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Identifying natural and anthropogenic drivers of prehistoric fire regimes through simulated charcoal records

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ABSTRACT

Archaeological and paleoecological studies demonstrate that human-caused fires have long-term influences on terrestrial and atmospheric systems, including the transformation of "wild" landscapes into managed, agricultural landscapes. Sedimentary charcoal accumulations alone provide only limited information about the influence of human-caused fires on long-term fire regimes. Computational modeling offers a new approach to anthropogenic fire that links social and biophysical processes in a "virtual laboratory" where long-term scenarios can be simulated and compared with empirical charcoal data. This paper presents CharRec, a computational model of landscape fire, charcoal dispersion, and deposition that simulates charcoal records formed by multiple natural and anthropogenic fire regimes. CharRec is applied to a case study in the Canal de Navarrés region in eastern Spain to reveal the role of human-driven fire regimes during the early and middle Holocene. A statistical comparison of simulated charcoal records and empirical charcoal data from the Canal de Navarrés indicates that anthropogenic burning, following the Neolithic transition to agro-pastoral subsistence, was a primary driver of fire activity during the middle Holocene.

1. Introduction

Humans are uniquely able to use fire as a tool to deliberately create and sustain changes in their environments (Boivin et al., 2016; Bowman et al., 2011; Ellis, 2015; Roos et al., 2014; Scott et al., 2016). Regular and controlled use of fire by hominins dates to the Middle Pleistocene, but measurable impacts of anthropogenic fire on terrestrial and atmospheric systems are most evident during the last several millennia (Bowman et al., 2011; Roebroeks and Villa, 2011; Shimelmitz et al., 2014). Multiple global syntheses of archaeological and ethnographic case studies identify fire's role in political, religious, and ecological realms, including burning practices associated with land clearing, warfare, driving game, propagating beneficial plant and animal species, and fire prevention (Bliege Bird et al., 2008; Bowman et al., 2011; Pyne, 2012; Scherjon et al., 2015; Trauernicht et al., 2015). Diversity in anthropogenic fire can create variation in local and regional fire regimes; however, evidence of human-driven ignitions is not readily observable in sedimentary charcoal records, particularly when these fires co-occur with large-scale changes in climate and fuels.

This paper presents the Charcoal Record Simulation Model (CharRec), a computational model that simulates the formation of sedimentary charcoal records based on varying fire regime components, including fire frequency, intensity, size, and spatial distribution. These components can be modified to represent fire regimes shaped by varying human and climate drivers. Following a pattern-oriented modeling approach, CharRec is built using a bottom-up strategy where observable patterns within target datasets inform programming decisions (Grimm et al., 2005). This strategy allows CharRec to function as a "virtual laboratory," where multiple model outputs are compared to patterns within empirical charcoal data to identify which combinations of fire regime components mostly likely contributed to the formation of the empirical record through time (Bankes et al., 2002).

1.1. Formation and interpretation of sedimentary charcoal records

Variation in the concentration of charcoal particles from lacustrine cores or terrestrial sediment samples is commonly used to identify paleoenvironmental trends in landscape fire (Bowman et al., 2011, 2009; Whitlock and Anderson, 2003; Whitlock and Larsen, 2001). Bridging the interpretive gap between charcoal abundance and fire history has remained at the forefront of paleoecological research for several decades. The theoretical relationships between charcoal transport and accumulation were first proposed by Clark (1988a,b) and have since been expanded to consider the influence of combustion and atmospheric conditions on primary charcoal dispersal, such as fire intensity, fire size, and charcoal morphology (Adolf et al., 2018; Clark et al., 1998; Clark and Royall, 1996, 1995; Higuera et al., 2011; Leys et al., 2015, 2017; Li et al., 2017; Lynch et al., 2004; Miller et al., 2017; Peters and

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Higuera, 2007; Vachula and Richter, 2018). Fire history interpretations from these models rely on two major underlying assumptions: 1) the physics of primary charcoal transport result in spatially discernible differences in the distribution of charcoal particles following a fire; and 2) secondary charcoal transport is minimal and does not obfuscate patterns of primary deposition and fire occurrence (Higuera et al., 2007).

The distribution and abundance of primary, aerially dispersed charcoal is assumed to be a function of charcoal attributes related to fuel combustion and atmospheric conditions during a fire (Aleman et al., 2013; Clark, 1988a; Clark et al., 1998; Duffin et al., 2008; Enache and Cumming, 2007, 2006; Lynch et al., 2004; Peters and Higuera, 2007; Vachula and Richter, 2018). Generally, the relationship between these variables results in spatially differentiated dispersion, where macroscopic charcoal particles (typically > 100 μm) are dispersed close to their source and are interpreted as local in origin; microscopic charcoal particles (typically < 100 μm) can be dispersed greater distances and are typically interpreted as representing regional fires (Clark, 1988b; Clark et al., 1998; Ohlson and Tryterud, 2000). This relationship assumes that atmospheric and combustion conditions remain constant throughout the duration of a fire; while this assumption may not always hold true, transport distances based on charcoal size have been empirically validated in multiple studies (Clark and Royall, 1996; Gardner and Whitlock, 2001; Lynch et al., 2004; Ohlson and Tryterud, 2000; Pisaric, 2002; Tinner et al., 2006; Whitlock and Millspaugh, 1996). More recent work has examined the impact of varying conditions on charcoal production and the mechanisms of primary charcoal transport, concluding that particle morphology, shape, and density are also important in interpreting fire origin (Duffin et al., 2008; Leys et al., 2015, 2017; Vachula and Richter, 2018).

Secondary charcoal refers to charcoal introduced into the sedimentary record during non-fire years by geomorphological processes such as run-off, post-depositional sediment mixing, or other landscape reservoir effects. Empirical studies of post-fire slope-wash estimate that the contribution of additional charcoal from non-fire years can continue for upwards of a decade, but in quantities small enough not to mask primary deposition (Carcaillet et al., 2006; Clark, 1988a; Clark et al., 1998; Lynch et al., 2004; Patterson et al., 1987; Whitlock and Millspaugh, 1996). Mixing within the sediment column can further blur, but not entirely obscure primary charcoal deposition. Statistical methods for peak detection and sampling strategies that capture the full extent of fire return intervals help to account for these processes (Clark, 1988b; Finsinger et al., 2014; Higuera et al., 2010; Kelly et al., 2011).

Peak detection methods rely on separating a charcoal series into its background and peak components. Background charcoal refers to low-frequency variations in macro-charcoal accumulation, as well as contributions from secondary charcoal transport (Higuera et al., 2010; Kelly et al., 2011). When background charcoal is statistically removed, peak charcoal related to primary transport and deposition is distinguishable (Finsinger et al., 2014). The distinction between background and peak charcoal components may be unclear in landscapes with both natural and anthropogenic ignition sources (Bowman et al., 2011). Ethnographic examples of managed fire indicate that ignitions are often spatially circumscribed, frequent, and at low intensities (Scherjon et al., 2015), hence it is possible that local anthropogenic burning may contribute to low-frequency accumulations of macro-charcoal without clear and discernible peaks. Thus, the anthropogenic signal may be misidentified or obscured, particularly if a sampling strategy is not designed to accommodate for short fire return intervals.

1.2. Anthropogenic fire in the archaeological record

Humans have intentionally set fires for millennia to transform the arrangement or diversity of resources within their landscape (Boivin et al., 2016; Pyne, 2012). Identifying prehistoric human influences on fire regimes remains difficult due to a mismatch between available archaeological data on human activities and paleoecological data on fire and vegetation change (Bowman et al., 2011). Prominent archaeological approaches to fire have centered on detecting evidence of landscape burning in relation to food production and hunter-gatherer impacts on ancient environments. Low-level food production (Smith, 2001), "fire-stick" farming (Bird et al., 2005; Bliege Bird et al., 2013, 2008), swidden agriculture (Levin and Ayres, 2017; Roos, 2008; Roos et al., 2016; Schier et al., 2013), and mitigating resource vulnerability (Freeman and Anderies, 2012) suggest that fire was an important tool for creating predictable resource mosaics within landscapes across the globe (*North America:* Liebmann et al., 2016; Roos, 2015; Roos et al., 2010; Sullivan et al., 2015; Sullivan and Forste, 2014; Swetnam et al., 2016; Taylor et al., 2016; Van de Water and Safford, 2011; Walsh et al., 2010; *Europe:* Doyen et al., 2013; Innes et al., 2013; *Southeast Asia/ Oceania:* Maxwell, 2004; McGlone, 2001; McWethy et al., 2010, 2009; Roos et al., 2016; *Neotropics:* Dull, 2004; Nevle et al., 2011).

Anthropogenic fire may also be a primary driver of fire regimes in regions with long-term histories of agricultural land-use (Carrión et al., 2010, 2001; Colombaroli et al., 2008; Vannière et al., 2008). For instance, Pitkänen et al. examined two lacustrine sediment cores from Lake Pönttölampi in eastern Finland to evaluate the formation of the local charcoal record and its association with documented "slash and burn" agricultural practices (Pitkänen et al., 1999; Pitkänen and Huttunen, 1999). By examining charcoal data in conjunction with historical maps of land-use and fire-scarred trees, Pitkänen and colleagues (1999) concluded that frequent, low-intensity fires associated with maintaining open woodlands contributed significantly to the sedimentary charcoal record and were the primary driver of local fire history. Unfortunately, the patterns reported by this study would be difficult to observe in prehistoric contexts that predate historic documents and living, fire-scarred trees. Simulation models provide an opportunity to examine multiple patterns of burning in prehistory while accommodating complex patterns of both natural and anthropogenic ignition sources. Evaluating simulations against empirical charcoal data allows multiple, alternative interpretations of prehistoric fire regimes to be tested, adapted, and improved.

2. Materials and methods

2.1. Introduction to CharRec and model design considerations

CharRec is a spatially explicit computational model developed to simulate the formation of long-term charcoal records based on empirically supported models of primary charcoal transport (Fig. 1). The model is an exploratory tool that assists researchers in interpreting how natural and anthropogenic fire regime components contribute to the formation of a sedimentary charcoal record. One of the most challenging aspects of developing computer simulations of social-ecological systems is including adequate complexity to address specific research questions while reducing the amount of uncertainty in the model structure and parameters. Pattern-oriented modeling offers a strategy for optimizing the relationship between complexity and uncertainty by focusing on multiple patterns observed in real systems at differing scales (Grimm et al., 2005). Such models focus on a small number of underlying processes that can be calibrated independently to influence the overall pattern of the system (Grimm et al., 2005:989). CharRec does not attempt to capture the extensive complexity of charcoal production, dispersion, and deposition. Instead, it utilizes four specific components that contribute to the overall patterning of primary charcoal in sedimentary records. These include fire spatial distribution, frequency, size, and intensity. These characteristics are highly susceptible to manipulation by humans, thus providing a means for testing the influence of burning practices related to land-use on the formation of charcoal records.

The following section describes the specific modules that compose CharRec and presents a statistical method for comparing simulated