



Evidence for biotic controls on topography and soil production

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ABSTRACT

The complex interplay of biological, physical, and chemical processes in pedogenesis and hillslope evolution limits our ability to predict and interpret landscape dynamics. Here, we synthesize a suite of observations from the steep, forested Oregon Coast Range to analyze the role of trees in topographic modification and bedrock-to-soil conversion. Using topographic data derived from airborne lidar, we demonstrate that the topographic signature of forest-driven soil and bedrock disturbance is pervasive. For length scales greater than 7.5 m, the land surface is defined by ridge-valley landforms, whereas smaller scales are dominated by pit-mound features generated by the turnover of large coniferous trees. From field surveys, the volume of bedrock incorporated in overturned rootwads increases rapidly with diameter for large conifers, reflecting the highly nonlinear increase in root biomass with tree diameter. Because trees younger than 60 years detach negligible bedrock, short timber harvest intervals may limit the extent to which root systems penetrate bedrock and facilitate bedrock fracturing and biogeochemical weathering. Using ground-penetrating radar, we show that the rootwads of large trees root achieve substantial penetration (1–3 m) into shallow bedrock. The radar transects also reveal that variations in soil thickness have characteristic length scales of 1 to 5 m, consistent with the scale of large rootwads, indicating that both the landscape surface and soil-bedrock interface exhibit a biogenic imprint. In our study area, the residence time of bedrock within dense rooting zones directly below large trees is similar to the time required for trees to occupy the entire forest floor through multiple cycles of forest succession, suggesting that biological modification of shallow bedrock is ubiquitous. Given increases in erosion rate, the ability of roots to initiate soil production may decline as bedrock exhumation through the biotic zone is rapid relative to the time required for successive forests and their associated root systems to fracture bedrock. As a result, in rapidly eroding terrain the coupling between biotic and abiotic weathering processes (such as exfoliation fracturing) may dictate the maximum rate of bedrock-to-soil conversion.

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1. Introduction

Soils (mixed and disaggregated material found atop saprolite, weathered bedrock, or fresh bedrock) co-evolve with biota, regulate hydrologic processes, and sustain civilizations (Thomas, 1956). In order for landscapes to maintain a mantling of soil, bedrock-to-soil conversion must keep pace with erosion (Heimsath et al., 1997; Montgomery, 2007). If erosion rates persistently exceed the ability of physical, chemical, and biological processes to produce soil, bedrock emerges and in doing so alters the geomorphic, hydrologic, and ecologic function of landscapes (Anderson et al., 2007). As such, the analytical form and parameterization of soil production functions are fundamental in our efforts to characterize and predict landscape dynamics.

Most soil production models indicate that soil thickness is the primary control on bedrock-to-soil conversion (e.g., Heimsath et al.,

1997; Small et al., 1999; Wilkinson et al., 2005), although recent efforts emphasize the role of bedrock properties and climate (Burke et al., 2007; Dixon et al., 2009). Empirical evidence exists for both exponential decay and ‘humped’ depth-dependent models (Heimsath et al., 1997; Wilkinson and Humphreys, 2005; Wilkinson et al., 2005; Heimsath et al., 2009), but a systematic explanation for these differing behaviors is lacking. Perhaps more importantly, sparse documentation exists regarding the actual mechanisms that convert bedrock to soil (Gabet and Mudd, in press), challenging our ability to predict how changes in land-use practices, climate, or baselevel lowering will affect short- and long-term patterns of hillslope evolution.

Recent contributions emphasize the need to better quantify biotic processes and their contribution to landscape modification and soil formation (Dietrich and Perron, 2006; Amundson et al., 2007; Corenblit and Steiger, 2009; Richter and Mobley, 2009; Reinhardt et al., 2010). Biotic disturbance processes expend energy in landscapes, some of which translates into net geomorphic work such as downslope soil transport or extrication of bedrock. Although coupling geomorphology and biology through the common currency of energy appears to be a fruitful endeavor (Yoo et al., 2005; Phillips, 2009),

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more definitive evidence and predictive capability demonstrating the biotic role in soil production and landscape alteration is necessary (Gabet et al., 2003; Amundson et al., 2007; Chorover et al., 2007).

Here, we present a suite of diverse datasets from the Oregon Coast Range suggesting that biotic activity plays a first-order role in land surface modification and soil production. On actively eroding slopes, we used: 1) airborne laser altimetry to quantify the topographic signature of tree turnover, 2) root inventories and a published soil production dataset to explore soil production mechanisms, 3) field surveys of tree turnover events to analyze biotic controls on bedrock detachment, and 4) ground-penetrating radar transects to map the biogenic soil-bedrock interface as well as root penetration into bedrock. These analyses highlight the frequency and vigor with which biota interact with bedrock and shape topography in actively eroding landscapes. Our results have implications for the management of timberlands given that the mechanical ability of trees to interact with bedrock varies significantly with forest stand age. Most importantly, however, our findings highlight the fundamental role that life plays in mechanically mixing near-surface environments and modulating the evolution of landscapes.

2. Study area: Oregon Coast Range

The Oregon Coast Range (OCR) is an unglaciated, humid, soil-mantled, mountainous landscape (Fig. 1, inset) largely underlain by the Tye Formation, a sand-rich sequence of turbidite deposits that overlies accreted volcanic basement (Heller and Dickinson, 1985). Uplift and erosion of the Oregon Coast Range commenced in the Miocene (McNeill et al., 2000) and continues today as evidenced by abandoned wave-cut platforms along the Oregon coast (Kelsey et al., 1996). Long-term rates of rock uplift along the central Oregon coast vary from 0.05 to 0.3 mm year⁻¹ with much of the variability deriving from local structural controls (Kelsey et al., 1996). Modern annual rainfall of 1 to 2 m supports a closed forest of Douglas fir and western Hemlock trees on slopes and diverse hardwood and understory species in riparian zones and recently disturbed locales. More than a century of timber harvesting has eliminated virtually all of the old-growth forest in the Oregon Coast Range, yet stumps are often visible and retain significant, albeit decaying, subsurface root systems.

The topography of the OCR is steep and highly dissected (Fig. 1A) with broad regions of relatively uniform ridge and valley terrain (Dietrich and Dunne, 1978). It has been proposed that soil production and transport are driven primarily by biogenic processes (Heimsath et al., 2001). Typically, soils are relatively thin (~0.4 m) on hilltops and sideslopes and thicker (~1 m) in unchanneled valleys (or hollows) that act as preferential source areas for shallow landslides that often initiate debris flows (Dietrich and Dunne, 1978). Long-term erosion rate estimates from cosmogenic radionuclides are remarkably consistent, 0.12 ± 0.03 mm year⁻¹, coincide with modern and radiocarbon-derived erosion estimates (Beschta, 1978; Reneau and Dietrich, 1991; Bierman et al., 2001; Heimsath et al., 2001), and coarsely coincide (within 50%) with rates of coastal uplift (Kelsey et al., 1996) and Holocene bedrock channel incision (Personius, 1995). This correspondence has been cited as support for an approximate balance between rock uplift and erosion in the OCR (Reneau and Dietrich, 1991; Roering et al., 1999; Montgomery, 2001). For areas underlain by the Tye Formation, the relative contribution of chemical denudation to total denudation has been calculated as approximately 10% (Anderson et al., 2002), suggesting that physical processes dominate mass removal.

3. Topographic signature of tree turnover

To quantify the extent to which tree-driven bioturbation leaves an imprint on the landscape surface, we analyzed airborne lidar data collected in 1995 along the Mettman Ridge study area (Roering et al.,

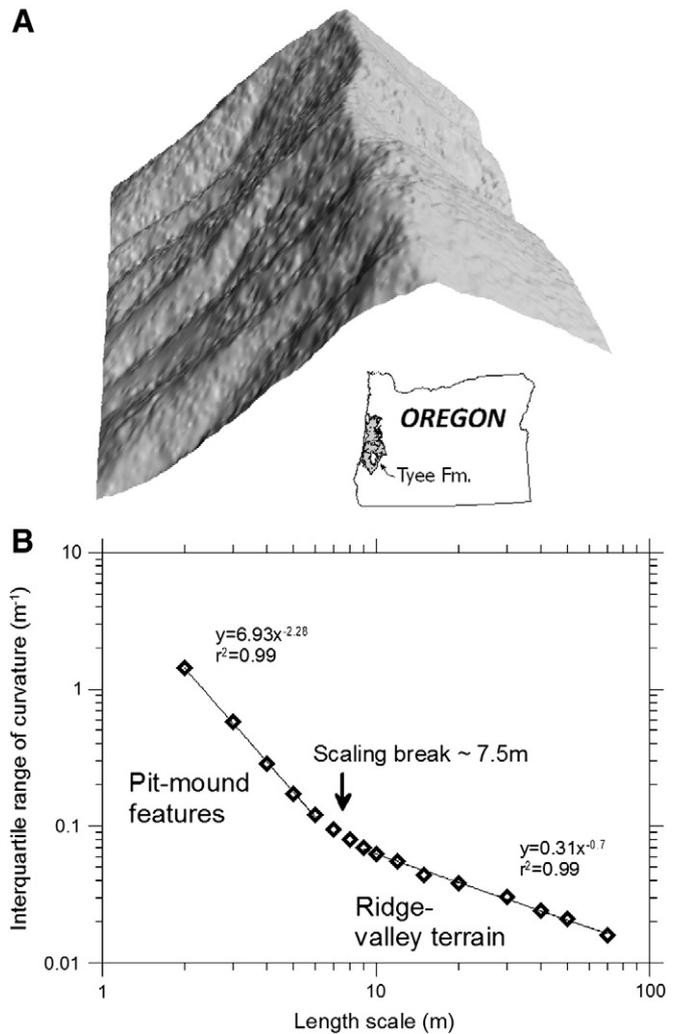


Fig. 1. Inset: Location map of Oregon Coast Range study area underlain by the Tye Formation. A) Shaded relief map of Mettman Ridge study area showing pit-mound features (as well as some real and artificial noise from logging debris and lidar processing) superimposed on ridge-valley topography. The DEM is 250×250 m² with 1 m grid spacing. B) Variation in the interquartile range (IQR) of curvature with diameter of the window (i.e., kernel) used to calculate curvature values. We fit a 2nd order polynomial to local patches of bare earth, ungridded xyz data points and used the coefficients of the 2nd order terms to calculate the laplacian operator (Roering et al., 1999). IQR values increase with decreasing diameter but a scaling break separates terrain shaped by pit-mound features from ridge-valley sequences.

1999). Much of the study site had been recently clearcut at the time of data acquisition, so we identified subregions with high bare earth point density (>0.5 points m⁻²) to accurately image meter-scale patterns in forest floor morphology. These areas contained some stumps and logging debris that contributed noise during lidar acquisition, but field checking demonstrated that prominent pit-mound features associated with the original (pre-industrial) forest were well represented in the bare earth lidar data. Because pit-mound features associated with forest floors are defined by concave and convex surface elements (Schaeztl and Follmer, 1990), we analyzed how the distribution of curvature, $\nabla^2 z$ (defined here as the laplacian operator of elevation), varies with the scale over which it is measured (Lashermes et al., 2007). Using the ungridded, bare earth lidar data, we calculated $\nabla^2 z$ by fitting a 2nd order polynomial to points within a specified radius and repeated this at thousands of locations within the study area, generating a distribution of curvature values. We generated additional curvature distributions by varying the patch radius used to perform the polynomial fit.

The interquartile range (IQR) of curvature values increases as the local patch size decreases (Fig. 1B). In essence, the terrain tends to exhibit greater topographic roughness with decreasing length scale. We also observed a distinct break in scaling at ~7.5 m such that for greater patch radii, the IQR of curvature varies modestly with scale, reflecting topographic patterns related to ridge-valley terrain. At length scales less than 7.5 m, however, the dispersion of curvature values increases rapidly with decreasing scale, reflecting the highly variable nature of the land surface generated by biotic processes. Consistent with our field surveys, the dimpled appearance shown by the lidar data reflects pit-mound features that persist long after the responsible overturned stem and root system have decayed (Fig. 1A). Our results suggest that in forested landscapes, biological agents can dominate land surface morphologic patterns at length scales less than 7.5 m and may thus constitute a topographic signature of life. This length scale is likely to depend on tree species and turnover rate as well as land management history (Lutz and Griswold, 1939).

4. Root density profiles and soil production data

To identify mechanisms that drive soil production in the Oregon Coast Range, we compared an empirical analysis of soil production rates with the depth distribution of tree roots in 100+ year forest stands. Heimsath et al. (2001) generated soil production data from 31 soil pits with accompanying bedrock erosion rates derived from in-situ cosmogenic radionuclides. For thin soils, soil production rates are somewhat variable with rapid rates (0.25 to 0.35 mm year⁻¹) occurring for thicknesses of 15 to 30 cm. For samples less than 15 cm, bedrock erosion rates approximate 0.15 mm year⁻¹ and below 25 cm, rates decrease rapidly as thickness increases (Fig. 2A). Although the near-surface data are somewhat equivocal (see Heimsath et al., 2001), these results appear to provide support for a ‘humped’ production function. Furthermore, the relatively continuous nonlinear decline for pits thicker than 25 cm suggests that the frequency and magnitude of bedrock disturbances decrease monotonically with increasing soil thickness.

We gathered root density data from 14 deep (>1 m) soil pits across the Oregon Coast Range (Schmidt et al., 2001; Gerber, 2004) for comparison with the soil production data. For this analysis, we assume that root density at the soil-bedrock interface: 1) is well represented by our root inventory data from deep soil pits, and 2) serves as a proxy for the frequency of bedrock disturbance through tree turnover or root penetration and dilation. The root inventory data were sampled several meters

from tree stems and thus do not incorporate large structural and tap roots that emanate directly beneath rootwads and penetrate deeply. In the upper 20 cm, high root densities are associated with understory vegetation, such as sword fern and Oregon grape (Fig. 2B). By contrast, root densities associated with Douglas fir trees have peak values around 15 cm depth and decrease exponentially below 20 cm depth. Although the root surveys do not include fine roots which typically dominate shallow soils (Fogel, 1983), the vertical pattern of coarse (>1 mm) root density is similar to the thickness-dependent soil production data (Fig. 2A). Specifically, peak densities and production rates occur at 15–25 cm depth and thickness, respectively, and below 25 cm both datasets show rapid decline. Although this analysis does not implicate a specific bedrock detachment process (such as tree turnover or rock breakage via root penetration and dilation), the similar patterns of root density and soil production data may signal a connection between biology and soil production.

5. Tree turnover and bedrock detachment

To quantify the magnitude of bedrock erosion induced by tree turnover events and estimate the volume of bedrock that rootwads penetrate, we surveyed the characteristics of trees and rootwads overturned during a western Oregon windstorm in February 2002 (Mort, 2003). In the summer of 2002, we documented tree species, diameter at breast height (dbh), rootwad volume (including biomass, soil, and bedrock components), and other variables at 56 turnover sites located within the Tye Formation.

Trees overturned during the storm were predominantly Douglas fir and their root systems entrained soil, weathered bedrock (bedrock altered by near-surface processes), and in rare instances, fresh bedrock. Trees with diameter less than 0.5 m entrained negligible volumes of bedrock, whereas larger diameter trees liberated highly variable volumes of bedrock (Fig. 3A). At least 4 of the larger trees surveyed detached greater than 10 m³ of weathered bedrock. On the other hand, several large diameter trees detached much smaller volumes (~2 m³). This variability in bedrock detachment for large trees appeared to result from site-specific conditions. In particular, soil depth varied significantly in the immediate vicinity of our turnover sites and large trees with small volumes of bedrock detachment tended to coincide with locally thick soils.

To account for the threshold-like behavior in our tree diameter-bedrock detachment data, we compiled physiological data for Douglas fir trees, specifically below-ground biomass. Consistent with

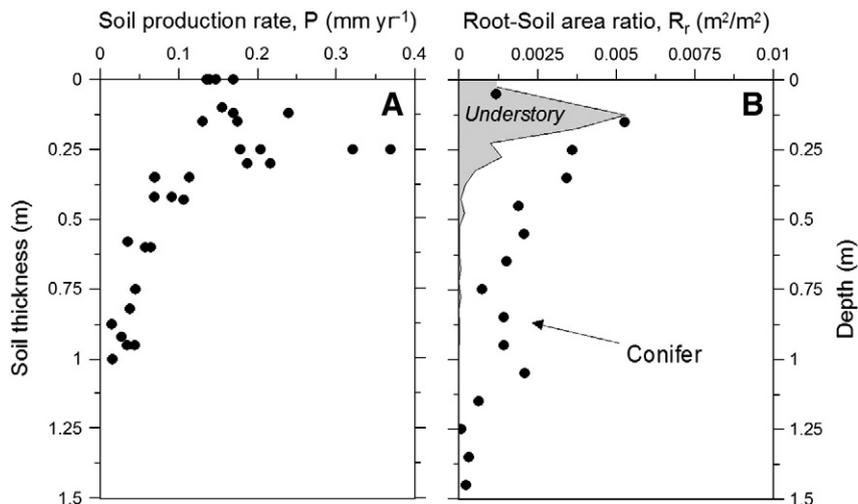


Fig. 2. A) Soil production function quantified in the Oregon Coast Range by Heimsath et al. (2001). B) Variation in root density (measured as the ratio of cross-sectional root area to vertical soil area) with depth. Both datasets show peak values between 15 and 25 cm and decline rapidly below 25 cm.

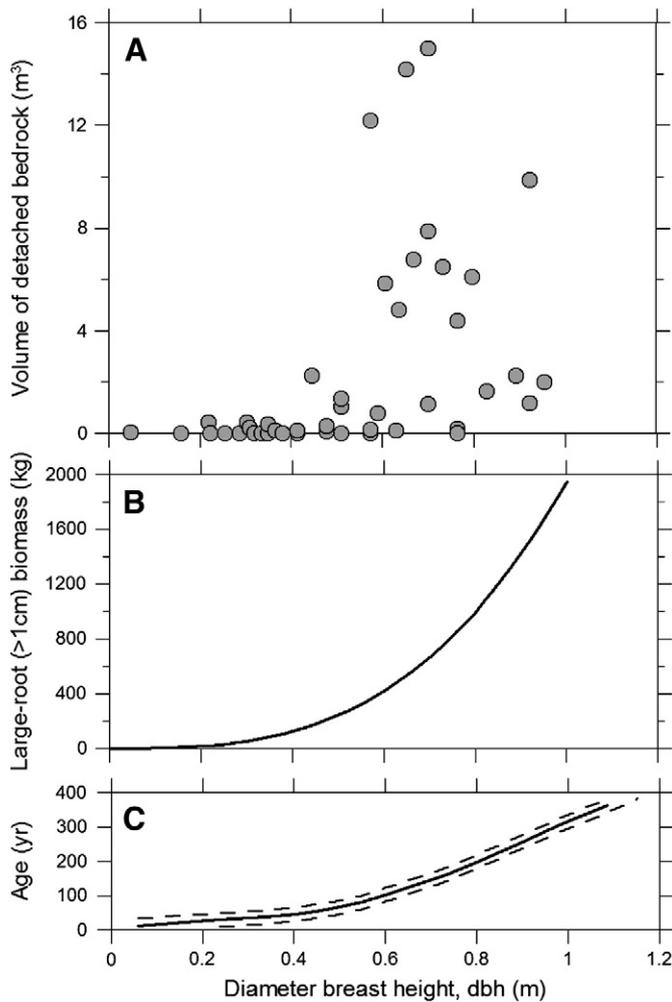


Fig. 3. A) Variation in bedrock detachment (filled grey circles) for individual tree throw events ($n=56$) with tree diameter at breast height (dbh). Turnover events occurred during a windstorm in February 2002. B) The empirical, power law relationship between large root biomass (kg) and tree diameter for Douglas fir trees in western Oregon, $y \propto x^3$ (Santantonio et al., 1977; Thies and Cunningham, 1996). C) Variation in tree age with diameter determined for western Oregon Douglas fir trees (Winter et al., 2002). The dashed lines above and below the solid line denote the standard deviation in age for a given diameter.

established biological scaling laws (e.g., Brown and West, 2000), root survey data suggest that the dry weight of large (>1 cm diameter) root biomass increases as the cube of tree diameter (Santantonio et al., 1977; Thies and Cunningham, 1996) (Fig. 3B). This power law relationship indicates that root biomass increases rapidly as diameter values approach 0.6 to 0.8 m (Fig. 3B), coincident with substantial bedrock detachment for trees of this diameter. Root network observations from excavations can account for the large volumes of bedrock we observed; as trees attain larger (>0.5 m) diameters, their root systems include numerous large structural members with average lengths of 2 m and diameters of 5–10 cm (McMinn, 1963; Eis, 1974). Our field observations demonstrate that many of these large roots permeated disc-shaped chunks of detached bedrock. Our results also indicate that small diameter Douglas fir trees may be mechanically inhibited from significantly disrupting bedrock in the shallow subsurface.

Based on growth curves reconstructed using tree rings in old-growth Douglas fir forests of Western Oregon (e.g., Winter et al., 2002), we plotted how tree diameter increases with age (Fig. 3C). During the first 30–50 years, diameter increases rapidly with time as trees attain diameters of 0.4 to 0.5 m. Subsequently, growth rates decrease and trees require 70–100 years to attain diameters of 0.6 m

and 250–350 years to become 1.0 m in diameter (Fig. 3C). Coupled with our bedrock detachment dataset (Fig. 3A), these data suggest that >70 years may be required for root systems to penetrate weathered bedrock in a mechanically significant fashion.

6. Ground-penetrating radar for mapping soil thickness and root systems

The morphology of the soil-bedrock interface may reflect the integrated history and character of soil production mechanisms. As proposed by Heimsath et al. (2001), stochastic disturbances such as those associated with tree rooting activity should generate variability in observed soil thickness. To map soil thickness with sufficient resolution (~10 cm) over extensive distances (>25 m), we collected a series of ground-penetrating radar transects along gentle hilltops in the Hadsall Creek catchment of the central Oregon Coast Range. Given the significant mass of roots (>2000 kg) associated with an individual large (>1 m) diameter tree, the propagation and dilation of roots in bedrock may be an effective soil production mechanism even in the absence of tree turnover. Along those same transects, we also processed the ground-penetrating radar data to map the extent of large root biomass and document root network penetration into shallow bedrock.

Ground-penetrating radar uses high-frequency electromagnetic waves to map subsurface features as dictated by their dielectric properties (Schrott and Sass, 2008). Inhomogeneities and layer boundaries that cause reflections can be used to locate changes in material properties and identify features such as soil thickness, sedimentary structures, water tables, and lithologic contrasts (Doolittle and Collins, 1995; Neal, 2004). Because the moisture and density of roots contrast strongly with that of surrounding rock and soil, they can be effectively imaged (al Hagrey, 2007), particularly in well-drained, coarse sediments like those of the Oregon Coast Range. Here, we used a 400 MHz antenna and sampled bandwidths of 200–800 MHz along six transects, which allowed for ~5 meter penetration depth as well as sufficient resolution for mapping soil depth and large root systems. Along several of the profiles, we guided the antenna as close as possible to large (0.5–1 m) larger conifer stumps in order to image the extent of their root systems in soil and shallow bedrock. Post-processing of the radar data included background removal and filtering (Butnor et al., 2003), which enabled us to identify the soil-bedrock boundary as well as other features. The depth to weathered bedrock was identified by major shifts in signal amplitude (Neal, 2004).

Average soil thicknesses were 0.5 m and we observed nearly meter-scale variations along our transects (Fig. 4C). We dug pits at numerous locations along the profiles to verify the predicted values of soil thickness and these values corresponded well (i.e., within ~10 cm) with the radar-derived values. In addition, we performed a fast Fourier transformation (FFT) of the soil depth profiles to quantify characteristic wavelengths of the soil-bedrock interface and test whether they may have a biological origin. We calculated power spectra for each of the six soil depth profiles and summed the resulting values across common frequencies (Fig. 5). A power law (as well as red noise fit) to the average power spectra highlights a broad spectral peak for wavelengths of 1–5 m, which generally coincides with the horizontal dimension of large Douglas fir rootwads (Eis, 1974). As such, both the land surface and soil-bedrock interface reflect the legacy of stochastic bedrock detachment and fracturing associated with the root systems of large trees.

To pinpoint the extent of large root systems in the soil and shallow bedrock, we performed a Hilbert transformation of the ground-penetrating radar data. This technique uses signal magnitude to decompose hyperbolic reflectors and multiple echoes and has been shown to be highly effective for mapping subsurface root biomass (Butnor et al., 2003). After calculating the Hilbert transformation, we

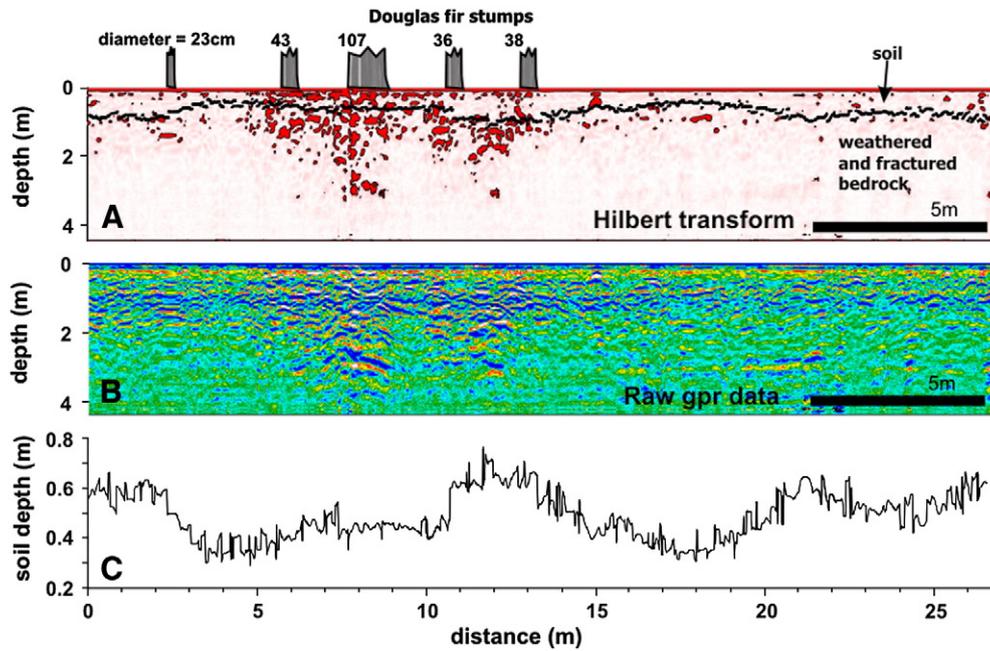


Fig. 4. Typical profile of ground-penetrating radar data (a total of six were collected) for a hilltop in the Hadsall Creek catchment, Oregon, showing the location of tree stumps within 1 m of the profile. A) Filtered and Hilbert transformed data according to the methodology of Butnor et al. (2003). Dimensionless values greater than 4500 are shown in red. B) Unfiltered, unprocessed radar data. C) Variation in soil depth estimated using peak identification of the radar data along the same transect. The location of prominent Douglas fir stumps (with diameters indicated) are shown atop A.

chose a normalized intensity threshold of 4500 to differentiate detectable roots (>2 cm) from signal noise. This value was chosen for its ability to identify several large near-surface roots mapped from pits along our study transects. This threshold value also had the effect of localizing high values directly under large stumps where high root biomass is expected (Fig. 4A). The width and depth of these dense root zones tend to correlate with stump size as the >1 m diameter stumps we surveyed exhibited large roots to ~3 m depth despite the presence of relatively thin (~40 cm) soils. Most generally, our analysis suggests that bedrock directly beneath large tree boles is highly prone to root penetration up to several meters depth. As observed in numerous roadcuts, these dense root masses can transform coherent bedrock

into a zone of highly disaggregated clasts, thus constituting the early stages of soil production. As such, these large root systems appear capable of mechanical soil production with or without turnover events.

7. Discussion

7.1. Model of root-bedrock interaction and landscape denudation

Observations from roadcuts and soil pits indicate that in the absence of tree turnover, the growth and dilation of rootwads directly below large tree stems can fracture weathered bedrock into loose clasts, a key step in the transformation of bedrock into soil. To evaluate potential role of this process in soil formation, we

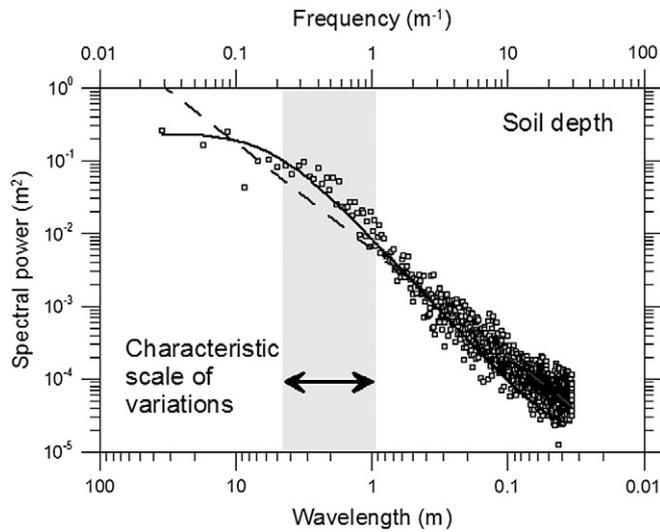


Fig. 5. Summed power spectra (filled black circles) for six soil depth transects generated via ground-penetrating radar. Power law (dashed line) and red noise (solid line, Torrence and Compo, 1997), with $\alpha = 0.978$ fits to the spectrum reveal a spectral peak at wavelengths of 1 to 5 m (shaded gray bar), reflecting the characteristic length scale of soil depth variations generated by biogenic activity.

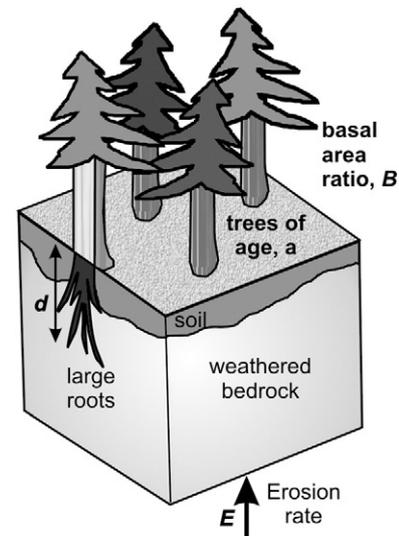


Fig. 6. Schematic showing parameters used to calculate root-bedrock interaction in an actively eroding landscape.

calculated the average residence time of shallow bedrock and soil in the narrow and deep, below-stem rooting zone and compared it to the time required for tree stems to occupy the entire forest floor through cycles of forest succession (Fig. 6). In essence, we seek to compare the rate at which bedrock is brought to the surface with the time-integrated ability of rootwads to penetrate and comminute bedrock. Although large conifers exhibit extensive lateral root networks, in this analysis we focus on large (>5 cm diameter) roots associated with rootwads as imaged by our ground-penetrating radar data. Based on our radar observations and previous studies (McMinn, 1963; Eis, 1974), we conservatively estimate the dense, below-stem rooting zone to have diameter equal to that of the tree stem. We also assume the location of new stems in successive forest stands to be random. The residence time of bedrock in the below-stem rooting zone, t_R , is calculated as $t_R = d/E$, where d is the rooting depth (m) and E is erosion rate (m year^{-1}). The time required for stems to occupy the entire forest floor, t_F , is given by $t_F = a/B$, where a is average forest age (years) and B is the basal area ratio of tree stems or fraction of the forest floor occupied by a tree ($\text{m}^2 \text{m}^{-2}$). Thus, the ratio t_R/t_F reflects the integrated efficacy of roots in penetrating and fracturing bedrock on actively eroding slopes. Although the intensity of biota-bedrock interactions is likely to increase as erosion rates increase and soils thin, this effect is not included in this calculation.

Although forest stands in Western Oregon can be highly diverse with respect to species, the age of Douglas fir trees (which dominate total basal area) tend to cluster as a result of their competitive advantage following large fires (Poage and Tappeiner, 2005). As a result, we use the late Quaternary fire frequency in the Oregon Coast Range to set the average forest age, a , to be 200 ± 50 years (Long et al., 1998). Estimates of the basal area, B , of Douglas fir forests in our study area range from 0.5 to 2% (0.005 to 0.02) and for a ~200-year old forest, the value is ~1% (0.01) (Kuiper, 1988; Tappeiner et al., 1997). From data presented here and in McMinn (1963), the average penetration depth of the below-stem root zone or rootwad, d , varies between 1.5 and 2.5 m for Douglas fir trees with diameter between 0.75 and 1.1 m, and here we set d to 2.0 m. Given the average erosion rate, E , for the Oregon Coast Range of $0.12 \text{ mm year}^{-1}$, we calculate t_R/t_F to be 0.83 ± 0.4 , indicating that nearly all of the near-surface bedrock and soil reside within the below-stem root zone at some point during their exhumation to the surface. Assuming constant values of d , B , and a ($Bd/a = 1.0 \times 10^{-4}$ for our Oregon Coast Range parameter values), the ratio t_R/t_F declines as an inverse function of

erosion rate (Fig. 7). As erosion rates exceed 0.1 mm year^{-1} , the fraction of the forest floor directly impacted by rootwads decreases rapidly, potentially precluding the ability of large roots to fracture near-surface bedrock and promote soil production. Abiotic weathering mechanisms may become prevalent in these rapidly eroding settings (Reneau and Dietrich, 1991), emphasizing the need to better understand the coupling between biotic and abiotic weathering processes.

7.2. Biotic signatures in topography and the subsurface

Our analysis suggests that a biotic signature may manifest on forested hillslopes and along the soil-bedrock interface. The prominent scaling break we observe is not an artifact of the lidar data or processing technique because other study areas without pit-mound features do not exhibit such a scaling break (Fig. S1). The details of pit-mound sequences and other disturbances on the forest floor record ecological processes integrated over decades to millennia (Lutz and Griswold, 1939; Gabet and Mudd, in press), such that land-use practices and climate-driven vegetation changes may be reflected in fine-scale topography. Nearly all hillslope evolution models treat soil production and transport as a continuous process (e.g., Kirkby, 1984; Tucker and Bras, 1998; Roering, 2008). In contrast, our findings provide a basis for testing and calibrating emerging models that incorporate the discrete events (ecological or otherwise) that drive slope change. This notion is emphasized in the tree turnover driven soil production model proposed by Gabet and Mudd (in press). In addition to proposing a mechanistic explanation of depth-dependent soil production, their results suggest that a patchy soil mantle may be maintained at extreme ($>1 \text{ mm year}^{-1}$) erosion rates.

In our field area, observed variability of the soil-bedrock interface is consistent with the findings of Heimsath et al. (2001) and their interpretation of stochastic processes controlling local soil thickness. The characteristic length scale of variations in the topographic surface and the soil-bedrock interface reported here are different because the source data do not have the same dimensionality and different techniques were used for the analyses. Our excavations to ground-truth the ground-penetrating radar data sometimes revealed diffuse soil-bedrock boundaries whereby heavily fractured and sometimes displaced bedrock clasts directly underlie coarse, organic-rich soils. In these cases, the ground-penetrating radar consistently identifies the boundary between unconsolidated materials typically of the B horizon and underlying fractured bedrock.

7.3. Soil production and root inventory data

Our root inventory-soil production comparison does not provide support for particular soil production mechanisms, nor does it address how faunal biota or abiotic processes may contribute to bedrock breakage. Mountain beaver (*Aplodontia rufa*), in particular, are pervasive in some portions of the Oregon Coast Range, although they typically burrow proximal to small streams or recent clearcuts because they require a large daily intake of water due to their inability to concentrate urine (Maser et al., 1981) and closed forest stands lack sufficient understory food sources (Martin, 1971). Thus, despite their sometimes deep burrowing habits, the specificity of mountain beaver ecology suggests that their influence on pedogenic processes may not as pervasive and vigorous as tree root activity. Other biota that may contribute to bedrock disruption include diverse invertebrates, although documentation is sparse and their contribution to subsurface biomass is minor compared with that of vascular plants. With respect to abiotic soil production processes, Reneau and Dietrich (1991) noted that roots often penetrate exfoliation sheets in shallow bedrock. Our observations suggest that tree roots exploit fractures of varying origin, particularly vertically-

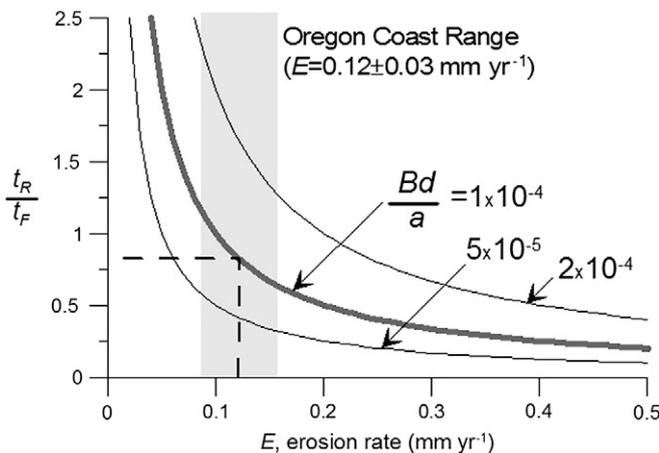


Fig. 7. Variation of t_R/t_F with erosion rate, E (see Section 7.1). With increasing erosion rate, the fraction of the forest floor directly impacted by tree root systems decreases rapidly. The value of Bd/a of 1.0×10^{-4} is associated with the Oregon Coast Range while other values (dash lines) show uncertainty (\pm standard error) in our study site parameters.

oriented joints. As such, the role of pre-existing bedrock discontinuities may be an important modulator of biotic soil production processes (Graham et al., 2010).

7.4. Bedrock detachment via tree turnover

Root entrainment and extension into fractured and weathered bedrock are common because the radial and axial stresses associated with root growth can approach 1–2 MPa (Gabet et al., 2003), enough to exceed the tensile strength of many rock types (Pollard and Fletcher, 2005). Following tree turnover events, large clasts of bedrock extricated by rootwads frequently exhibited substantial breakdown via crumbling, exfoliation, and rainsplash. Thus, tree turnover may be an important catalyst that initiates pedogenic processes that would not otherwise occur in a closed forest setting (Gabet and Mudd, in press). Other studies note the rapidity of bedrock weathering following turnover events (Phillips et al., 2008), although absolute rates are highly dependent on lithologic properties, including the in-situ state of weathering. Consistent with our data, previous studies suggest that the area and depth of disturbed ground increases with the diameter of fallen trees, although the maximum bedrock volumes detached by individual trees we observed appear to exceed those recorded elsewhere (Schaetzl et al., 1990).

Our tree turnover and radar data suggest that young (<60 year) trees do not feature structural roots of sufficient depth and diameter to break significant volumes of bedrock. As a result, timber harvesting on short time intervals may curtail root-driven physical breakdown of shallow weathered bedrock regardless of whether turnover occurs or not. Analyses of excavated Douglas fir root systems show that with increasing stand age, a dense zone of large roots forms (McMinn, 1963; Eis, 1974). For 70+ year old trees, the average length of primary (>10 cm diameter) and secondary (>5 cm diameter) roots was approximately 2 and 6 m, respectively. In coarse soils, these main roots typically show a downward trajectory and proliferate into several branches upon reaching an obstructing layer such as fractured bedrock. This bifurcating behavior likely evolved in response to fire protection and water and nutrient uptake needs during the dry growing season (Waring and Franklin, 1979).

7.5. Ground-penetrating radar and root penetration into shallow bedrock

Our ground-penetrating radar analysis revealed surprisingly deep zones of high root density below large Douglas fir stumps. This finding is consistent with recent mechanical modeling results showing that tree turnover events do not involve the deepest fraction of the root network (Dupuy et al., 2005). As a result, tree turnover datasets (including our own) likely underestimate the total volume of bedrock affected by deep rooting. Furthermore, the significant penetration of large roots in weathered bedrock suggests that bedrock breakage and comminution occurs in the absence of tree turnover. For example, the volume of large roots associated with a single ~1 m diameter Douglas fir tree exceeds 4 m³ (Santantonio et al., 1977), the growth of which generates enough cumulative stress to fracture a substantial volume of bedrock. As documented by Phillips and Marion (2006), rock fragment rings called baumsteins and stump rot pits attest to the extent of soil mixing and disturbance accomplished by trees that do not turnover.

7.6. Co-evolution of soil and evergreen trees in the Pacific Northwest?

In the Pacific Northwest region, deep root systems may be critical for the long-term (>1 Myr) persistence of large coniferous forests. Pacific Northwest evergreen coniferous trees experience sustained growth in diameter, height, and biomass enabling them to incorporate large volumes of sapwood, dampening the effect of dry summer

months. The massiveness and dominance of these large conifers has been attributed to a suite of factors, including the lack of typhoons or hurricanes that might otherwise topple large trees on a frequent basis (Waring and Franklin, 1979). Evergreens appear to out-compete deciduous trees because their nutrient needs are low during summer months when requirements are high and supply is low and their canopies maximize photosynthetic energy during mild winter months. Given the active tectonic setting of the Pacific Northwest, our results suggest that the persistent downward growth of coniferous root systems into continually exhumed bedrock results in vigorous root-bedrock interaction that drives the initial stages of soil formation. In turn, this interaction facilitates the maintenance of mineral-rich soils and closed evergreen forest ecosystems that characterize the region.

8. Conclusion

Our results suggest a significant biological role in sculpting landscapes and driving the physical conversion of bedrock to soil both with and without the aid of tree turnover events. In our Oregon Coast Range study area, the topographic signature of tree throw manifests as a scaling break in the dispersion of curvature values that occurs at ~7.5 m. At larger length scales the terrain is characterized by ridge and valley sequences, while at shorter length scales, pit-mound features dominate topography. A previously published empirical soil production function shows a general correspondence with the depth distribution of conifer root density. Specifically, both curves exhibit peak values at 15–20 cm depth and decay exponentially at deeper depths. Field surveys of bedrock erosion associated with tree turnover events demonstrate that small diameter (<0.5 m) Douglas fir trees detach negligible volumes of bedrock whereas larger trees can extricate increasingly large volumes of bedrock. Ground-penetrating radar surveys show that variations in soil depth have a characteristic length scale of 1–5 m, consistent with the scale of tree rootwads and pit-mound features near the surface. This pattern serves as evidence for a biotic control on the soil-bedrock interface. Ground-penetrating radar surveys also show large concentrations of root biomass 2 to 3 m into bedrock below large conifer stumps, suggesting that root systems can disaggregate large volumes of bedrock in the absence of tree turnover. We propose a simple model that incorporates forest ecology parameters to quantify the extent to which root systems interact with bedrock as it is exhumed in actively eroding systems. As erosion rates increase, root-bedrock interaction decreases and abiotic weathering mechanisms may become more prevalent. Because large trees in the Pacific Northwest are implicated in much of the shallow bedrock disturbance observed in our study area, our results suggest that timber harvesting on short (<50 year) time intervals may compromise the ability of root networks to physically disturb bedrock and initiate soil formation.

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