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Long-distance transport of macroscopic charcoal by an intensive crown fire in the Swiss Alps – implications for fire history reconstruction

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Abstract: The correct interpretation of charcoal records in a palaeoecological context requires the understanding of the sources and transport of charcoal particles. Conventionally, it is assumed that macroscopic charcoal particles are not transported far from fires (*c.* 200 m). Therefore macroscopic charcoal records are used to reconstruct local fire frequencies. However, the general scarcity of empirical and experimental evidence impedes a thorough check of this assumption. In this study we present the first unambiguous evidence of kilometre-scaled macroscopic charcoal transport in Europe. During the hot summer of 2003 an intensive crown fire occurred in Leuk, central Swiss Alps. It affected 300 ha of forest as well as 10 ha of pasture and fallow land. Litter traps and nets had been located approximately 5 km west and east of the burned area. The downwind site in the east (Jeizinen) recorded a strong charcoal fallout at 5.3 km from the fire edge. The observed charcoal influx of fragments with a size up to 1.3 cm reached average values of 0.144 and 0.098 mm^2/cm^2 per fire (or yr) in five traps and two nets, respectively. These values are comparable with charcoal accumulations measured at only *c.* 50 m from large fires, suggesting that macroscopic charcoal transport does not decay rapidly to zero with increasing distance from the fire. We suggest a long-distance dispersal model for transport of macroscopic charcoal during large fire events. Reconstructions of local fire regimes may be affected by long-distance transport of macroscopic charcoal, although this problem is mitigated by the tendency of most macroscopic charcoal particles to be deposited within very short distances (< 50 m) from the fire edge.

Key words: Charcoal analysis, macroscopic charcoal, Mean Fire Interval (MFI), plant macrofossils, palaeoecology, Valais, Central Alps.

Introduction

Fire is a prominent disturbance agent in terrestrial ecosystems. It can alter vegetational composition on different scales over years to centuries, depending on the successional processes involved. Understanding fire regimes and their impact on vegetation requires the reconstruction of past fire events (Whitlock, 2004). Different approaches are used for palaeofire reconstructions, such as dendrochronology (Dansereau and Bergeron, 1993; Wright and Agee, 2004), historical evaluations (Tinner *et al.*, 1998) or sedimentary charcoal records (Clark, 1988; MacDonald *et al.*, 1991; Whitlock and Larsen, 2001). However, a correct reconstruction of fire regimes (eg, fire frequency) requires an understanding of how far charcoal particles can be transported in fire events. Estimates of transport distances of charcoal particles during fire events

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range from decametres to kilometres, depending on many different aspects, such as particle size, height of the convective column and wind speed (eg, Clark, 1988; Clark and Royall, 1995; Tinner *et al.*, 1998; Carcaillet *et al.*, 2001; Lynch *et al.*, 2004).

Owing to the scarcity of large (> 100 ha) high-intensity crown fires, there is an almost complete lack of empirical evidence for the long-distance transport of macroscopic particles (> 0.1–0.2 mm) by fire in forested ecosystems of Europe. A few partly non-systematic field observations from other continents show that high-intensity wildfires might be able to carry centimetre-sized charred particles for several kilometres (McArthur, 1967; Anderson, 1968; Pisaric, 2002). Empirical investigations (Benedict, 2002) and theoretical considerations (Garstang *et al.*, 1997) support these observations, whereas experimental studies suggest that most large charcoal particles are not transported far from the fire edge (Clark *et al.*, 1998; Ohlson and Tryterud, 2000; Lynch *et al.*, 2004). This seeming contradiction has not been addressed in detail so far.

In this study we present the first unambiguous evidence of long-distance charcoal transport from Europe. A fire was set by an arsonist during the exceptionally hot summer 2003 (Luterbacher *et al.*, 2004) at *c.* 5.3 km distance from plots equipped with litter traps since 2002. The traps located east of the fire received a lot of air-transported charcoal that originated from the forest fire. The main aim of this study is to present evidence for the kilometre-scaled transport of millimetre-sized charcoal particles by forest fires. We compare our results with previous reports and with results of experimental studies and of stratigraphic charcoal records. Finally, we address the implications of our study for the reconstruction of fire and vegetation history.

Material and methods

The Leuk fire and the study area

On the evening of 13 August 2003 a fire was started by an arsonist above the town of Leuk in the main valley of the Canton Valais, Switzerland (Figure 1). Because of the exceptionally dry and hot summer, the litter, dead branches and even living trees were highly flammable, so that a fast-spreading crown fire developed on the slope above the ignition point. The fire moved uphill and was stopped only by timberline. It burned 300 ha of forest along a vegetational gradient from mixed oak–pine (*Quercus pubescens*, *Pinus sylvestris*) in the lower part to spruce (*Picea abie*s) and to open larch (*Larix decidua*) forests at timberline. A total of 10 ha of pasture and fallow land were also burned (see Figure 1; Wohlgemuth *et al.*, 2005). The complete extinction of the residual fire embers was not possible until 5, September 2003, more than three weeks after the fire started. Field observation on a systematic grid after the fire and comparisons with pre- and post-fire vegetation revealed high fire intensities along the entire slope (900–2100 m a.s.l), with highest values of ash accumulation between 1200 and 1600 m a.s.l. (data not shown).

The two sites Salgesch (46°19′27″ N, 7°34′40″ E, 975 m a.s.l) and Jeizinen (46°19′21″ N, 7°43′30″ E, 1270 m a.s.l; Figure 1), equipped with litter traps and nets for an ecophysiological long-term project (Zweifel *et al.*, 2005), were located on the same south-facing slope as Leuk, in the main valley of Valais. This part of the Valais region is characterized by a dry climate, which is mainly caused by the so-called innervalley shielding. The valley of Valais is oriented SW–NE, and the high mountains confine precipitation to the main storm tracks from the west. Total precipitation and mean temperature in the period April–October, 2003 were 318 mm and 17.3°C for Salgesch and 262 mm and 15.2°C for Jeizinen (Zeugin, 2004). These temperature values exceed the ordinary long-term means (1961–1990) by *c.* 5°C (MeteoSchweiz, 2004). Salgesch is situated 5.4 km west and Jeizinen 5.3 km east of the fire edge. In Salgesch *Quercus pubescens* (downy oak) and *Pinus sylvestris* (Scots pine) are the most abundant tree species, whereas *Juniperus communis* (juniper) is the most abundant woody shrub. In Jeizinen *Q. pubescens* and *P. sylvestris* are also dominant, but the deeper soil has a greater water–holding capacity and thus permits trees to grow higher and closer together than at Salgesch. Because of these more humid conditions *Picea abies* (Norway spruce) is intermingled in the pine–oak stands. During summer 2003 a total fire ban and a very efficient fire alert system existed. The fire records of the Canton of Valais as well as weekly personnel controls until the end of October exclude the occurrence of even tiny local fires in Salgesch and Jeizinen during the summer of 2003.

Sampling

Five litter traps and two litter nets were positioned during the growing season 2003 (April–October) at each of the two sites Salgesch and Jeizinen. Litter traps were placed randomly within a plot of 20 m × 20 m. They were constructed from plywood 15 cm wide so that the top (litter income) was 40 m × 40 cm. A fibreglass net with 1.4 mm × 1.4 mm mesh width was attached to the bottom of the case to allow periodic cleaning. In the same plots litter nets were hung under the branches of *Quercus pubescens* trees. The nets were the same as used for the traps. One net had a size of *c.* 6 m^2, the other of *c.* 14 m^2. During the period April–October 2003 the content of the litter traps was collected monthly, that of the litter nets weekly. *Quercus pubescens*, *Pinus sylvestris* and *Picea abies* remains found in the litter traps and nets were gathered and counted, as well as charred particles. Plant remains of other taxa were summarized in the group ‘indeterminate plant remains’.

Results

No charcoal fallout was recorded at the study sites of Salgesch during and after the fire of 13 August, whereas considerable amounts of charred material were collected in the litter traps and nets at Jeizinen. The litter traps at Jeizinen recorded the local biomass losses during the months April to October 2003 (Figure 2). *Pinus sylvestris* and *Quercus pubescens* dominate the biomass deposition, and other important taxa are *Picea abies*, *Juniperus communis* and *Betula.* Charcoal particles were found in the traps only in and after August, the month of the forest fire (Figure 2). The highest amount was found in August, though charcoal particles were also present in smaller quantities in September and October. On a total we counted 2487 macroscopic charcoal particles in the traps and nets of Jeizinen. The largest charred particle had a size of 1.3 cm. The charred fragments mostly consisted of charred needles or pieces of needles (Figure 2), and the second most frequent material was burned wood. The mean length, area and weight of charred needles were 8.9 mm, 9.0 mm^2 and 3.2 mg, respectively. The mean size and weight of other charred remains were 2.7 mm, 5.5 mm^2 and 2.0 mg. The litter nets permitted a more detailed view on the deposition dynamics, since they were emptied weekly (Figure 3). The highest charred-needle deposition was reached in week 34, the week of the fire. In the two subsequent weeks the accumulation rates diminished but were still high. Finally in the fourth week charcoal accumulation almost ceased. Accumulation rates of charred particles were higher in the traps than in the nets (Table 1, Figure 3), whereas

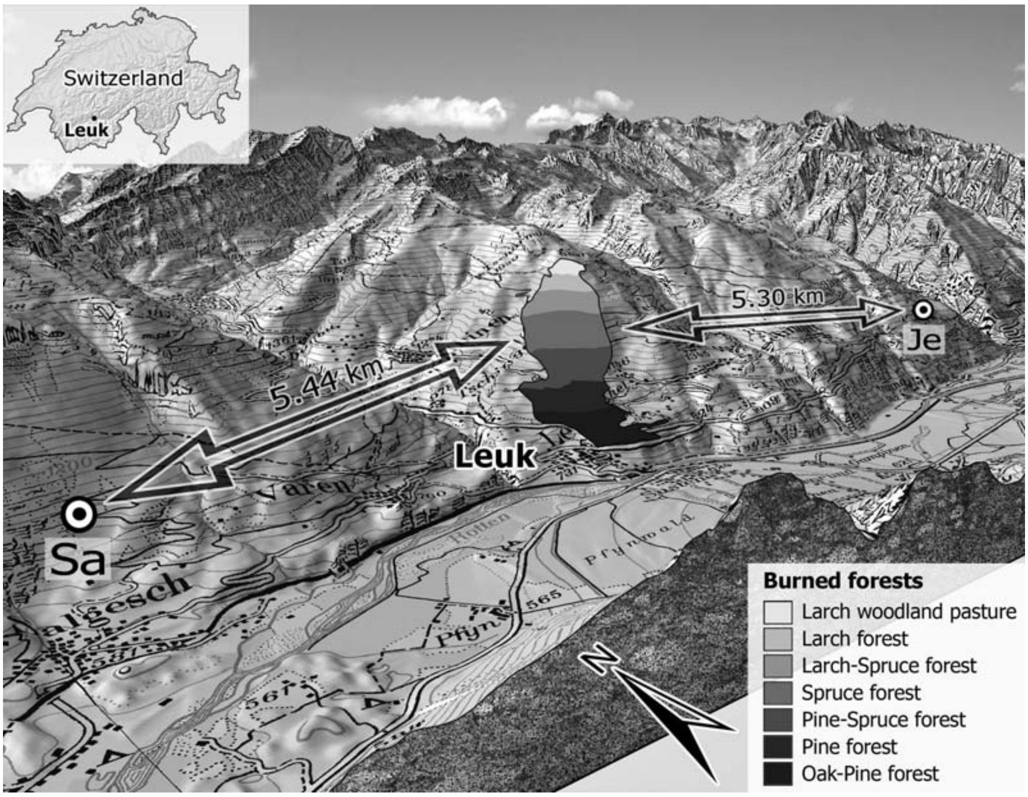

Figure 1 Map of the study area including the burned area (310 ha) and the two long-term study sites Salgesch (Sa, 46°19′27″ N, 7°34′40″ E, 975 m a.s.l) and Jeizinen (Je, 46°19′21″ N, 7°43′30″ E, 1270 m a.s.l). Map and landscape model DHM25 © 2004 swisstopo, (BA056894), image calculation with RaVis ©, Geoinformationsysteme ETH Zürich, elaboration: P. Krebs, WSL, Sottostazione Sud delle Alpi

the difference is less pronounced for mass and area values (Table 1).

Discussion

Interpretation of data

The presence of charcoal particles in Jeizinen as well as their absence in Salgesch can be explained by the main wind direction from the west during the fire event, when wind speed reached maximum values of about 3–4 m/s in Jeizinen (10-min mean; Zeugin, 2004). Since it is certain that none of the trees in Jeizinen burned during the fire event and during the whole study period, we can unambiguously infer that the charred *Picea abies* needles and the other charcoal particles found in the litter traps and nets originated from the Leuk fire. The charred *Picea* remains show that the charcoal must have primarily originated from the large stands of *Picea abies* in the subalpine belt above Leuk (Figure 1). The traps in Jeizinen were possibly more affected by re-deposition of charred particles from the ground than the hanging nets, considering that charcoal deposition was almost absent in the nets but not in the traps during the months of September and October (Figure 3, the litter net records end at the end of week 43, ie, 17 October). The almost irrelevant charcoal deposition in the nets after the fire event can be explained by crown washout eg, during storms and/or rainfall. Re-deposition effects would explain the slightly higher charcoal values in the traps. However, values in the nets probably underestimate charcoal influx if compared with the traps, because as a result of the hanging of the nets their projection areas were slightly smaller than their surfaces.

Besides charred material, strong fires can also transport considerable amounts of uncharred plant pieces such as branches and cones (Pisaric, 2002). Unfortunately, it is impossible to infer such effects from our data, since the traps were situated in a forest stand with continuous production of dead biomass. The litter biomass of *Quercus pubescens* and *Pinus sylvestris* accumulated in the traps is so high when compared with the trapped charcoal particles (Figure 2; 50–100 × higher) that any peak of wood or other plant pieces

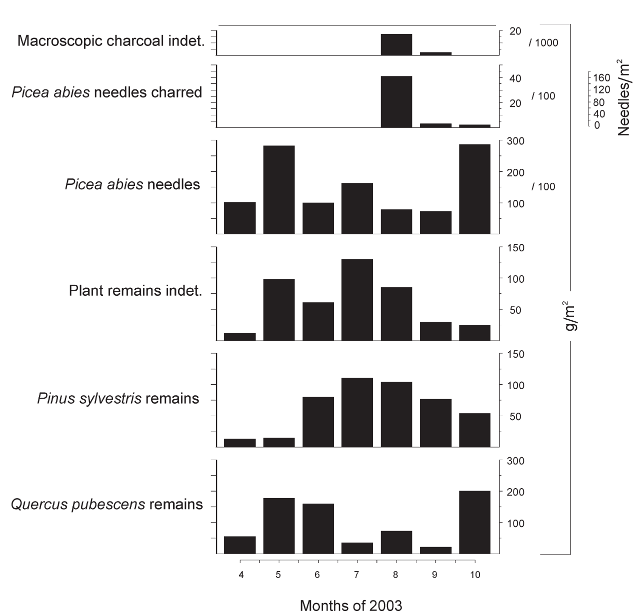

Figure 2 Monthly mean values (g/m^2) of the plant remains found in the litter traps. Numbers per m^2 are reported for charred *Picea* needles. The fraction 'macroscopic charcoal indet.' consists mainly of charred plant remains such as wood and periderm. Uncharred plant remains were deposited throughout the observation period, whereas charred remains were found only during and after the month of the fire (two curves at the top)

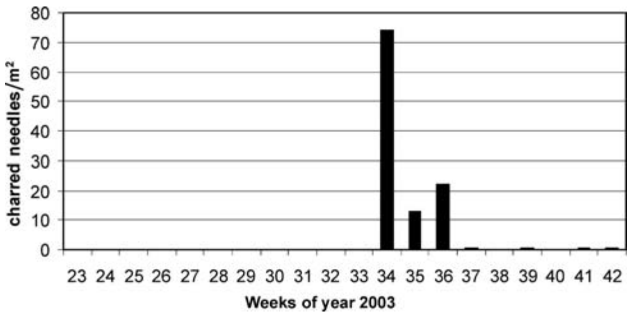

Figure 3 Mean number per m^2 of charred *Picea* needles with weekly resolution

related to the fire event would be blurred by local litter amounts. However, we assume that no exceptionally high transport of uncharred *Picea abies* needles occurred, for the values are comparable with or even lower than in the months prior to the fire (April to July). The dominance of *Picea abies* needles in the charcoal record suggests that charred needles were more easily released and/or transported than other plant material. Pisaric (2002) obtained similar results, in that 91% of the total plant remains transported by the Purdy Creek fire in the Rocky Mountains were conifer needles.

Previous experimental studies and field observations

Only a few experimental studies or observations are available to quantify charcoal accumulation rates during a fire event. The experimental study of Clark *et al.* (1998) registered an influx of 1–3 mm^2/cm^2 per yr (or fire) within the burned area, but the influx values declined rapidly within the short distance of 5 m. A recent experimental study (Lynch *et al.*, 2004) estimated that charcoal accumulation can reach 0.21 mm^2/cm^2 per fire at 10–60 m and 0.01 mm^2/cm^2 per fire at 80 m from the burn edge. Outside the burned area (< 200 m distant) average particle production was 0.01 mg/cm^2 per fire. It is striking that our traps recorded similar values of macroscopic charcoal influx at more than 5 km distant from the burn edge. Charcoal area accumulation rates reached 0.131 ± 0.032 (mean $\pm$ standard deviation) mm^2/cm^2 per fire in the five traps and two nets (Table 1), and the average charcoal particle production was about 0.05 mg/cm^2 per fire, ie, *c.* 5 × higher than in the close proximity of the experimental fire of Lynch *et al.* (2004). Our five traps and two nets were randomly distributed over a plot of 400 m^2, and the small variance among the traps and nets suggests that the high charcoal accumulation rates reflect a consistent deposition pattern, rather than a casual and extreme outlier. The high charcoal production and accumulation rates must be a consequence of the size and intensity of the Leuk fire. With a burned area of 310 ha it is much larger than the experimental fires conducted so far (eg, 0.8, 4.2 and 30 ha in Ohlson and Tryterud, 2000, 50 ha in Clark *et al.*, 1998, and 2.5 ha in Lynch *et al.*, 2004).

Table 1 Charcoal accumulation rates in the Jeizinen litter traps and nets

Litter traps and litter nets	Charcoal mg/cm^2 per fire	Charcoal part./cm^2 per fire	Charcoal mm^2/cm^2 per fire
trap 1	0.061	0.029	0.165
trap 2	0.059	0.021	0.162
trap 3	0.045	0.016	0.127
trap 4	0.059	0.021	0.161
trap 5	0.037	0.013	0.105
net small	0.030	0.009	0.084
net big	0.040	0.013	0.113

In total 2487 charred particles were found in the traps and nets. The accumulation rates were calculated by dividing the original values by the surface area in cm^2 of the litter traps and nets.

Experimental studies suggest that macroscopic charcoal accumulation rates decrease rapidly with increasing distance from fire (eg, Clark *et al.*, 1998; Lynch *et al.*, 2004). However, because these studies placed traps at only max. 60 m (Clark *et al.*, 1998) and 200 m (Lynch *et al.*, 2004) distance from the fire, it is impossible to check whether the experimental fires would have resulted in similar long-distance transport as in the case of the Leuk fire. On the basis of our results it is possible to hypothesize that macroscopic charcoal distribution does not decrease exponentially to reach zero values within a short distance (eg, < 200 m) from the fire. Instead, it seems that some fires can transport millimetre to centimetre-sized particles over kilometres, leading to relatively high accumulation rates of charred particles. Although our study is the first attempt to quantitatively estimate charcoal accumulation rates over such long distances, similar conclusions were reached by previous investigations. McArthur (1967) reported spot fires in Australia ignited by burning plant debris at 19–24 km distant from the main fire. Anderson (1968) collected charred debris, such as cones, needles and small branches at 16–19 km from the Sundance fire in Idaho (USA). This fire was very intensive and had a size of 20 000 ha. Wind speed was 6 m/s at the beginning and 23 m/s at the end of the fire. Large-scale blowdowns of trees indicate that firestorms generated local wind speeds up to 43 m/s. Pisaric (2002) documented the transport of charred needles, buds and cones for *c.* 20 km. The Purdy Creek fire (Montana, USA) was fanned by strong winds (14 m/s) and reached a size of 1300 ha (Pisaric, 2002).

Relevance for fire-history reconstruction

Macroscopic-charcoal influx values are widely used to infer past fire occurrence and especially past fire frequency (eg, mean fire interval, MFI). Since the charcoal influx values of Jeizinen are as high as those observed in very close proximity of rather large fires, our new data challenge the assumption of most charcoal analysts that macroscopic peak values reflect the occurrence of local fire (eg, Carcaillet and Thinon, 1996; Clark and Royall, 1996; Tinner *et al.*, 1998; Ohlson and Tryterud, 2000; Whitlock and Larsen, 2001; Carcaillet *et al.*, 2001). So far only a few calibration attempts have been undertaken to relate the past occurrence of fire as recorded by independent evidences (eg, fire scars, historical records) to the sedimentary charcoal record. However, all available investigations suggest that macroscopic charcoal records are good indicators of past local fire occurrence (eg Clark, 1990; MacDonald *et al.* 1991; Whitlock and Millspaugh, 1996; Tinner *et al.*, 1998; Whitlock *et al.,* 2004, Higuera *et al.*, 2005). Nevertheless, charcoal accumulation rates as observed in our study may influence sedimentary charcoal records. In boreal and alpine situations sedimentary macroscopic charcoal peaks used to infer MFI may be as small as < 0.05 mm^2/cm^2 per yr (eg, Stähli, 2004; Lynch *et al.,* 2004), whereas in temperate ecosystems peak values usually range between 10 and > 100 mm^2/cm^2 per yr (eg, Clark and Royall, 1995, 1996; Tinner *et al.*, 1998). These huge differences in charcoal-area accumulations may be explained by different amounts of burnable biomass, by the predominant fire regime types (eg, surface fires versus crown fires), and by the techniques used to quantify macroscopic charcoal influx (the lower values originate from sieving, the higher values from thin section estimates). A comparison with sedimentary records reporting particle number influx (particles/cm^2 per yr) suggests that our influx values (mean of 0.017 particles/cm^2 per fire, Table 1) are significantly below the peaks that are usually used to reconstruct MFI. For instance, Millspaugh *et al.* (2000) identified values between 0.05 and 6 particles/cm^2 per yr as charcoal peaks. Similarly values between 1 and 70 particles/cm^2 per yr were used to reconstruct the MFI by Long *et al.* (1998). However, such comparisons seem more problematic for particle number than for area influx, since our macroscopic particles are large and breakable. It is conceivable that the number influx would have increased if the particles had been exposed to taphonomic processes such as transport through saltation, erosion and bioturbation. Moreover, sediment sampling and sieving may lead to a breakage of large particles such as charred needles and thus increase the number influx (see Weng, 2005).

The seeming contradiction between our findings and the studies reporting that macroscopic charcoal records primarily concern local fires is explainable by two theoretical considerations: (1) If charcoal particles are distributed and deposited equally in space during a fire, macroscopic charcoal influx must decrease exponentially with increasing distance because of the exponential increase of the land area covered by charcoal fallout. (2) In a case such as the Leuk fire, where charcoal transport is channelled by wind and/or surface topography, macroscopic charcoal influx to the surface is still high after several kilometres, whereas the relative land area covered by charcoal fallout decreases exponentially with increasing distance. In addition, experimental studies clearly document that most charcoal particles are deposited within distances as short as <50 m from intensive fires (Figure 4). These considerations imply that–independent of long-distance transport–sedimentary macroscopic charcoal records have a strong tendency to reflect past local fire events.

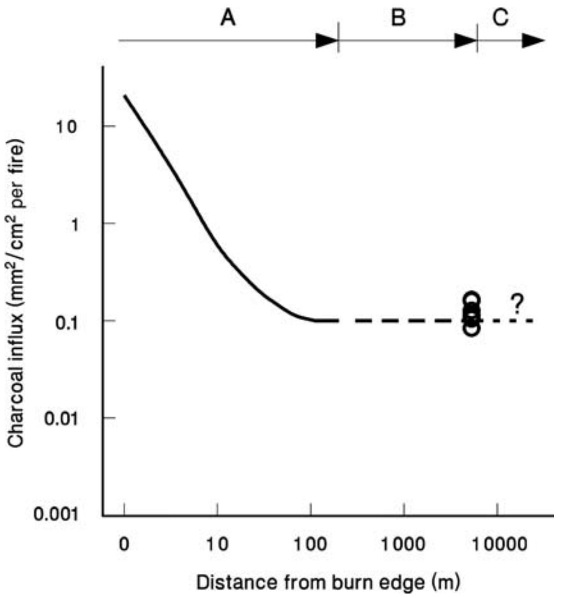

Figure 4 Long-distance transport model for charcoal influx, channelled transport trough wind and/or surface topography. A, values derived from experimental studies (Clark *et al.*, 1998; Lynch *et al.*, 2004). B, fire of Leuk, this study, the dots show the accumulation rates for 5 traps and 2 nets in Jeizinen. C, long-distance transport (up to 24 km) derived from field observations (McArthur, 1967; Anderson, 1968; Pisaric, 2002), charcoal accumulation rates are not given for these studies. The large amounts of deposited charcoal suggest values similar to those of the Leuk fire

One implication of this study is that future experimental studies should include traps more distant from the fire edge than used so far (eg, 60 m in Clark *et al.*, 1998; 100 m in Ohlson and Tryterud, 2000; and 200 m in Lynch *et al.*, 2004). Another implication concerns macrofossil analysis. Macrofossil analysts assume that macroscopic plant remains are not transported very far from their point of origin (Birks, 2001). Our study shows that charred macroscopic plant remains may originate from widely distant areas. Most if not all uncharred plant remains originated from the local oak–pine forest. Conversely, all charred macroscopic remains originated from very distant sources. The distinction of charred and uncharred plant remains is therefore mandatory for a correct reconstruction of local vegetational conditions through macrofossil analysis.

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