

Fire and the evolution of steep, soil-mantled 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 millennial time scales. A diverse set of geomorphic processes is often invoked following fire; the magnitude of postfire 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, 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 Oregon Coast Range, 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 gullyng was observed. Using a field-based data set for fire-induced dry ravel transport, we calibrated a physically based transport model that 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. By using a high-resolution topographic data set generated via airborne-laser swath mapping, we modeled the spatial pattern of postfire and long-term erosion rates. Postfire erosion rates exceed long-term rates (which average $0.1 \text{ mm}\cdot\text{yr}^{-1}$) by a factor of six, and subtle topographic variations generated local patches of rapid postfire erosion, commonly $>1 \text{ mm}\cdot\text{yr}^{-1}$. Our simulations indicate that fire-related processes may account for $\sim 50\%$ 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 Oregon Coast Range drainage basins. Given the sensitivity of steep hillslopes to fire-driven transport, changes in climate and fire frequency may affect soil resources by perturbing the balance between soil transport and production.

Keywords: fire, Oregon Coast Range, hillslope erosion, nonlinear soil transport, dry ravel, airborne laser altimetry.

INTRODUCTION

In mountainous landscapes postfire geomorphic response can be profound and has been well documented for many historical events. 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 (see review in 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 gullyng. 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 rates by an order of magnitude or greater (e.g., 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 postfire geomorphic response affects sediment production and landscape evolution over millennial (and longer) time scales requires both documentation of long-term variation in fire frequency and quantification of fire-related geomorphic processes. Although temporal variations in fire-related sedimentation have been observed in several studies (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 link among 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 have enabled us to document how the pace of postfire geomorphic processes compares with long-term rates of transport and erosion established from previous studies. We use a high-resolution topographic data set acquired via airborne-laser swath mapping (ALSM) to simulate the spatial pattern of postfire 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 Oregon Coast Range, regional aggradation and a peak in fire frequency coincide during the early Holocene (Personius et al., 1993; Long et al., 1998), 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 among soil, vegetation, and fire on steep hillslopes.

TOPOGRAPHY, DENUDATION, AND FIRE IN THE OREGON COAST RANGE

The Oregon Coast Range is a steep, forested, soil-mantled landscape composed largely of Eocene sedimentary bedrock. The region has undergone uplift since the Miocene, and long-term rates average $0.1\text{--}0.3 \text{ mm}\cdot\text{yr}^{-1}$ according to marine-terrace records (Kelsey et al., 1996). The topography of the range has been characterized as steep and highly dissected with relatively uniform ridge and valley terrain (Dietrich and Dunne, 1978). Soils are typically clast rich and thin ($<0.5 \text{ m}$) on hilltops and side slopes and thicker ($\sim 1\text{--}2 \text{ m}$) in unchanneled valleys that act as preferential source areas for shallow landslides. Erosion rates estimated by short- ($\sim 10 \text{ yr}$) and long-term ($\sim 5000 \text{ yr}$) analyses are commonly $0.05\text{--}0.3 \text{ mm}\cdot\text{yr}^{-1}$ (Reneau and Dietrich, 1991; Heimsath et al., 2001) and may approximately balance rock uplift.

The Oregon Coast Range 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-

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TABLE 1. DESCRIPTION AND LOCATION OF RECENT OREGON COAST RANGE FIRES

Name, year	Size (acres)	Forest age	Latitude	Longitude
Austa, 1990	1062	Mixed	44°00'46"N	123°39'42"W
Siuslaw, 2002	860	Mixed	43°58'21"N	123°37'05"W
Sulphur, 2003	650	Mixed	43°58'47"N	123°48'45"W

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 (Table 1) and spawned immediate and extensive transport via dry ravel resulting from the incineration and disturbance of understory vegetation. Prior to fire, subcanopy 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 >0.6. The erosional response was highly variable as widespread soil stripping (often exceeding several centimeters) and bedrock emergence occurred across localized areas (~1000 m²) of high steepness.

Long et al. (1998) documented a 9 k.y. record of fire frequency in the Oregon Coast Range using high-resolution charcoal analysis of sediment cores from Little Lake, Siuslaw River basin. In the early Holocene (9000–6850 yr B.P.), 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 past 2750 yr, which have been characterized by cool, humid conditions (Worona and Whitlock, 1995). Along several Oregon Coast Range rivers, Personius et al. (1993) characterized a continuous, alluvium-mantled strath terrace that exhibits radiocarbon ages of 7.8–12 ka (7.8 ± 0.3 ka in the Siuslaw basin). These terraces likely reflect increased sediment supply and regional aggradation, although mechanistic links among 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

$$q_s = \frac{K \nabla z}{1 - (|\nabla z|/S_c)^2}, \quad (1)$$

where K is a transport rate coefficient (in m²·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 that indicate that flux increases rapidly as $|\nabla z|$ approaches S_c have been used to simulate transport via bioturbation, dry ravel, granular creep, and small soil slips (Gabet, 2000, 2003; Roering et al., 2002). In the Oregon Coast Range, K and S_c values were previously calibrated ($K = 30 \pm 15$ cm²·yr⁻¹ and $S_c = 1.27 \pm 0.1$) using ALSM-based topographic data and the assumption that erosion rates are locally ~0.1 mm·yr⁻¹ (Roering et al., 1999). These values represent long-term (~10 k.y.) average transport rates and do not reflect short-term perturbations associated with fire or other disturbances (Fig. 1).

To quantify postfire erosion characteristics of Oregon Coast Range hillslopes, Bennett (1982) installed 22 sediment traps before broadcast

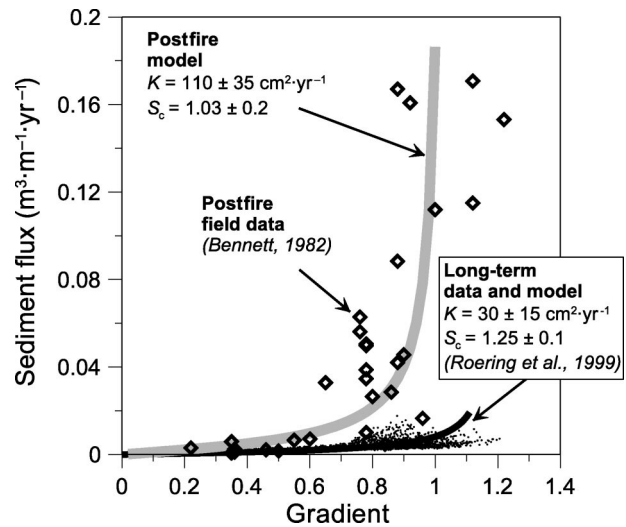


Figure 1. Variation of long-term and postfire sediment flux with hillslope gradient. Small filled circles near base of plot represent long-term flux-gradient relationship established by assuming locally uniform erosion rate of 0.1 mm·yr⁻¹. Equation 1 (see text) was fit to long-term data, yielding calibrated values of K and S_c (see Roering et al., 1999). Open diamonds are sediment flux estimates from field-based study whereby sediment traps were installed before broadcast and slash burns and monitored for sediment accumulation over 2 yr (Bennett, 1982). We omitted one anomalously high sediment-flux data point as it likely reflected disturbance. We fit equation 1 (thick gray line) to postfire data set using nonlinear curve-fitting algorithm. In both cases, flux increases nonlinearly with gradient, but postfire flux rates exceed long-term rates by nearly order of magnitude on steep slopes.

and slash burns at 7 sites and measured sediment accumulation for 2 yr following the fires. Here we reanalyze 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). Postfire fluxes are low on gentle slopes and increase rapidly between gradients of 0.6 and 0.8. For steep slopes ($|\nabla z| > 0.8$), postfire transport rates exceed long-term rates by an order of magnitude or more. We calibrated our nonlinear model using the postfire data and estimated $K = 110 \pm 35$ cm²·yr⁻¹ and $S_c = 1.03 \pm 0.2$. The postfire 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 postfire K value is nearly three times larger than the long-term value, reflecting 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 0.18 km² catchment using our nonlinear model and an ALSM data set acquired in the central Oregon Coast Range. Long-term values of K and S_c were previously calibrated at the site depicted in Figure 2 (Roering et al., 1999), which contains numerous hillslope and valley sequences characteristic of topography in the Oregon Coast Range, including the three burned study sites. We calculated the spatial distribution of long-term and postfire erosion rates by combining equation 1 with a two-dimensional version of the continuity equation (equation 9 in Roering et al., 1999). For this study,

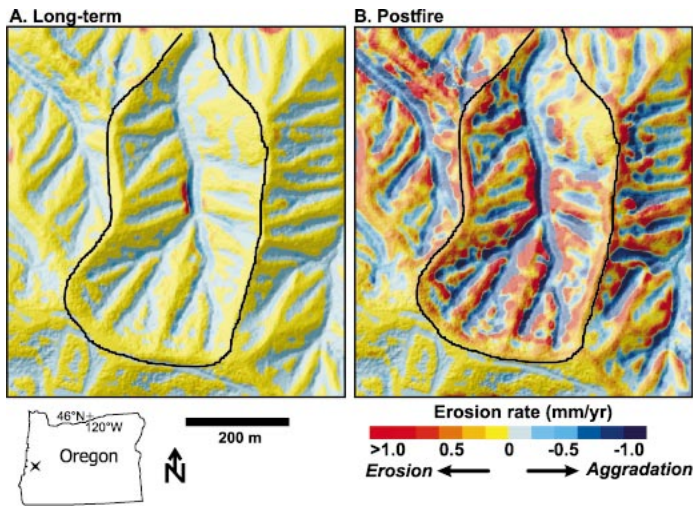


Figure 2. Spatial distribution of modeled hillslope erosion rates using airborne-laser swath-mapping data set (with ~2 m data spacing) and our nonlinear transport model (equation 1). Study catchment (outlined) is tributary to Sullivan Creek in central Oregon Coast Range (43°27'50"N, 124°07'13"W). Warm colors reflect landscape lowering (erosion) on hillslopes and cool colors represent aggradation (or deposition) in valleys. **A:** Long-term average erosion rate using $K = 30 \text{ cm}^2\text{-yr}^{-1}$ and $S_c = 1.27$ (see text). Erosion rates on hillslopes are relatively uniform for long-term case (~0.1 mm-yr⁻¹). **B:** Postfire erosion rates using $K = 110 \text{ cm}^2\text{-yr}^{-1}$ and $S_c = 1.03$. Postfire rates vary considerably due to subtle topographic differences. Local steep areas have high erosion rates (>1.0 mm-yr⁻¹).

our analysis is restricted to hillslope denudation as fluvial and debris flow processes dictate the fate of colluvium delivered to the valley network. Consistent with evidence for locally uniform denudation in the Oregon Coast Range, 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).

For the postfire simulation, denudation is significantly higher as >87% of the slopes have erosion rates >0.2 mm-yr⁻¹ and 21% erode faster than 1 mm-yr⁻¹ (Figs. 2B and 3). Postfire erosion rates are spatially variable (Fig. 2B); some hillslopes exhibit somewhat modest increases in erosion (2–3 times the long-term value), whereas others have large patches with erosion rates >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 undergo soil thinning that outpaces soil production. At our three burned sites, we often observed charred in situ plant and tree root systems perched along steep bedrock side slopes, reflecting the presence of a thin (10–30 cm) but relatively continuous soil mantle that existed prior to fire.

To quantify the contribution of fire to long-term denudation, we used equation 1 to model postfire and long-term transport rates. Because the time-integrated effect of fire depends on burn frequency, we applied the postfire transport parameters for fire intervals of 100, 200, and 300 yr (Fig. 4A). For a range of gradients, we calculated the ratio of postfire to long-term soil flux ($q_{\text{fire}}/q_{\text{long}}$) using the parameters calibrated above (see Fig. 1). For these analyses, we assumed that postfire conditions persist for 3 yr based on field-based analysis of nearby conifer-dominated ecosystems (Swanson, 1981). The contribution of fire to long-term average transport increases nonlinearly with gradient and decreases with fire interval (Fig. 4B). Given a 100 yr interval, fires may account for nearly 20% of soil transport on slopes with gradient equal to 0.8. Considering the median hillslope gradient of 0.8 in our study site, this result indicates that on 50% of the hillslope area, fire

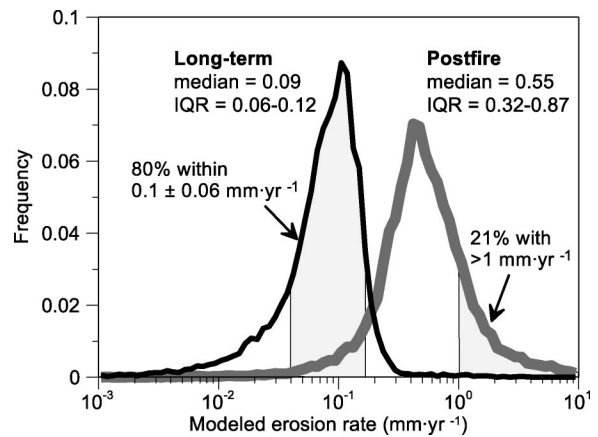


Figure 3. Distribution of modeled hillslope erosion rates for simulation shown in Figure 2. **A:** Long-term distribution (shown with thin black line) shows rates clustered around median value of 0.1 mm-yr⁻¹. **B:** Postfire distribution (thick gray line) is shifted toward high rates. IQR is interquartile range for each distribution. In this analysis, we excluded aggradation in valleys or topographic hollows (i.e., convergent areas with negative erosion).

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. Owing 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 Oregon Coast Range.

DISCUSSION AND CONCLUSIONS

The influence of fire on soil transport and hillslope evolution is modulated by topographic variability at the process scale. Our results couple a physically based transport model and high-resolution to-

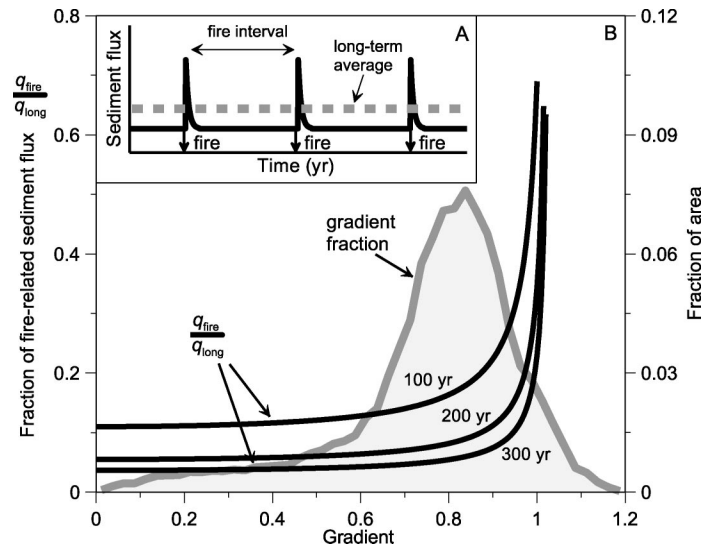


Figure 4. Postfire contribution to long-term sediment flux. **A:** Conceptual model for impact of fire on sediment flux with time (after Swanson, 1981). Long-term average sediment flux reflects integrated effect of fire and nonfire processes. **B:** Fraction of postfire to long-term sediment flux as function of gradient. Long-term and postfire parameters (Fig. 1) were used to calculate curves for different fire intervals (dark lines). Fraction of fire-related flux increases with gradient and decreases with fire interval. Infilled gray line shows gradient distribution for hillslopes (nonconvergent areas) within our airborne-laser swath-mapping study area.

pographic data set 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 digital elevation models having a 10 m or 30 m grid spacing. The prediction of postfire 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. On the basis of postfire 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 simulation does not address sediment routing by fluvial processes or debris flows, our results are generally consistent, indicating that postfire rates of hillslope erosion and valley infilling exceed background rates by a factor of five or greater. Our simulations of the spatial pattern of erosion only reflect the impact of fire for 1 yr, 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 Oregon Coast Range, 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 and/or runoff, vegetation, and soil production, however, may be significant in modulating the strength of the coupling between hillslope processes and valley dynamics (Reneau and Dietrich, 1990; Dunne, 1991).

At our burned study sites, we observed broad patches of recently exposed bedrock across many hillslopes, suggesting that soil production may limit sediment delivery during periods of accelerated transport. Soil-production processes (such as centimeter-scale foliation of rock and bioturbation) became prominent following fire, although it is unclear how long it will take to regenerate a substantial soil mantle. According to a soil-production function calibrated for the Oregon Coast Range (Heimsath et al., 2001), a 20 cm soil mantle requires ~1 k.y. to be established. Considering postfire 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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