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Charcoal signatures defined by multivariate analysis of charcoal records from 10 lakes in northwest Wisconsin (USA)

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ABSTRACT

We show how sedimentary charcoal records from multiple sites within a single landscape can be used to compare fire histories and reveal small scale patterns in fire regimes. Our objective is to develop strategies for classifying and comparing late-Holocene charcoal records in Midwestern oak- and pine-dominated sand plain ecosystems where fire regimes include a mix of surface and crown fires. Using standard techniques for the analysis of charcoal from lake sediments, we compiled 1000- to 4000-yr-long records of charcoal accumulation and charcoal peak frequencies from 10 small lakes across a sand plain in northwestern Wisconsin. We used cluster analysis to identify six types of charcoal signatures that differ in their charcoal influx rates, amount of grass charcoal, and frequency and magnitude of charcoal peaks. The charcoal records demonstrate that while fire histories vary among sites, there are regional patterns in the occurrence of charcoal signature types that are consistent with expected differences in fire regimes based on regional climate and vegetation reconstructions. The fire histories also show periods of regional change in charcoal signatures occurring during times of regional climate changes at ~700, 1000, and 3500 cal yr BP.

Introduction

Across subcontinental scales, fire regimes are influenced by climate (Clark and Royall, 1996; Whitlock et al., 2003); however, relatively fine-scale landscape features such as topographic fire breaks also affect the incidence of fire (Heinselman, 1973; Engelmark, 1987; Larsen, 1997; Hellberg et al., 2004; Gavin et al., 2006). Local fire regimes may also depend on site-specific differences in soil texture and nutrient availability, which can influence the productivity or flammability of vegetation. Heterogeneity in soil quality may create variability in fire frequency or intensity through its influence on the type, amount, and moisture of fuel. In general, fire incidence decreases as average annual precipitation increases, but at sites where the lack of moisture limits primary productivity late-Holocene increases in precipitation lead to higher productivity and more frequent or more intense fires (Umbanhowar, 1996; Clark et al., 2001, 2002; Brown et al., 2005). Similarly, in a landscape with excessively well-drained soils, sites with somewhat more mesic soils (and higher productivity) might support a higher incidence or intensity of fire than drier sites.

The variability of fire regimes across relatively fine spatial scales presents challenges to restoration and management planning and also to modeling projected ecosystem responses to climate change. Charcoal records derived from contiguous samples of lake sediments can provide information about the range of variability in prehistoric fire regimes (Hallett and Walker, 2000; Millspaugh et al., 2000). Fire histories based on sedimentary charcoal records from upper Great Lakes ecosystems demonstrate that fire was an integral part of pine and pine-oak ecosystems for centuries before 20th-century fire suppression and that fire regimes were affected by late-Holocene climatic fluctuations (e.g., Swain, 1978; Gajewski et al., 1985; Clark, 1990; Lytle, 2005; Lynch et al., 2006; Jensen et al., 2007; Tweiten et al., 2009). As more charcoal-based fire histories become available it may be possible to document the landscape-scale variability in fire regimes and develop a more mechanistic understanding of the interactions among climate, vegetation, and fire.

The purpose of this study was to use sedimentary charcoal records to examine variability in prehistoric fire regimes on spatial scales useful in addressing questions about ecosystem management and function. We applied paleoecological techniques to reconstruct fire histories from the sediments of 10 small lakes on the 450 km^2 sand plain in northwest Wisconsin to explore the variability in fire regimes across a landscape. A standard approach to interpreting sedimentary charcoal records involves separating the high-variability "peaks" in charcoal accumulation rate (CHAR) from the low frequency "background" signal. The frequency of charcoal peaks is then used as a proxy for local fire events (composed of one or more fires), and the "background" component as an indicator of the regional importance of fire (Clark et al., 1996; Long et al., 1998; Gavin et al., 2006; Higuera et al., 2009; but see discussion of background signal

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in Higuera et al., 2007). To compare fire regimes in records from multiple sites we developed a quantitative strategy for classifying and comparing charcoal records based on multivariate analysis of charcoal records, including background charcoal inputs, frequency of charcoal peaks, magnitude in charcoal influx rates, and the influx of grass charcoal (Jensen et al., 2007). This approach maximizes the potential information about fire regimes extracted from charcoal records while collapsing that information into a classification of charcoal signatures.

Study area

The northwest Wisconsin sand plain is an extensive area of glacial outwash occupying approximately 450 km^2 in Douglas, Bayfield, Burnett, and Washburn Counties (Fig. 1). The climate is humid continental, with daily mean temperatures of −12.5°C in January and 20°C in July (1971–2000 averages from weather stations in Ashland, Danbury, Drummond, Gordon, and Minong, WI; Midwest Regional Climate Center, 2007). Summer temperatures are similar at all stations but mean January temperature is ~1.5°C lower in Gordon (central sand plain) than at other locations. Mean annual precipitation ranges from 75 cm in Minong, on the central sand plain, to 87 cm in Drummond, located immediately east of the sand plain in Bayfield County. Lake-effect precipitation from Lake Superior also influences the northern sand plain, located on the highlands of the Bayfield Peninsula, but there are no weather data available from this area.

The topography of the sand plain is flat to gently rolling, and streams are rare. Seepage lakes are common in the south where the groundwater table is high. Soils across the sand plain are nutrient-poor sands with low water-holding capacity (Fig. 1; Radeloff et al., 1999; Natural Resource Conservation Service Soil Survey Geographic [SSURGO] database). In the central portion of the sand-plain soils are primarily excessively well-drained sands, while the northern and southern sand plain regions have finer-textured loamy sands and sandy loams. Coarse, well-drained soils make the entire region prone to drought and fires, favoring pine and oaks which are adapted to frequent fire (Curtis, 1959; Pregitzer and Saunders, 1999; Radeloff et al., 1999).

Radeloff et al. (1998, 1999) examined Public Land Survey (PLS) witness tree records from the surveys conducted in the AD 1850s to document the spatial patterns in vegetation immediately before European-American settlement of the sand plain. They observed that differences in soil quality and topographic and hydrologic features corresponded to vegetation patterns across the sand plain. Jack pine (*Pinus banksiana*) was widely distributed across the sand plain but dominated on the coarsest soils of the central sand plain where it was probably maintained by frequent stand-replacing fires. The rolling topography of the Bayfield Peninsula in the northern part of the sand plain had forests composed of jack pine, red pine (*Pinus resinosa*), white pine (*Pinus strobus*), and red oak (*Quercus rubra*) and occasional openings with no trees. The composition and structure of these forests suggest a fire regime with less frequent but intense crown fires. In a review of published studies of fire histories derived from PLS notes and pollen and charcoal records from the upper Great Lakes region, Cleland (2004) reported that on coarse sandy soils with jack pine and mixed pine vegetation, return intervals for stand-replacing fires were 26–69 yr, while on sandy and loamy sand soils with mixed red-white-jack pine vegetation, stand-replacing fires occurred at 83–250 yr return intervals. The southern portion of the sand plain has numerous lakes and wetlands that may act as fire breaks. The PLS vegetation here was more patchy with mixed pine and oak stands and isolated savannas with widely scattered large-diameter bur oaks (*Quercus macrocarpa*), especially near lakes (Radeloff et al., 1998). Fires with lower intensity but perhaps higher frequency may have allowed the development of more open woodlands and savannas in this region (Radeloff et al., 1999). Differences in vegetation among the north, central, and south portions of the sand plain persisted through the last 2000 years, with more pine and birch in the north, jack pine in the central sand plain, and more oak in the south (Hotchkiss et al., 2007b). Previous studies demonstrate that in parts of the sand plain,

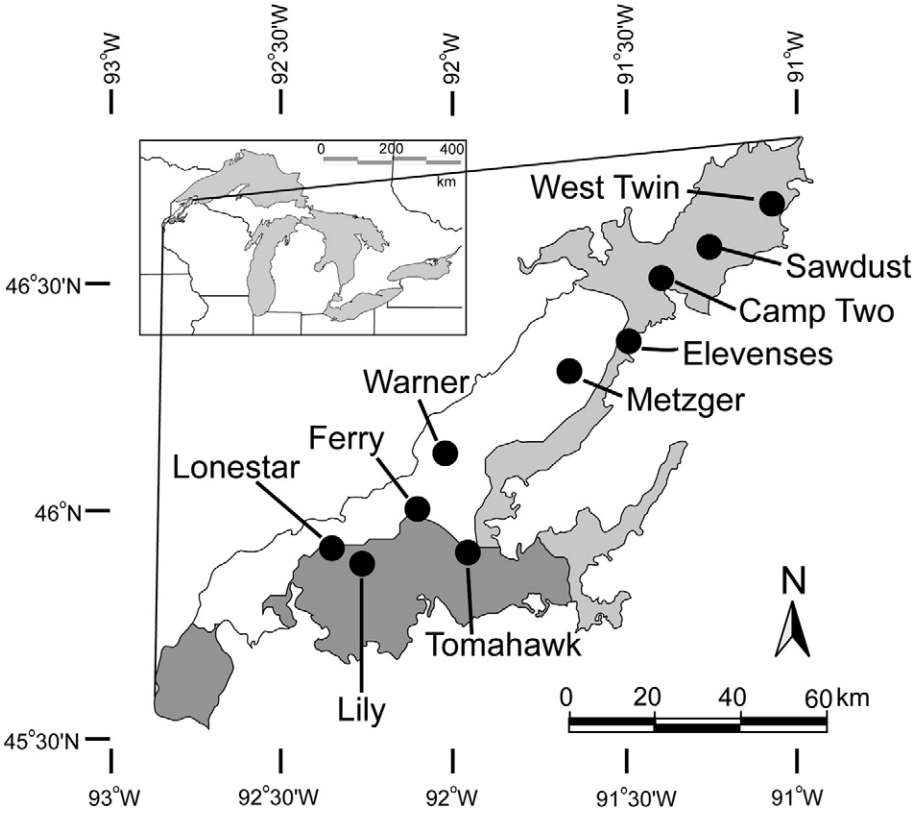

Figure 1. Location of sand plain and 10 study lakes.