

How steady are steady-state landscapes? Using visible–near-infrared soil spectroscopy to quantify erosional variability

Kristin E. Sweeney^{1*}, Joshua J. Roering¹, Peter Almond², and Till Reckling²

¹Department of Geological Sciences, University of Oregon, Eugene, Oregon 97403, USA

²Soil and Physical Sciences Department, P.O. Box 84, Lincoln University, Christchurch, New Zealand

ABSTRACT

Although topographic steady state is often used as a simplifying assumption in sediment yield studies and landscape evolution models, the temporal and spatial scales over which this assumption applies in natural landscapes are poorly defined. We used visible–near-infrared (visNIR) spectroscopy to measure the weathering of hilltop soils and quantify local erosional variability in two watersheds in the Oregon Coast Range (United States). One watershed appears adjusted to base-level lowering driven by rock uplift in the Cascadia forearc, while the other is pinned by a gabbroic dike that locally slows river incision and hillslope erosion. Models for uniformly eroding hillslopes imply uniform soil residence times; instead, we observe significant variability around the mean value of 18.8 k.y. (+31.2/–11.8 k.y.) for our adjusted watershed. The magnitude of erosional variability likely reflects the time scales associated with stochastic processes that drive bedrock weathering, soil production, and soil transport (e.g., tree turnover). The residence time distribution for our pinned watershed has a mean value of 72.9 k.y. (+165.6/–50.6 k.y.) and is highly skewed with a substantial fraction of long residence time soils. We speculate that this pattern results from the lithologic control of base level and lateral divide migration driven by erosional contrasts with neighboring catchments. Our novel and inexpensive methodology enables us to quantify for the first time the magnitude of erosional variability in a natural landscape, and thus provides important geomorphic context for studies characterizing regolith development. More generally, we demonstrate that soils can record catchment-scale landscape dynamics that may arise from lithologic controls or forcing due to climate or tectonics.

INTRODUCTION

Topographic steady state, the assumption of constant landscape form through the perfect balance of erosion and rock uplift, is the theoretical endpoint of landscape adjustment to constant climatic and tectonic forcing (Fernandes and Dietrich, 1997; Willett and Brandon, 2002). Assumptions of topographic steady state in geomorphology simplify the calibration and testing of sediment transport equations. Furthermore, numerical models of landscape response to perturbations in climate and tectonics often use steady-state topography as the initial condition (Rinaldo et al., 1995) and experimental models are generally run until they achieve some approximation of steady-state topography (Lague, 2003). Erosion data derived from stream sediment in the Oregon Coast Range (OCR; United States) and other settings suggest that topographic steady state may exist in some natural landscapes, but the scale at which this equilibrium applies is poorly defined (Reneau and Dietrich, 1991; Meigs et al., 1999)

Strict steady-state denudation does not necessarily hold in numerical and experimental landscapes, even under constant forcing. For example, previous work has documented frequent divide migration and drainage reorganization in an experimental watershed (Hasbargen and Paola, 2000). Pelletier (2004) created similar behavior in a numerical model by distributing flow with a weighted drainage area algorithm rather than one driven by steepest descent. These findings give rise to the questions: how much variability can be expected in steady natural landscapes, and how can such local unsteadiness be measured?

Advances in cosmogenic radionuclide techniques have enabled increasingly precise measurements of soil production and erosion rates and corresponding inferences about landscape processes (e.g., Riebe et al., 2004). Although cosmogenic radionuclides are a powerful tool, the high cost of processing limits information to a handful of samples for a given watershed or catchment-wide averages, often insufficient to quantify local erosional variability.

If soil-forming factors other than time are held constant, the rate of erosion in soil-mantled landscapes can be inferred from soil features (Birkeland, 1999). The progression of chemical weathering, for example, can manifest over time as monotonic losses of primary minerals or increases in pedogenic minerals. During weathering, accumulation of the secondary Fe mineral hematite gives older soils a distinctive red color (McFadden and Hendricks, 1985); this signature can be captured analytically with visible–near-infrared (visNIR) spectroscopy (Scheinost, 1998; Viscarra Rossel et al., 2010). By calibrating a spectroscopy-based weathering function in a given landscape, we can estimate the soil residence time, defined as the average transit time of particles in the soil column, and thus quantify relative variations in erosion rate (Almond et al., 2007; Mudd and Yoo, 2010).

In this study we use visNIR soil spectroscopy to quantify the statistics of erosional variability at the local and watershed scale. We collected 137 samples from hilltops in two watersheds with different erosional settings in the OCR, a humid soil-mantled landscape with relatively homogeneous lithology often considered the classic example for topographic steady state (Reneau and Dietrich, 1991). We calibrate our weathering function with data from a chronosequence of alluvial terraces along the Siuslaw River, Oregon (Almond et al., 2007), and show that the visNIR spectrum changes systematically with terrace age. Our findings demonstrate that erosional variability in uniformly eroding landscapes can reflect sediment transport processes and that soil data can be used to document catchment dynamics over geologic time scales.

STUDY SITE

The humid, steep, soil-mantled landscape of the OCR is underlain by the Tye Formation, a relatively undeformed turbidite sandstone (Heller and Dickinson, 1985). Igneous dikes crop out locally, often forming the highest elevation ridgelines in the region. Most of the OCR is covered in Douglas fir forest, and has annual rainfall between 1 and 2 m. In upland catchments, sediment transport is dominated by shallow landslides and debris flows in valley networks (Stock and Dietrich, 2003), and by bioturbation and small soil slips on hillslopes (Gabet and Mudd, 2010). Reneau and Dietrich (1991) used colluvial hollows in the OCR to measure bedrock exfoliation rates of 0.09 mm/yr, similar to their basin-wide denudation rates of 0.05–0.08 mm/yr. These rates are comparable to soil production estimates of 0.02–0.16 mm/yr (Heimsath et al., 2001) and catchment-averaged erosion rates of 0.137 mm/yr generated by cosmogenic radionuclides (Bierman, 2001). Measurements of uplift are variable (0.06–0.2 mm/yr) due to local structural controls, but are grossly similar (Personius, 1995). These data suggest that the OCR may be in approximate flux steady state such that rock uplift balances erosion. Furthermore, the uniform ridge-valley topography that characterizes much of the OCR has been presented as evidence for topographic steady state, whereby the smoothing effect of hillslope erosion is balanced by landscape roughening via valley-forming

*E-mail: sweeney3@uoregon.edu.

processes (Perron et al., 2009). The time and spatial scales over which the steady-state approximation applies have not been rigorously characterized for the OCR, although previous work acknowledges that local variability around steady state likely arises from the stochasticity of hillslope processes, and, more broadly, from knickpoints that modulate local base level (Heimsath et al., 2001; Stock and Dietrich, 2003; Roering et al., 2010).

Here we consider erosional patterns in two watersheds in the OCR (Fig. 1), selected to compare the erosional dynamics of adjusted (approximately steady state) and pinned (slowly eroding) landscapes. Hoffman Creek (HC) drains directly into the Siuslaw River and contains no mapped lithologic contacts. The topography is steep (mean slope 60%) and highly dissected with evenly spaced ridge-valley sequences. In contrast, the North Fork Smith River (NFSR) is pinned by an ~100-m-wide gabbroic dike that forms a 70-m-high knickpoint. This elevated local base level is reflected by gentler slopes (mean 39%) and broad alluvial valleys upstream of the knickpoint (Fig. 1), suggesting that this catchment is eroding more slowly.

Our weathering function is calibrated with data from a soil chronosequence of seven alluvial terraces (T1–T7) on the Siuslaw River described by Almond et al. (2007). The chronosequence is within the same precipitation regime as our two study watersheds and is also underlain by the Tye Formation. Gravels along the strath-alluvium interface of these terraces are geochemically indistinguishable from unweathered bedrock (Almond, unpublished data). Radiocarbon dates from T1 and T2 yield an estimated incision rate of 0.15 mm/yr on the Siuslaw River, similar to average erosion estimates for the OCR. This rate and terrace surveys allowed us to

extrapolate ages for T3–T7, assuming that incision has been broadly consistent for the past 1 m.y. (Almond et al., 2007).

SOIL WEATHERING AND RESIDENCE TIME

In the time between detachment from bedrock and delivery to the valley network, soil particles are subject to chemical weathering. The extent and manner of this alteration depend on parent material, biology, topography, climate, and time (Jenny, 1941). By collecting samples in the Tye Formation from hilltops (i.e., sites with ~0 slope) in a small geographic area, we can assume that soil forming factors are similar at sampling locations and that variations in weathering between samples can be attributed to the difference in time that particles spend in the soil column.

Using measurements of soil weathering to quantify landscape dynamics requires that we define the relationship between weathering extent and erosion rate (e.g., Mudd and Yoo, 2010). Residence time, the average transit time of a particle in the soil column, is a measure of the time that soils are exposed to weathering and is thus inversely related to erosion rate. In other words, soil residence time can be directly estimated from soil properties and yield information about erosional patterns in the landscape.

For a hillslope with steady, uniform erosion, residence time τ depends on mobile soil depth h , erosion rate E , and soil-bedrock density contrast ρ_s/ρ_r (Almond et al., 2007):

$$\tau = \frac{h \rho_s}{E \rho_r} \quad (1)$$

To link residence time and the degree of soil weathering, we follow the methodology in Almond et al. (2007), and define an exponential weathering function for soil particles

$$W(t) = W_0 + K(1 - e^{-\lambda t}), \quad (2)$$

where W_0 is the weathering state of rock entering the mobile layer, K and λ are fit parameters describing how the state of weathering varies over time, and t is the transit time. The extent of weathering for a given soil profile is equal to the average weathering extent of the particles composing it. To average weathering in the soil column, we integrate Equation 2 along the hillslope and obtain the relationship between residence time τ and weathering extent W , assuming that bedrock enters the soil column with a constant weathering signature W_0 :

$$\tau = \frac{W - W_0}{\lambda[\kappa - (W - W_0)]} \quad (3)$$

Fitting Equation 2 to our chronosequence data provides parameter estimates such that we can use Equation 3 to calculate soil residence times from the weathering extent of hilltop soils in the HC and NFSR catchments. These soil residence times can then be used to infer local erosion rates from Equation 1.

We use hematite content as a proxy for the degree of soil weathering because it is well expressed in soil color. The release of iron cations during weathering produces either goethite or hematite, depending on pedogenic conditions (Schwertmann and Taylor, 1989), and the low soil moisture of OCR hilltop soils favor hematite production (Patching, 1987). Sampling the B horizon standardizes the hematite signal in our spectra, as the B horizon is less vulnerable to frequent physical disturbance than the upper portion of the soil column and is the preferred zone of pedogenic iron accumulation (Birkeland, 1999).

SPECTRAL ANALYSIS AND CALIBRATION

VisNIR reflectance spectroscopy measures the reflectance (R) of a sample relative to a white standard at wavelengths of 350–1000 nm. The magnitude of the spectrum is affected by the distance from the sensor and the grain size and/or roughness of the material, while the mineral

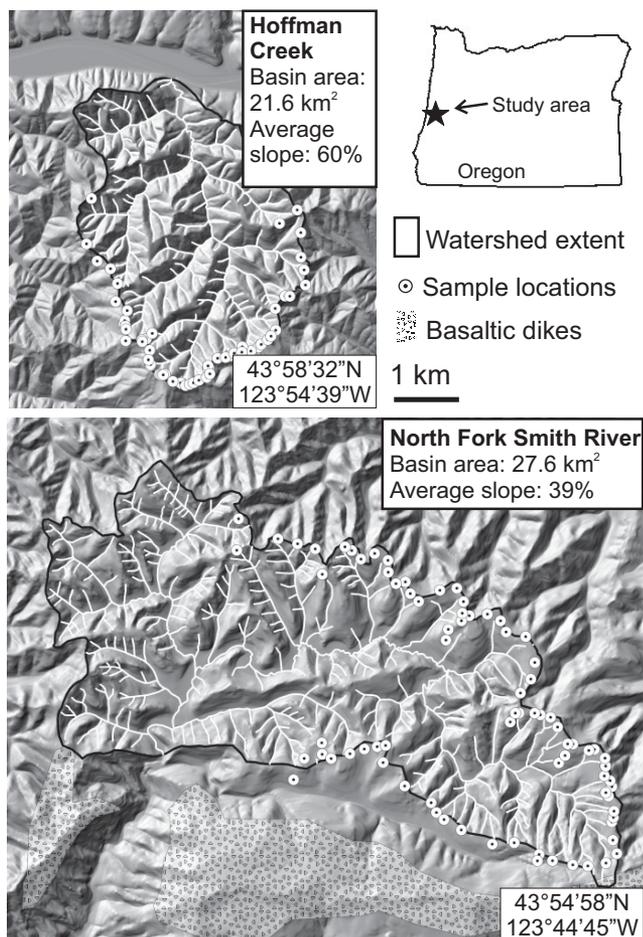


Figure 1. Study watersheds with sample locations and mapped igneous dikes. Latitude and longitude labels are for bottom right corner of each watershed map. Oregon state outline shows geographic location of study area.

composition of the sample controls the spectrum shape. Characteristic peaks (seen as dips in reflectance spectra) are due to mineral electron transitions. Previous work has shown that hematite has a characteristic peak at 880 nm (Scheinost, 1998).

We collected samples from the B horizons of T1–T7, typically at 40–50 cm depth. Each sample was dried, sieved to 63 μm , and packed in a petri dish to provide an even surface for spectroscopic analysis. VisNIR spectra from the seven terraces of the chronosequence display a characteristic shape with some important differences (Fig. 2A). Typical visNIR analysis normalizes spectra to remove background slopes that may obscure the signal (Clark and Roush, 1984). Because the hematite peak in our data is readily apparent without normalization, we analyzed raw spectra. The slope of the spectra between 790 nm and 880 nm (shaded box in Fig. 2A) is a measure of the relative magnitude of the 880 nm hematite peak.

The chronosequence soils show a systematic trend of reddening (Fig. 2B). Spectral slopes between 790 and 880 nm decrease with terrace age from 0.04 R/nm to -0.05 R/nm (Fig. 2C). Using Equation 2, the best fit model for the chronosequence measurements ($r^2 = 0.97$) has $W_0 = 0.0544$ (± 0.009), $K = -0.0981$ (± 0.009), and $\lambda = 0.0120$ (± 0.003) (Fig. 2C).

RESIDENCE TIME OF HILLTOP SOILS AND EROSIONAL VARIABILITY

We took samples from the B horizons of 137 hilltop locations, 59 in the morphologically uniform HC, and 78 in the gentle uplands of NFSR.

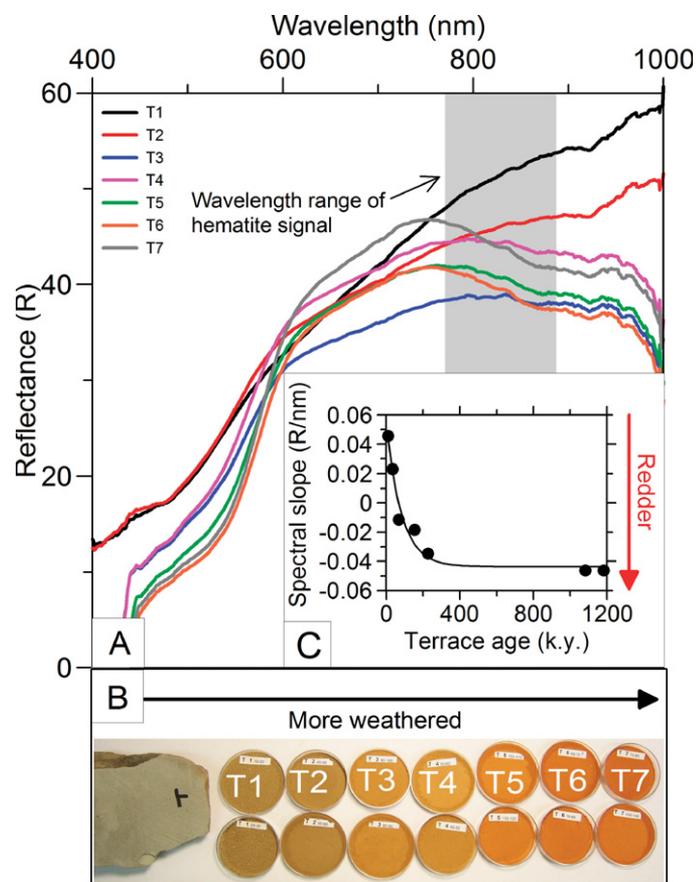


Figure 2. Spectral analysis of terrace chronosequence. **A:** Raw spectra from chronosequence. Shaded gray box highlights section of spectra used for analysis; note that slopes of spectra in this interval decrease with terrace age. **B:** Samples from chronosequence showing reddening with age. Rock is fresh bedrock from Tye Formation. **C:** Spectral slopes (dots) fit by exponential weathering function (line; see text Equation 2), with $W_0 = -0.0544$, $K = 0.0981$, and $\lambda = 0.0120$ ($r^2 = 0.97$) (see text). Error bars are smaller than symbol radius.

To calculate residence times from spectral measurements, we used Equation 3 fit with the chronosequence parameters (solid line in Fig. 2C). Residence times in both watersheds can be described by skewed distributions, which have been log-transformed to emphasize the distinctive shapes of the two distributions (Fig. 3). Mean soil residence time in HC is 18.8 k.y. ($+31.2/-11.8$ k.y.), whereas the mean residence time for NFSR is 72.9 k.y. ($+165.6/-50.6$ k.y.).

The distribution of residence times for HC, our adjusted watershed, shows that soil residence times exhibit substantial variation, suggesting that steady uniform erosion does not hold in real landscapes. The semi-variogram of HC residence times (Fig. DR1 in the GSA Data Repository¹) shows that at lags >100 m our measurements are spatially uncorrelated, implying that the process dominating erosional variability occurs at smaller scales. Despite local variability, the mean soil residence time for HC agrees with the expected value. Using Equation 1 and previously estimated parameters for the OCR ($h = 0.5$ – 1.0 m, $E = 0.1$ mm/yr, and $\rho_s/\rho_r = 0.5$; Heimsath et al., 2001), we expect a mean soil residence time of 2.5–5 k.y. The higher mean residence time in our distribution (18.8 k.y.) suggests that pedogenic hematite formation begins below the bedrock-soil interface, an interpretation supported by the presence of weathered bedrock in OCR rootwads (Roering et al., 2010).

We hypothesize that local erosional variability in the HC study site is dominated by the stochasticity of hillslope processes related to root-wad turnover and tree root activity. Tree throw results in a patchwork of soil disturbance history and local variations in soil production and erosion rate (Norton, 1989). Near-surface fractures in bedrock observed in OCR roadcuts provide pathways for weathering reactions, and enable the establishment of deep tree roots that bring blocks of weathered rock into the mobile layer (Roering et al., 2010). The similarity between the Roering et al. (2010) estimate of the time scale of total landscape turnover via tree throw (15–20 k.y.) and the standard deviation for the HC residence time distribution ($+31.2/-11.8$ k.y.) suggests that bioturbation may control the magnitude of residence time variability in the HC watershed. If hillslope transport regimes in soil-mantled landscapes are dominated by physical disturbance (Gabet, 2000; Roering et al., 2010), we postulate that local erosional variability in steady landscapes reflects the scale of soil production and transport mechanisms.

By contrast, a lithologic base-level control may be responsible for the significant proportion of long residence time soils along NFSR hilltops. The deviation of the weakly bimodal NFSR residence time distribution from the log-normal shape of the HC data suggests that the hilltop soils of NFSR may record an imbalance between local controls and regional

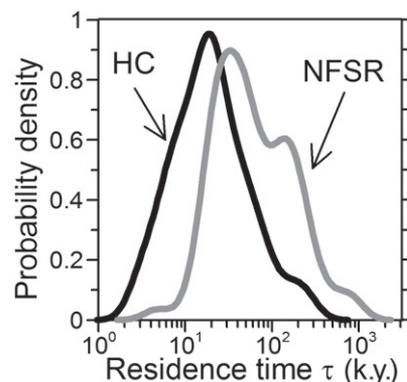


Figure 3. Probability density function of soil residence times for Hoffman Creek (HC) and North Fork Smith River (NFSR). Uncertainty from Gaussian error propagation is 30%–40%. Probability density function smoothing window is 1.5 k.y. Mean and standard deviation calculated from log-transformed distributions.

¹GSA Data Repository item 2012228, Figure DR1 (experimental semi-variogram of HC residence time measurements) and Figure DR2 (map of HC and NFSR watersheds with sample locations colored by residence time), is available online at www.geosociety.org/pubs/ft2012.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

base-level lowering driven by rock uplift. Past work suggests that persistent differential erosion across divides may result in ridge migration (Mudd and Furbish, 2005). This mechanism may drive south-directed divide migration along the northern edge of the NFSR catchment (Fig. 1; Fig. DR2). We speculate that the smaller and older peak in the distribution (at 200 k.y.) reflects slower hillslope erosion set by the base level of the gabbroic dike downstream, while the larger peak (~30 k.y.) derives from the impingement of steep, highly dissected watersheds on the northern margin of the NFSR watershed.

DISCUSSION AND CONCLUSIONS

The low cost of visNIR spectroscopy recommends it as a method for addressing surface processes in the OCR and elsewhere. In the OCR, the residence time of nearly unweathered material (<2 k.y.) and old soils (>350 k.y.) are not well predicted by our weathering function (Fig. 2) because time is required for the weathering signal to manifest and the concentration of weathering products plateaus after a few hundred millennia. These upper and lower limits likely differ between landscapes as a function of lithology, climate, and vegetation.

Our model for soil residence times assumes that the weathering front extends only to the soil-bedrock interface, i.e., that bedrock entering the soil column has a constant weathering signature (W_0). This assumption is violated if some weathered bedrock enters the mobile soil layer due to stochastic production processes or if erosion rates are sufficiently slow that all bedrock entering the soil column is pervasively weathered (Mudd and Yoo 2010). Roadcuts and auger samples in our NFSR site indicate that such deep weathering profiles occur in limited instances.

The residence time distributions for our two watersheds (1) reflect the magnitude of erosional variability due to stochastic hillslope processes, and (2) reveal the signature of base-level controls that can lead to divide migration and catchment reorganization. Our results suggest that soil residence time distributions may enable us to distinguish between steady and transient watersheds and to define the legacy of climate-driven variations in hillslope processes.

ACKNOWLEDGMENTS

This work benefitted from the data collection and analysis efforts of National Science Foundation (NSF) funded UCORE (Undergraduate Catalytic Outreach and Research Experiences) interns Brent Deyo and Micah Perry at the University of Oregon and funding from NSF grant EAR-208931. We thank Martin Hurst, Suzanne Anerson, and an anonymous reviewer for insightful comments that greatly improved the manuscript.

REFERENCES CITED

- Almond, P., Roering, J., and Hales, T.C., 2007, Using soil residence time to delineate spatial and temporal patterns of transient landscape response: *Journal of Geophysical Research*, v. 112, F03S17, doi:10.1029/2006JF000568.
- Bierman, P., Clapp, E., Nichols, K., Gillespie, A., and Caffee, M.W., 2001, Using cosmogenic nuclide measurements in sediments to understand background rates of erosion and sediment transport, in Harmon, R.S., and Doe, W.M. eds., *Landscape Erosion and Evolution Modelling*: New York, Kluwer, p. 89–116.
- Birkeland, P.W., 1999, *Soils and geomorphology*: Oxford, UK, Oxford University Press, 430 p.
- Clark, R.N., and Roush, T.L., 1984, Reflectance spectroscopy: Quantitative analysis techniques for remote sensing applications: *Journal of Geophysical Research*, v. 89, no. B7, p. 6329–6340, doi:10.1029/JB089iB07p06329.
- Fernandes, N.F., and Dietrich, W.E., 1997, Hillslope evolution by diffusive processes: The timescale for equilibrium adjustments: *Water Resources Research*, v. 33, p. 1307–1318, doi:10.1029/97WR00534.
- Gabet, E.J., 2000, Gopher bioturbation: Field evidence for non-linear hillslope diffusion: *Earth Surface Processes and Landforms*, v. 25, p. 1419–1428, doi:10.1002/1096-9837(200012)25:13<1419:AID-ESP148>3.0.CO;2-1.
- Gabet, E.J., and Mudd, S.M., 2010, Bedrock erosion by root fracture and tree throw: A coupled biogeomorphic model to explore the humped soil production function and the persistence of hillslope soils: *Journal of Geophysical Research*, v. 115, no. F4, p. 1–14, doi:10.1029/2009JF001526.
- Hasbargen, L., and Paola, C., 2000, Landscape instability in an experimental drainage basin: *Geology*, v. 28, p. 1067–1070, doi:10.1130/0091-7613(2000)28<1067:LIIAED>2.0.CO;2.
- Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., and Finkel, R.C., 2001, Stochastic processes of soil production and transport: Erosion rates, topographic variation and cosmogenic nuclides in the Oregon Coast Range: *Earth Surface Processes and Landforms*, v. 26, p. 531–552, doi:10.1002/esp.209.
- Heller, P.L., and Dickinson, W.R., 1985, Submarine ramp facies model for delta-fed, sand-rich turbidite systems: *American Association of Petroleum Geologists Bulletin*, v. 69, p. 960–976.
- Jenny, H., 1941, *Factors of soil formation: A system of quantitative pedology*: New York, McGraw Hill, 281 p.
- Lague, D., 2003, Laboratory experiments simulating the geomorphic response to tectonic uplift: *Journal of Geophysical Research*, v. 108, doi:10.1029/2002JB001785.
- McFadden, L.D., and Hendricks, D.M., 1985, Changes in the content and composition of pedogenic iron oxyhydroxides in a chronosequence of soils in southern California: *Quaternary Research*, v. 23, p. 189–204, doi:10.1016/0033-5894(85)90028-6.
- Meigs, A., Brozovic, N., and Johnson, M.L., 1999, Steady, balanced rates of uplift and erosion of the Santa Monica Mountains, California: *Basin Research*, v. 11, p. 59–73, doi:10.1046/j.1365-2117.1999.00083.x.
- Mudd, S.M., and Furbish, D.J., 2005, Lateral migration of hillcrests in response to channel incision in soil-mantled landscapes: *Journal of Geophysical Research*, v. 110, no. F4, p. 1–18, doi:10.1029/2005JF000313.
- Mudd, S.M., and Yoo, K., 2010, Reservoir theory for studying the geochemical evolution of soils: *Journal of Geophysical Research*, v. 115, no. F3, p. 1–13, doi:10.1029/2009JF001591.
- Norton, D.A., 1989, Tree windthrow and forest soil turnover: *Canadian Journal of Forest Research*, v. 19, p. 386–389, doi:10.1139/x89-059.
- Patching, W.R., 1987, *Soil survey of Lane County area, Oregon*: Washington, D.C., U.S. Department of Agriculture, Soil Conservation Service, 369 p.
- Pelletier, J.D., 2004, Persistent drainage migration in a numerical landscape evolution model: *Geophysical Research Letters*, v. 31, p. 4–7, doi:10.1029/2004GL020802.
- Perron, J.T., Kirchner, J.W., and Dietrich, W.E., 2009, Formation of evenly spaced ridges and valleys: *Nature*, v. 460, no. 7254, p. 502–505, doi:10.1038/nature08174.
- Personius, S.F., 1995, Late Quaternary stream incision and uplift in the forearc of the Cascadia subduction zone, western Oregon: *Journal of Geophysical Research*, v. 100, no. B10, p. 20193–20210, doi:10.1029/95JB01684.
- Reneau, S.L., and Dietrich, W.E., 1991, Erosion rates in the southern Oregon Coast Range: Evidence for an equilibrium between hillslope erosion and sediment yield: *Earth Surface Processes and Landforms*, v. 16, p. 307–322, doi:10.1002/esp.3290160405.
- Riebe, C.S., Kirchner, J.W., and Finkel, R.C., 2004, Erosional and climatic effects on long-term chemical weathering rates in granitic landscapes spanning diverse climate regimes: *Earth and Planetary Science Letters*, v. 224, p. 547–562, doi:10.1016/j.epsl.2004.05.019.
- Rinaldo, A., Dietrich, W.E., Rigon, R., Vogel, G.K., and Rodriguez-Iturbe, I., 1995, Geomorphological signatures of varying climate: *Nature*, v. 374, no. 6523, p. 632–635, doi:10.1038/374632a0.
- Roering, J.J., Marshall, J., Booth, A.M., Mort, M., and Jin, Q., 2010, Evidence for biotic controls on topography and soil production: *Earth and Planetary Science Letters*, v. 298, p. 183–190, doi:10.1016/j.epsl.2010.07.040.
- Scheinost, C., 1998, Use and limitations of second-derivative diffuse reflectance spectroscopy in the visible to near-infrared range to identify and quantify Fe oxide minerals in soils: *Clays and Clay Minerals*, v. 46, p. 528–536, doi:10.1346/CCMN.1998.0460506.
- Schwertmann, U., and Taylor, R.M., 1989, *Iron oxides*, in Dixon, J.B., and Weed, S.B., eds., *Minerals in soil environments* (second edition): Madison, Wisconsin, Soil Science Society of America Book Series 1, p. 379–438.
- Stock, J., and Dietrich, W.E., 2003, Valley incision by debris flows: Evidence of a topographic signature: *Water Resources Research*, v. 39, 1089, doi:10.1029/2001WR001057.
- Viscarra Rossel, R.A., Bui, E.N., de Caritat, P., and McKenzie, N.J., 2010, Mapping iron oxides and the color of Australian soil using visible–near-infrared reflectance spectra: *Journal of Geophysical Research*, v. 115, F04031, doi:10.1029/2009JF001645.
- Willett, S.D., and Brandon, M.T., 2002, On steady states in mountain belts: *Geology*, v. 30, p. 175–178, doi:10.1130/0091-7613(2002)030<0175:OSSIMB>2.0.CO;2.

Manuscript received 30 December 2011

Revised manuscript received 14 March 2012

Manuscript accepted 28 March 2012

Printed in USA