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Willy Tinner and Feng Sheng Hu
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Size parameters, size-class distribution and area-number relationship of microscopic charcoal: relevance for fire reconstruction

Willy Tinner* and Feng Sheng Hu

(Department of Plant Biology, University of Illinois, 505 South Goodwin Avenue, Urbana, Illinois, 61801, USA)

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Abstract: Charcoal analysis was conducted on sediment cores from three lakes to assess the relationship between the area and number of charcoal particles. Three charcoal-size parameters (maximum breadth, maximum length and area) were measured on sediment samples representing various vegetation types, including shrub tundra, boreal forest and temperate forest. These parameters and charcoal size-class distributions do not differ statistically between two sites where the same preparation technique (glycerine pollen slides) was used, but they differ for the same core when different techniques were applied. Results suggest that differences in charcoal size and size-class distribution are mainly caused by different preparation techniques and are not related to vegetation-type variation. At all three sites, the area and number concentrations of charcoal particles are highly correlated in standard pollen slides; 82–83% of the variability of the charcoal-area concentration can be explained by the particle-number concentration. Comparisons between predicted and measured area concentrations show that regression equations linking charcoal number and area concentrations can be used across sites as long as the same pollen-preparation technique is used. Thus it is concluded that it is unnecessary to measure charcoal areas in standard pollen slides – a time-consuming and tedious process.

Key words: Charcoal analysis, microscopic charcoal, pollen slides, thin sections, fire history.

Introduction

The quantification of microscopic charcoal particles preserved in lake sediments and mires is commonly used by palaeoecologists to study the occurrence of past fires and their effects on ecosystems. Recently, charcoal analysis has also been applied to understanding the role of biomass burning in climatic change and carbon cycle (e.g., Clark *et al.*, 1997). However, spatial comparisons of charcoal records are often difficult because different methods (e.g., pollen slides, thin sections, sieving, combustion/digestion, spectrographic analysis) have been used in previous studies (e.g., Patterson *et al.*, 1987; MacDonald *et al.*, 1991; Tinner *et al.*, 1998; Carcaillet *et al.*, 2001) and because few studies have systematically compared these methods. Among these methods, the pollen-slide technique remains one of the most commonly applied for charcoal quantification. Its popularity can be attributed to the prominent role of palynology in palaeoecological studies and to interests in understanding long-term impacts of fire on vegetation at the regional scale.

Both theoretical (Clark, 1988a) and empirical studies (e.g., MacDonald *et al.*, 1991; Clark and Royall, 1995; Tinner *et al.*, 1998) show that charcoal particles in pollen slides mainly come from regional sources (20 to 100 km around the study site). Moreover, several studies have found significant correlations between pollen and charcoal (e.g., Odgaard, 1992; Tinner *et al.*, 1999), suggesting that microscopic charcoal and pollen have comparable source areas in some vegetation types. It has been commonly assumed that large charcoal particles in pollen slides provide additional palaeofire information and that area determinations give better estimates of charcoal quantity (Patterson *et al.*, 1987). Thus the area of charcoal particles is often painstakingly measured to derive an index of charcoal abundance. However, several studies have demonstrated that different charcoal-size classes often covary (Mehringer *et al.*, 1977; MacDonald *et al.*, 1991) and that the measured total charcoal area is highly correlated with the number of charcoal particles in pollen slides (Tolonen, 1985; Tinner *et al.*, 1998). Such observations led Patterson *et al.* (1987) to raise the following question: 'if the area-number relationship is

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*Author for correspondence: Present address: Institut für Pflanzenwissenschaften, Universität Bern, Altenbergrain 21, CH 3013 Bern, Switzerland (e-mail: willy.tinner@ips.unibe.ch)

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significantly correlated, then is there much to be gained in measuring total charcoal areas or even point sample estimation?' This question is important partially because it is much faster to determine the charcoal number than to estimate the charcoal area in a pollen slide. To address this question, we analysed charcoal in pollen slides of Holocene sediments from three lakes: Lago di Origlio (46°03′ N, 8°57′ E, Switzerland), Wien Lake (64°20′ N, 152°16′ W, Alaska) and Grizzly Lake (62°43′ N, 144°12′ W, Alaska). Our objectives were (1) to compare charcoal-size parameters and charcoal-size distributions among samples from different sites and (2) to assess the feasibility of predicting the charcoal area from the charcoal number.

Material and methods

Charcoal analysis on pollen slides

Sediment cores were obtained with a modified Livingstone piston corer (Wright *et al.*, 1984) at Wien Lake and Grizzly Lake and with a freeze corer containing dry ice and alcohol (Wright, 1991) at Lago di Origlio. *Lycopodium* tablets (Stockmarr, 1971) were added to subsamples of 1 cm^3 (Wien Lake, Grizzly Lake) and 2 cm^3 (Lago di Origlio) for estimation of pollen and charcoal concentrations (particles cm^{-3}). We used two different protocols to prepare samples for pollen and charcoal analyses. The samples of Lago di Origlio and Grizzly Lake were processed at the Institute of Plant Sciences in Bern following the protocol for glycerine pollen slides (Moore *et al.,* 1991). The samples of Wien Lake were prepared at the University of Washington following the PALE protocol for silicon-oil pollen slides (PALE, 1994). The main difference between these protocols affecting our charcoal results is that, in order to remove large particles, the former used a 500 μm mesh sieve along with repeated decanting after settlement of heavy particles, whereas the latter used a 180 μm mesh sieve without repeated decanting as well as a 7 μm mesh sieve to remove small particles. Detailed pollen data from Wien Lake and Lago di Origlio have been published elsewhere (e.g., Hu *et al.*, 1993; Tinner *et al.*, 1998; 1999).

Samples used for charcoal analysis in this study represent various postglacial vegetation types. At Wien Lake, we analysed 10 lateglacial samples, five early-Holocene samples, and four middle- and late-Holocene samples; pollen-inferred vegetation types were shrub birch (*Betula glandulosa*) tundra, poplar (*Populus*) forests and boreal forests dominated by spruce (*P. mariana* and *Picea glauca*), respectively. At Grizzly Lake, we analysed 24 samples spanning the past 7000 years, and the palaeovegetation was characterized by spruce forests throughout this period. At Lago di Origlio, we analysed 180 samples (90 in pollen samples, 90 in thin sections), and the charcoal in all of these samples originated from warm-temperate chestnut forests (*Castanea sativa*) between AD 1920 and 1994.

Charcoal particles were identified with a light microscope at × 200 magnification. Charcoal selection was restricted to fragments that are black, completely opaque and angular (Swain, 1973; Clark, 1988b). Each charcoal particle >75 μm^2 (or *c.* 10 μm long; Patterson *et al.*, 1987; MacDonald *et al.*, 1991) was measured for its maximum length, maximum breadth and total area with an image analyser.

Thin sections

The same frozen core from Lago di Origlio as for pollen analysis was cut into 9 cm × 3 cm segments, which were then dehydrated by freeze-drying and embedded in epoxy resin. To ensure an even thickness of 30 μm for all stratigraphic levels, we measured each thin section at 10 points with a light microscope. Charcoal analysis of thin sections followed the same criteria and procedures as for pollen slides.

Table 1 Comparison of medians (z values for median scores) and size-class distributions (χ^2 test) for different sites and preparation methods

	OP	GY	WI	OT
OP	L:	L: 5.830	L: 65.603	L: 208.321
	A:	A: 1.508	A: 41.479	A: 289.285
GY	L: –2.549	L:	L: 32.565	L: 66.733
	A: –1.875	A:	A: 21.691	A: 70.757
WI	L: –8.117	L: –2.745	L:	L: 171.635
	A: –7.128	A: –4.097	A:	A: 158.360
OT	L: 16.307	L: –9.566	L: 15.019	L:
	A: 18.000	A: –9.626	A: 10.497	A:

z values on the left, χ^2 values on the right (shaded).

Null hypothesis for comparison of medians: the medians are not different, H_0: $med_1 = med_2$, two-tailed: confidence limit ($\alpha = 0.05$) adjusted for multiple tests: $z = 2.58$.

Null hypothesis for comparison of size-class distributions: the probability distributions are not different: H_0: $p_1 = p_2$, one-tailed: confidence limit ($\alpha = 0.05$) adjusted for multiple tests: $\chi^2 = 11.34$ (3 DF) for length distribution, $\chi^2 = 13.28$ (4 DF) for area distribution.

L = length of charcoal particles, A = area; for other abbreviations, see Figure 1.

Statistical analysis

We compared our charcoal length and area data between sites and between preparation methods using a non-parametric analysis of median scores (SAS/STAT, 1994; Table 1). The median test was selected because it is powerful for exponential distributions (SAS/STAT, 1994) and because our data are exponentially distributed. Because we performed a six pair-wise comparison, we determined the confidence limits ($z = 2.58$) at a significance level of 0.01, which approximately corresponds to a (conservative) Bonferroni-correction for a significance level of 0.05 ($\alpha_{bonferroni} = 0.0083$, $z = 2.64$; Dufner *et al.*, 1992). We applied the same test to compare charcoal length and areas between vegetation types (Table 2). Because we performed a three pair-wise comparison, the confidence limit was adjusted to $z = 2.33$ ($\alpha = 0.02$), which approximately corresponds to a (conservative) Bonferroni-correction for a significance level of 0.05 ($\alpha_{bonferroni} = 0.017$).

We performed homogeneity tests (Dufner *et al.*, 1992; SAS, 1994) to compare charcoal size-class distributions between sites

Table 2 Comparison of medians (z values for median scores) and size-class distributions (χ^2 test) for different vegetation types at Wien Lake

	WS	WP	WT
WS	L:	L: 0.973*	L: 4.177*
	A:	A: 0.690*	A: 3.217
WP	L: 1.004	L:	L: 2.209*
	A: –0.056	A:	A: 4.691
WT	L: –0.732	L: –2.179	L:
	A: –3.181	A: –3.339	A:

z values on the left, χ^2 values on the right (shaded).

Null hypothesis for comparison of medians: the medians are not different, H_0: $med_1 = med_2$, two-tailed; confidence limit ($\alpha = 0.05$) adjusted for multiple tests: $z = 2.33$.

Null hypothesis for comparison of size-class distributions: the probability distributions are not different: H_0: $p_1 = p_2$, one-tailed: confidence limit ($\alpha = 0.05$) adjusted: $\chi^2 = 9.84$ (3 DF) for length distribution, $\chi^2 = 11.67$ (4 DF) for area distribution. * = The two last size classes were amalgamated because frequency cells had expected counts less than 5: $\chi^2 = 7.82$ (2 DF) for length distribution, $\chi^2 = 9.84$ (3 DF) for area distribution.

WS = Wien Lake, *Picea* forest samples. WP = Wien Lake, *Populus* forest samples. WT = Wien Lake, *Betula* shrub tundra samples. L = length of charcoal particles, A = area.

and between methods (Table 1) at a significance level of 0.01, which approximately corresponds to a (conservative) Bonferroni-correction for a significance level of 0.05 ($\alpha_{\text{bonferroni}}$= 0.0083, χ^2 values; Table 1). To calculate the differences between observed and expected frequencies, we followed Patterson *et al.* (1987) and built charcoal-size classes with a length interval of 20 μm (10–30, 30–50, 50–70 and >70 μm) and an area interval of 200 μm^2 (75–275, 275–474, 475–675, 675–875 and >875 μm^2). We applied the same test to compare charcoal-size class distributions between vegetation types at a significance level of 0.02, which approximately corresponds to a (conservative) Bonferroni-correction at a significance level of 0.05 ($\alpha_{\text{bonferroni}}$ = 0.017, χ^2values; Table 2). The homogeneity test is one of several possible measures of the difference between two probability distributions. We chose this method because it offered a simple, non-parametric comparison of size-class distributions.

Three regression models were calculated to assess the relationship between the number and area of charcoal particles in pollen slides (Riedwyl, 1992; SAS/STAT, 1994). Because we made a three pair-wise comparison, the significance level of 0.05 was adjusted to 0.017 (= $\alpha_{\text{bonferroni}}$) resulting in a corrected F value of 5.71 (Table 3). To test the hypothesis that model-estimated area concentrations are not different from those measured through image analysis, we applied a centred Wilcoxon signed rank test for comparison of paired data (SAS, 1994; SAS/STAT, 1994). This non-parametric statistical technique was selected because the new difference variable is not normally distributed.

Results and discussion

Size parameters and size-class distribution of charcoal particles

The median length of charcoal in pollen slides is 21 μm for Lago di Origlio (OP), 20 μm for Grizzly Lake (GY) and 19 μm for Wien Lake (WI). In the thin sections of Lago di Origlio (OT), charcoal has a median length of 24 μm. The charcoal median area is 161 μm^2 for OP, 154 μm^2 for GY, 132 μm^2 for WI and 203 μm^2 for OT. The mean length to breadth ratio is 1.9 for both OP and OT, 1.7 for GY and 1.6 for WI. Thus these charcoal parameters appear similar among the three sites regardless of the preparation techniques (Figure 1). However, median tests show that, with the exception of OP versus GY, the medians of charcoal length and area differ significantly between the sites and between the methods used in all cases (Table 1). In addition, maximum charcoal lengths differ greatly among sites (OP > WI > GY), and the largest charcoal areas are considerably smaller for OP than for OT (Figure 2).

Size-class distributions of charcoal are similar among sites and between preparation methods. The charcoal-length frequency distribution shows a comparable course for all four records, with the closest match between GY and OP (Figure 2). The charcoal-area frequency distribution also appears similar among these records (Figure 2), and again the GY and OP curves are the closest. Despite these similarities, chi-square (χ^2) tests of homogeneity show that the distributions of both charcoal length and area differ statistically (p = < 0.05 adjusted) in all cases with one exception: OP versus GY (Table 1).

The differences in the size parameters and size-class distribution of charcoal particles between OP and OT are not surprising. Charcoal particles in thin sections are undisturbed by preparation techniques (Clark, 1988b; Clark and Hussey, 1996). In contrast, the steps normally used for pollen preparation can significantly reduce the total area and number of charcoal particles by physical or chemical removal. For example, sieving and decanting during pollen preparation to eliminate large pieces alter the original size distribution of charcoal particles. Tinner *et al.* (1998) showed that, in comparison with thin sections, the preparation of pollen samples strongly affected the upper size limit (= < mesh width of sieves) of charcoal results, in extreme cases leading to missing charcoal peaks in pollen slides. Comparisons of annually resolved charcoal data from pollen slides with historical fire records further showed that this effect may impede the reconstruction of local fire events (Clark and Royall, 1995; Tinner *et al.*, 1998; Carcaillet *et al*, 2001). However, the general consistencies between historic fire data and pollen-slide charcoal records at various sites (e.g., MacDonald *et al.*, 1991; Tinner *et al.*, 1998) suggest that the selective effects of pollen preparation do not affect the suitability of the pollen-slide method for fire reconstruction at regional scales.

In contrast to the differences in size parameters and size-class distribution, the ratio of charcoal length to breadth is identical (1.9) for OP and OT, suggesting that pollen preparation does not alter this ratio. In addition, the total charcoal number is higher for OT than for OP, arguing against charcoal-particle breakage during pollen processing, which would have increased the number of charcoal particles. These data are consistent with Clark (1984) who found that an increase of particle number (and hence particle breakage) was only observed when ultrasonic baths were used for pollen preparation, a method seldom used in palynology and not applied in our study.

Among the three pollen-slide charcoal records, the statistical differences of size parameters and size-class distribution between OP and WI and between GY and WI may be accounted for by the fact that the WI data represent samples of several vegetational types, including *Betula* shrub tundra, *Populus* forests and *Picea*-dominated boreal forests whereas all the OP and GY samples represent forested environments. For example, it is possible that tundra shrubs and trees produced charcoal particles with different sizes and morphological features. To address this possibility, we divided the WI charcoal data based on pollen-inferred vegetational types: WT (*Betula* shrub tundra), WP (*Populus* forests) and WS (*Picea*-dominated forests) (Table 2). Charcoal median lengths and size-class distributions do not differ significantly among these three groups, and charcoal median areas do not differ significantly between WP and WS. These patterns, along with the lack of statistical differences in all charcoal parameters between OP and GY, suggest that vegetational types do not significantly affect charcoal-size parameters and size-class distribution of charcoal particles in pollen slides at our sites. However, the median charcoal area is significantly larger, instead of smaller, for WT than for WP or WS, reflecting the greater breadth of the WT charcoal. These data cannot explain our observation that the median length and area are smaller for WI than for OP and GY. A more likely cause for the smaller length and area of the WI charcoal is that during pollen preparation we used a sieve of smaller openings (180 μm) for the WI samples than that (500 μm) for the OP and GY samples.

Taken together, our results suggest that differences in charcoal size and size-class distribution between sites are mainly induced by different preparation techniques. However, differences in vegetation type or other factors (e.g., changes in fire regime related to different climatic conditions) are unimportant. This conclusion is remarkable given the drastic differences in vegetation composition among different pollen zones at Wien Lake and among the three sites (Hu *et al.,* 1993; Tinner *et al.,* 1998). We do not know the specific pollen-procedure related reasons giving rise to the similarity in charcoal size and size-class distribution. Removal of large charcoal particles through sieving and decanting is almost certainly a contributing factor, but it cannot be solely responsible given the large ranges of microscopic-charcoal particle sizes (Figure 1). It is unlikely that the charcoal similarity was caused by the same general types of trees burned in each case (e.g., similar fire-sensitive woody species) because dominant species differ greatly through time at Wien and among the three sites (Hu *et al.*,

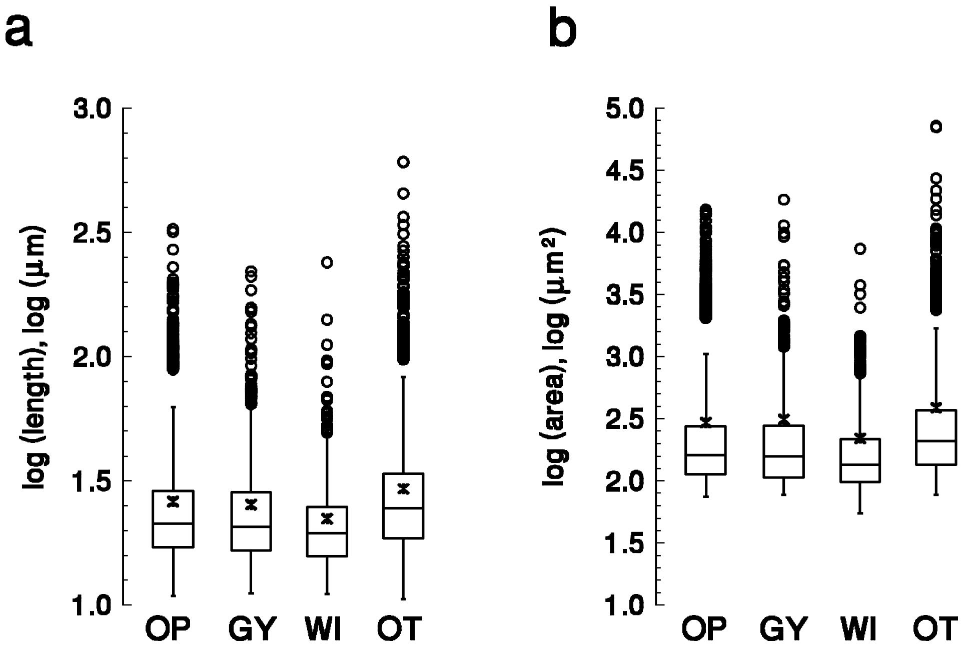

Figure 1 Box plots showing medians (central horizontal line), means (asterisk), 25% and 75% quantiles (bottom and top borders of boxes) and extreme values (empty circles) of (a) charcoal-particle length and (b) charcoal-particle area. Central vertical lines indicate 1.5 interquartile ranges. OP = pollen slides of Lago di Origlio (Switzerland), GY = pollen slides of Grizzly Lake (Alaska), WI = pollen slides of Wien Lake, OT = thin sections of Lago di Origlio. Number of measured charcoal particles (N) = 11157 for OP; 1257 for GY; 1011 for WI; 9669 for OT.

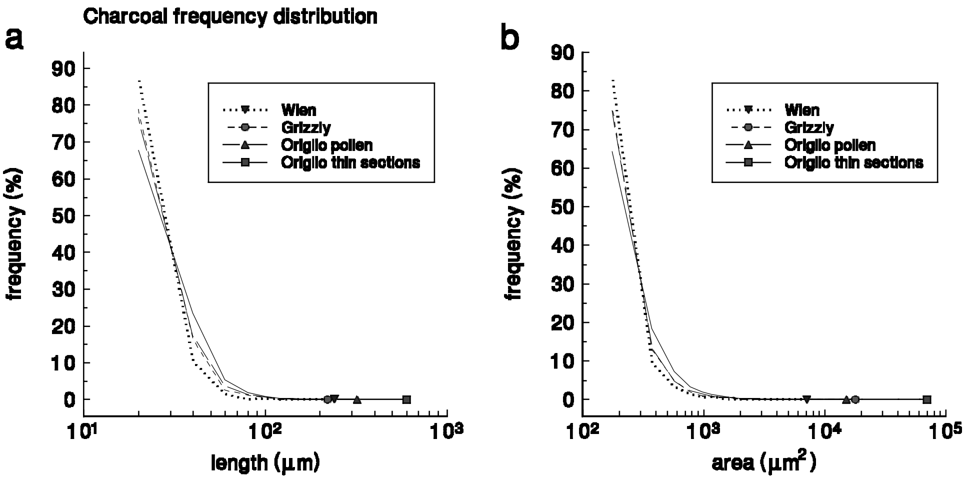

Figure 2 Charcoal-size class distributions. (a) Frequency distribution of charcoal-length classes (20 µm intervals). The dot, triangles and box on the curves indicate the maximum lengths of particles found at various sites. (b) Frequency distribution of charcoal-area classes (200 µm² intervals). The dot, triangles and box indicate the maximum areas of particles found at various sites.

1993; Tinner *et al.*, 1998). Similar wood-anatomical characteristics of coniferous and deciduous species (Schweingruber, 1990) may account for comparable particle morphologies (e.g., length:-breadth ratios; Umbanhowar and McGrath, 1998), but they do not explain size and size-distribution variations. Another possibility is that fire, weather or short-term variations in climate affected fuels and the processes of charcoal formation in similar ways, which seems inconceivable since our three charcoal records came from four biome types in two continents and spanned up to 12500 years.

Charcoal number-area relationship in pollen slides: linear-regression models

The area concentration (mm^2 cm^{-3}) and number concentration (number of charcoal particles cm^{-3}) of charcoal particles in pollen slides are strongly correlated at all of our three sites (Figure 3). Within each site, they co-vary stratigraphically; even minor changes in area concentration are mirrored by those in number concentration (Figure 4). The regression equations linking these two variables are:

$\ln A = -7.418 + 0.936 \ln N$ for OP; ($r^2 = 0.83$, $n = 90$)
$\ln A = -8.661 + 1.013 \ln N$ for WI; ($r^2 = 0.83$, $n = 19$)
$\ln A = -11.022 + 1.242 \ln N$ for GY; ($r^2 = 0.82$, $n = 24$)

where A is the area concentration and N is the number concentration of charcoal particles >75 µm^2 (or *c.* 10 µm long) in pollen slides. For OP, the 95% confidence intervals (CIs, parameter ±1.96 standard errors) are from –6.708 to –8.128 for the intercept and from 0.874 to 0.998 for the slope. For WI, the 95% CIs are from –6.138 to –11.184 for the intercept and from 0.795 to 1.231

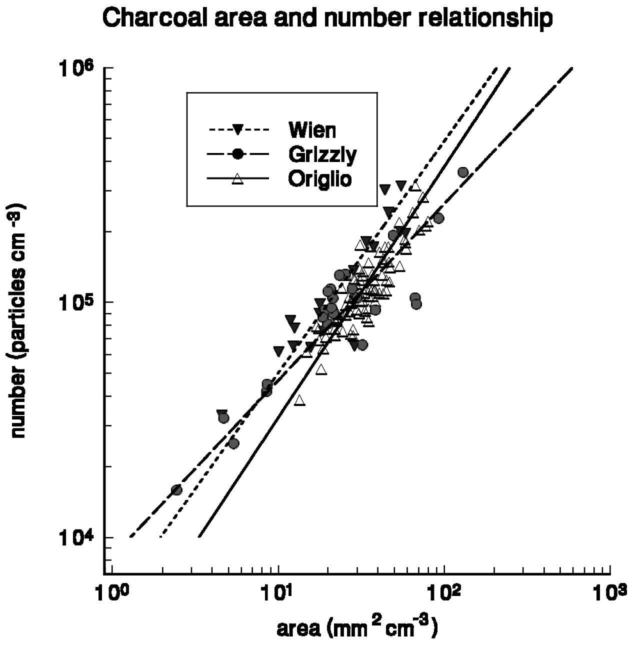

Figure 3 Charcoal number-area relationships. The lines indicate the linear-regression models of ln-transformed variables.

for the slope. For GY, the 95% CIs are from –8.284 to –13.760 for the intercept and from 1.001 to 1.483 for the slope. The slope and intercept parameters of the OP model are within the CIs of the WI model, and the latter is within the CIs of the GY model. In agreement, the slopes do not differ statistically ($p = > 0.05$ adjusted) between WI and OP or between WI and GY (Table 3). However, the slopes differ between GY and OP, and the intercepts differ for both cases with similar slopes (Table 3).

The OP model has been tested statistically against the charcoal data set of the entire Holocene from Lago di Origlio (Tinner *et al.*, 1998), and the authors concluded that the charcoal-number concentrations accurately predicted area concentration. Our new results from WI and GY support this conclusion. These three models consistently indicate that the charcoal-number explains 82–83% of the charcoal-area concentration variability. The high number-area correlation is partially because we eliminated large particles during pollen processing, which tend to dominate the total area concentration, and disregarded small particles (<75 μm^2 or ~10 μm in diameter) in charcoal counting. Thus this conclusion is only valid for charcoal analysis in pollen slides.

Given these high correlation values, it seems unnecessary to strenuously measure (image analysis) or estimate (e.g., square eye-piece grid method: Swain, 1973; point-count method: Clark, 1982) the area of charcoal particles in pollen slides, because little additional information can be gained. It is unlikely that the unexplained 17–18% resulted from the removal of large, rare charcoal particles during pollen processing, which should have improved the correlation between area and number concentrations. Conversely, one may argue that the unexplained 17–18% contains information on local fire signals, as rare but large charcoal fragments cannot be predicted correctly by our regression equations. This reservation is irrelevant for charcoal analysis on pollen slides, given that microscopic charcoal records are unsuitable for the reconstruction of local fire events (e.g., Clark, 1988a; Clark and Royall, 1995; Tinner *et al.*, 1998; Carcaillet *et al.*, 2001).

Can the model from one site reliably predict concentration of charcoal areas from concentrations of charcoal numbers at another site? Although most fire-history studies have reported results in terms of charcoal areas, others have reported charcoal-number data. Thus, this question is relevant for the comparability of number and area estimates. To address it, we compared measured area concentration for one site with those predicted by an equation from another (Table 4). These comparisons show that, in all cases, predicted area concentrations are similar to the measured values ($r = 0.86$ to 0.89; see Table 4 and Figure 5 for WI and GY using the OP equation). If plotted against depth, the curves of the measured and predicted area concentrations appear very similar (Figure 4).

For quantitative comparisons we calculated the area-concentration difference between model predictions and measurements for each sample of WI, GY and OP. We used the two-sided Wilcoxon rank sum test to evaluate whether the mean difference is

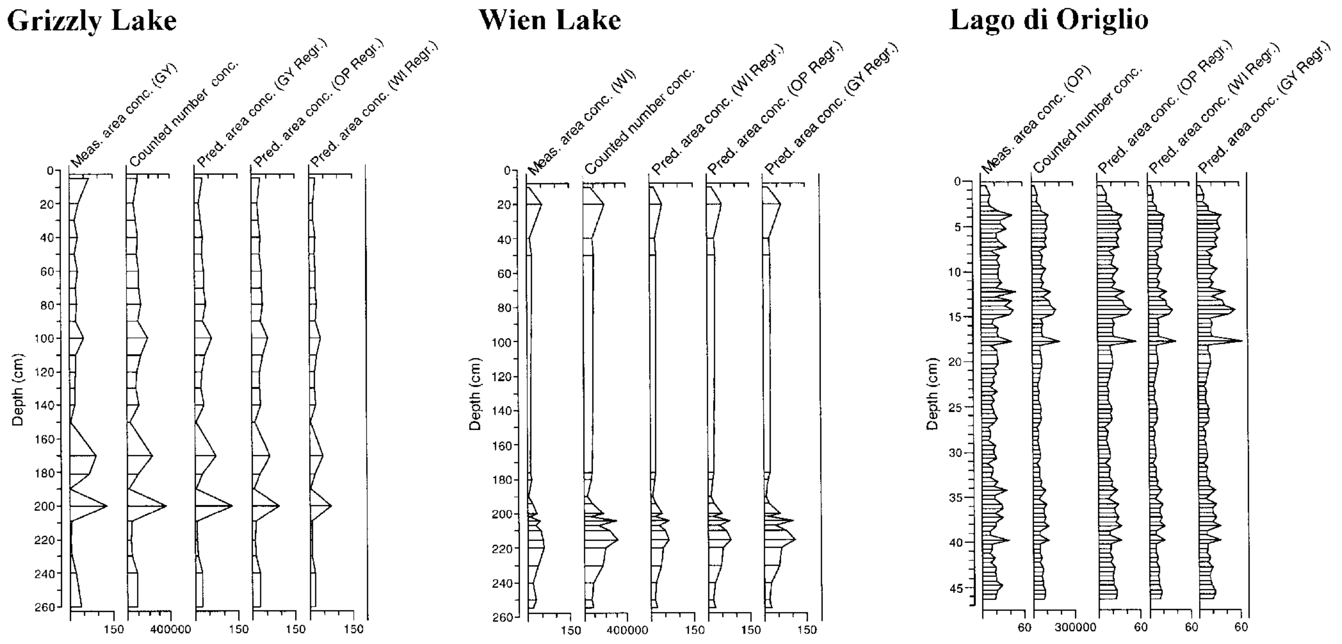

Figure 4 Charcoal concentration diagrams for Grizzly Lake, Wien Lake and Lago di Origlio. Charcoal area concentrations ($mm^2\ cm^{-3}$) measured by image analysis are compared with number concentrations (number cm^{-3}) and with number-predicted area concentrations ($mm^2\ cm^{-3}$). Number-predicted area concentrations were computed using the regression equations of Grizzly Lake, Lago di Origlio and Wien Lake.

Table 3 Comparison of the regression parameters

Hypothesis	F value	Common resulting equations
H_0: β_1WI = β_1OP	0.890	lnA = –7.559 + 0.949 ln N (Origlio) lnA = –7.910 + 0.949 ln N (Wien)
H_0: β_1WI = β_1OP, β_0WI = β_0OP	52.749	
H_0: β1GY = β_1WI	1.721	lnA = –10.270 + 1.152 ln N (Grizzly) lnA = –9.998 + 1.152 ln N (Wien)
H_0: β_1GY = β_1WI, β_0GY = β_0WI	5.763	
H_0: β_1GY = β_1OP	15.770	

Null hypothesis for comparison of slopes: the slopes are not different, H_0: $\beta_1 X = \beta_1 Y$. Confidence limit ($\alpha = 0.05$) adjusted for multiple tests F = 5.71. Null hypothesis for comparison of intercepts: intercepts are not different while slopes do not differ H_0: $\beta_1 X = \beta_1 Y$, $\beta_0 X = \beta_0 Y$.

Table 4 Statistical comparison of measured and predicted charcoal area concentrations

Model used	Mean MAC	Mean diff.	Sd.d. diff.	R	P (R = 0)	W.S.R.	P (mn = 0)
OP→GY	32.32	2.18	16.49	0.87	0.0001	–26	0.4693
OP→WI	27.72	–9.74	10.58	0.89	0.0001	–81	0.0004
WI→GY	32.32	10.83	18.64	0.87	0.0001	88	0.0087
GY→WI	27.72	–12.51	18.46	0.87	0.0001	–78	0.0008
WI→OP	34.93	10.77	7.51	0.87	0.0001	2028	0.0001
GY→OP	34.93	1.08	8.88	0.86	0.0001	571	0.0208

OP→GY = Grizzly area concentrations (mm^2 cm^{-3}) predicted by the Origlio equation.
Mean MAC = the mean of measured charcoal area concentrations (mm^2 cm^{-3}).
Mean diff. = the mean of the differences (mm^2 cm^{-3}) between pairs of measured and predicted charcoal area concentrations.
Sd.d. diff. = standard deviation (mm^2 cm^{-3}) of the differences between pairs of measured and predicted charcoal area concentrations.
P (R = 0): P values for the null hypothesis that the Pearson correlation coefficients are not different from zero.
W.S.R. = Wilcoxon Signed Rank.
P (mn = 0): P values for the null hypothesis that the difference between the means of predicted and measured charcoal area concentrations is not different from zero.

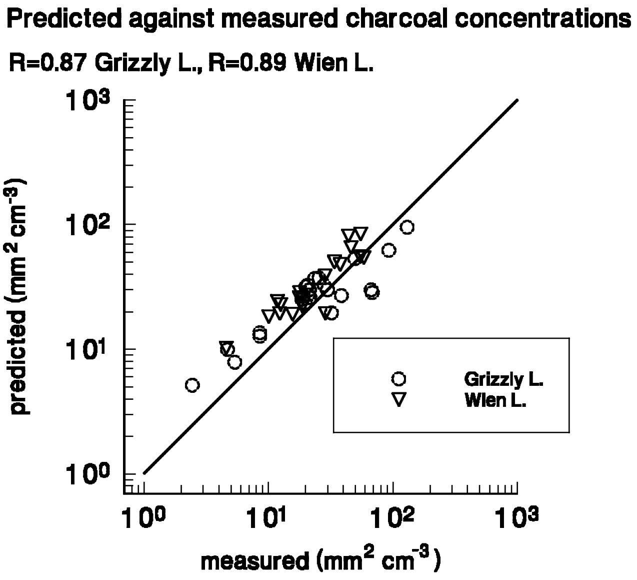

Figure 5 Predicted versus measured charcoal concentrations for Grizzly Lake and Wien Lake. The predicted charcoal concentrations were calculated by applying the linear regression of ln-transformed variables from Lago di Origlio to the number concentration data from Grizzly Lake and Wien Lake.

significantly different from zero. The models from WI and GY produce predictions for each other that are less accurate than those for these two sites based on the OP model (Table 4), and the GY model produces reasonably accurate predictions for OP (mean overestimation of 1.08 mm^2 cm^{-3}, which corresponds to +3.1% if compared with the measured values; Table 4). However, the tests show that the measured and model-predicted area concentrations differ statistically ($p = < 0.05$) in all cases with one exception: OP versus GY ($p = 0.47$; Table 4).

The smaller difference between GY and OP than between the other comparisons probably reflects the fact that size parameters and size-class distributions do not differ between GY and OP but do differ between WI and OP and between WI and GY, as discussed above. Thus, it seems that for the vegetation types we compared (shrub tundra, boreal and temperate forests) the equation from one site can be used to estimate area concentrations from number concentrations at another site as long as the same pollen-preparation technique is used. This interpretation should be tested with additional studies of microscopic charcoal in the lake sediments of other sites.

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