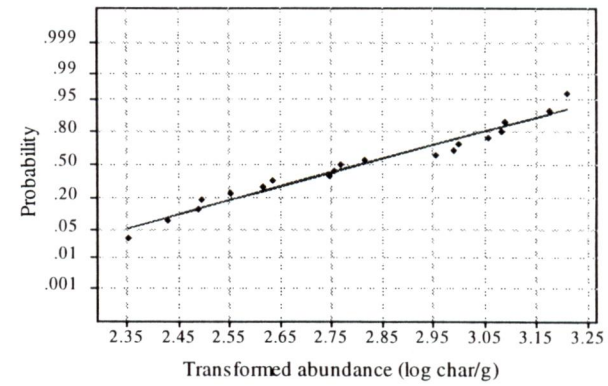
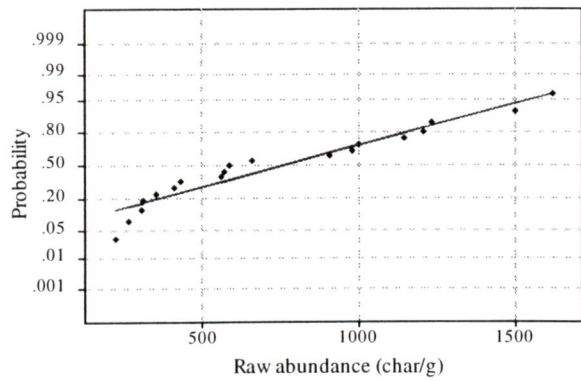
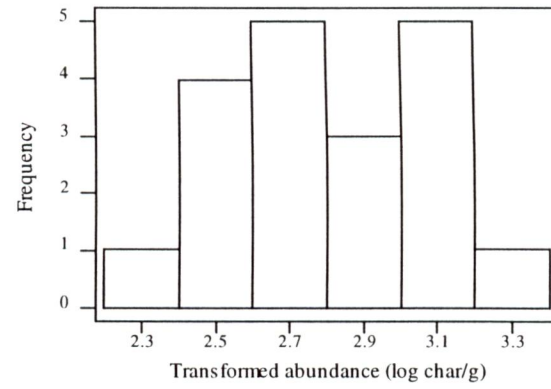
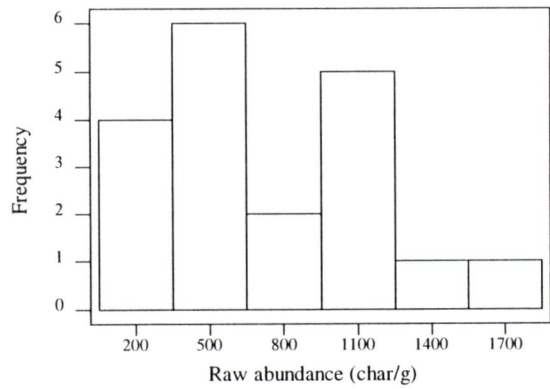


Figure 4. Histograms and normal probability plots illustrate the distributions of raw and transformed charcoal abundance in the top samples (0-2 cm depth) of cores from burned sites.

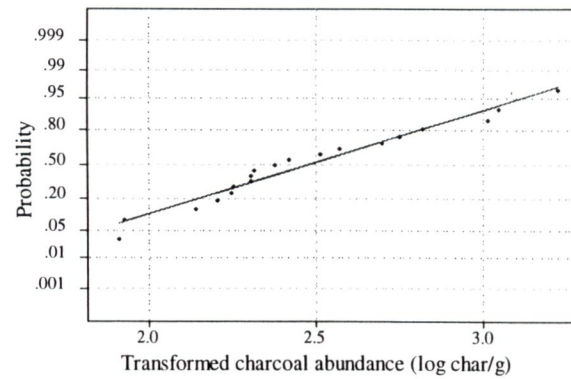
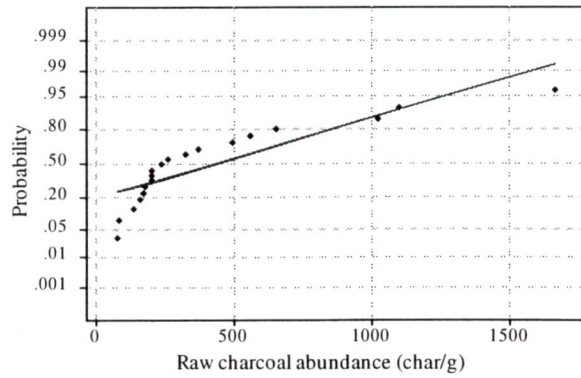
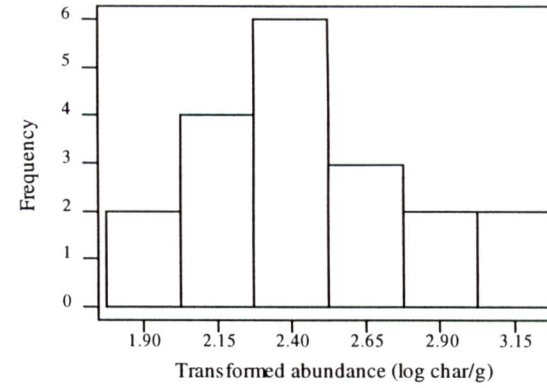
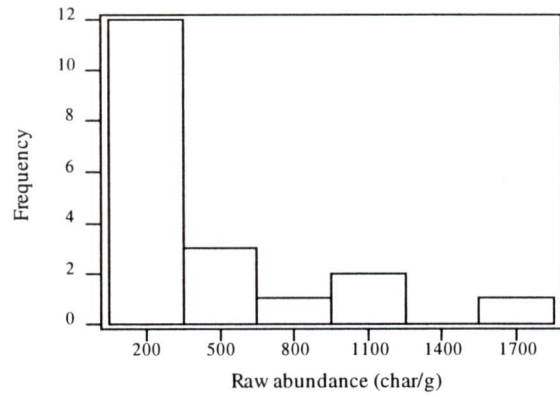


Figure 5. Histograms and normal probability plots illustrate the distributions of raw and transformed charcoal abundance in the second samples (2-4 cm depth) of cores from burned sites.

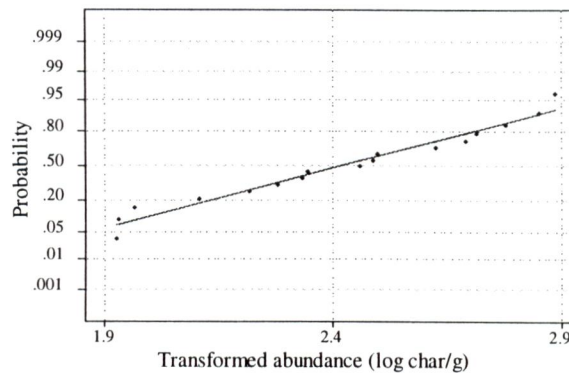
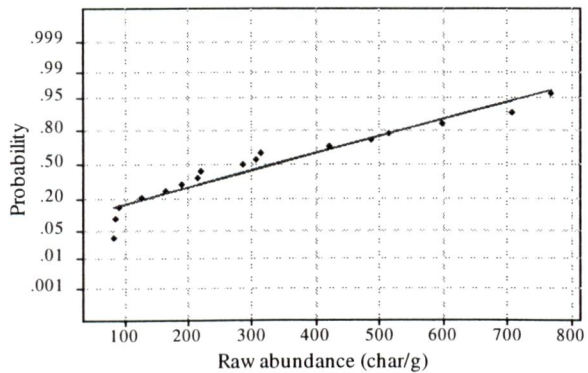
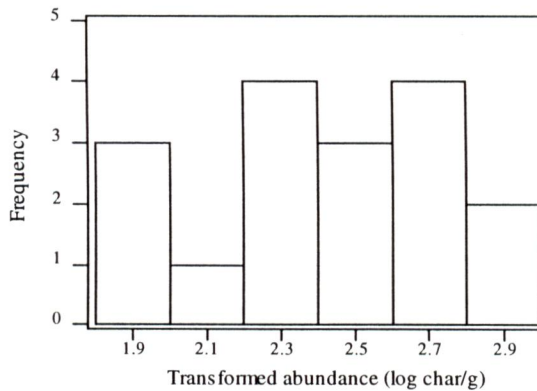
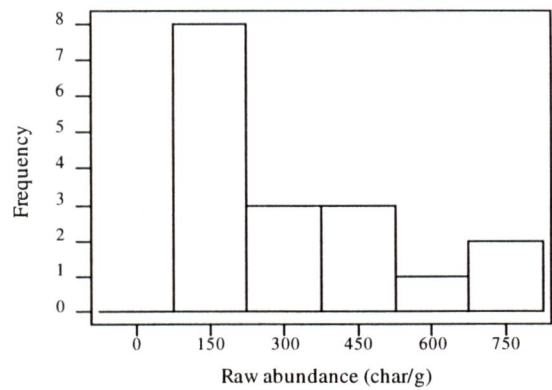


Figure 6. Histograms and normal probability plots illustrate the distributions of raw and transformed charcoal abundance in the top samples (0-2 cm depth) of cores from unburned sites.

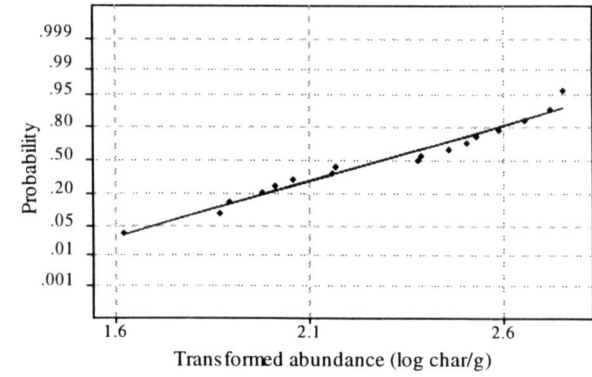
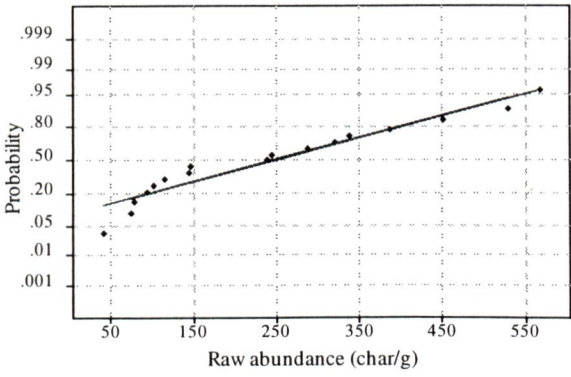
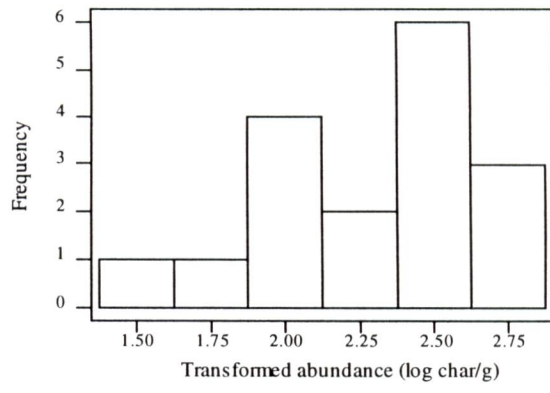
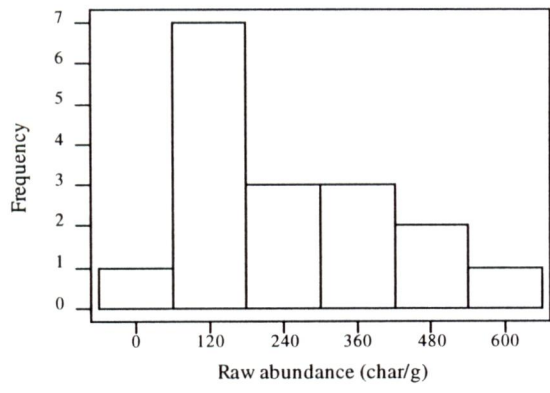


Figure 7. Histograms and normal probability plots illustrate the distributions of raw and transformed charcoal abundance in the second samples (2-4 cm depth) of cores from unburned sites.

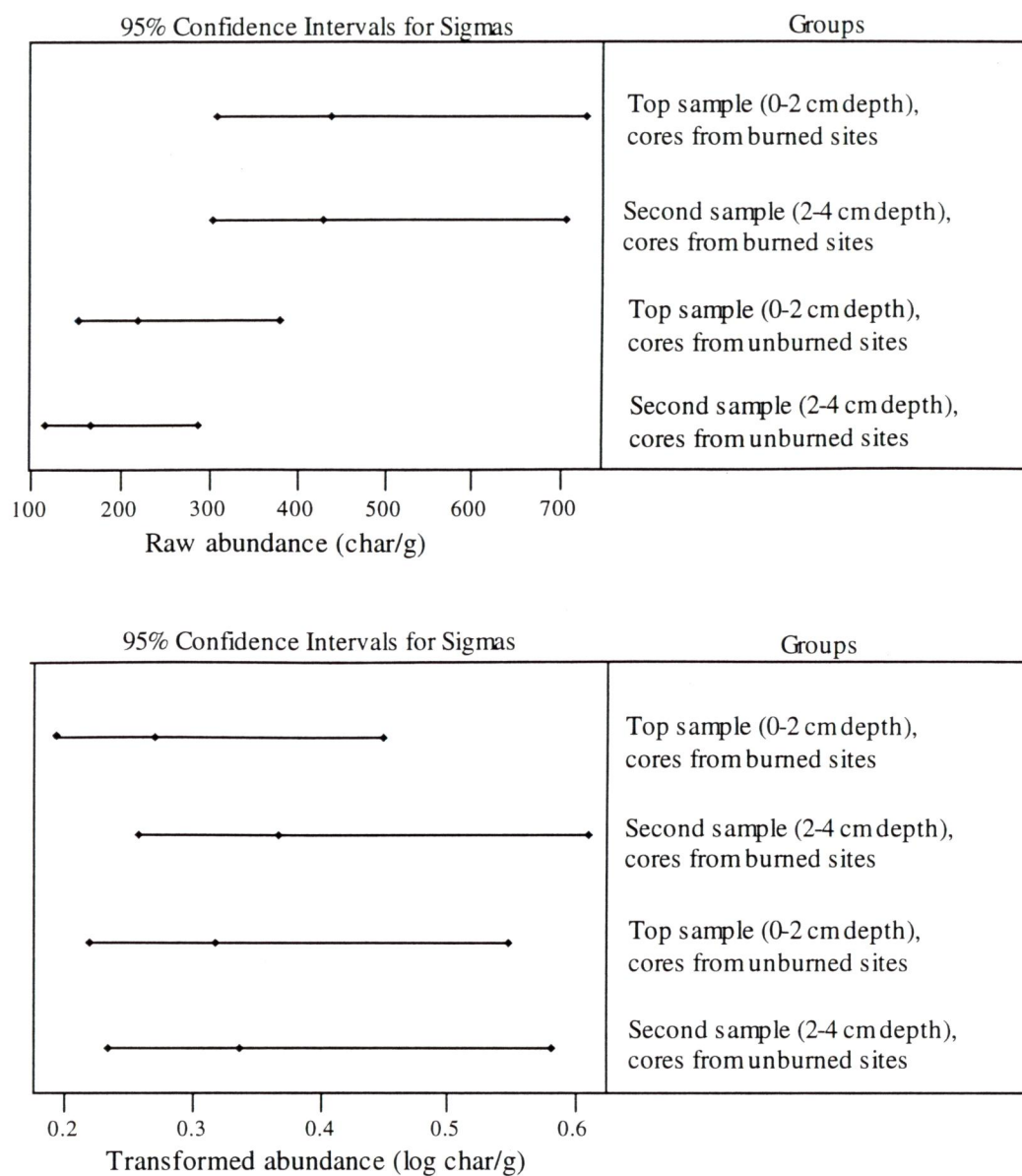


Figure 8. The 95% confidence intervals for the standard deviation of charcoal abundance for each group (from burned and unburned sites) of raw (top graph) and transformed (bottom graph) data.

sites were equal for both raw ( $F=1.736$ ,  $p=0.280$ ) and transformed data ( $F=1.125$ ,  $p=0.817$ ) (Figure 8). However, the variances of charcoal abundance in the top samples from burned and unburned sites were not equal for raw data ( $F=3.981$ , and  $p=0.008$ ) but were statistically equal for transformed data ( $F=0.415$ ,  $p=0.493$ ) (Figure 8). The charcoal abundance data (char/g) were logarithmically transformed in order to meet the assumptions of paired and two-sample t-tests. Hereafter, the term charcoal abundance refers to the logarithmic values (log char/g).

The stratigraphic trends of charcoal abundance in cores from burned and unburned sites indicated (1) significant decreases in charcoal abundance with depth in cores from both burned and unburned sites and (2) a greater decrease from the top (0-2 cm depth) to the second sample (2-4 cm depth) in cores from burned sites than in cores from unburned sites. These results suggest that both burned and unburned sites received charcoal from the 1996 fire, but burned sites received more charcoal than unburned. This distinction is further supported by the greater charcoal abundance in the top samples (0-2 cm depth) from burned than unburned sites.

The stratigraphic variations of charcoal abundance in cores from burned and unburned sites were plotted (Figure 9) and the geometric means highlighted the stratigraphic trends among cores from burned and unburned sites (Figure 10). The 95% confident limits of the geometric means of the top sample interval

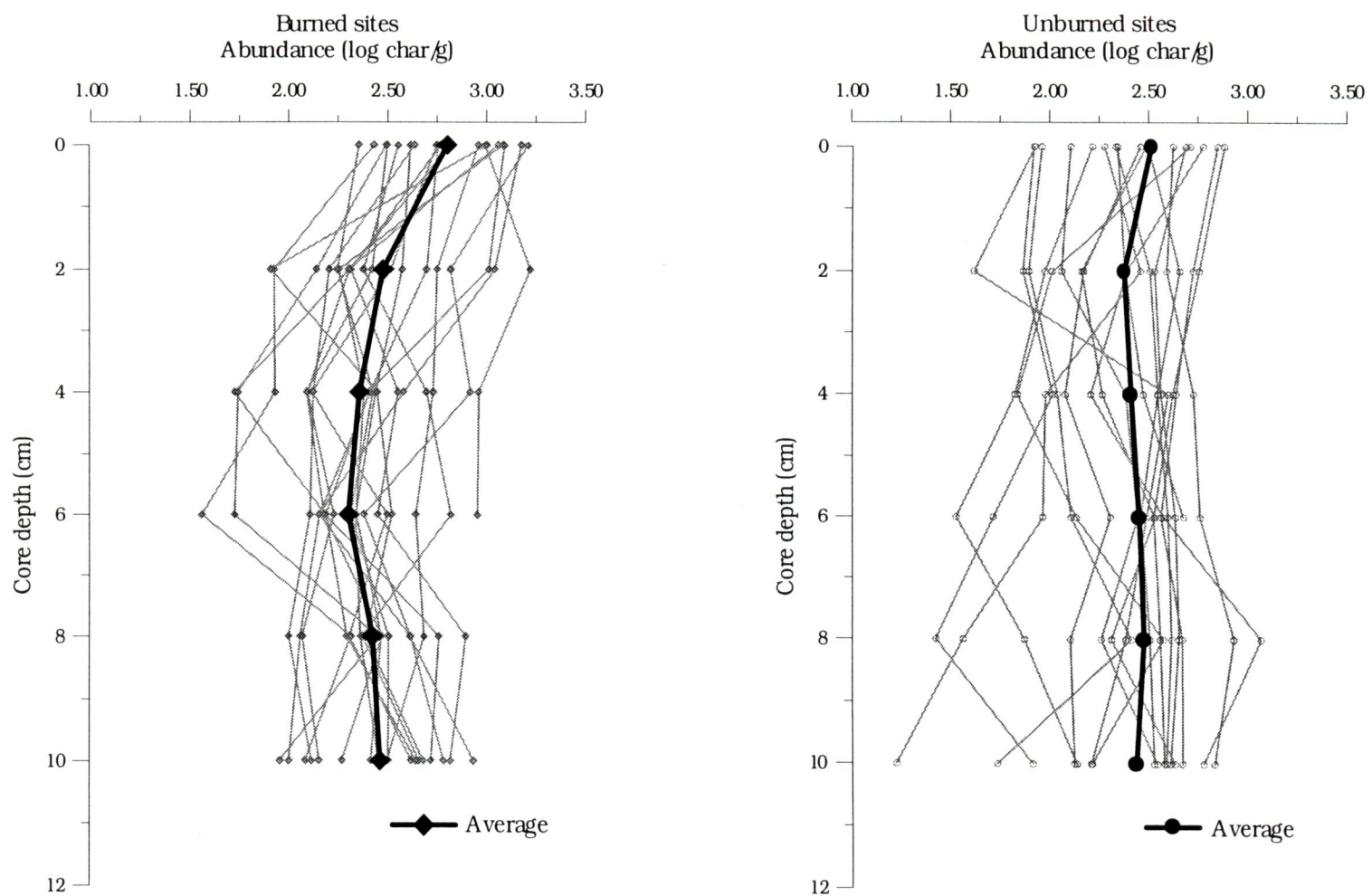


Figure 9. Stratigraphic variations of charcoal abundance plotted for all cores and grouped by burn status.

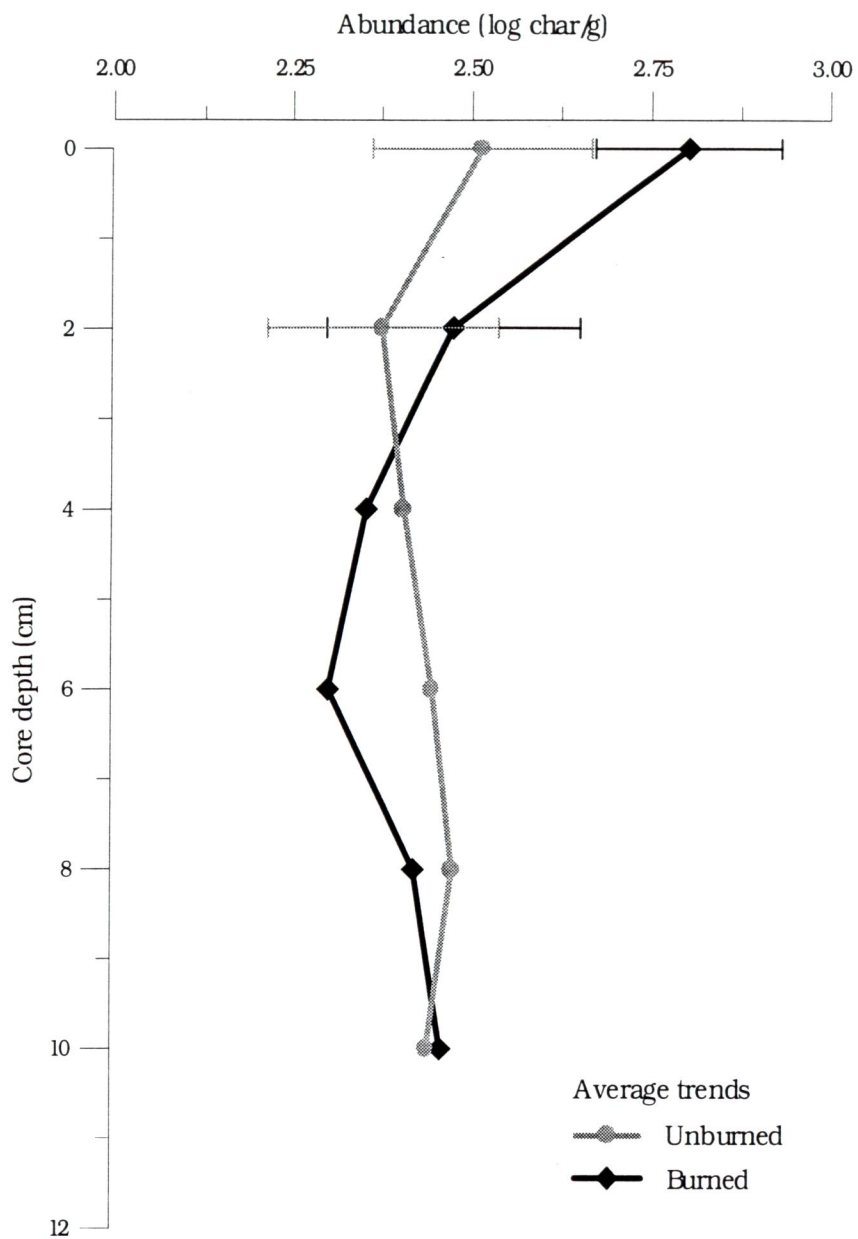


Figure 10. Comparison of stratigraphic trends of charcoal abundance in cores from unburned and burned sites. The 95% confidence limits are indicated for the top and second sample of both trends.

(0-2 cm depth) did not overlap (Figure 10). On average, cores from burned sites had a greater decrease in charcoal abundance from the top to the second sample than those from unburned sites (Figure 11). The greater decrease was evident in the trend of the geometric means (Figure 10). Charcoal abundance trends decreased with depth for both burned and unburned sites. The mean for cores from burned sites decreased from 634 char/g in the top sample to 298 char/g in the second sample (Figure 10). The mean continued to decrease to 203 char/g in the fourth sample (6-8 cm depth). The mean for unburned sites also decreased slightly from 260 char/g in the top sample to 190 char/g in the second sample (Figure 10).

Decreases in charcoal abundance with depth (Figure 11) were statistically significant for both burned and unburned sites. The assumptions of a paired t-test were satisfied for all relevant statistical samples. Charcoal abundance values of the top and second samples from both burned and unburned sites were normally distributed and homoscedastic. The mean of the differences between the top and second samples of cores from burned sites were statistically different from zero ( $t=4.41, p<0.00$ ). Similarly, the mean of the differences between the top and second samples of cores from unburned sites was also significantly different from zero ( $t=2.50, p<0.024$ ).

However, the decrease in the mean charcoal abundance in the top to the second sample from burned sites was greater in magnitude than from unburned

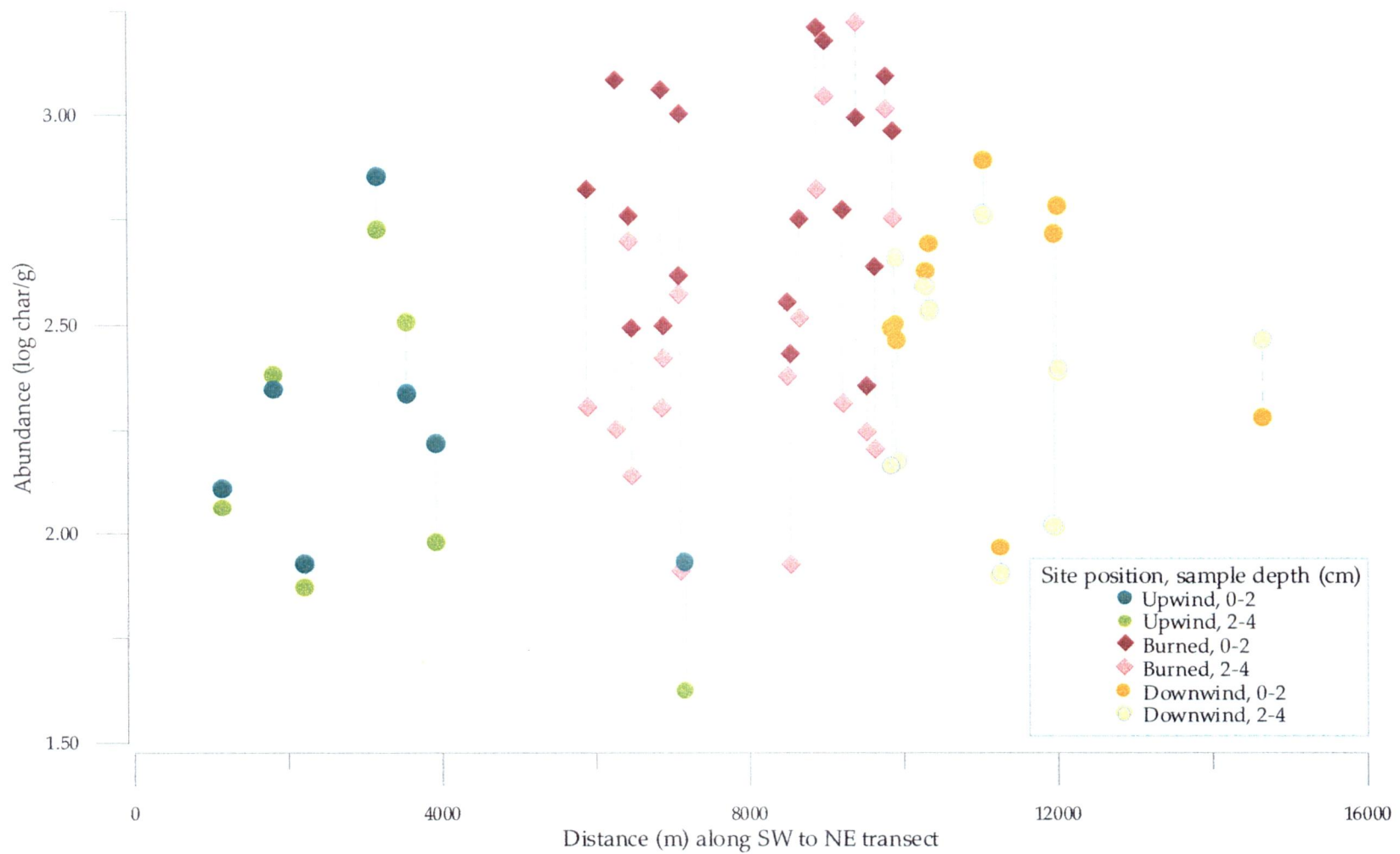


Figure 11. Comparison of charcoal abundance in the top and second samples from cores collected from upwind (unburned), burned, and downwind (unburned) sites.

sites (Figure 10). In burned sites, the difference between the mean of the top sample and second sample was 336 char/g. In unburned sites, the difference was 70 char/g, approximately one quarter the decrease from burned sites. Therefore, the peaks in charcoal abundance in the uppermost samples from burned sites tended to be better defined than in samples from unburned sites (Figure 11).

Cores from burned sites tended to have greater charcoal abundance in the top sample than those from unburned sites (Figure 11). The means of the top samples (0-2 cm depth) from burned (634 char/g) and unburned (260 char/g) sites were statistically different ( $t=3.92$ ,  $p<0.0004$ ). The significant difference supports the conclusion that the amount of charcoal received by lakes in burned sites is greater than in unburned sites adjacent to a fire.

In summary, these results suggest that both burned and unburned sites received charcoal from the Charlton fire. While the uppermost lake sediments from all sites tended to have peaks in charcoal abundance, the peaks from burned sites were better defined than those from unburned sites. In addition, the average amount of charcoal in the top sample (0-2 cm depth) from burned sites was statistically greater than from unburned sites.

The assumptions of paired and two-sample t-tests were evaluated for charcoal abundance from the top (0-2 cm depth) and second (2-4 cm depth) samples from upwind and downwind sites. The histograms and normal

probability plots for each of the four groups (Figures 12-15) indicated that (1) logarithmic transformation produced a normal distribution for the group whose raw charcoal abundance was not normally distributed and (2) logarithmic transformation did not dramatically alter the normal distributions of the other three groups (Table 5). The variances of charcoal abundance in the top and second samples from upwind sites were equal for both the raw ( $F=1.559$ ,  $p=0.603$ ) and transformed data ( $F=1.485$ ,  $p=0.643$ ) (Figure 16). Similarly, the variances of charcoal abundance in the top and second samples from cores from downwind sites were equal for both raw ( $F=1.539$ ,  $p=0.531$ ) and transformed data ( $F=1.153$ ,  $p=0.836$ ) (Figure 16). The variances of charcoal abundance in the top samples from cores from upwind and downwind sites were equal for raw data ( $F=1.180$ , and  $p=0.790$ ) and transformed data ( $F=1.410$ ,  $p=0.617$ ) (Figure 16). The charcoal abundance data were logarithmically transformed in order to meet

Table 5. Description of Charcoal Data from Upwind and Downwind Sites

Data	Site group	Sample depth (cm)	Ryan-Joiner Normality Test		Normal distribution
			r	p	
Raw	Upwind	0-2	0.82	<0.01	No
		2-4	0.93	>0.10	Yes
	Downwind	0-2	0.99	>0.10	Yes
		2-4	0.97	>0.10	Yes
Transformed	Upwind	0-2	0.94	>0.10	Yes
		2-4	0.99	>0.10	Yes
	Downwind	0-2	0.96	>0.10	Yes
		2-4	0.98	>0.10	Yes

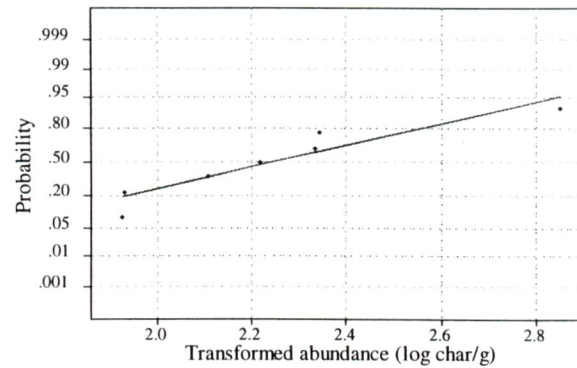
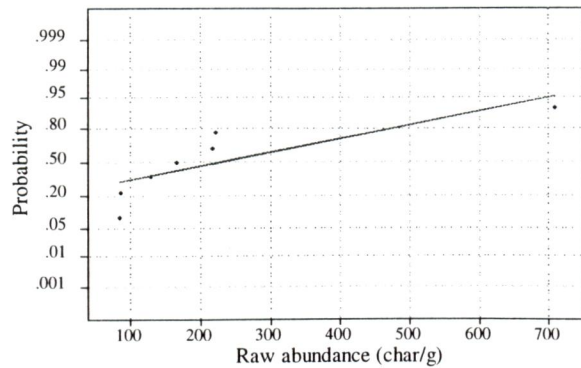
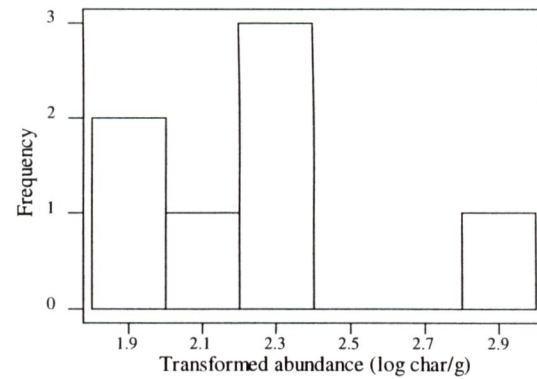
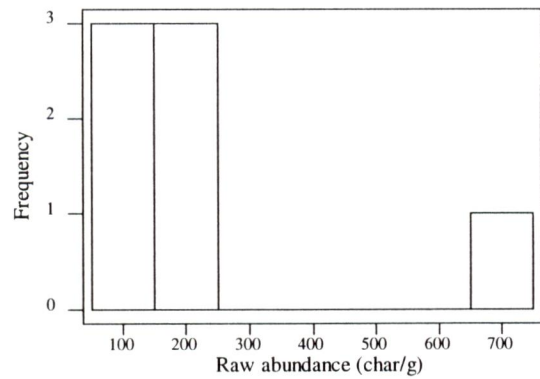


Figure 12. Histograms and normal probability plots illustrate the distributions of raw and transformed charcoal abundance in the top samples (0-2 cm depth) of cores from upwind sites.



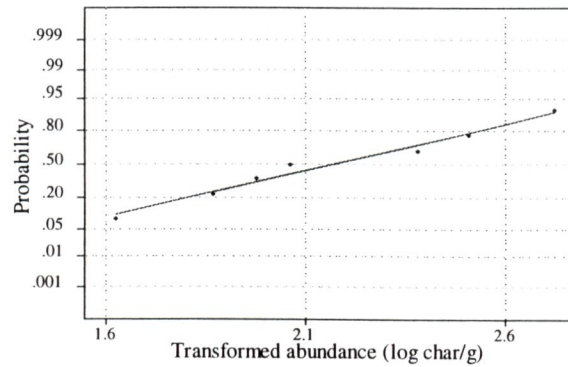
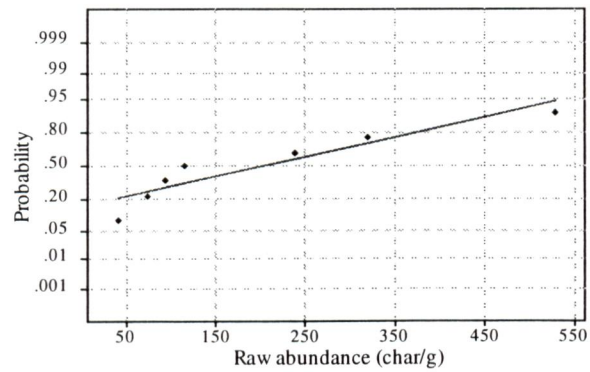
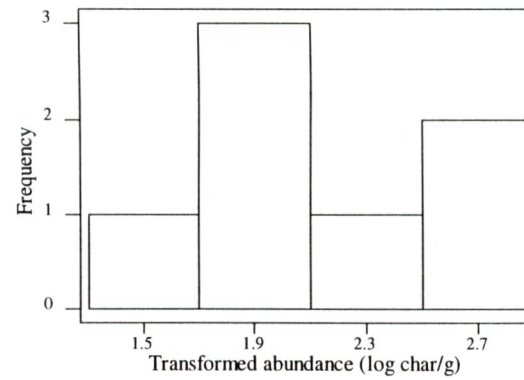
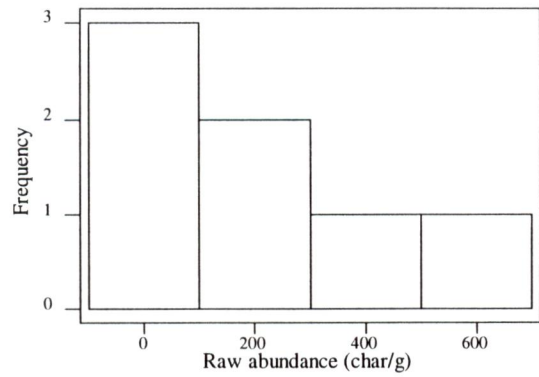


Figure 13. Histograms and normal probability plots illustrate the distributions of raw and transformed charcoal abundance in the second samples (2-4 cm depth) of cores from upwind sites.

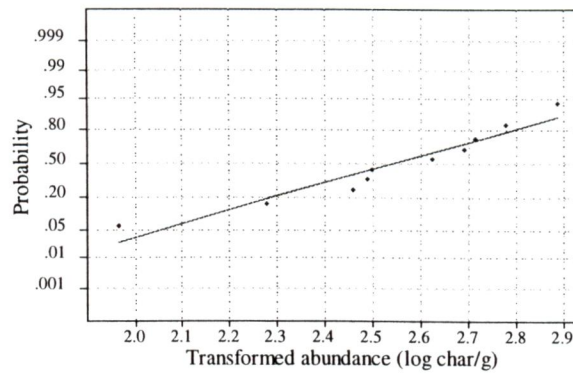
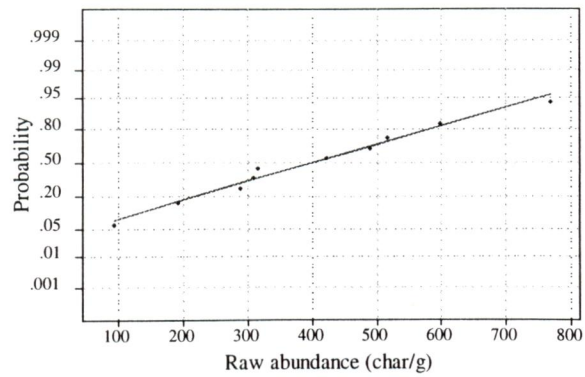
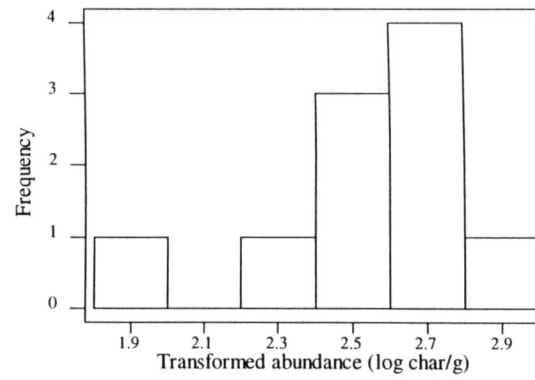
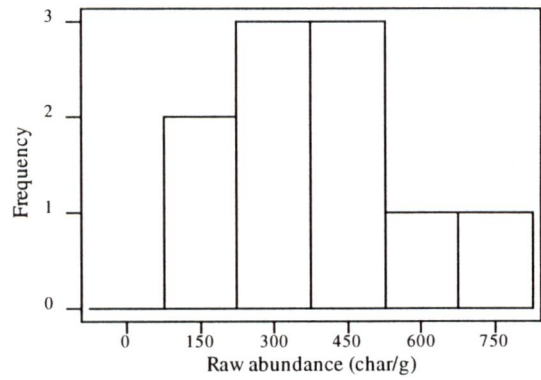


Figure 14. Histograms and normal probability plots illustrate the distributions of raw and transformed charcoal abundance in the top samples (0-2 cm depth) of cores from downwind sites.

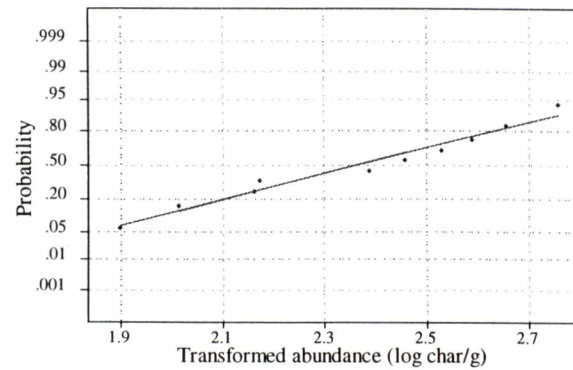
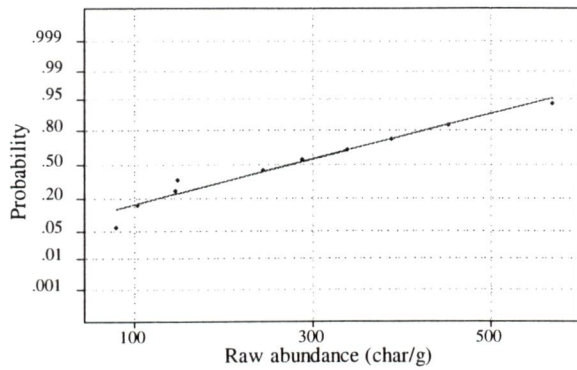
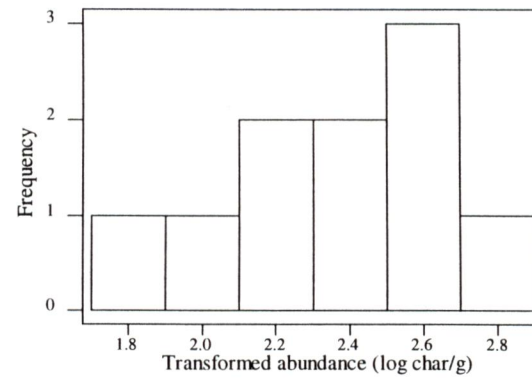
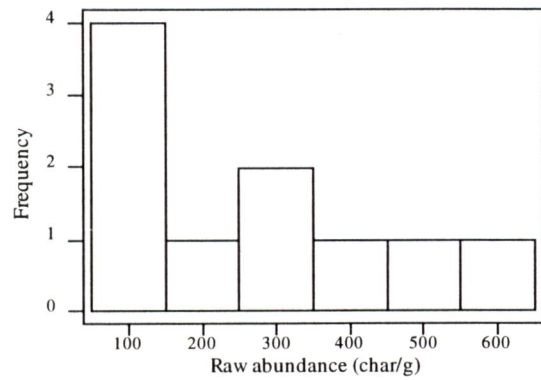


Figure 15. Histograms and normal probability plots illustrate the distributions of raw and transformed charcoal abundance in the second samples (2-4 cm depth) of cores from downwind sites.

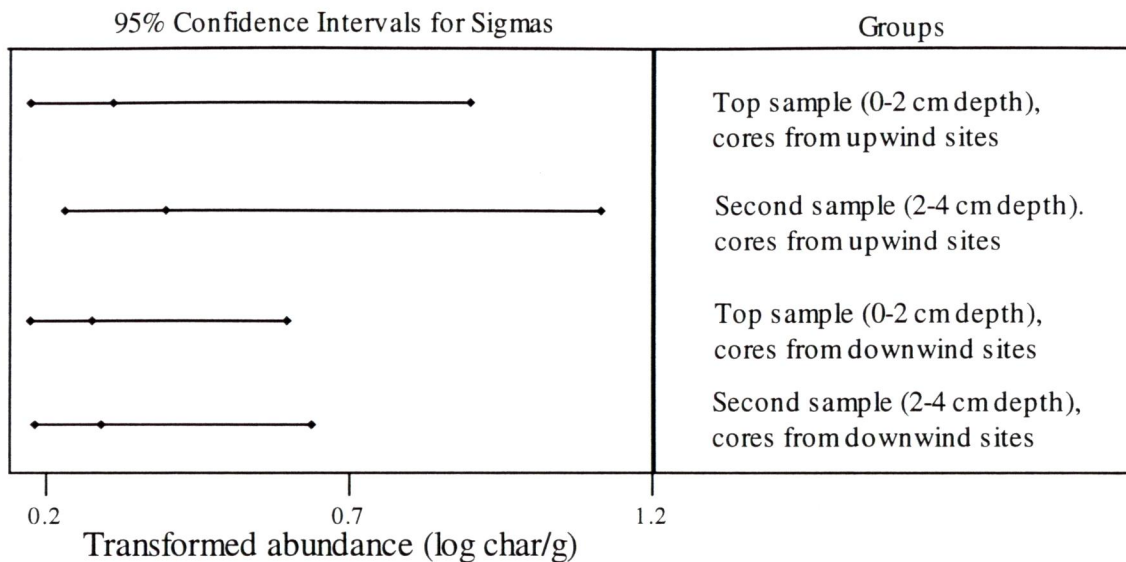
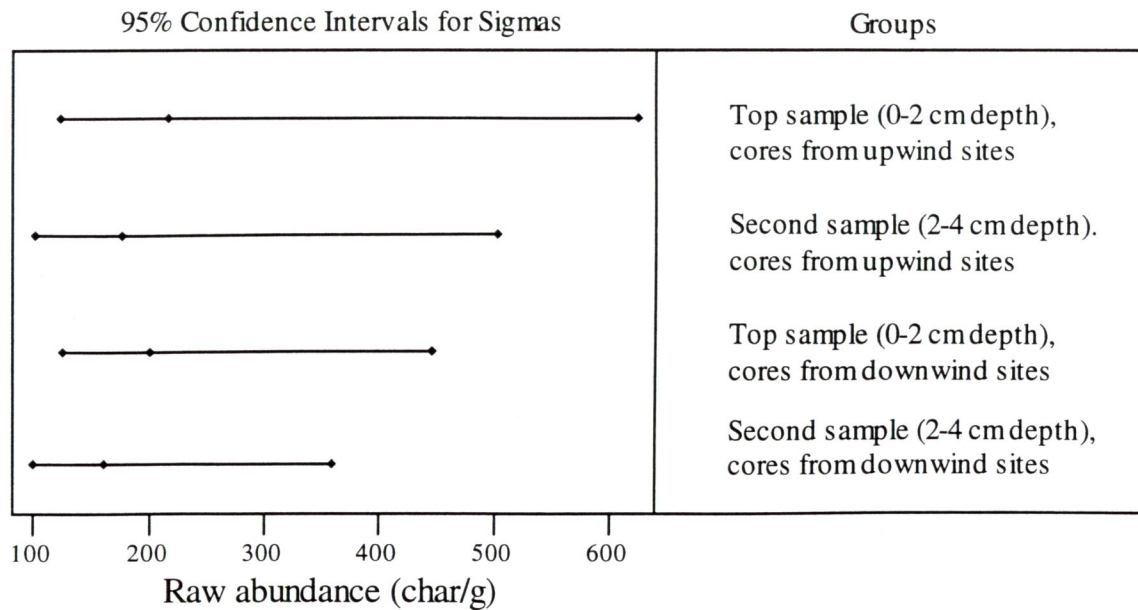


Figure 16. The 95% confidence intervals for the standard deviation of charcoal abundance for each group (from upwind and downwind sites) of raw (top graph) and transformed (bottom graph) data.

the assumptions of paired and two-sample t-tests.

Stratigraphic trends in cores from upwind and downwind sites indicated a significant decrease in charcoal abundance with core depth in downwind sites but not upwind sites. These results suggest that the prevailing winds during the fire increased the amount of charcoal found in downwind lakes. This distinction is further supported by the significant difference in charcoal abundance between the top samples (0-2 cm depth) from upwind and downwind sites.

Stratigraphic variations of charcoal abundance in cores from upwind and downwind sites were plotted separately (Figure 17). Downwind sites tended to have a greater decrease in charcoal abundance from the top to the second sample than upwind sites, which was evident in the trends of the geometric means (Figure 18). The 95% confident limits of the geometric means of the top sample interval (0-2 cm depth) from upwind and downwind sites overlap and charcoal abundance trends decreased with depth for cores from both upwind and downwind sites (Figure 13). Mean charcoal abundance from upwind sites decreased from 175 char/g in the top sample to 145 char/g in the second sample; whereas, for downwind sites it decreased from 344 char/g in the top sample to 192 char/g in the third sample (4-6 cm depth).

Decreases in charcoal abundance with depth were statistically significant in cores from downwind sites but not in those from upwind sites. Assumptions of a paired t-test were satisfied for all relevant statistical samples. Charcoal

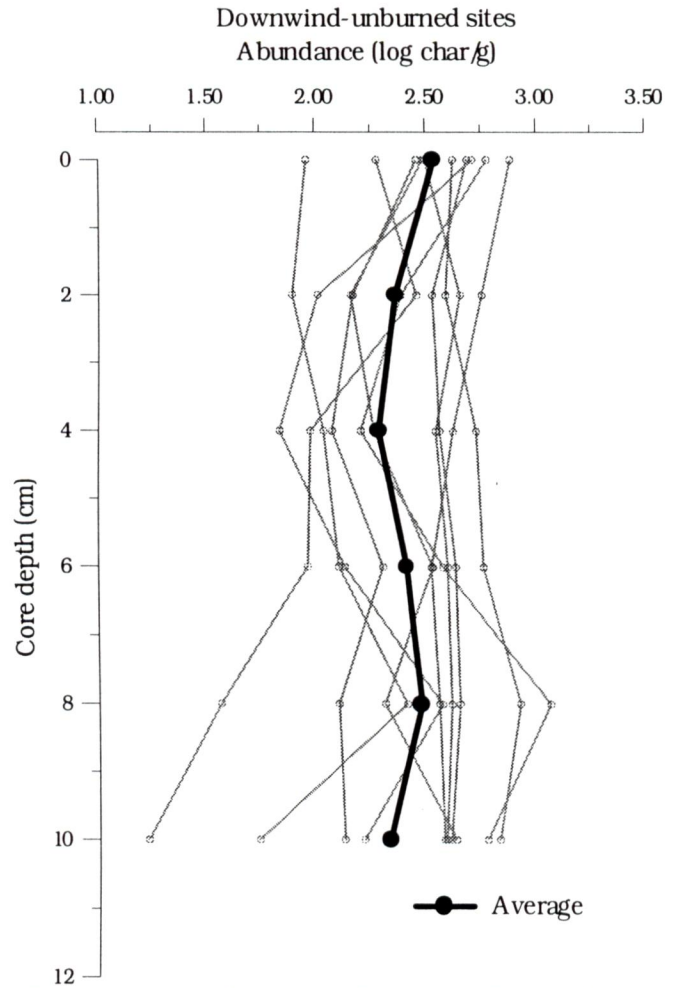
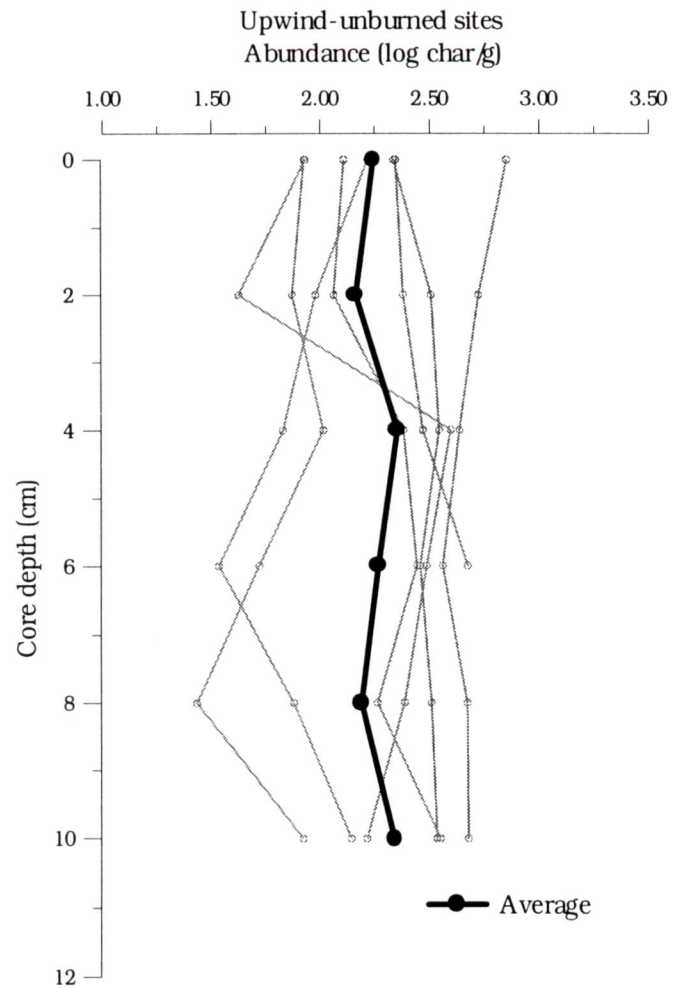


Figure 17. Stratigraphic variations of charcoal abundance plotted for unburned sites and grouped by relative position to the fire, either upwind or downwind.

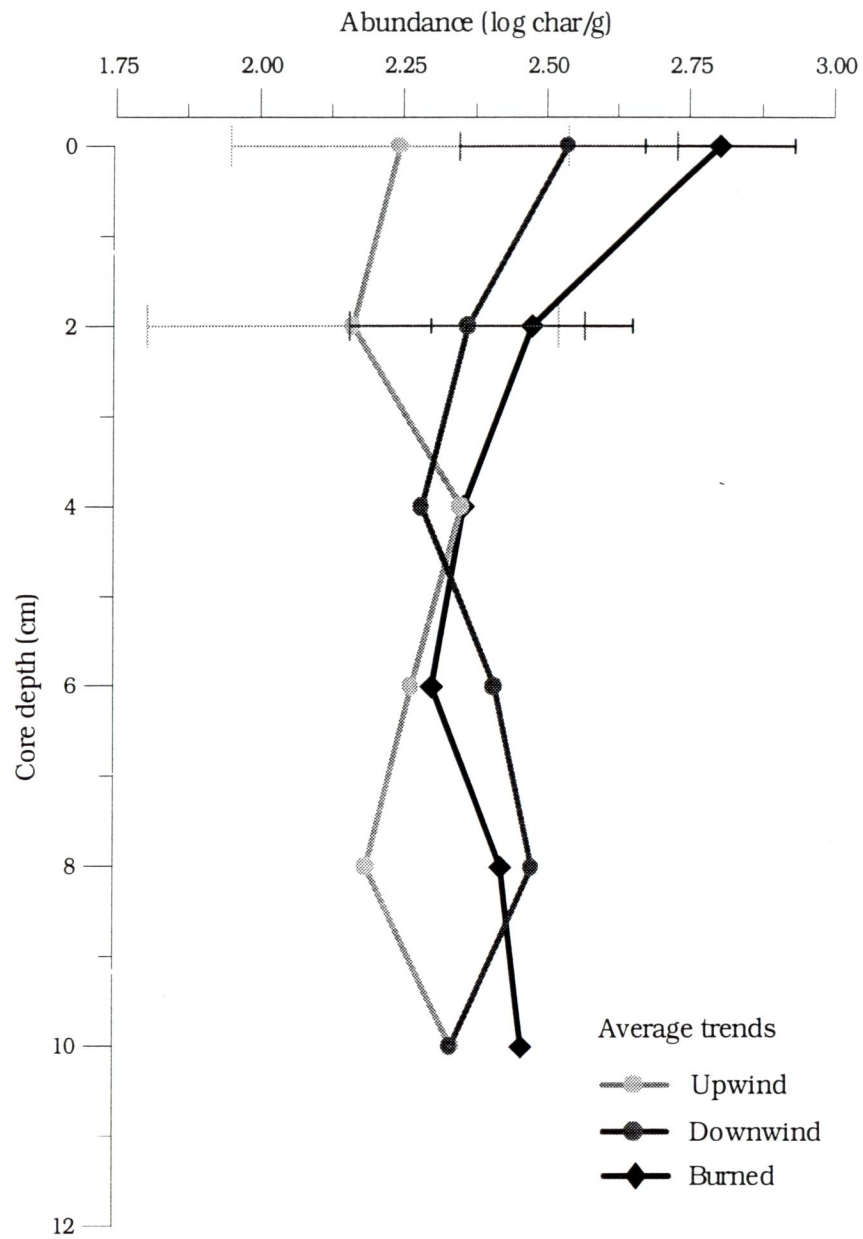


Figure 18. Comparison of stratigraphic trends of charcoal abundance in cores from upwind, downwind, and burned sites. The 95% confidence limits are indicated for the top and second sample interval of all three trends.

abundance in both the top (0-2 cm depth) and second samples (2-4 cm depth) from upwind sites were both normally distributed and homoscedastic. Similarly, charcoal abundance in both the top and second samples of cores from downwind sites were also normally distributed and homoscedastic. The mean of the differences between the top and second samples of cores from upwind sites was not statistically different from zero ( $T=1.33$ ,  $p<0.115$ ), but it was significantly different from zero for downwind sites ( $T=2.11$ ,  $p<0.032$ ).

The decrease in the average charcoal abundance from the top and second sample from downwind sites was greater than from upwind sites (Figure 13). In downwind sites, the difference between the mean of the top and second samples was 115 char/g, whereas for upwind sites, the difference was only 30 char/g. These results, in conjunction with the results of the paired t-tests, indicate that the peaks in charcoal abundance in cores from downwind sites were better defined than in cores from upwind sites.

On average, downwind sites had greater charcoal abundance in the top sample than upwind sites (Figure 11). The mean charcoal abundance of the top samples from upwind (175 char/g) and downwind (345 char/g) sites were statistically different ( $T=2.06$ ,  $p<0.034$ ). This significant difference supports the conclusion that a greater amount of charcoal was received by downwind sites than by upwind sites.

In summary, sediments from downwind sites tended to have better defined charcoal peaks than those from upwind sites (Figure 11). Cores from downwind sites had more charcoal in the top (0-2 cm depth) sample than those from upwind sites. These results suggest that prevailing winds in the Charlton area during the fire increased the amount of charcoal found in lakes downwind of the fire.

#### 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 on the top sample is supported by the slow sedimentation rates of lakes in the Charlton area.  $^{210}\text{Pb}$  dating of sediments from two lakes in the study area, Harvey and Irish Lakes, indicate sedimentation rates of ca. 0.04 cm/yr (C. Whitlock, unpublished data, 1999). Based upon this information, the top samples from the study sites are likely to span the last 50 yrs. The possibility that some of the charcoal from the 1996 fire is also present in the second sample interval (2-4 cm depth) cannot be ruled out, however. The dendrochronological record suggests that there have been no fires within the study area in the last 100 years, which makes it also reasonable to assume that charcoal in the top sample was from the 1996 Charlton Burn and not from previous fire events.

Two variables provide similar information about fire characteristics: burn status and severity (Table 2). Burn status divides the sites into burned and unburned categories. Severity provides additional information about the percentage of tree mortality and whether the canopy of forest at the site was scorched or consumed by the fire. In creating regression models, either burn status or severity was used, but not both. The inclusion of either burn status or severity as a variable was the basis for two separate series of models. Series I incorporated the variable burn status and consisted of a full and a reduced model. Best sub-sets regression was used to simplify Full Model I to Reduced Model I. Series II used the variable severity and also consisted of a full and a reduced model. All regression models used the logarithm of charcoal abundance as the dependent variable.

Histograms and normal probability plots of the distributions of the numeric variables (charcoal abundance, area, depth, and distance from the center of the fire) indicated that the raw data of all four variables lacked normal distributions and that the logarithmically transformed data were normally distributed (Figures 19-22; Table 6). Transformed values of charcoal abundance, area, depth and distance were used in the regression analysis. Hereafter, the terms charcoal abundance, area, depth, and distance refer to the logarithmically transformed data.

Table 6. Description of Raw and Transformed Numeric Variables

Data	Variable	Ryan-Joiner Normality Test		Normal distribution
		r	p	
Raw	Charcoal abundance	0.94	<0.01	No
	Surface area	0.75	<0.01	No
	Maximum water depth	0.83	<0.01	No
	Distance from center	0.94	<0.01	No
Transformed	Charcoal abundance	0.99	>0.10	Yes
	Surface area	0.98	>0.10	Yes
	Maximum water depth	0.99	>0.10	Yes
	Distance from center	0.98	>0.10	Yes

Area and depth, which describe bathymetric characteristics, were highly correlated ( $r=0.75$ ). Best sub-sets 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.

The sources of variation in charcoal abundance included fire and lake characteristics. Charcoal abundance in the upper sediments was related primarily to whether or not the site had burned and secondarily to the surface area of the lake. In the full models of both series the relative position of unburned sites, depth, distance, slope, and riparian margin were not important variables in explaining the variation in charcoal abundance. In the reduced models, burn status (or severity) and area significantly explained the variability of charcoal abundance. Burn status and severity were directly related to charcoal

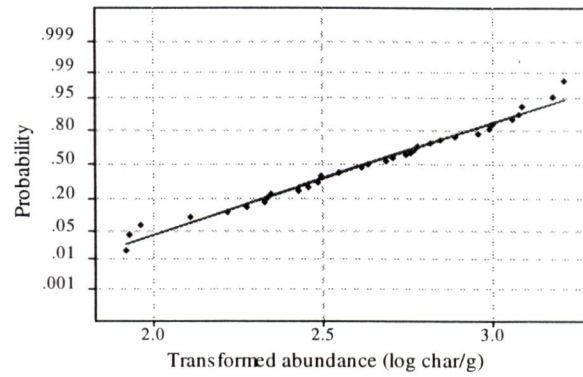
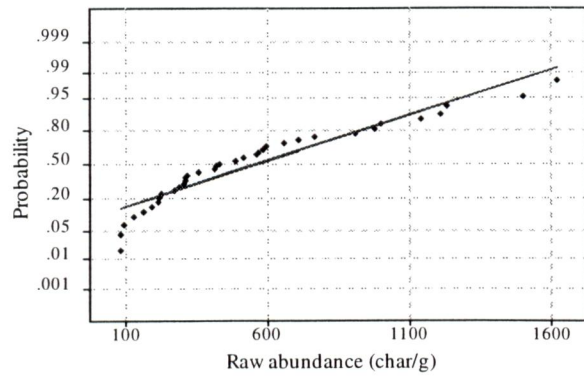
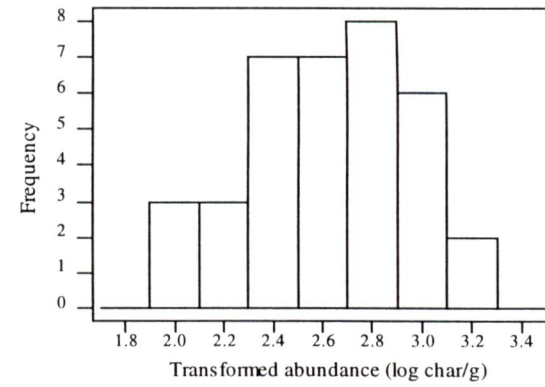
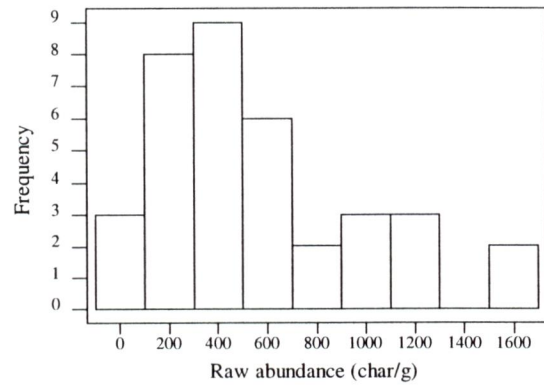


Figure 19. Histograms and normal probability plots illustrate the distributions raw and transformed charcoal abundance in the top samples (0-2 cm depth) from all cores.

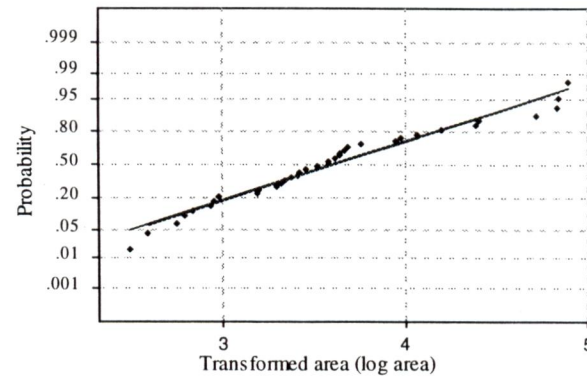
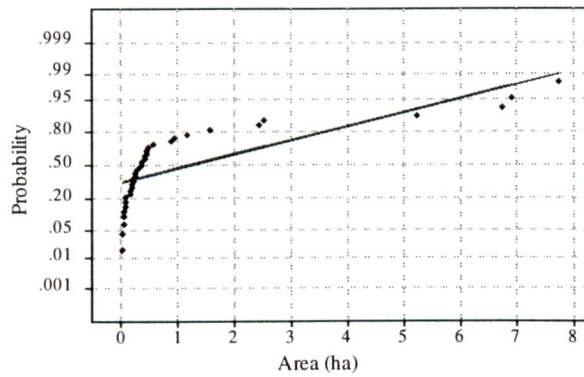
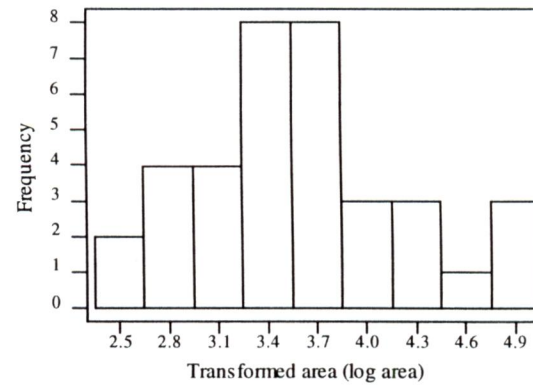
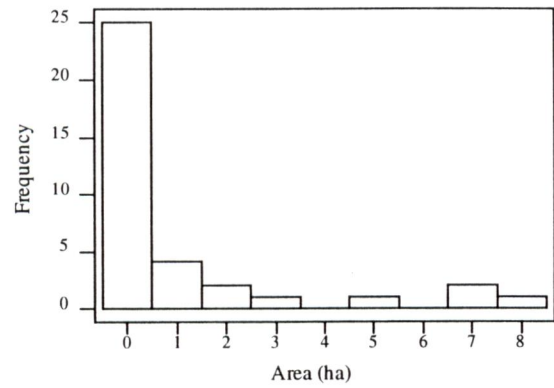


Figure 20. Histograms and normal probability plots illustrate the distributions raw and transformed surface area values from all lakes.

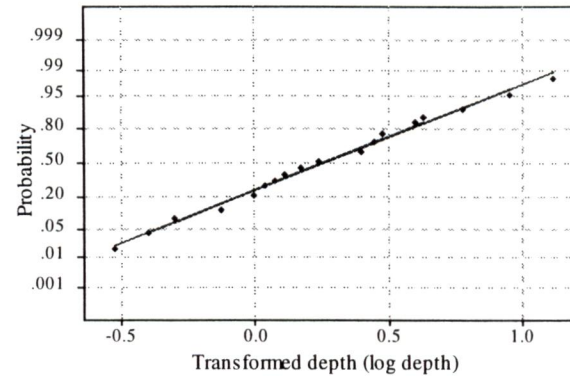
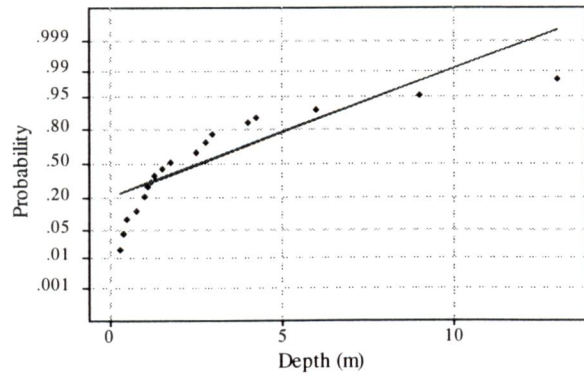
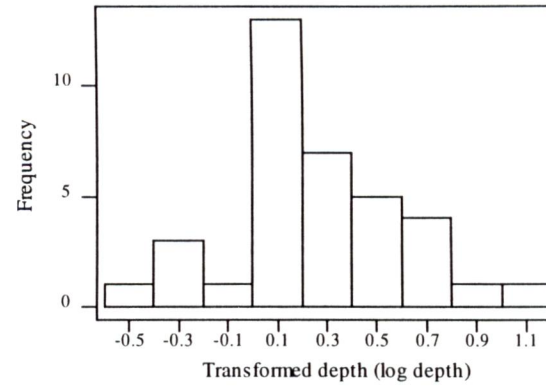
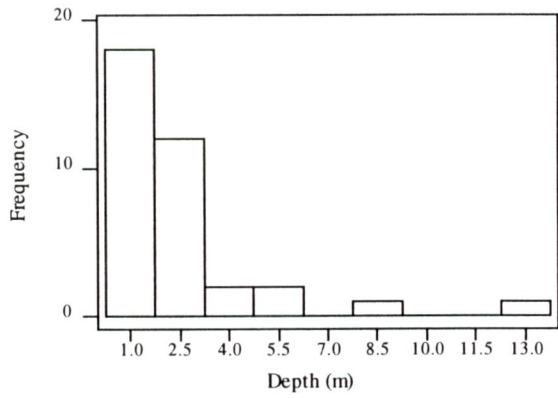


Figure 21. Histograms and normal probability plots illustrate the distributions of raw and transformed maximum water depths from all lakes.

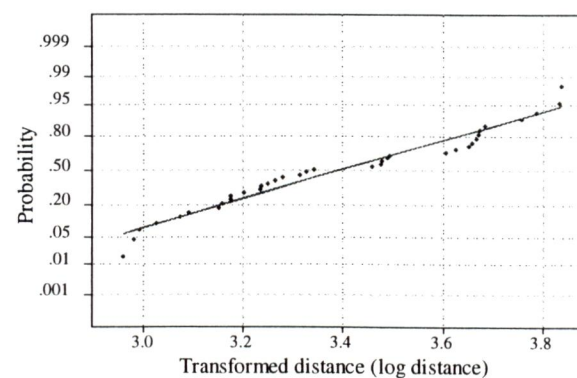
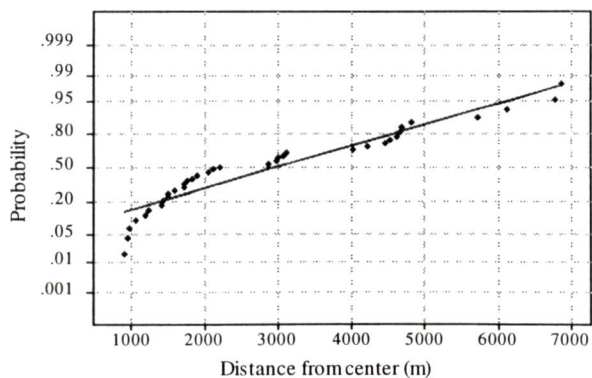
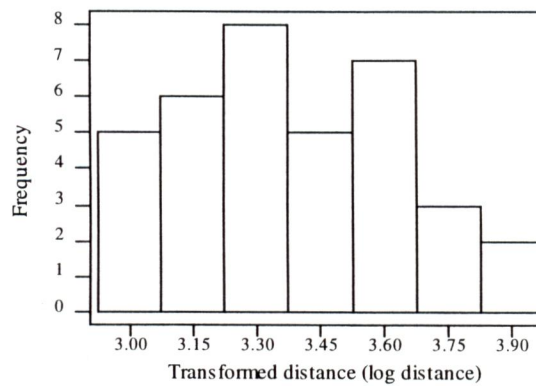
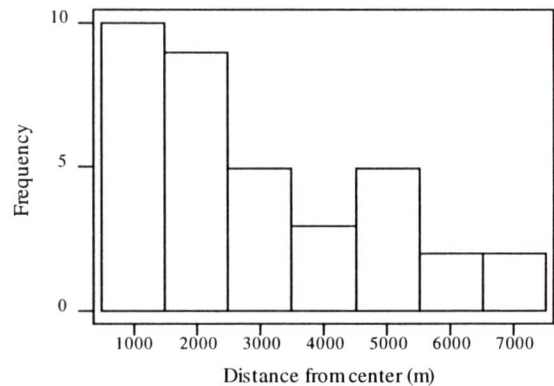


Figure 22. Histograms and normal probability plots illustrate the distributions of raw and transformed distances of lakes from the geographic center of the fire.

abundance while area was inversely related. The most important variable controlling charcoal abundance in the top sample interval was burn status or severity.

In the full models of both series, the relative position of unburned sites, depth, distance, slope, and riparian margin were not important variables in explaining the variability in charcoal abundance. In Full Model I (Table 7), a significant relationship existed 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) with charcoal

Table 7. Full Model I

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	0.117
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

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

abundance when all of the variables were included in the model. A significant relationship also existed in Full Model II (Table 8) between at least one independent variable and charcoal abundance ( $F=5.45$ ,  $p=0.000$ ). Similar to Full

Model I, most of the variables were not significant ( $p > 0.05$ ). 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.  $R^2_{\text{adj}}$  for Full Model II ( $R^2_{\text{adj}} = 58.3\%$ ) was 11.4% higher than  $R^2_{\text{adj}}$  for Full Model I ( $R^2_{\text{adj}} = 46.9\%$ ).

Table 8. Full Model II

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,  $p = 0.000$

Using best sub-sets regression, variables from the full models were removed one at a time until only variables that significantly explained the variation in charcoal abundance were left. In the resulting reduced models, the variables burn status (or severity) and area significantly explained the variation in charcoal abundance. Reduced Model I (Table 9) was a significant regression model ( $F = 5.45$ ,  $p = 0.000$ ). The independent variables burn status and area had

significant relationships with charcoal abundance ( $p=0.000$  and  $p=0.001$ , respectively). Despite the fact that Reduced Model I only included two

Table 9. Reduced Model I

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

$R^2 = 51.6\%$     $R^2_{adj} = 48.7\%$   
 F-ratio = 17.61,  $p = 0.00$

independent variables, its  $R^2_{adj}$  ( $R^2_{adj}=48.7\%$ ) was slightly higher than the  $R^2_{adj}$  of Full Model I ( $R^2_{adj}=46.9\%$ ). Therefore, in Reduced Model I the level of correlation between the observed and predicted values of charcoal abundance was higher than in Full Model I. Residuals were normally distributed and no pattern was evident in the plot of residuals vs. fits for Reduced Model I. Reduced Model II (Table 10) was also significant a regression equation ( $F=11.16$ ,  $p=0.00$ ) and all of the variables considered were also significant (all  $p$ -values were  $<0.05$ ). Reduced

Table 10. Reduced Model II

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

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

Model II, which incorporated severity and area, had an  $R^2_{\text{adj}}$  value ( $R^2_{\text{adj}}=53.7\%$ ) that was 5% higher than Reduced Model I ( $R^2_{\text{adj}}=48.7\%$ ), which simply accounted for whether a lake was in a burned or unburned watershed and surface area. The difference in the  $R^2_{\text{adj}}$  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. For Reduced Model II, residuals were normally distributed and no pattern was evident in the plot of residuals vs. fits.

When the relationship between charcoal abundance and burn status alone was examined,  $R^2_{\text{adj}}$  was 29.5%. For charcoal abundance and severity,  $R^2_{\text{adj}}$  was 31.7%. Finally, for charcoal abundance and area,  $R^2_{\text{adj}}$  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, predicting the value of charcoal abundance was not enhanced by examining many of the variables that were chosen as potential controls of charcoal abundance in lake sediments. Charcoal abundance was directly related to burn status and severity and was negatively related to area; as the surface area of a lake increased the amount of charcoal in the deep-water sediments decreased. The most important variables influencing how much charcoal accumulated in lakes after the Charlton Burn was whether or not the

watershed burned, or some measure of burn severity, and the surface area of the lake.

### Summary of results

The stratigraphic trends in cores from burned and unburned sites suggest that all sites received charcoal from the Charlton Burn. While the uppermost lake sediments from burned and unburned sites both tended to have peaks in charcoal abundance, peaks from burned sites were better defined than those from unburned sites. In addition, lakes from burned sites had more charcoal in the top two centimeters of sediment than unburned sites.

The stratigraphic trends in cores from upwind and downwind sites indicated that downwind sites had 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 in the study area during the fire increased the amount of charcoal found downwind of the fire.

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 center of the fire, maximum adjacent slope, and width of riparian vegetation were not important controls of charcoal abundance at these sites.

## CHAPTER V

### DISCUSSION

The interpretation of charcoal data rests upon understanding the processes that control charcoal accumulation in lake sediments after a fire. This study addresses three questions to clarify the interpretation of charcoal data. First, do macroscopic charcoal particles ( $>125\ \mu\text{m}$ ) record a signal of a local fire? Second, do the prevailing winds during a fire affect the source area of macroscopic charcoal? Finally, is the abundance of macroscopic charcoal controlled by variables that influence the production, transportation, and deposition of charcoal?

#### Use of Charcoal to Identify Local Fire Events

The results of this study offer evidence that macroscopic charcoal particles provide a record of local fire. Although the average trends of charcoal abundance in the uppermost lake-sediments from 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 two centimeters of sediment from burned sites was

statistically greater than that from unburned sites. These results are consistent with theoretical models (Clark, 1988a; Patterson *et al.*, 1987) and empirical studies (Clark *et al.*, 1998; Whitlock and Millspaugh, 1996) that suggest macroscopic particles (>100  $\mu\text{m}$  in diameter) provide a record of local fire whereas microscopic particles (<100  $\mu\text{m}$  in diameter) come from a larger area.

In theory, the settling of macroscopic charcoal particles occurs sooner and closer to a fire than the settling of microscopic particles (Clark, 1988a; Patterson *et al.*, 1987). Patterson *et al.* (1987) proposed a simple theoretical model of charcoal transportation that showed a decrease in the number and size of charcoal particles with increasing distance from a fire. Clark (1988a) used particle motion theory to estimate the quantity and source area of charcoal particles, of different diameters, released from a convection plume at specified heights. The model showed that particles which differed in size by several orders of magnitude (i.e., macroscopic vs. microscopic) exhibited different aerodynamic properties (Clark, 1988a). Large particles were more abundant near the charcoal source (a fire) and small particles were more abundant farther away. The aerodynamic properties of microscopic charcoal particles make them difficult to lift off of the ground, but once aloft they may remain in suspension for long periods and travel great distances before deposition (Clark, 1988a). In contrast, macroscopic particles (especially particles ranging from 130-150  $\mu\text{m}$ ) are easy to lift but are not

transported far (Clark, 1988a). Thus, small-particle distributions cover a greater area beyond a fire than large-particle distributions (Clark, 1988a).

Only two empirical studies have examined the accumulation of macroscopic charcoal particles ( $>100\ \mu\text{m}$ ) after a modern fire (Clark *et al.*, 1998; 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 (Clark *et al.*, 1998). Charcoal abundance was high in traps within the burn and extremely low in traps outside of the burn (Clark *et al.*, 1998). These results support the theoretical prediction that large particles are not transported far from a fire and thus an abundance of macroscopic charcoal particles in lake sediments signals local fire.

Following the 1988 fires in Yellowstone National Park, Whitlock and Millspaugh (1996) sampled macroscopic charcoal (ranging from 125-250  $\mu\text{m}$ , diameter) in five lakes in burned watersheds and three lakes in unburned watersheds. Sediment cores were collected from the deepest area of each lake for five years after the fires. All lakes received some macroscopic charcoal during the fire, as evidenced by the presence of charcoal in sediment samples collected a few months after the fire (Whitlock and Millspaugh, 1996). In subsequent years, charcoal abundance significantly increased in the deep-water sediments of

burned sites but not in unburned sites. An increase in charcoal in the sediments of burned sites was attributed to a greater amount of airborne charcoal deposited on the lake surfaces during the fire, which was later reworked from the littoral zone to the deep-water. The increase may also have reflected additional charcoal introduced to the lake after the fire from standing dead trees (Whitlock and Millspaugh, 1996). The greater abundance of charcoal in burned sites suggested that relatively little macroscopic charcoal was carried beyond the burned area (Whitlock and Millspaugh, 1996).

Many fire-history studies have found good agreement between macroscopic charcoal peaks in sedimentary records and local fires inferred from dendrochronologic and documentary data, further suggesting a local source for macroscopic charcoal. At three small lakes in northwestern Minnesota, local fires indicated by fire-scarred rings from trees within one kilometer of the lakes matched well with peaks in macroscopic charcoal abundance quantified from thin-sections of varved lake sediments (Clark, 1988b; Clark, 1990). Millspaugh and Whitlock (1995) found that fires inferred from stand-age data corresponded well with macroscopic charcoal peaks in three small lakes and one large lake in Yellowstone National Park. MacDonald *et al.* (1991) reported that peaks in macroscopic charcoal from a varved lake in northeastern Alberta, Canada did not closely match local fires indicated by fire scars on trees within two kilometers of the lake. However, three of the six fires in the last 175 years identified by fire

scars and stand-age data matched peaks in macroscopic charcoal abundance and the largest peak occurred in the year of a watershed fire (MacDonald *et al.*, 1991).

Assumptions concerning the source area of the charcoal in lake sediments influences the ecological interpretation of the charcoal data. The results of the Charlton study suggest that a macroscopic-charcoal peak occurs when the site burns. This result is important because it validates a basic assumption of charcoal analysis: that there is a relationship between charcoal abundance and fire events, enabling the reconstruction of a local fire history from charcoal data.

#### Influence of Prevailing Winds on Charcoal Accumulation

The results from this study indicate that the prevailing winds during the fire increased the amount of charcoal transported to lakes downwind of the fire. The average trends of charcoal abundance in cores from unburned sites (classified as either upwind or downwind of the fire) indicated a statistically-significant peak in the trend from downwind sites. The trend from upwind sites did not have a statistically-significant peak in the upper sediments. In addition, the average amount of charcoal in the top sample (0-2 cm depth) from downwind sites was statistically greater than that from upwind sites.

Prevailing winds are expected, on the basis of the theoretical models, to deposit macroscopic particles relatively close to the perimeter of a fire lead to a greater abundance of charcoal downwind than upwind of the fire (Clark, 1988a;

Clark *et al.*, 1998; Patterson *et al.*, 1987). Few empirical studies have addressed the effect of prevailing winds on charcoal transportation and subsequent accumulation in lake sediments. Clark *et al.* (1998) did not evaluate the influence of prevailing winds in Siberia because the plume was not significantly affected by the low-speed winds on the day of the burn. Whitlock and Millspaugh (1996) reported a minimal increase in charcoal accumulation in deep-water sediments from unburned sites during the five years after the 1988 fire event in Yellowstone National Park. However, of the unburned sites, they noted consistently more charcoal in the two lakes located seven and the five kilometers downwind of fire storms than in the one located a greater distance (13 km) downwind of a fire. In the Charlton Burn study, lakes as far as three kilometers downwind of the fire had charcoal peaks in the upper sediments similar in magnitude to those from burned sites (Figure 11).

Theoretical models and these empirical studies indicate that the prevailing winds during a fire influence the transportation of macroscopic charcoal particles and enlarge the area over which macroscopic charcoal is deposited in abundance. Depending on the fire and weather conditions of a particular event, a peak in charcoal abundance in lake sediments could indicate that a fire burned to the edge of a lake or that a fire occurred within several kilometers of the lake. This distinction may be important if asking a research question at a very small scale,

but it probably is not important in the interpretation of sedimentary records for most fire-history studies.

#### Other Variables that Influence Charcoal Accumulation

The Charlton results indicate that charcoal abundance in the uppermost sediments (0-2 cm depth) 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 center of the fire, maximum adjacent slope, and the width of riparian vegetation were statistically shown to be unimportant. Despite the trends in charcoal abundance from unburned sites described in the previous section, the relative position of unburned lakes was also shown to be statistically unimportant given the other variables in the models. 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. 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.

Clark *et al.* (1998) suggested that charcoal records provide an opportunity to calculate biomass consumption during past fires. If so, factors that influence secondary charcoal transportation and deposition would not significantly affect

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

The calculation of biomass consumed from 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 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. The Charlton Burn study provides evidence that a peak in macroscopic charcoal signals a local fire event. Peaks from burned sites were weakly related to fire severity, suggesting a relationship between the magnitude of a charcoal peak and the amount of charcoal produced. It must be noted, however, that the pattern of fire severity in the Charlton Burn was relatively homogeneous, with much of the area burned experiencing >95% tree

mortality. Charcoal production may influence variations in charcoal abundance to an even greater extent in a more heterogeneous fire.

The relationship between the amount of charcoal produced and charcoal abundance is further complicated by the potential of charcoal transportation after a fire event. Sources of secondary charcoal include: (1) charcoal carried by saltation or in surface run-off, (2) charcoal from burned trees near the lake shore, and (3) charcoal redeposited within a lake, from the littoral zone to deep water (Clark, 1988a; Whitlock *et al.*, 1997). If these processes consistently influence charcoal abundance in a predictable way, calculating biomass from charcoal abundance may be possible. However, if these processes are not systematic, they may make the calculation impossible.

Saltation and overland flow 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, 1988a). However, overland flow has been considered to be unimportant except at sites with steep slopes, impermeable soils, and frequent severe rain storms (Clark, 1988a). In the Charlton Study, two variables related to saltation and overland flow were specifically examined in this study 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 saltation or overland flow 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 at the Charlton sites. However, the region is not characterized by steep slopes nor are areas of riparian vegetation extensive. To assess the importance of secondary transportation processes, additional studies in more heterogeneous areas are necessary.

Evidence of secondary remobilization increasing charcoal abundance in lake sediments is suggested by Clark *et al.* (1988a) and Whitlock and Millspaugh (1996). Charcoal levels a sedimentary record from Bor Lake, located near the prescribed burn in Siberia, were higher than those in traps following the modern fire (Clark, 1988a). Clark *et al.* (1998) attributed the additional charcoal to saltation or surface flow of secondary charcoal following past fires, although he had no specific evidence that this had occurred (Clark *et al.*, 1998). Whitlock and Millspaugh (1996) reported an increase in charcoal abundance at all stations along transects with time, implying the addition of charcoal to the lakes after the fire event.

Bathymetric characteristics may also influence amounts of charcoal deposited in deep-water 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 deep-water 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 (1993). Smaller, shallower lakes (i.e., <5 ha and <5 m deep) rarely are thermally stratified and sediments across such sites are likely to be disturbed by wave action and wind-driven currents (Larsen and MacDonald, 1993). Larger, deeper lakes (i.e., >5 ha and >5 m deep) may be thermally stratified, only sediments in the littoral zone are greatly disturbed by wave action, and wind-driven currents are less likely to disturb sediments in the deepest part of the lake (Larsen and MacDonald, 1993). These processes may limit the redistribution of charcoal from the littoral zone to the deep-water sediments, resulting in low charcoal abundance in deep-water sediments in large lakes relative to small lakes.

Secondary deposition within lakes has been shown to be important by Bradbury (1996) and Whitlock and Millspaugh (1996). 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 the 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, 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 deep-water sampling locations than at shallow ones, implying the redeposition of charcoal within the lake from shallow- to deep-water sediments. 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 rate of charcoal increase in deep-water sediments was greater for lakes in burned watersheds than in unburned watersheds.

In Charlton study, charcoal abundance in the top sample (0-2 cm depth) was different in cores from burned and unburned sites within 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 time span 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, for the Charlton sites, charcoal abundance 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. Whitlock and Millspaugh (1996) defined charcoal abundance as the number of charcoal

particles per square centimeter of sediment ( $\text{char}/\text{cm}^2$ ). Third, the charcoal signal from the Charlton Burn may have been strengthened by the small shallow nature of most of the 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  $\leq 1.5$  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 of time, whereas charcoal introduced to larger lakes may be initially concentrated in the littoral zone and then reworked to deep-water sediments over a period of 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

In summary, this study provides strong evidence that macroscopic charcoal records the signal of local fire. Prevailing winds affected 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.

The results of this study support a basic assumption of charcoal analysis: 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. Processes leading to greater sediment mixing in small lakes, implicated by the greater charcoal abundance in small lakes, are influenced by bathymetric characteristics. Surface area and maximum water depth are important variables in the selection of fire-history study sites because they determine the likelihood of sediment mixing. The results from this study also indicate that other site characteristics, such as steepness of the surrounding topography 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.

APPENDIX A

LAKE STUDY EXPERIMENTAL  
DESIGN AND SITE SELECTION

Interactive Effects of Fire and Introduced Trout

**On Aquatic Biodiversity in High-Elevation Lentic Ecosystems**

**(Project 11-17)**

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## EXPERIMENTAL DESIGN

Beginning in July 1997, we sampled 32 lakes (16 lakes in areas that had been burned and 16 in unburned areas). Only lakes that were located in intensely burned drainages were included in the experimental (burned) lake population. In order to limit variables that might influence postfire response and to insure an adequate sample size for statistical comparisons, sampling was limited to lakes that did not have fish populations. Because most lakes with surface areas > 1.0 hectare had fish, only lakes >1.5 hectares were included in this study.

Individual study lakes were selected by two-stage cluster sampling (Cochran 1977; Scheaffer et al. 1990) from a sampling frame that included 410 permanent lakes without fish. Many of the lakes in the study area occurred in groups, and this method of sample selection was used to minimize the amount of travel time between sample lakes. Initially the area was divided into 0.25 km<sup>2</sup> quadrants, and all of the lakes in individual quadrants were identified. Each lake was assigned to a size class in the following categories: <.25 hectare; .251 - .50 ha; .501 - .75 ha; .751 - 1.5 ha (only 1 lake > 1.0 ha). A total of 27 quadrants (from a population of 380 quadrants) were drawn at random, and one lake from each size class was then chosen randomly from the pool of lakes occurring in the selected quadrant. This procedure yielded four lakes in each size category (ranging from 0.01 to 1.47 hectares) and a total of 16 lakes in each (burned and unburned) area (Gresswell *et al.*, 1998, unpublished report, p.4).

Cochran, W. G. 1977. Sampling techniques. Wiley, New York.

Scheaffer, R. L., W. Mendenhall, and L. Ott. 1990. Elementary survey sampling. PWS-Kent Publishing Company, Boston.

## APPENDIX B

CHARCOAL CONCENTRATIONS, WET AND DRY WEIGHTS,  
PERCENTAGE WATER, AND CALCULATED  
CHARCOAL ABUNDANCE

Site #	Lake id. <sup>a</sup>	Sample depth (cm)	Total (char/5cm <sup>3</sup> )	Char/cm <sup>3</sup>	Wet weight (g) of 1 cm <sup>3</sup>	Dry weight (g) of 1 cm <sup>3</sup>	% Water	Char/g
1	302	0-2	53	10.6	1.1437	0.0825	92.8	128
		2-4	122	24.4	1.2606	0.2129	83.1	115
		4-6	260	52.0	1.3600	0.2165	84.1	240
		6-8	276	55.2	1.3811	0.1992	85.6	277
		8-10	202	40.4	1.3721	0.2216	83.8	182
		10-12	374	74.8	1.2866	0.2131	83.4	351
2	290	0-2	130	26.0	1.0161	0.1178	88.4	221
		2-4	211	42.2	1.0273	0.1766	82.8	239
		4-6	247	49.4	0.9895	0.1682	83.0	294
		6-8	430	86.0	0.9690	0.1822	81.2	472
		8-10	*	*	*	*	*	*
		10-12	*	*	*	*	*	*
3	Chetlo	0-2	49	9.8	1.0010	0.1171	88.3	84
		2-4	40	8.0	1.0374	0.1084	89.6	74
		4-6	49	9.8	0.9869	0.0952	90.4	103
		6-8	33	6.6	1.0360	0.1263	87.8	52
		8-10	26	5.2	1.0798	0.1896	82.4	27
		10-12	36	7.2	1.0371	0.0870	91.6	83
4	259	0-2	184	36.8	0.9156	0.0520	94.3	708
		2-4	235	47.0	1.0203	0.0889	91.3	529
		4-6	211	42.2	1.0003	0.0974	90.3	433
		6-8	185	37.0	0.9793	0.1021	89.6	362
		8-10	255	51.0	0.9810	0.1093	88.9	467
		10-12	285	57.0	0.9941	0.1208	87.8	472
5	233	0-2	87	17.4	1.0439	0.0805	92.3	216
		2-4	251	50.2	1.0719	0.1568	85.4	320
		4-6	226	45.2	1.0921	0.1295	88.1	349
		6-8	179	35.8	1.0844	0.1253	88.4	286
		8-10	203	40.6	1.0666	0.1270	88.1	320
		10-12	213	42.6	1.0014	0.1257	87.4	339
6	263	0-2	74	14.8	1.1663	0.0899	92.3	165
		2-4	58	11.6	1.2687	0.1218	90.4	95
		4-6	42	8.4	1.3388	0.1250	90.7	67
		6-8	52	10.4	1.3872	0.3043	78.1	34
		8-10	71	14.2	1.2257	0.1903	84.5	75
		10-12	79	15.8	1.1049	0.1141	89.7	138

<sup>a</sup> Corresponding lake identification used by Gresswell et al. (1998, unpublished report) or USDI Geological Survey 7.5' topographic map lake name.

Site #	Lake id.	Sample depth (cm)	Total (char/5cm <sup>3</sup> )	Char/cm <sup>3</sup>	Wet weight (g) of 1 cm <sup>3</sup>	Dry weight (g) of 1 cm <sup>3</sup>	% Water	Char/g
7	271	0-2	81	16.2	0.9745	0.0284	97.1	570
		2-4	72	14.4	0.9544	0.0289	97.0	498
		4-6	44	8.8	0.9413	0.0342	96.4	257
		6-8	33	6.6	0.9396	0.0460	95.1	143
		8-10	29	5.8	0.9542	0.0509	94.7	114
		10-12	30	6.0	0.9412	0.0602	93.6	100
8	241	0-2	16	3.2	1.0081	0.0375	96.3	85
		2-4	19	3.8	0.9514	0.0898	90.6	42
		4-6	194	38.8	0.9238	0.0984	89.3	394
		6-8	124	24.8	0.8941	0.0810	90.9	306
		8-10	161	32.2	0.9777	0.1332	86.4	242
		10-12	74	14.8	0.9634	0.0906	90.6	163
9	L. Rigdon	0-2	145	29.0	0.9827	0.0440	95.5	659
		2-4	46	9.2	0.9896	0.0456	95.4	202
		4-6	28	5.6	0.9687	0.0452	95.3	124
		6-8	39	7.8	0.9757	0.0462	95.3	169
		8-10	31	6.2	0.9899	0.0530	94.6	117
		10-12	36	7.2	0.9702	0.0508	94.8	142
10	208	0-2	89	17.8	0.8659	0.0147	98.3	1211
		2-4	25	5.0	0.9057	0.0279	96.9	179
		4-6	45	9.0	0.8628	0.0376	95.6	239
		6-8	42	8.4	0.9290	0.0384	95.9	219
		8-10	88	17.6	0.9344	0.0601	93.6	293
		10-12	112	22.4	0.9415	0.0860	90.9	260
11	201	0-2	102	20.4	0.8485	0.0178	97.9	1146
		2-4	40	8.0	1.1280	0.0399	96.5	201
		4-6	18	3.6	1.3824	0.0683	95.1	53
		6-8	53	10.6	1.1018	0.0692	93.7	153
		8-10	235	47.0	1.1434	0.0818	92.8	575
		10-12	260	52.0	1.1305	0.0993	91.2	524
12	Mickey	0-2	61	12.2	0.9633	0.0393	95.9	310
		2-4	32	6.4	0.9700	0.0463	95.2	138
		4-6	16	3.2	0.9505	0.0584	93.9	55
		6-8	16	3.2	0.9856	0.0607	93.8	53
		8-10	79	15.8	0.9703	0.0564	94.2	280
		10-12	44	8.8	0.9780	0.0975	90.0	90

Site #	Lake id.	Sample depth (cm)	Total (char/5cm <sup>3</sup> )	Char/cm <sup>3</sup>	Wet weight (g) of 1 cm <sup>3</sup>	Dry weight (g) of 1 cm <sup>3</sup>	% Water	Char/g
13	Harvey	0-2	72	14.4	0.9970	0.0458	95.4	314
		2-4	62	12.4	0.9794	0.0471	95.2	263
		4-6	30	6.0	0.9890	0.0489	95.1	123
		6-8	40	8.0	0.9834	0.0530	94.6	151
		8-10	80	16.0	0.9960	0.0543	94.5	295
		10-12	58	11.6	1.0047	0.0623	93.8	186
14	171	0-2	71	14.2	0.9868	0.0344	96.5	413
		2-4	79	15.8	0.9792	0.0424	95.7	373
		4-6	61	12.2	0.9837	0.0445	95.5	274
		6-8	70	14.0	1.0129	0.0641	93.7	218
		8-10	81	16.2	0.9826	0.0704	92.8	230
		10-12	126	25.2	0.9591	0.0890	90.7	283
15	176	0-2	211	42.2	0.9499	0.0421	95.6	1002
		2-4	24	4.8	0.8696	0.0591	93.2	81
		4-6	91	18.2	0.9121	0.0653	92.8	279
		6-8	110	22.0	0.9061	0.0663	92.7	332
		8-10	85	17.0	0.8697	0.0698	92.0	244
		10-12	186	37.2	0.9044	0.0779	91.4	478
16	186	0-2	363	72.6	1.1244	0.2035	81.9	357
		2-4	325	65.0	1.1190	0.2728	75.6	238
		4-6	672	134.4	1.0783	0.2712	74.8	496
		6-8	1150	230.0	1.1340	0.3481	69.3	661
		8-10	471	94.2	1.1879	0.4008	66.3	235
		10-12	904	180.8	1.1611	0.3974	65.8	455
17	188	0-2	123	24.6	0.9080	0.0439	95.2	560
		2-4	97	19.4	0.8786	0.0594	93.2	327
		4-6	55	11.0	0.9319	0.0838	91.0	131
		6-8	154	30.8	0.9399	0.0980	89.6	314
		8-10	107	21.4	0.9438	0.1055	88.8	203
		10-12	218	43.6	0.9392	0.1048	88.8	416
18	149	0-2	197	39.4	1.0135	0.0243	97.6	1621
		2-4	109	21.8	1.0032	0.0332	96.7	657
		4-6	169	33.8	1.0106	0.0410	95.9	824
		6-8	64	12.8	1.0095	0.0536	94.7	239
		8-10	138	27.6	0.9528	0.0669	93.0	413
		10-12	261	52.2	0.9783	0.0860	91.2	607

Site #	Lake id.	Sample depth (cm)	Total (char/5cm <sup>3</sup> )	Char/cm <sup>3</sup>	Wet weight (g) of 1 cm <sup>3</sup>	Dry weight (g) of 1 cm <sup>3</sup>	% Water	Char/g
19	144	0-2	118	23.6	0.9690	0.0157	98.4	1503
		2-4	108	21.6	0.9825	0.0196	98.0	1102
		4-6	58	11.6	0.9528	0.0306	96.8	379
		6-8	25	5.0	0.9721	0.0352	96.4	142
		8-10	82	16.4	0.9637	0.0401	95.8	409
		10-12	184	36.8	0.9179	0.0429	95.3	858
20	121	0-2	112	22.4	1.0594	0.0381	96.4	588
		2-4	45	9.0	1.0474	0.0437	95.8	206
		4-6	85	17.0	0.9627	0.0478	95.0	356
		6-8	75	15.0	0.9673	0.0534	94.5	281
		8-10	243	48.6	0.9653	0.0619	93.6	785
		10-12	280	56.0	1.0036	0.0852	91.5	657
21	Whig	0-2	36	7.2	1.0074	0.0268	97.3	269
		2-4	14	2.8	1.0136	0.0332	96.7	84
		4-6	12	2.4	1.0114	0.0282	97.2	85
		6-8	5	1.0	1.0548	0.0275	97.4	36
		8-10	30	6.0	1.0033	0.0291	97.1	206
		10-12	26	5.2	0.9882	0.0429	95.7	121
22	112	0-2	166	33.2	1.0645	0.0766	92.8	433
		2-4	107	21.4	1.0514	0.1339	87.3	160
		4-6	100	20.0	1.0383	0.1501	85.5	133
		6-8	82	16.4	0.9623	0.1285	86.6	128
		8-10	81	16.2	1.0371	0.1624	84.3	100
		10-12	122	24.4	1.0313	0.1881	81.8	130
23	108	0-2	235	47.0	1.0282	0.0381	96.3	1234
		2-4	229	45.8	0.9835	0.0446	95.5	1027
		4-6	57	11.4	0.9772	0.0449	95.4	254
		6-8	41	8.2	1.0135	0.0534	94.7	154
		8-10	79	15.8	0.9570	0.0801	91.6	197
		10-12	218	43.6	0.9661	0.0991	89.7	440
24	101.1	0-2	137	27.4	1.0358	0.0280	97.3	979
		2-4	319	63.8	0.9253	0.0383	95.9	1666
		4-6	250	50.0	0.9356	0.0550	94.1	909
		6-8	416	83.2	1.0176	0.0928	90.9	897
		8-10	*	*	*	*	*	*
		10-12	*	*	*	*	*	*

Site #	Lake id.	Sample depth (cm)	Total (char/5cm <sup>3</sup> )	Char/cm <sup>3</sup>	Wet weight (g) of 1 cm <sup>3</sup>	Dry weight (g) of 1 cm <sup>3</sup>	% Water	Char/g
25	101	0-2	44	8.8	0.9759	0.0389	96.0	226
		2-4	55	11.0	0.9741	0.0626	93.6	176
		4-6	112	22.4	0.9896	0.0846	91.5	265
		6-8	163	32.6	1.0187	0.1584	84.5	206
		8-10	269	53.8	1.0182	0.1686	83.4	319
		10-12	275	55.0	1.1085	0.1732	84.4	318
26	101.2	0-2	552	110.4	1.0117	0.1215	88.0	909
		2-4	471	94.2	1.0266	0.1676	83.7	562
		4-6	598	119.6	1.0913	0.2237	79.5	535
		6-8	649	129.8	1.1081	0.2964	73.3	438
		8-10	596	119.2	1.0724	0.2467	77.0	483
		10-12	602	120.4	1.1589	0.3845	66.8	313
27	73	0-2	99	19.8	0.9381	0.0642	93.2	308
		2-4	79	15.8	0.9738	0.1092	88.8	145
		4-6	96	19.2	0.9876	0.1051	89.4	183
		6-8	197	39.4	0.9856	0.1168	88.1	337
		8-10	155	31.0	1.0382	0.1511	85.4	205
		10-12	322	64.4	0.9649	0.1492	84.5	432
28	66.1	0-2	79	15.8	1.0173	0.0502	95.1	315
		2-4	151	30.2	1.0204	0.0668	93.5	452
		4-6	116	23.2	1.0285	0.0666	93.5	348
		6-8	196	39.2	0.9989	0.0997	90.0	393
		8-10	182	36.4	1.0099	0.0883	91.3	412
		10-12	205	41.0	0.9581	0.1049	89.1	391
29	Helen	0-2	54	10.8	1.0202	0.0375	96.3	288
		2-4	36	7.2	1.0118	0.0485	95.2	148
		4-6	29	5.8	0.9658	0.0486	95.0	119
		6-8	60	12.0	0.9930	0.0597	94.0	201
		8-10	60	12.0	0.9671	0.0942	90.3	127
		10-12	93	18.6	1.0343	0.1385	86.6	134
30	69	0-2	94	18.8	0.9193	0.0385	95.8	488
		2-4	85	17.0	0.9661	0.0503	94.8	338
		4-6	85	17.0	0.9975	0.0470	95.3	362
		6-8	111	22.2	0.9897	0.0517	94.8	429
		8-10	134	26.8	0.9089	0.0597	93.4	449
		10-12	119	23.8	0.9743	0.0581	94.0	410

Site #	Lake id.	Sample depth (cm)	Total (char/5cm <sup>3</sup> )	Char/cm <sup>3</sup>	Wet weight (g) of 1 cm <sup>3</sup>	Dry weight (g) of 1 cm <sup>3</sup>	% Water	Char/g
31	43	0-2	73	14.6	0.9959	0.0347	96.5	421
		2-4	116	23.2	0.9589	0.0598	93.8	388
		4-6	167	33.4	0.9543	0.0630	93.4	530
		6-8	188	37.6	0.9931	0.0655	93.4	574
		8-10	289	57.8	0.9580	0.0681	92.9	849
		10-12	251	50.2	0.9813	0.0733	92.5	685
32	37.1	0-2	215	43.0	0.9818	0.0560	94.3	768
		2-4	247	49.4	0.9239	0.0869	90.6	568
		4-6	181	36.2	0.9668	0.0870	91.0	416
		6-8	194	38.8	1.0188	0.1164	88.6	333
		8-10	243	48.6	0.9905	0.1345	86.4	361
		10-12	255	51.0	0.9805	0.1335	86.4	382
33	19	0-2	26	5.2	0.9726	0.0567	94.2	92
		2-4	37	7.4	0.9705	0.0939	90.3	79
		4-6	49	9.8	0.9783	0.0897	90.8	109
		6-8	64	12.8	1.0181	0.1009	90.1	127
		8-10	126	25.2	0.9936	0.0972	90.2	259
		10-12	25	5.0	0.9568	0.0905	90.5	55
34	12	0-2	76	15.2	0.8409	0.0295	96.5	515
		2-4	25	5.0	0.8773	0.0485	94.5	103
		4-6	19	3.8	0.9189	0.0548	94.0	69
		6-8	49	9.8	0.9533	0.0727	92.4	135
		8-10	184	36.8	0.9317	0.0986	89.4	373
		10-12	52	10.4	0.8862	0.0630	92.9	165
35	26	0-2	99	19.8	1.0341	0.0331	96.8	598
		2-4	52	10.4	0.9530	0.0426	95.5	244
		4-6	30	6.0	0.9338	0.0374	96.0	160
		6-8	82	16.4	0.9702	0.0437	95.5	375
		8-10	327	65.4	0.9544	0.0562	94.1	1164
		10-12	194	38.8	0.9328	0.0643	93.1	603
36	W Hanks	0-2	41	8.2	1.0135	0.0431	95.7	190
		2-4	68	13.6	0.9932	0.0474	95.2	287
		4-6	22	4.4	0.9555	0.0463	95.2	95
		6-8	24	4.8	1.0022	0.0524	94.8	92
		8-10	30	6.0	1.0714	0.1637	84.7	37
		10-12	37	7.4	1.2477	0.4338	65.2	17

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