Fire and the evolution of mountainous landscapes

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ABSTRACT

Recent burns in the western United States attest to the significant geomorphic impact of fire in mountainous landscapes, yet we lack the ability to predict and interpret fire-related erosion over millenial timescales. A diverse set of geomorphic processes is often invoked following fire; the magnitude of post-fire erosional processes coupled with temporal variations in fire frequency dictate the extent to which fires affect sediment production and landscape evolution. In the Oregon Coast Range (OCR), several models for long-term rates of soil production and transport have been tested and calibrated, although treatment of fire-related processes has been limited. Following recent fires in the OCR, we observed extensive colluvial transport via dry ravel, localized bedrock emergence due to excess transport, and talus-like accumulation in adjacent low-order valleys. Soils exhibited extreme but discontinuous hydrophobicity and no evidence for rilling or gullying was observed. Using a field-based dataset for fire-induced dry ravel transport, we calibrated a physically-based, transport model which indicates that soil flux varies nonlinearly with gradient. The post-fire critical gradient (1.03), which governs the slope at which flux increases rapidly, is lower than the previously estimated long-term value (1.27), reflecting the reduction of slope roughness from incineration of vegetation. Using a high-resolution topographic dataset generated via airborne laser swath mapping, we modeled the spatial pattern of post-fire and long-term erosion rates. Post-fire erosion rates exceed long-term rates (which average 0.1 mm yr^{-1}) by a factor of 6

and subtle topographic variations generated local patches of rapid post-fire erosion, often exceeding 1 mm yr^{-1}. Our simulations indicate that fire-related processes may account for ~50% of temporally-averaged sediment production on steep hillslopes. Our analysis provides a mechanistic explanation for the coincident early Holocene timing of increased fire frequency and regional aggradation in OCR drainage basins. Given the sensitivity of steep hillslopes to fire-driven transport, changes in climate and fire frequency may impact soil resources by perturbing the balance between soil transport and production.

INTRODUCTION

In mountainous landscapes, post-fire geomorphic response can be profound and has been well documented for many historical events (e.g., Franke, 2000). Following fire, significant changes in soil, vegetation, and hydrologic properties are common and often invoke a distinct suite of geomorphic processes not present between burns (Wondzell and King, 2003). Enhanced hydrophobicity in soils and removal of ground litter can decrease infiltration rates and generate extensive overland flow erosion by rilling and gullying. Incineration of vegetation and drying of cohesive soil aggregates on steep slopes can induce dry ravel, whereby soil and colluvial clasts move downslope via rolling, bouncing, and sliding. Reduction of root strength in the years following fire increases the propensity for colluvial hollows to spawn shallow landslides during subsequent rainstorms. Runoff during storms can also initiate debris flows by entraining fire-related sediment accumulated in valley bottoms (Cannon et al., 2001). For historical fires in the western United States, rates of sediment transport and erosion associated with these processes tend to be high and often exceed long-term (temporally averaged) rates by an order of magnitude or greater (Wells, 1985). Given the frequency of fire in many mountainous landscapes, the contribution of fire-related processes to the long-term pattern of sediment yield may be considerable, yet we lack a systematic methodology for interpreting and predicting the role of fire in landscape dynamics.

Deciphering how post-fire geomorphic response affects sediment production and landscape evolution over millennial (and longer) timescales requires both documentation of long-term variation in fire frequency and quantification of fire-related geomorphic processes. Although several studies have inferred temporal variations in fire-related sedimentation from alluvial and debris flow deposition (e.g., Meyer et al., 1995; Lave and Burbank, 2004), few physically-based models of fire-driven sediment transport have been tested and calibrated for predicting sediment dynamics in natural landscapes (Wilson et al., 2001). As a result, fundamental questions regarding the geomorphic role of fire remain elusive. Given a change in fire frequency, how will rates of sediment delivery to channels vary? Is there a mechanistic linkage between fire, sediment supply, and valley aggradation in mountainous landscapes? How might increased fire frequency affect soil sustainability and the balance between soil production and transport?

Recent fires in the Oregon Coast Range (OCR) have enabled us to document how the pace of post-fire geomorphic processes compares with long-term rates of transport and erosion established from previous studies. We use a high-resolution topographic dataset acquired via airborne laser swath mapping (ALSM) to simulate the spatial pattern of post-fire erosion. Although hillslope morphology appears qualitatively similar across our study area, our analyses reveal how subtle topographic variations can significantly affect sediment delivery to channel networks. In the OCR, regional aggradation and a peak in fire frequency coincide during the early Holocene, yet mechanisms linking these events are unknown. Our analyses enable us to quantify how variations in fire frequency affect sediment production and hillslope evolution through the intimate connection between soil, vegetation, and fire on steep hillslopes.

TOPOGRAPHY, DENUDATION, AND FIRE IN THE OREGON COAST RANGE

The OCR is a steep, forested, soil-mantled landscape composed largely of Eocene sedimentary rocks. The region has experienced rock uplift since the Miocene and long-term rates average 0.1 to 0.3 mm yr^{-1} according to marine terrace records (Kelsey et al., 1996). The topography of the OCR has been characterized as steep and highly dissected with relatively uniform ridge and valley terrain. Soils are typically clast-rich and thin (<0.5 m) on hilltops and sideslopes and thicker (~ 1-2 m) in unchanneled valleys that act as preferential source areas for shallow landslides (Dietrich and Dunne, 1978). Erosion rates estimated by short- (~10 yr) and long-term (~ 5,000 yr) analyses are commonly 0.05 to 0.3 mm yr^{-1} (Reneau and Dietrich, 1991; Heimsath et al., 2001) and may approximately balance rock uplift.

The OCR has been a fertile landscape for testing, calibrating, and validating process-based models for sediment transport and production (Dietrich et al., 2003), but few studies have considered the influence of episodic fires apart from their role in modulating root strength decline and shallow landslide susceptibility (e.g., Benda and Dunne, 1997). Fires of variable intensity in 1999, 2002, and 2003, occurred in forests of mixed stand age and spawned immediate and extensive transport via dry ravel resulting from the incineration and disturbance of understory vegetation (Table 1). Prior to fire, sub-canopy vegetation (particularly sword fern, *Polystichum munitum*) is pervasive, adds sub-meter scale roughness to hillslopes, and acts as natural sediment traps. At the burn sites within the Siuslaw river basin, we observed no evidence for erosion by overland flow. Soils exhibited a discontinuous pattern of hydrophobicity at the sub-meter scale, which obviated the initiation of rilling and gullying during subsequent rainstorms (Gerber, 2004). Instead, within hours of each fire, valleys exhibited extensive deposition due to dry ravel as loose colluvium was readily mobilized on slopes with gradients exceeding 0.6. The erosional response was highly variable as some hillslopes experienced wholesale soil stripping and bedrock emergence over localized areas (~1000 m^2) of high steepness.

Long et al. (1998) documented a 9,000-yr record of fire frequency in the OCR using high-resolution charcoal analysis of sediment cores from Little Lake, Siuslaw River basin. In the early Holocene (9000 to 6850 ya), fire intervals averaged 110 ±20 yr during a climatic period warmer and drier than today. Fire intervals increased progressively with time, attaining 230 ±30 yr over the last 2750 yr, which have been characterized by cool, humid conditions (Worona and Whitlock, 1995). Along several OCR rivers, Personius et al. (1993) characterized a continuous alluvium-mantled strath terrace that exhibits radiocarbon ages of 7.8-12 kya (7.8 ±0.3 kya in the Siuslaw basin). These terraces likely reflect increased sediment supply and regional aggradation, although mechanistic linkages between sediment production, climate variability, and fire frequency have not been established.

FIRE AND SOIL TRANSPORT

The transport of soil in the absence of overland flow has been extensively modeled using slope-dependent transport models. According to a physically-based model proposed by Roering et al. (1999), volumetric soil flux, q_s, varies nonlinearly with hillslope gradient (∇z) according to:

$$q_s = -K \frac{\nabla z}{1-\left(\left|\nabla z\right|/S_c\right)^2} \tag{1}$$

where K is a transport rate coefficient ($m^2\ yr^{-1}$) that reflects the efficacy of disturbance processes that drive soil movement and S_c is the critical gradient. Equation 1 and similar models which indicate that flux increases rapidly as $\left|\nabla z\right|$ approaches S_c have been used to simulate transport via bioturbation, dry ravel, granular creep, and small soil slips (Gabet, 2000; Roering et al., 2002; Gabet, 2003). In the OCR, K and S_c values were calibrated ($K=30 \pm 15\ cm^2\ yr^{-1}$ and $S_c=1.27 \pm 0.1$) using ALSM-based topographic data and the assumption that erosion rates locally approximate 0.1 mm yr^{-1} (Roering et al., 1999). These values represent long-term (~10 kyr) average transport rates and do not reflect short-term perturbations associated with fire or other disturbances (Fig. 1).

To quantify post-fire erosion in the OCR, Bennett (1982) installed 22 sediment traps before prescribed burns at seven sites and measured sediment accumulation for 2 years following fire. Here, we re-analyze Bennett's (1982) field data by converting estimates of sediment accumulation in traps to volumetric transport rates. We plotted transport rate against local hillslope gradient and observed a nonlinear relationship that is well-represented by equation 1 (Fig. 1). Post-fire fluxes are low on gentle slopes and increase rapidly between gradients of 0.6 and 0.8. For steep slopes ($\left|\nabla z\right| > 0.8$), post-fire transport rates exceed long-term rates by an order of magnitude or more. We calibrated our nonlinear model using the post-fire data and estimated $K=110 \pm 35$ cm^2 yr^{-1} and $S_c=1.03 \pm 0.2$. The post-fire S_c-value is 25% lower than the long-term value, reflecting the alteration of slope conditions from incineration of clast-binding vegetation. In particular, local roughness is reduced after fire such that mobile clasts encounter less frictional resistance during downslope movement. In addition, the post-fire K-value is nearly three times larger than the long-term value, which reflects the effectiveness of fire-related disturbances in initiating soil movement.

MODELING THE EVOLUTION OF FIRE-PRONE HILLSLOPES

To document how fire-driven increases in transport affect soil thickness, hillslope morphology, and sediment delivery to channel networks, we simulated erosion rates for a ~180,000 m^2 catchment using our nonlinear model and an ALSM dataset acquired in the central OCR (Roering et al., 1999). The site depicted in Figure 2 contains numerous hillslope-valley sequences characteristic of topography in the OCR, including the three burned study sites. We used calibrated parameters to calculate the spatial distribution of long-term and post-fire erosion rates by combining equation 1 with a two-dimensional version of the continuity equation (eqn. 9 in Roering, et al., 1999). Consistent with evidence for locally uniform denudation in the OCR (Reneau and Dietrich, 1991), rates of hillslope erosion for our long-term simulation are clustered around 0.1 mm yr^{-1} (Fig. 2A), as 80% of the slopes exhibit erosion rates between 0.04 and 0.16 mm yr^{-1} and only 3% erode faster than 0.2 mm yr^{-1} (Fig. 3). Our model estimates aggradation in the valley network (shown by blue colors in Fig. 2), although here we focus on the erosion of convex and planar sections of the landscape.

For the post-fire simulation, denudation is significantly higher as over 87% of the slopes have erosion rates greater than 0.2 mm yr^{-1} and 21% erode faster than 1 mm yr^{-1} (Fig. 2B and 3). Post-fire erosion rates are spatially variable (Fig. 2B); some hillslopes exhibit somewhat moderate increases in erosion (2-3 times the long-term value), whereas others have large patches with erosion rates exceeding 1 mm yr^{-1}. Areas of rapid erosion tend to be exceedingly steep ($|\nabla z| > 1.0$), such that transport rates are effectively infinite according to equation 1. Actual soil transport rates, however, are limited by the availability of soil. Given frequent fires, such steep areas may experience soil thinning that outpaces soil production. At our three burned sites, charred in-situ plant and tree root systems are draped across steep bedrock sideslopes, reflecting the presence of a thin (10-30 cm) but relatively continuous pre-fire soil mantle.

To quantify the contribution of fire to long-term denudation, we used equation 1 to model the magnitude of post-fire transport rates relative to long-term rates. Because the time-integrated effect of fire depends on burn frequency, we applied the post-fire transport parameters for fire intervals of 100, 250, and 500 years (Fig. 4A). For a range of gradients, we calculated the ratio of post-fire to long-term soil flux (q_{fire}/q_{long}) using the parameters calibrated above (see Fig. 1). The contribution of fire to long-term average transport increases nonlinearly with gradient and decreases with fire interval length (Fig. 4B). Given a 100-yr interval, fires may account for nearly 25% of soil transport on slopes with gradient equal to 0.8. Given the median hillslope gradient of 0.8 in our study site, this indicates that on 50% of the hillslopes, fire drives at least 25% of long-term soil flux. On extremely steep slopes ($|\nabla z| \approx 1.0$), our analysis indicates that 40-80% of the total soil flux is associated with fire. Due to the nonlinearity of equation 1, these calculations are sensitive to calibrated values of S_c. By accounting for parameter uncertainty our results vary, but consistently emphasize the importance of fire on the denudation of steep slopes characteristic of the OCR.

DISCUSSION AND CONCLUSIONS

The influence of fire on soil transport and hillslope evolution is modulated by topographic variability at the process scale. Our results coupling a physically-based transport model and high-resolution topographic dataset are consistent with previous dry ravel studies indicating a rapid increase in flux as local slope gradients approach 0.8 (see review in Gabet, 2003). As a result, landscape sensitivity to fire is highly dependent on the distribution of hillslope gradient, which is often poorly represented with readily available DEMs having a 10- or 30-m grid spacing. The prediction of post-fire site response for land-use management likely requires meter-scale depiction of topography, such as that provided by ALSM datasets.

On steep, soil-mantled hillslopes, fire may account for a substantial fraction of long-term average soil transport. Based on post-fire sediment yield data for a small catchment in the western Cascade Range, Oregon, Swanson (1981) estimated that fire accounts for 25% of long-term sediment yield. Although our calculations do not address sediment routing by fluvial processes or debris flows, our results are generally consistent, indicating that post-fire rates of hillslope erosion and valley infilling exceed background rates by a factor of 5 or greater. Our erosion rate simulations (Fig. 2) only reflect the impact of fire for one year, whereas the ecological (and geomorphic) impacts likely persist for several years (Swanson, 1981). During periods of frequent fire, rapid sediment delivery to channel networks via dry ravel coupled with depressed root reinforcement and increased shallow landsliding may be sufficient to eclipse transport capacity and cause widespread aggradation of high-order valleys. In the OCR, the early Holocene coincidence of regional aggradation (Personius et al., 1993) and a peak in fire frequency (Long et al., 1998) suggests a link between fire and increased sediment production. Additional factors, including variations in rainfall/runoff, vegetation, and soil production, however, may modulate the strength of the coupling between hillslopes processes and valley dynamics (Reneau and Dietrich, 1990; Dunne, 1991).

At our burned study sites, we observed broad patches of exposed bedrock across many hillslopes. These areas accounted for a substantial fraction of several hillslopes, suggesting that soil production may limit sediment delivery during periods of accelerated transport. At our sites, soil production processes (such as cm-scale foliation of rock and bioturbation) became prominent in the years following fire, although it's unclear how long it will take to regenerate a substantial soil mantle. According to a soil production function calibrated for the OCR (Heimsath et al., 2001), a 20-cm soil mantle requires ~1000 yr to be established. Considering post-fire erosion rates and fire interval estimates, this calculation suggests that the balance between soil production and transport may be highly sensitive to fire, such that soils may be thinner and less continuous during periods of frequent burns. Given projections for climate change and increased fire frequency in the Pacific Northwest, the maintenance of soil on steep slopes may become tenuous.

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TABLES

TABLE 1. RECENT OREGON COAST RANGE FIRE DESCRIPTION AND LOCATION.

Name	Size (acres)	Forest age	Latitude (N)	Longitude (W)
Austa, 1999	1062	Mixed	44° 00’ 47”	123° 39’ 42”
Siuslaw, 2002	860	Mixed	43° 58’ 21”	123° 37’ 05”
Sulphur, 2003	650	Mixed	43° 58’ 47”	123° 48’ 45”

FIGURE CAPTIONS

Fig. 1. Variation of long-term and post-fire sediment flux with hillslope gradient. The small filled circles near the base of the plot represent the long-term flux-gradient relationship established assuming a locally uniform erosion rate of 0.1 mm yr^{-1} (see Roering et al., 1999). Equation 1 was fit to the long-term data yielding calibrated values of K and S_c. The open diamonds are sediment flux estimates from a field-based study whereby sediment traps were installed before prescribed burns and monitored for sediment accumulation over two years (Bennett, 1982). We omitted one anomalously high sediment flux data point as it likely reflected disturbance. We fit equation 1 (thick gray line) to the post-fire dataset using a nonlinear curve-fitting algorithm. For both cases, flux increases nonlinearly with gradient, but post-fire flux rates exceed long-term rates by nearly an order magnitude.

Fig. 2. Spatial distribution of modeled hillslope erosion rates using an airborne laser swath mapping dataset and our nonlinear transport model (equation 1). The datasets captures meter-scale topographic variations that control the process-scale pattern of erosion. The study catchment (outlined) is a tributary to Sullivan Creek in the central OCR (43°27'50"N, 124°07'13"W). Warm colors reflect landscape lowering (erosion) on hillslopes, whereas cool colors represent aggradation (or deposition) in valleys. A) Long-term average erosion rate using K=30 cm^2 yr^{-1} and S_c=1.27. Erosion rates on hillslopes are relatively uniform for the long-term case (~0.1 mm yr^{-1}). B) Post-fire erosion rates using K=110 cm^2 yr^{-1} and S_c=1.03. Post-fire rates vary considerably due to subtle topographic differences. Local steep areas have high erosion rates (>1.0 mm yr^{-1}) and may experience soil stripping.

Fig. 3. Distribution of modeled hillslope erosion rates for the simulation shown in Fig. 2. A) The long-term distribution (shown with thin black line) shows rates clustered around the median value of 0.1 mm yr^{-1}, as less than 20% of the hillslopes have erosion rates less than 0.04 mm yr^{-1} or greater than 0.16 mm yr^{-1}. B) For the post-fire distribution (thick gray line), the distribution becomes skewed toward high rates

as over 21% erode faster than 1.0 mm yr^{-1}. The median post-fire hillslope erosion rate is 0.55 mm yr^{-1}, over 5 times faster than the long-term average. IQR is the inter-quartile range for each distribution. In these datasets, we excluded aggradation in valleys or topographic hollows (i.e., covergent areas with negative erosion).

Fig. 4. Post-fire contribution to long-term sediment flux. A) Conceptual model for the impact of fire on sediment flux with time (after Swanson, 1981). The long-term average sediment flux reflects the integrated effect of fire and "non-fire" processes. B) Fraction of post-fire to long-term sediment flux as a function of gradient. Long-term and post-fire parameters (Fig. 1) were used to calculate curves for different fire intervals (see dark lines of varying thickness). The fraction of flux driven by fire increases with gradient and decreases with fire interval. The infilled gray line shows the gradient distribution for hillslopes (non-covergent areas) within our ALSM study area. The median gradient is 0.8, such that fire accounts for 25% or more of the total sediment flux on ~50% of the hillslopes.

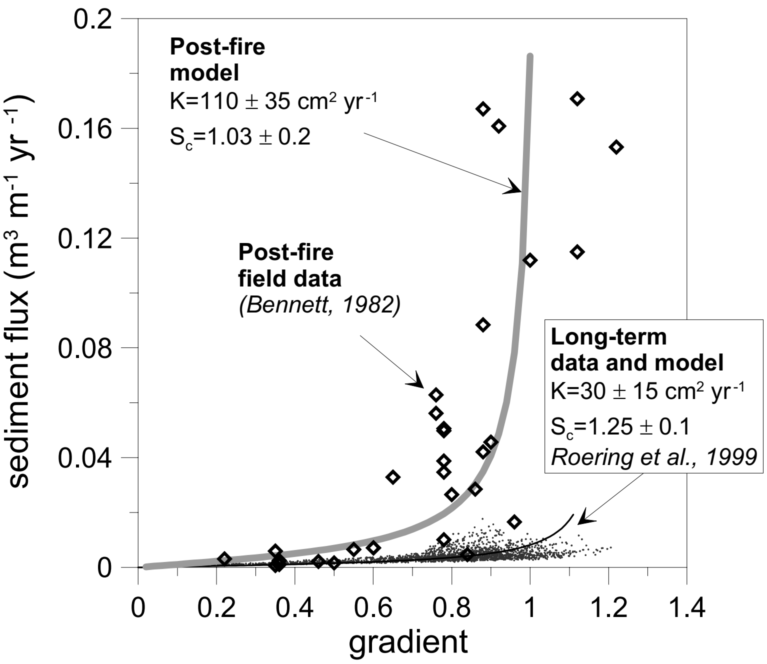

Figure 1

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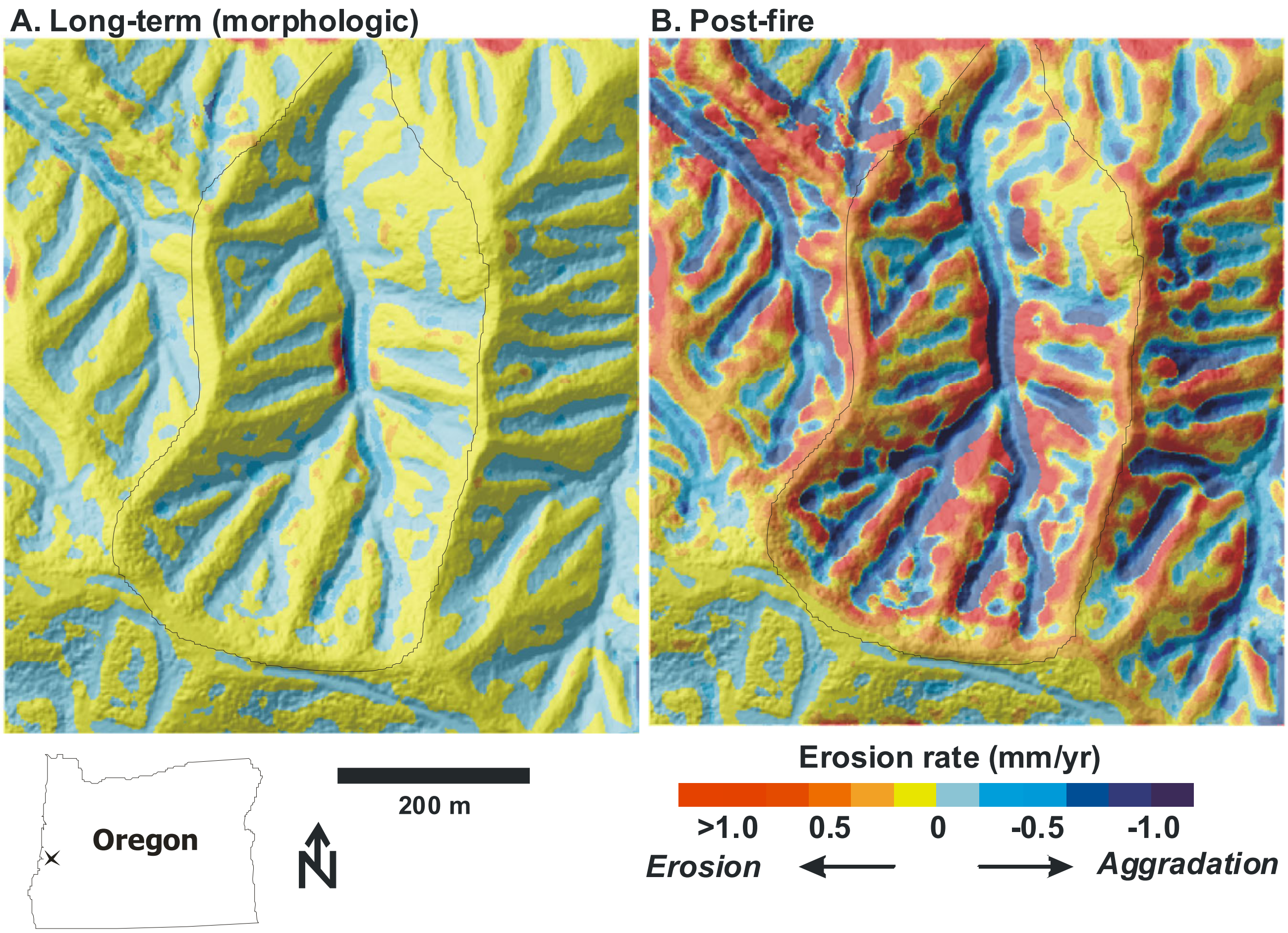

Figure 2

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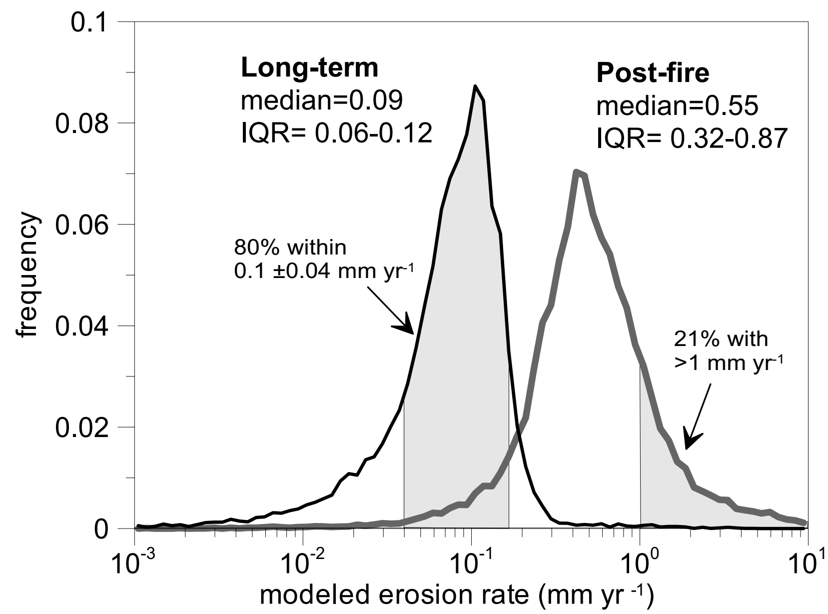

Figure 3

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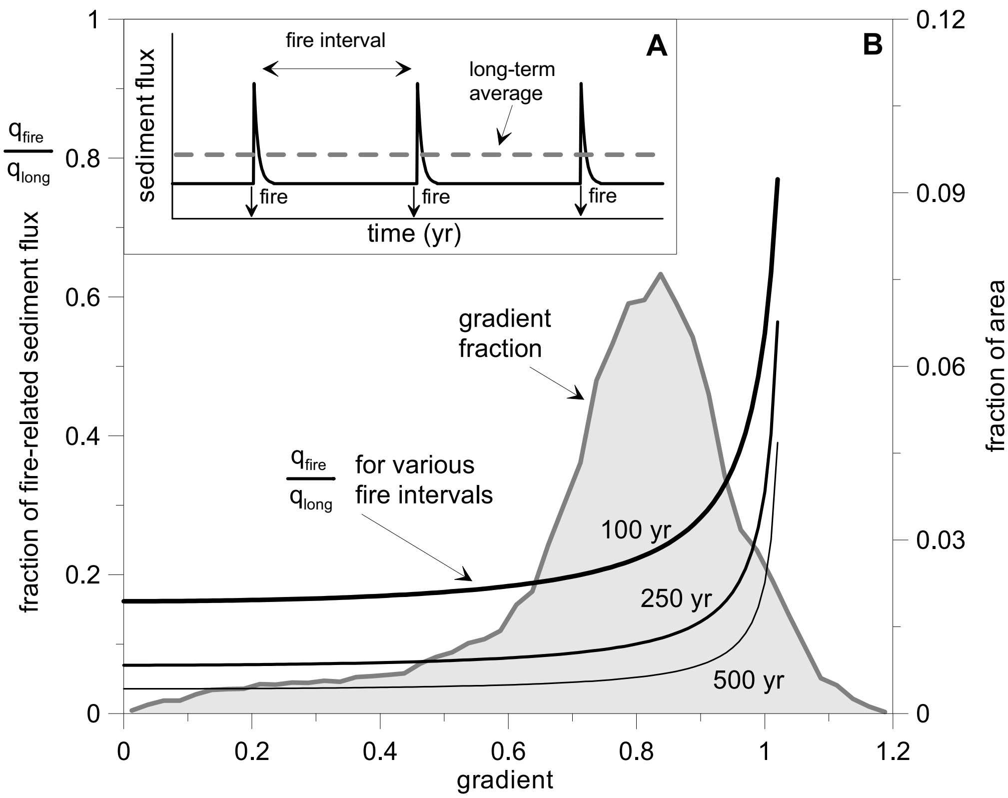

Figure 4

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