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Short Paper

Quantifying the source area of macroscopic charcoal with a particle dispersal model

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Abstract

To aid interpreting the source area of charcoal in lake-sediment records, we compare charcoal deposition from an experimental fire to predictions from a particle dispersal model. This provides both a theoretical framework for understanding how lake sediments reflect fire history and a foundation for simulating sediment-charcoal records. The dispersal model captures the two-dimensional patterns in the empirical data (predicted vs. observed $r^2=0.67$, $p<0.001$). We further develop the model to calculate the potential charcoal source area (PCSA) for several classes of fires. Results suggest that (1) variations in airborne charcoal deposition can be explained largely by the size of PCSAs relative to fire sizes and (2) macroscopic charcoal travels many kilometers, longer than suggested by dispersal data from experimental fires but consistent with dispersal data from uncontrolled fires.

Keywords: Charcoal analysis; Charcoal dispersal; Charcoal source area; Dispersal model; Experimental burn; Fire history

Introduction

Sediment-charcoal studies began with the analysis of charcoal on pollen slides in an effort to reconstruct watershed-scale fire history over centennial to millennial time scales (Iversen, 1941; Swain, 1973; Cwynar, 1978; Green, 1982). As summarized by Patterson et al. (1987), these and other early efforts found ambiguous relationships between charcoal abundance and either known or hypothesized fire histories. To explain these ambiguities, Clark (1988a) presented a one-dimensional model of charcoal transport and dispersal for particles of varying sizes and fall speeds. This model predicts that charcoal dispersal distances should increase with wind speed and injection height and decrease with particle size and particle density. Due to the physical differences between microscopic and macroscopic charcoal,[3] the former travels long distances (10^0–10^2 km) while the latter is more locally dispersed (10^1–10^3 m). The differences in dispersal distances led Clark (1988a) to suggest that the source area of microscopic charcoal was substantially larger than that of macroscopic charcoal, with microscopic-charcoal records representing regional burning and macroscopic-charcoal records representing fires within several hundred meters of a lake. This suggestion has received empirical support from many studies (MacDonald et al., 1991; Clark and Royall, 1995, 1996; Whitlock and Millspaugh, 1996; Tinner et al., 1998; Carcaillet et al., 2001b; Gardner and Whitlock, 2001; Lynch et al., 2004a; Higuera et al., 2005), and Clark (1988a) has been heavily cited in the charcoal literature. However, the theory described by Clark (1988a) remains untested and has

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[3] We use the term "microscopic charcoal" to refer to charcoal on pollen slides, typically $<\approx 50$ μm in diameter (Patterson et al., 1987). We use the terms "macroscopic charcoal" or "thin-section charcoal" to refer to charcoal pieces $>\approx 50$ μm quantified via the sieving method (Whitlock et al., 2003) or thin-section analysis (Clark, 1988b).

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received little additional attention. In contrast to palynology, which has benefited greatly from theoretical studies of pollen source area (e.g., Prentice, 1985; Sugita, 1993, 1994), efforts to both infer fire history from charcoal stratigraphy, and predict charcoal stratigraphy given hypothetical fire histories, remain limited by an imprecise understanding of charcoal source areas (Whitlock and Anderson, 2003).

To explicitly calculate charcoal source areas, Clark's (1988a) one-dimensional model must be expanded into its two-dimensional form. In this paper, we (1) present the two-dimensional form of the dispersal model used by Clark (1988a), (2) evaluate the model's suitability for simulating charcoal dispersal by comparing its predictions to charcoal deposition from an experimental fire, and (3) expand the model to produce a visual and numerical representation of the charcoal source area for several classes of fires. This exercise utilizes the same dispersal model used by Prentice (1985) and Sugita (1993, 1994) to establish and refine the theoretical foundations of pollen analysis. In many ways our work is analogous to Prentice and Sugita's, and it aids the interpretation of fossil charcoal records by illustrating relationships between charcoal source area, fire size, and temporal patterns of airborne charcoal deposition. The framework developed here also serves as a foundation for more complex modeling approaches that are needed to understand the effects of fire size, charcoal dispersal and charcoal taphonomy on charcoal accumulation in sediment records (Higuera, 2006).

Theory

Incidents of gas warfare during World War One led the British government to establish a research program in the 1930s to study the diffusion and transport of particles in the lower atmosphere. Results of this work were published in two papers by Sutton (1947a,b), the second of which presents general formulas for the concentration of smoke particles reaching any point as a function of the particles emitted from a continuous point source at an arbitrary height. Particle deposition in these results was purposely ignored. Chamberlain (1953) generalized Sutton's work to allow for deposition and presented closed-form solutions for the concentration of particles deposited at the ground as:

$$\chi(x,y) = \frac{2v_g Q(x)}{u\pi C_y C_z x^{2-n}} \exp\left(\frac{-y^2}{C_y^2 x^{2-n}}\right) \exp\left(\frac{-h^2}{C_z^2 x^{2-n}}\right) \quad (1)$$

$$Q(x) = Q_0 \exp\left\{ \frac{4v_g}{nuC_z\sqrt{\pi}} \left[-x^{n/2}e^{-\xi} + \left(\frac{h}{C_z}\right)^{2m} \times (\Gamma(-m+1) - \Gamma_\xi(-m+1)) \right] \right\} \quad (2)$$

Eqs. (1)–(2) depend on the parameters described in Table 1. χ is the concentration of particles deposited on the ground at the point (x, y), assuming the source to be at $x=0$, $y=0$, and height h. $Q(x)$ represents the concentration of emitted particles transported beyond x for all y. Note that Eqs. (1)–(2) assume the wind to be blowing parallel to the x-axis and the units on Q_0 are arbitrary; in practice we take Q_0 to have dimension $m^2 \times 100$ so that χ is expressed in $mm^2\ cm^{-2}$. Eq. (2) is the same as Eq. (6) in Clark (1988a). Consequently, Clark's one-dimensional results (i.e. Fig. 4 in Clark, 1988a) can be interpreted as the integral over all y of the two-dimensional results in Figure 1.

Eqs. (1)–(2) can be understood physically as a map of the proportion of charcoal deposited at varying distances from a single point source. For example, macroscopic charcoal released from a source at $x=y=0$, height $h=14$ m, with a 5 m s^{-1} wind blowing from left to right would result in charcoal deposition illustrated in Figure 1a. The non-zero skip distance (i.e. no charcoal deposition) in Figure 1a results from the unrealistic (but mathematically precise) release of particles from a single injection height. In the crosswind (y) direction, the deposition is Gaussian for any x (Fig. 1b), and the integral over y (Fig. 1c) is analogous to Figure 4 in Clark (1988a).

Due to the symmetry inherent in the solutions of (1)–(2), Figure 1 has an alternate interpretation (also explained by Clark, 1988a). It can also be viewed as a map of the proportion of total charcoal deposited at the point $x=y=0$ (i.e., the lake center) from each point in the surrounding landscape when the entire landscape burns in an infinitely large fire and wind blows from right to left. Thus Figure 1 also gives a visual depiction of the potential area contributing charcoal to the lake center under the stated assumptions on wind and injection height. Areas burned outside of the contoured source area do not contribute charcoal to the lake center via direct airborne fallout.

To make this precise, we define potential charcoal source areas (PCSA) as two dimensional maps analogous to those in Figure 1a. Each map is normalized by the total accumulated charcoal at the lake center, resulting in a probability density

Table 1
Description of the parameters in Eqs. (1)–(2)

Parameter	Description/source
x	Distance downwind (m)
y	Distance crosswind (m)
v_g	Deposition velocity (m s^{-1})
Q_0	Source strength ($m^2 \times 100$)
u	Mean wind speed (see Sutton, 1947a) (m s^{-1})
C_y, C_z	Diffusion constants (we use $C_y=0.21$, $C_z=0.12$; see Sutton, 1947a) ($m^{1/8}$)
h	Source height (m)
n	Measure of turbulence near ground (we use 1/4; see Sutton, 1947a) (dimensionless)
m	$n/(4-2n)$ (dimensionless)
ξ	$h^2/(x^{2-n}C_z^2)$ (dimensionless)
$(\Gamma(-m+1)-\Gamma_\xi(-m+1))$	$= -m\int_\xi^\infty e^{-t}t^{-m-1}dt$ (dimensionless)

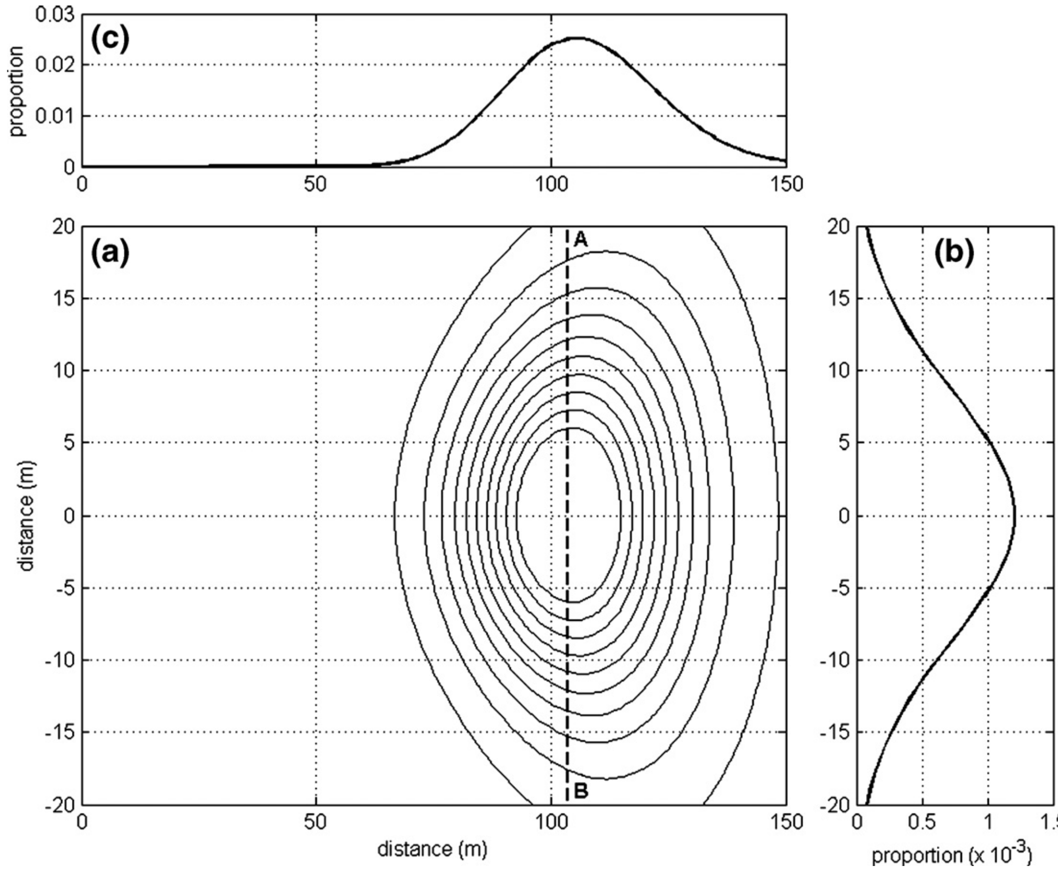

Figure 1. (a) Map illustrating the proportion of charcoal density on a flat landscape deposited from a continuous point source located at $x=y=0$ m and height $h=14$ m, with wind blowing from left to right with wind speed $u=5$ m s^{-1}. The depositional velocity $v_g=1.56$ m s^{-1} was calculated from empirical data collected by Lynch et al. (2004a), as described in "Methods". Contour intervals are 10^{-4}, with contours running from 5×10^{-5} to 9.5×10^{-4}. (b) A cross section in the y-direction along the line labeled A–B in part (a). (c) The integral over all y.

function (pdf).[4] The term "potential" emphasizes that any single fire does not necessarily contribute charcoal from the entire source area.

Methods and rationale

Comparison of theory and empirical data

The PCSA described above gives the proportion of charcoal deposited at an arbitrary point from an arbitrary source location; the integral of the PCSA over the area of an entire fire then yields the total charcoal deposited at a given point (e.g., a lake).[5] To test the realism of this theoretical depiction, we evaluated the ability of Eqs. (1)–(2) to reproduce two-dimensional charcoal deposition patterns from a prescribed fire in boreal Canada (Lynch et al., 2004a) by fixing observed parameters and computing optimum values of the remaining free parameters in the non-linear least squares sense. In an effort to constrain the number of free parameters and to test the model in its most basic configuration, we assume a single value for each of the dependent variables in (1) as in Figure 1.

The 2.25-ha fire studied by Lynch et al. (2004a) was one of several experimental fires in the International Crown Fire Modeling Experiment (ICFME, Stocks et al., 2004). Data from four evenly spaced transects of charcoal traps located 10–200 m from the edge of this fire showed significant variation in charcoal density (mm^2 cm^{-2}) with distance from the fire edge (Fig. 2a, based on Fig. 2 in Lynch et al., 2004a). Lynch et al. (2004a) fit a negative-exponential curve to data from traps located inside as well as outside the fire, which confounded airborne deposition with in situ charcoal production. We disregard the data from traps inside the fire, as our goal is to test the model for airborne charcoal dispersal away from burned areas. We do not use data from another experimental fire (Clark et al., 1998) because charcoal deposition reported in the Clark et al. study did not vary substantially within the distances sampled.

We calculated the expected fall speed for each piece of charcoal collected by Lynch et al. (2004a) using Eq. (1) from Clark et al. (1998). This equation predicts fall speed as a function of particle size, particle density, acceleration due to gravity, and the density and viscosity of air (Clark, 1988a; Clark et al., 1998). Since (1)–(2) are relatively insensitive to variations in fall speed compared to injection height (see Results below), we used the mean fall speed of all samples in all transects in the subsequent analysis.

[4] The PCSA is defined to be PCSA $(x,y)=\chi(x,y)/\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\chi(x,y)\mathrm{d}x\mathrm{d}y$.
[5] The total accumulated charcoal for a fire is equal to $Q_{\mathrm{fire}}\int\int_{fire} PCSA(x,y)\,\mathrm{d}x\mathrm{d}y=\int\int_{fire}\chi(x,y)\mathrm{d}x\mathrm{d}y$ *where* $Q_{\mathrm{fire}}=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\chi(x,y)\mathrm{d}x\mathrm{d}y$.

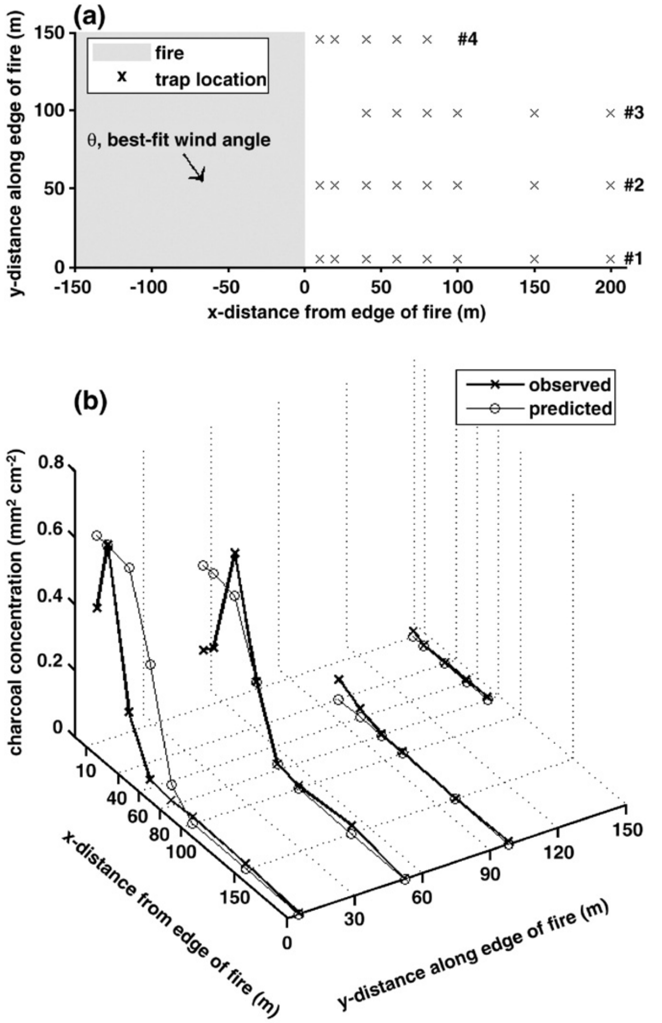

Figure 2. Result of fitting the dispersal models (1)–(2) to the observed data from the ICFME fire studied by Lynch et al. (2004a). (a) Layout of the fire studied by Lynch et al. (2004a), trap locations with transect numbers, and the best-fit wind angle. (b) Predicted (X symbols) and observed (O symbols) charcoal densities for the four transects.

In the six fires of the ICFME, mean wind speeds at 10-m height varied between 3 and 7 m s^{-1} during burning (Taylor et al., 2004); we use $u = 5$ m s^{-1} as the estimated wind speed in the following analysis. Although the wind direction observed at the time of the burn was generally away from the fire and parallel to the direction of the transects (Jason Lynch, May 2004, personal communication), the systematic difference in the magnitude of the charcoal deposited in transects 1, 2 vs. 3, 4 (Fig. 2) suggests wind direction was at some angle θ to transect direction. We allow for this possibility by treating wind direction as a free parameter. The injection height and source strength Q_0 (i.e. charcoal production) are less constrained by observations. Accordingly, we take the effective injection height h to be a free parameter and scale source strength Q_0 to the maximum observed charcoal density in the charcoal traps. With these choices, we can calculate the total charcoal transported to each of the traps using Eqs. (1)–(2). We then use the observe charcoal density in the traps to compute optimum values of θ and h in the non-linear least-squares sense (i.e. θ and h minimize the root-mean-square error of the difference between predicted and observed charcoal density in each of the 27 traps).

Sensitivity testing and expansion of the analytical model

The Lynch et al. (2004a) fire was small compared to naturally occurring wildfires in boreal forests (Kasischke et al., 2002). Given that plume heights are a function of heat release (Chandler et al., 1983, cited in Clark, 1988a), which in turn is related to fire intensity and arguably to fire size, the optimum injection height from our comparison with Lynch et al.'s (2004a) experimental burn is probably at the lower bound of actual injection heights. We therefore consider the sensitivity of results from (1)–(2) to a range of injection heights h. In addition, fall speed v_g and wind speed u are expected to exhibit large variability both within and between fires. Since v_g and u only appear in (1)–(2) as the ratio v_g/u, we examine sensitivity to changes in either parameter from changes in u solely. We assess the sensitivity of (1)–(2) to both injection height h and wind speed u by varying each parameter independently while holding all other parameters constant.

Variations in wind direction become important as fire size and duration increase. To calculate PCSAs that include variations in wind direction, we assume that wind directions vary proportionally to the average June–August wind directions recorded in Bettles, Alaska (1971–2000) and that each fire lasts long enough to adequately sample this distribution. To include variations in injection heights, we assume a distribution of h, characterized by modal injection heights h_{mode} of 10, 100, 1000 m. We also assume that this distribution is negatively skewed, with a peak at large injection heights and a long tail at smaller heights (Fig. 4, row 1), based on two observations. First, small charcoal particles that dominate charcoal deposition in experimental burns (Clark, 1988a; Lynch et al., 2004a) are lofted to greater heights in a fire's turbulent plume than are larger particles, leading to an upward bias in injection heights. Second, fire activity is favored in warm, dry atmospheric conditions, often accompanied by strong inversions. These inversions place a cap on plume height by trapping smoke below the inversion. In practice, the shape of the h distribution has a predictable effect on the shape of the PCSA as explained below. All other parameters for calculating each PCSA are the same as used for predicting the Lynch et al. (2004a) dataset.

We present PCSAs by displaying (1) the cumulative amount of charcoal reaching a lake from within a range of radial distances, and (2) a map of total charcoal reaching a lake from each part of the PCSA. Both approaches illustrate the size of the PCSA; the second shows the variability in charcoal deposition from within the PCSA due to varying wind direction and distance from the lake.

Results

The two-dimensional model captured the spatial pattern of charcoal dispersal (with $\theta = 55°$ and $h = 14$ m) by predicting the strong dependence of charcoal density (mm^2 cm^{-2}) on both x

and y distances (Fig. 2b). Quantitatively, the model explained 67% of the variation in the observed data ($r^2=0.67$, $p<0.001$). The less-than-perfect correlation occurs because observed charcoal densities peak at 40 m but the model predicts nearly constant density from 10–40 m, with a rapid decrease at greater distances.

Both the size of the charcoal source area and the skip distance resulting from (1)–(2) are highly sensitive to injection height h, scaling approximately with h^2 and h, respectively (Fig. 3a). In contrast, source area and skip distance are relatively insensitive to wind speed u (Fig. 3b). Thus the dependence of (1)–(2) on wind speed can be neglected given realistic variability in injection heights.

Charcoal transport for the 10-, 100-, and 1000-m h_{mode} scenarios is inconsequential from distances greater than of ~200, 1500, and 15,000 m, respectively (Fig. 4, row 2), and skip distances are negligible as compared to those in Figure 3b. In each scenario, the center of the domain (i.e. the lake) receives a nearly constant proportion of charcoal from each distance, resulting in a nearly linear increase in cumulative charcoal deposition until the edge of the PCSA, where charcoal density rapidly decreases to zero (Fig. 4, rows 2–3). Most airborne charcoal deposited at the lake comes from pixels closest to the lake and from pixels "up-wind" of the lake and along the dominant wind directions (darkest portions of Fig. 4, row 3).

Discussion

Our explicit method for computing charcoal deposition on a two-dimensional landscape reasonably depicts the charcoal deposited from an experimental fire. The largest drawback to our method is that it remains untested for large, uncontrolled fires and for dispersal distances greater than 200 m. Large fires would create greater spatial and temporal complexity than the experimental burn we examined, and it is unclear how this complexity would affect our assumptions (e.g., of injection heights). In addition, the theory underlying the analytical model was developed from smoke diffusion experiments and previously remained untested for particles as large as macroscopic charcoal. Despite these caveats, the agreement between predictions from the model and observed charcoal deposition patterns (Fig. 2; Lynch et al., 2004a) suggests that the model is a reasonable depiction of the processes of airborne charcoal dispersal and charcoal source areas.

Our simulated PCSAs motivate two simple hypotheses about conditions creating variable peak heights in sediment-charcoal records. First, the variability in airborne charcoal deposition to a lake depends on the relationship between PCSAs and fire sizes (i.e. the source-area to fire-size ratio). For example, if a 100-ha fire originates within a small PCSA (e.g. ~30 ha, represented by the 10-m h_{mode} scenario; Fig. 4, column 1), it will almost

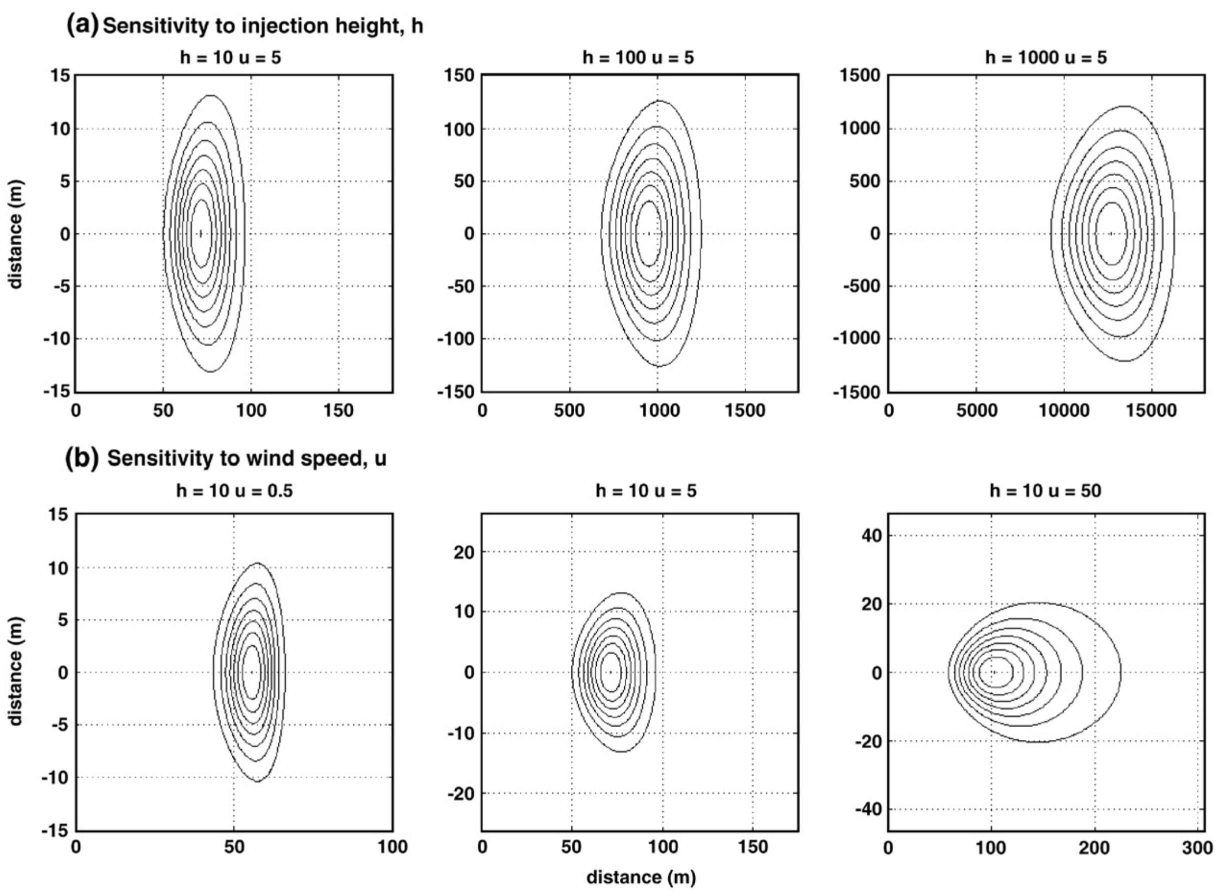

Figure 3. Sensitivity of the dispersal models (1)–(2) to injection height and wind speed. All plots as in Figure 1a, except note that the horizontal scale in (a) varies across two orders of magnitude, whereas the scale in (b) remains relatively constant. (a) Injection heights of 10 m, 100 m and 1000 m, from left to right, with the wind held constant at 5 m s^{-1}. (b) Wind speeds of 0.5, 5 and 50 m s^{-1}, from left to right, with the injection height held constant at 10 m.

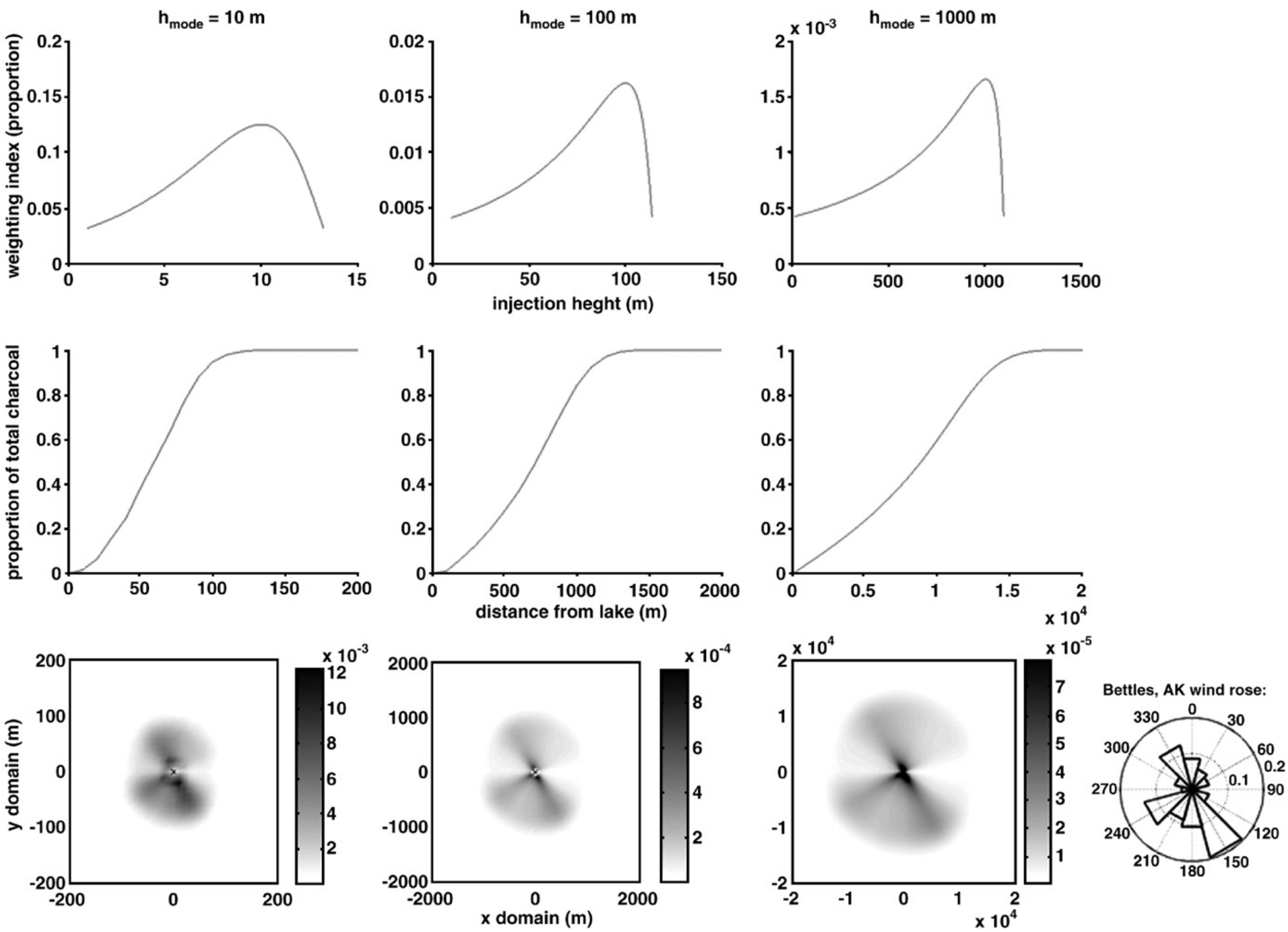

Figure 4. Potential charcoal source area (PCSA) for three modal injection height scenarios (columns), including distribution of injection heights (row one), cumulative charcoal deposited at the lake at increasing distances (row two), and a map of the PCSA, including the empirical wind data form Bettles, Alaska, used to simulate variable wind direction (row three). Grayscale bars in row three represent charcoal density.

always cover the entire PCSA, resulting in charcoal peaks equal to one. In this scenario, multiple 100-ha fires would create a nearly binary pattern of airborne charcoal deposition through time, with distinct peaks when fires burn within the source area and no charcoal otherwise. With larger PCSAs (represented by 100- and 1000-m h_{mode} scenarios; Fig. 4, row 3), the number of potential locations of 100-ha fires within the PSCA increases. This would result in greater variability in airborne charcoal deposition due to location alone, because fires close to a lake deposit more charcoal than fires far from a lake. A larger PCSA also allows for more fires of varying sizes to occur within the PCSA, creating further variability in charcoal deposition through time.

Second, boreal-forest PCSAs are likely larger than those implied by Lynch et al. (2004a; Fig. 4) and similar charcoal-dispersal datasets (Clark et al., 1998; Ohlson and Tryterud, 2000). In particular, the lack of binary patterns of charcoal deposition in boreal forest sediment records (e.g. Carcaillet et al., 2001a; Lynch et al., 2002, 2004b), as describe above, argues against the short charcoal dispersal distances suggested by these studies. Larger PCSAs should result in variability in charcoal peak heights resembling empirical records, because a large range of fire sizes can burn within a PCSA. Given that the potential area for fires to burn increases by the square of radial distance, increased area at long distances provides more opportunities for long-distance (e.g., >1–10 km) rather than short-distance dispersal. Several recent studies have measured significant charcoal deposition in lake sediments (Whitlock and Millspaugh, 1996; Hallett et al., 2003) or charcoal traps (Pisaric, 2002; Tinner et al., 2006) at distances several to tens of kilometers away from uncontrolled fires. Thus, even while charcoal dispersal is strongly biased towards short distances, both empirical studies (cited above) and our theoretical work suggest that charcoal from long distances can ultimately comprise a significant proportion of overall charcoal reaching a lake (Fig. 4, row 2).

Overall, our results suggest that the variability in sediment-charcoal records can largely be explained by the fundamental characteristics of charcoal deposition. Based on explicit representations of PCSAs, we propose that variations in the source-area to fire-size ratio and the size and location of fires within PCSAs significantly affect patterns of charcoal deposition. An explicit simulation-modeling approach should be fruitful for testing this hypothesis and understanding these patterns in greater detail. The theoretical framework and analytical model developed here are a foundation for this next step in modeling the effects of charcoal deposition on sediment-charcoal records (Higuera, 2006).

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