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Assessing the spatial fidelity of sedimentary charcoal size fractions as fire history proxies with a high-resolution sediment record and historical data

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ABSTRACT

Fire reconstructions provide context for modern rates of burning and inform predictions of fire regimes' responses to climate and/or ecological changes. Charcoal particles preserved in lake sediments are a widely employed fire proxy. Although many studies have calibrated the charcoal proxy, the spatial scales of charcoal dispersal and source area remain disputed. Understanding the spatial fidelity of charcoal accumulation is increasingly important in light of recent efforts to aggregate multiple charcoal records to infer changes in regional, continental- and global-scale fire regimes. Using a high-resolution sediment record from Swamp Lake, California, we compare charcoal accumulation rate (CHAR) variations of three size fractions of sedimentary charcoal (63–150, > 150, and > 250 μm) to historical area burned data. We find that macroscopic (> 250 and > 150 μm) and mesoscopic (63–150 μm) charcoal source areas are within 25, 35, and 150 km of Swamp Lake, respectively. We also use a dispersal model to confirm these findings. Our estimates of charcoal source area fall within the large range of estimates for forest fires in the literature. Further, our methodology shows potential for constraining source areas of charcoal in sedimentary records, which is requisite for the reliable inference of the spatial extent of fire in paleorecords.

1. Introduction

Fire has played an important role in the evolution of vascular plants and terrestrial ecosystems since the late Devonian Period (Pausas and Keeley, 2009; Scott, 2000; Scott et al., 2014), and influences the biogeographic distribution of ecosystems observed on Earth today (Bond et al., 2004). Major wildfires frequently cause costly damages in populated areas (Gorte, 2013). In light of global climate change projections and consequent increases in wildfire risk and frequency (Field et al., 2014; Stocker, 2014), a thorough understanding of the underlying mechanisms controlling fire regime responses to climate variability is critical for conservation and management efforts.

Much of what we have learned about the interactions between fire and climate, and the role of fire in shaping modern ecosystems is derived from sedimentary charcoal records and, in particular, from the accumulation rate of charcoal particles in lake sediments (Conedera et al., 2009; Whitlock and Larsen, 2002). The spatial scales of charcoal dispersal, and therefore charcoal source area, are requisite considerations for the interpretation of charcoal records and spatially-dependent fire regime metrics (e.g. fire return interval) that inform land managers and policy-makers (Dellasala et al., 2004; Higuera et al., 2007; Kelly et al., 2013). However, the exact spatial scales of total charcoal source area remain ambiguous.

Great efforts have been made to identify the spatial footprint of fire events determined by peak analysis of charcoal accumulation rates. Peak analysis decomposes accumulation rate time series into background and peak components, which reflect regional burning (> 1 km) and local fire events (< 1 km), respectively (Finsinger et al., 2014; Higuera et al., 2010; Long et al., 1998; Whitlock and Larsen, 2002). Studies generally agree that macroscopic charcoal can undergo long-distance transport (> 1 km; Table 1 and references therein), but that the majority of particles are deposited locally (< 1 km; Table 1 and references therein). One of the lowest estimates suggests < 1% of particles are transported beyond 20 m from the fire edge (Lynch et al., 2004), but other studies indicate that long-distance atmospheric transport is a key mechanism for charcoal dispersal (Table 1 and references therein). Despite disagreements, there is a consensus that finer particles are generally transported longer distances through the

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Table 1
Summary of maximum dispersal distance or source area estimates in the literature.

Study	Geographic location	Vegetation	Charcoal size	Maximum dispersal distance or source area
Atmospheric sediment traps				
(Clark et al., 1998)	Siberia, Russia	Taiga	> 180 µm	60 m
(Leys et al., 2015)	Great Plains, U.S.A.	Grassland	125 to 1000 µm	5 km
(Lynch et al., 2004)	Northwest Territories, Canada	Boreal forest	> 180 µm	80 m
(Ohlson and Tryterud, 2000)	Norway and Sweden	Boreal forest	500 to 2000 µm	100 m
			> 2000 µm	100 m
(Pisaric, 2002)	Montana, U.S.A.	Temperate forest	2000 to 7000 µm	20 km
(Tinner et al., 2006)	Switzerland	Alpine forest	10^3 to 10^4 µm	5.3 km
(Li et al., 2017)	northeastern China	Temperate forests	0 to 500 µm	> 5 km
Lake sediment traps				
(Adolf et al., 2017)	Europe	Boreal, alpine, and temperate forests; steppe	10 to 500 µm	40 km
			> 100 µm	40 km
(Oris et al., 2014)	Quebec, Canada	Boreal forest	> 150 µm	32 km
Lake sediment cores				
(Aleman et al., 2013)	Central African Republic	Forest, savannah, and Forest-savannah mosaic	> 160 µm	5 km
(Enache and Cumming, 2006)[c]	British Columbia, Canada	Boreal forest	> 150 µm	20 km
(Kelly et al., 2013)	Alaska, U.S.A.	Boreal forest	> 180 µm	20 km
(MacDonald et al., 1991)	Alberta, Canada	Boreal forest	> 75 um^2	120 km
(Miller et al., 2017)	Maine, U.S.A.	Temperate forest	> 125 µm	80 km
(Tinner et al., 1998)	Switzerland	Temperate forest	> 75 µm^2	20 to 50 km
Lake sediment cores (tree ring comparison)				
(Gavin et al., 2003)[b]	Vancouver Island, Canada	Boreal forest	150 to 500 µm	500 m
(Higuera et al., 2011)	Yellowstone National Park, U.S.A.	Subalpine forest	125 to 250 µm	6 to 51 km
Lake surface sediments				
(Duffin et al., 2008)	South Africa	Savannah	> 50 µm	5 km
			< 50 µm	15 km
(Gardner and Whitlock, 2001)	Cascade Range, U.S.A.	Temperate forest	> 125 µm	3 km
(Leys et al., 2017)	Great Plains, U.S.A.	Grassland	60 to 1000 µm	1060 m
(Whitlock and Millspaugh, 1996)	Yellowstone National Park, U.S.A.	Subalpine forest	125 to 250 µm	13 km
Modeling				
(Clark, 1988)	N/A	N/A	200 µm	50 m to 10 km
			20 µm	100 m to 20 km
			5 µm	200 m to 30 km
(Higuera et al., 2007); (Peters and Higuera, 2007)[a]		Boreal forest	> 180 µm	10^0 to 10^1 km
(Vachula and Richter, 2017)	N/A	N/A	150 to 300 µm	15 km

[a] Charcoal size fall velocity equivalents used in model. Model output compared to boreal forest lake sediment charcoal record.
[b] Only charcoal peaks considered in this study.
[c] Not all morphotypes exhibited the same behavior, but the bulk of the data suggest dispersal can be at least 20 km.

atmosphere than coarser particles (e.g. Clark et al., 1998; Ohlson and Tryterud, 2000; Patterson et al., 1987). As such, macroscopic charcoal (> 150 µm) accumulation peaks are thought to represent local (< 1 km) fire history, despite total charcoal accumulation (background and peak components) being influenced by a larger area (Higuera et al., 2007). However, the exact boundaries of this broader source area of total charcoal accumulation are not as well constrained (e.g. Duffin et al., 2008; Higuera et al., 2011; Kelly et al., 2013). It is becoming more and more important to constrain this source area in light of ongoing efforts to aggregate charcoal-based fire records to examine fire history on continental and global scales (Marlon et al., 2013, 2012, 2008; Power et al., 2010, 2007).

Previous studies have used innovative spatial analyses to compare charcoal accumulation to observational records of fire history to estimate the source area of total charcoal accumulation (Adolf et al., 2017; Aleman et al., 2013; Duffin et al., 2008; Enache and Cumming, 2006; Higuera et al., 2011; Kelly et al., 2013; Leys et al., 2015, 2017; Tinner et al., 1998). These studies generally agree that total charcoal source area is on the order of one to tens of kilometers and depends greatly upon particle size (Table 1). Each of these studies offers unique insight into charcoal source area and they use a variety of innovative approaches including atmospheric sediment traps (Clark et al., 1998; Leys et al., 2015; Li et al., 2017; Lynch et al., 2004; Ohlson and Tryterud, 2000; Pisaric, 2002; Tinner et al., 2006), lacustrine sediment traps (Adolf et al., 2017; Oris et al., 2014), comparison with observational data (Aleman et al., 2013; Enache and Cumming, 2006; Kelly et al., 2013; MacDonald et al., 1991; Miller et al., 2017; Tinner et al., 1998), and comparisons with tree ring-based fire records (Gavin et al., 2003; Higuera et al., 2011). However, due to the complexity of the processes affecting charcoal particle transport and burial, considerable variability exists among estimates of total charcoal source area (Table 1).

Each of these studies sheds new light on the source area of charcoal particles in lake sediments; however, every study has its limitations. For example, existing studies can be limited by the spatial or temporal scope or resolution of the observational record (e.g. Higuera et al., 2011), coarse resolution or limited spatial scales of interest in observational records (e.g. Enache and Cumming, 2006; Tinner et al., 1998), and/or the examination of only one charcoal particle size fraction (e.g. Kelly et al., 2013). Furthermore, these studies sometimes neglect the spatiotemporal variability of the observational fire record itself, which could preclude the identification of inherent limitations of