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Sensitivity and complacency of sedimentary biogeochemical records to climate-mediated forest disturbances

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ABSTRACT

We provide a synthesis and framework for using lacustrine sedimentary records to study the biogeochemical outcomes of landscape disturbances. Although disturbance regimes can now be effectively reconstructed in sedimentary records, biogeochemical responses to disturbance events are less frequently assessed. Further, there is a lack of consensus on the characteristics of disturbances or ecosystems that would lead to biogeochemical resilience. Both sensitivity (a change in a biogeochemical proxy following a disturbance event relative to a pre-disturbance condition) and complacency (absence of change in a biogeochemical proxy after a disturbance event) have been observed in paleorecords. Here, we discuss the factors that contribute to sensitivity/complacency as well as the short- and long-term biogeochemical effects of terrestrial disturbance agents such as fire and insect outbreaks. We discuss the appropriate strategies for sampling lacustrine sediment cores to assess the biogeochemical outcomes of disturbances and provide a review of the appropriate data scaling techniques for analyzing multiple records in space and time.

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1. Introduction

Increasing temperatures in the lower atmosphere mediate the frequency and severity of forest disturbances, such as wildfire, insect and pathogen outbreaks, drought, and windthrow (Raffa et al., 2008; Pechony and Shindell, 2010; van Mantgem et al., 2013). Disturbances are discrete events in time that reduce biomass and regulate material and energy flow through ecosystems (Pickett and White, 1985). High severity disturbances shift ecosystem structure and function across spatial scales. Potentially, these shifts can provide positive feedbacks to a warming climate system by converting biomass to greenhouse gases, including carbon dioxide (CO_2) and methane (CH_4). For instance, during the 1997 fire season, over 8 million ha of tropical rainforest burned across Indonesia releasing 40% equivalent in CO_2 emissions from all fossil fuel sources during the same year (Page et al., 2002). Recent model projections forecast that temperature-mediated disturbances will increase in severity and frequency during the coming century, which will exacerbate pervasive moisture deficiencies and the legacies of historical land use (Bentz et al., 2010; Williams et al., 2012).

Paleoenvironmental reconstructions provide detailed understanding of past environmental conditions across a range of temporal and spatial scales (Marlon et al., 2012; Salonen et al., 2012). A key research area focuses on understanding how biogeochemical and nutrient stocks at the landscape-scale respond to climate-mediated shifts in disturbance regimes. Information about the biogeochemical outcomes of disturbances can be assessed from geologic archives, namely environmental reconstructions from lacustrine sedimentary records. Sediment-based studies focus on the analysis of proxy data, such as pollen and charcoal, and reveal past vegetation composition and wildfire dynamics within small catchments with minimal inflow. Stable isotopes and elemental concentrations can be used to determine the biogeochemical response of ecosystem disturbances detected by pollen, charcoal, and other macrofossil indicators. Forest disturbances reconstructed at the catchment-scale using lake sediment records is permitted because severe disturbances alter surficial processes, including erosion rates, the spatial pattern of erosion, fluxes in sediment delivery, activating new sediment sources, and augmenting connectivity of transport pathways to the catchment. These processes are influenced by the biotic and abiotic characteristics of the catchment, such as detrital sources, slope, and aspect. Therefore sedimentary records integrate materials and processes that occur during the recovery following a disturbance, which are measured in proxy records as short-term shifts in depositional materials relative to a baseline condition.

Wildfire disturbance events can now be detected reasonably well in paleorecords. The increasing number of high temporal resolution, multiproxy lacustrine records with well-constrained chronologies has made reconstruction of past fire events almost routine and during the last few years, during which paleofire studies have been published from six continents (e.g., Aleman et al., 2013; Fletcher et al., 2014; Higuera et al., 2014; Iglesias et al., 2014; Kuosmanen et al., 2014; Long et al., 2014). These reconstructions are most fruitful in forested landscapes prone to high severity fire events and/or episodic burning, because fires burn significant biomass and decades to centuries elapse between burning episodes (e.g., Clear et al., 2014). In high severity fire regimes, time between fire events permits the study of ecological responses (including biogeochemical outcomes) to the disturbance. For example, a recent study from Colorado USA investigated the impacts of high-severity fires on ecosystem-level biogeochemical processes, including N dynamics (Dunnette et al., 2014). Additionally, advances in charcoal morphometric techniques (Enache and Cumming, 2007) enable the examination of the biogeochemical outcomes of forest vs. grassland fire regimes at ecotonal sites in Wisconsin USA (Morris et al., 2014a).

Reconstructions of fire events and their biogeochemical impacts are important because, frequent and/or high severity disturbances can lead to nutrient limitations that ultimately govern the capability of a landscape to return to its pre-disturbed condition. Yet ecosystem consequences are rarely examined alongside fire histories, which make it difficult to assess the carbon or nutrient consequences of biomass burning. Despite infrequent evaluation of biogeochemical records in paleoecological studies, longer time scales are essential to understanding ecosystem trajectories during periods of rapid environmental change due to shifting climate and disturbance regimes (McLauchlan et al., 2014). Further, one would not expect all ecosystems to exhibit a biogeochemical response to a disturbance. Specifically, some ecosystems are biogeochemically sensitive to disturbance events while others are unexpectedly complacent. We define *sensitivity* as the measure of change in a biogeochemical property following a disturbance relative to its pre-disturbance level. By contrast, we define *complacency* as an absence of change in a biogeochemical property after a disturbance event (i.e., sensitivity of 0). Quantifying the sensitivity of a biogeochemical property depends upon if and how the signal of biogeochemical change is transmitted from the ecosystem to a given proxy. Thus a biogeochemical response may not be detected after a disturbance event for at least three reasons: (1) the biogeochemical property may truly be complacent; (2) the biogeochemical property may be sensitive, but the signal may not be transmitted to the proxy being measured; or (3) the variable may be sensitive, and the signal transmitted, but the sampling protocol may not be sufficient to detect the signal.

Here, we provide a synthesis and propose a conceptual framework to reconstructing biogeochemical responses to disturbances from lacustrine sedimentary records. This template can be tested with further data acquisition, as it predicts under what conditions a lacustrine sedimentary sequence would (or would not) record a biogeochemical response to a terrestrial disturbance. To sufficiently address disturbance-mediated controls on biogeochemical cycles, paleoecology now requires formalization of the appropriate protocols for site selection, minimum sample resolution, spatial and temporal data scaling methods, and statistical approaches. Specifically, understanding the longer-term drivers and controls on key nutrient stocks, including nitrogen (N), phosphorus (P), sulfur (S), and potassium (K), is a priority question identified by the paleoecological research community (Seddon et al., 2014). To better identify the controls on sensitivity and complacency of sediment-derived biogeochemical records, we address the following questions:

(1) Under what circumstances do ecosystems exhibit biogeochemical responses to disturbance events?
(2) How are disturbance signals transmitted to depositional environments?
(3) What are the appropriate approaches to aggregating biogeochemical data across multiple spatial and temporal scales?

2. When is ecosystem biogeochemistry sensitive to disturbance events?

The sensitivity of a biogeochemical property to disturbance events varies by disturbance agent, disturbance severity (i.e., proportion of vegetation killed), and pre- and post-disturbance vegetation composition and structure (Fig. 1). The biogeochemical consequences of landscape disturbances can either diminish or increase bioavailability of nutrients from an ecosystem. Fire is a well-studied, common depleting disturbance agent, and a keystone ecological process in many landscapes (Bowman et al., 2009). The rate and severity of fires varies greatly over time and across space, which is controlled largely by fuel quantity and moisture, ignition rates, and wind speed, in addition to other local-scale and site-specific factors such as slope and aspect. Non-fire depleting disturbances include outbreaks of phytophagus and/or defoliating insects, plant pathogens, windthrow, and snow avalanches.

2.1. Fire

As high severity burns are required to enhance the ferromagnetic properties of soils or enhanced flux of eroded soils, observational