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Quantification of long-term erosion rates from root exposure/tree age relationships in an alpine meadow catchment

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ABSTRACT

Erosion rates derived using dendrogeomorphology have been used to quantify slope degradation in many localities globally. However, with the exception of the western United States, most of these estimates are derived from short-lived trees whose lifetimes may not adequately reflect the complete range of slope processes which can include erosion, deposition, impacts of extreme events and even long-term hiatuses. Erosion rate estimates at a given site using standard techniques therefore reflect censored local point erosion estimates rather than long-term rates. We applied a modified dendrogeomorphic approach to rapidly estimate erosion rates from dbh/age relationships to assess the difference between short and long-term rates and found that the mean short-term rate was ~0.13 cm/yr with high variability, while the uncensored long-term rate was ~0.06 cm/yr. The results indicate that rates calculated from short-lived trees, while possibly appropriate for local short-term point estimates of erosion, are highly variable and may overestimate regional long-term rates by >50%. While these findings do not invalidate the use of dendrogeomorphology to estimate erosion rates they do suggest that care must be taken to select older trees that incorporate a range of slope histories in order to best approximate regional long-term rates.

1. Introduction

Meadows, while comprising only a small portion of the mountain environment, provide a number of critical ecosystem services. Small catchments surrounding these meadows can be impacted by change in geomorphic and hydrologic regimes making them highly responsive to climatic variability (MacDonald and Coe, 2007). Over time this change can produce alterations in sediment generation and delivery to meadows. Resultant modification of meadow surface and channel characteristics, including channel cut-and-fill events and accompanying change in water table depth and modification of surface vegetative cover, can severely impact biogeochemical cycling, carbon sequestration and ecohydrology potentially leading to a loss of ecosystem function (Rundel et al., 2014).

Data on erosion and sediment production rates at fine scale is critical for improving our understanding of the dynamics and rates of erosion within meadow catchments and subsequent deposition of these sediments within meadows. However, there are relatively few studies of soil erosion processes and soil erosion rates in alpine regions applicable to meadow environments (Konz et al., 2012) and in alpine areas quantification of erosion rates and the magnitude and time-scale of sediment production is still the weakest part of understanding the sediment budget (Otto et al., 2009).

The relatively coarse nature of temporal and spatial measures of weathering, sediment production, erosion and transport, has been a major impediment to a clearer understanding of the links between climate, erosion rates and subsequent landscape response. While dendrogeomorphic analysis of root exposure has allowed estimation of hillslope denudation rates in response to climatic variability (LaMarche, 1961, 1963, 1968; Alestalo, 1971; Dunne et al., 1978; Carrara and Carroll, 1979; Danzer, 1996; McAuliffe et al., 2006; Scuderi et al., 2008, Stoffel et al., 2010; Bahrami et al., 2011) several important issues related to temporal and spatial sampling and their impact on the estimation of long-term rates remain.

Of key importance, we note that there is no "typical" or "average" short-term erosion rate for an area because of local random variability in rates (de Vente and Poesen, 2005; Schumer et al., 2011). When deriving and interpreting erosion rates both the temporal and spatial distribution of erosional processes must be taken into account. From a temporal perspective, total erosion at a given location is a function of the integrated erosional history at a site and can include intervals of deposition and erosion as well as hiatuses where no change in surface elevation takes place (Sadler, 1981). Estimates derived from trees with life spans significantly shorter than the time scale of topologic evolution of the surface (Schumer et al., 2011), given the highly non-normal time-dependent behavior of erosion (García-Ruiz et al., 2015), significantly

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reduces the reliability of estimated long-term erosion rates. Short temporal samples therefore represent censored "snapshots" of total erosion rates producing highly skewed results with possible over or under estimation of local and regional long-term rates (Boardman and Favis-Mortlock, 1999; Stoffel et al., 2013a,b). Extreme precipitation events also can significantly skew short-term rate estimation.

Calculation of average erosion with insufficient representation of the spatial distribution of erosion variability may also fail to capture the long-term erosion rate (de Vente and Poesen, 2005; Schumer et al., 2011). Diffusive processes similar to a random walk have been shown to best simulate surface elevation change over time (Pelletier and Turcotte, 1997; Metzler and Klafter, 2000). This implies that spatial "snapshots" for a given site, and especially those arrived at in conjunction with short time frames, may result in biased local point erosion estimates. Measurement limitations, as well as difficulties in precisely defining original surface elevations, may also introduce significant errors in point erosion rate estimation (Saez et al., 2011, 2012; Ballesteros-Cánovas et al., 2013; Stotts et al., 2014; Bodoque et al., 2015; Ballesteros-Cánovas et al., 2015).

The goal of this study is to evaluate the time and space dependent behavior of dendrogeomorphic erosion rate estimates and to explore the value of temporal and spatial integration of rate estimates using nontraditional root exposure methods for determining long-term erosion rates. In this study we combine dendrogeomorphic techniques and Geographic Information System (GIS) analysis to determine long-term erosion rates from forested surfaces to estimate the rate of and processes involved in surface lowering, sediment generation and transport in Sierra Nevada meadow catchments over the last 1200 years. Following a brief overview of study site characteristics and root exposure erosion measurement approaches we, (i) determine the local long-term erosion rate in catchments above an alpine meadow, (ii) reconstruct the spatial distribution of erosion rates across the study area and analyze the variability of these rates based on local topographic variability, (iii) analyze the effects of short-term censoring of erosion rate estimates, and (iv) evaluate the impacts of a recent rare large-scale precipitation event on erosion and deposition.

2. Study site

Horseshoe and Round Meadows (~36.4 N 118.2 W ~ 3000 m) located in the southern Sierra Nevada ~18 km southwest of Lone Pine, California (Fig. 1), are small ~0.5 km wide areas of alluvial fill (Qal) bordered by narrow zones of in-situ weathered rock, grus and sand. The meadows are situated between moraine-covered outcrops of the Whitney granodiorite (Chen and Moore, 1982; du Bray and Moore, 1985) with surrounding catchment slopes generally less than 12°.

Sierran meadows are believed to have formed in response to increasingly wetter (Wood, 1975; Anderson and Smith, 1994; Clark and Gillespie, 1997; Konrad and Clark, 1998) and colder conditions (Scuderi, 1987a,1987b; Anderson, 1990) in the late-Holocene between 2500 and 1200 years ago (Wood, 1975; Anderson and Smith, 1994; Scuderi and Fawcett, 2013). Following their establishment, erosion of surrounding forested catchments has produced small sediment fans deposited directly over older meadow sediments (Fig. 1). Though the study meadows have not been cored, surface and subsurface deposits are likely similar to other Sierran meadows where recent coarse sediments interfinger with fine-grained sediments deposited between 2500 and 1200 years ago (Wood, 1975). These sediments overlie a sandy unit derived from an early to mid-Holocene forested surface (Wood, 1975; Anderson, 1990; Scuderi and Fawcett, 2013). In turn these sediments lie on an older basal layer of coarse inorganic alluvium formed during late-Pleistocene deglaciation (Wood, 1975).

Regionally alpine tree line occurs at approximately 3600 m (Scuderi, 1987a,b, 1993), however, numerous low-lying areas as much as 700 m

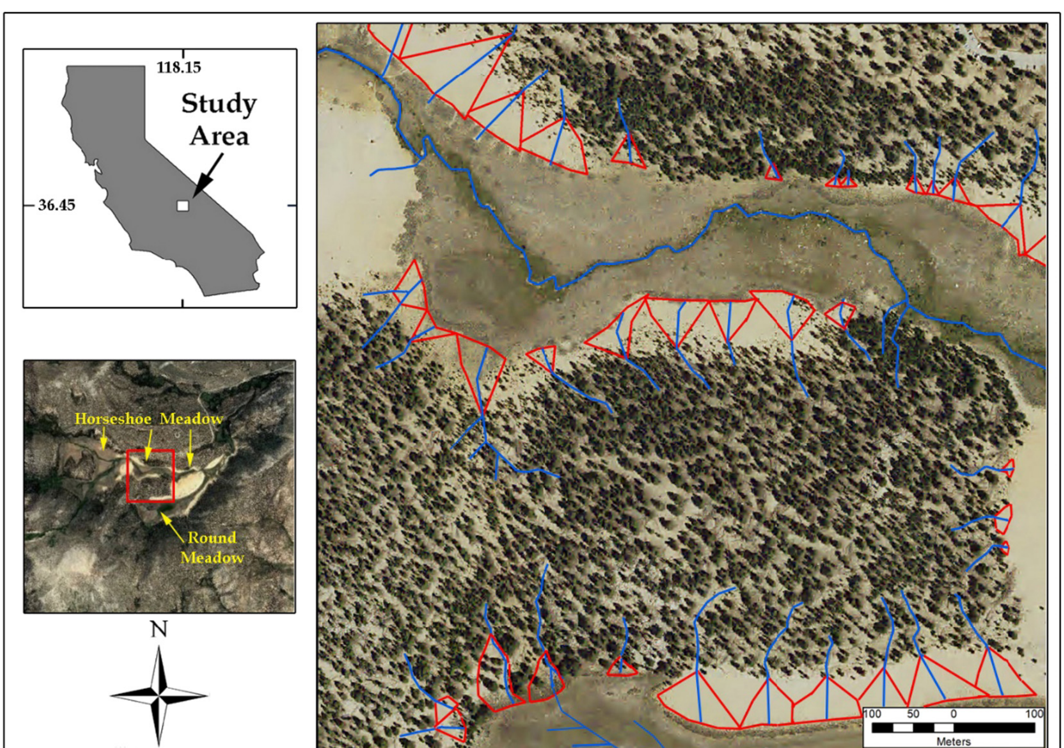

Fig. 1. The Horseshoe and Round Meadow study area in the southern Sierra Nevada, California located at 3000 m just above the eastern escarpment of the Sierra Nevada. Drainage lines derived using ARCMap hydrologic network extraction (ESRI, 2016) from a 10 m Digital Elevation Model and confirmed in the field are shown in blue. Associated active fan distributary areas are shown in red. Interfan areas with tributary drainage (Weissmann et al., 2010) lie between the delineated fans and the forest boundary. A tributary of Cottonwood Creek that drains from the main Sierra crest 3 km to the west flows through Horseshoe Meadow. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)