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The illusion of diffusion: Field evidence for depth-dependent sediment transport

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ABSTRACT

Soil-covered upland landscapes are common in much of the habitable world, and our understanding of their evolution as a function of different climatic, tectonic, and geologic regimes is important across a wide range of disciplines. Erosion laws direct quantiative study of the processes shaping Earth’s surface and form the basis of landscape evolution modeling, but are based on limited field data. Here we use in-situ-produced cosmogenic 10Be and 26Al concentrations from granitic saprolite to quantify an exponential decline in soil production with increasing soil thickness for a new field site in Point Reyes, California. Results are similar to soil production functions from two different, previously studied field sites, and are used with extensive measurements of soil thickness to quantify depth-integrated sediment transport flux. Plots of calculated sediment fluxes against the product of soil depth and hillslope gradient provide the first field-based evidence that soil transport is a nonlinear, depth-dependent function. Data from all sites suggest that the widely used linear diffusion equation is only appropriate for shallow gradient, convex-up regions, while the depth-dependent transport law is more broadly applicable. Quantifying both the mobile soil thickness and landscape morphology is therefore critical to understanding how landscapes evolve.

Keywords: erosion, geomorphology, cosmogenic nuclides, landscape evolution, soil transport.

INTRODUCTION

Upland landscapes across a large part of Earth’s surface are soil mantled. Erosional processes transport soil from these uplands into networks of stream channels, and ultimately into sediment sinks, but the mathematical relationships used to model these processes are based on limited field data (Dietrich et al., 2003; Furbish, 2003). The persistence of soil across the landscape depends in large part on the production of soil from the underlying bedrock at rates at least equal to the erosion rate (Anderson and Humphrey, 1989; Carson and Kirkby, 1972; Dietrich et al., 1995; Heimsath et al., 1997). Cosmogenic nuclide-based techniques determined soil production functions under different climatic, lithologic, and tectonic conditions (Heimsath et al., 1997, 2000), while field-based quantification of a soil transport function remains elusive (Dietrich et al., 2003).

Transport of soil is widely assumed to depend linearly on topographic slope, which results in a differential equation similar to the diffusion equation when used in continuity equations (e.g., Dietrich et al., 1995). There are, however, limited field data supporting a linear transport law, and its appeal rests with its mathematical simplicity rather than its process-based confirmation. The term diffusion refers not to the processes, but to how the land surface might be evolving. Other work (e.g., Andrews and Buckman, 1975) suggested that transport depends nonlinearly on slope, especially on steeper gradients, but the only direct measurements are from experimental modeling (Roering et al., 2001) and analyses of fire-induced dry ravel (Gabet, 2003; Roering and Gerber, 2005). Many workers have explored transport processes (e.g., Fleming and Johnson, 1975; Gabet, 2000; McKean et al., 1993), but field or measurement constraints often obscure the detailed processes of transport. Here we combine new cosmogenic nuclide-based soil production rates with topographic surveys and extensive measurements of soil depth across three different landscapes to provide the first field-based evidence of a nonlinear, depth-dependent transport function.

SOIL TRANSPORT MODELS

The conceptual framework used here is based on the equation of mass conservation for physically mobile soil overlying its parent material (Carson and Kirkby, 1972; Dietrich et al., 1995). Typically, the boundary between soil and the underlying weathered (or fresh) bedrock is abrupt and can be defined within a few centimeters. Soil is produced and transported by mechanical processes, and soil production rates decline exponentially with depth (Heimsath et al., 1997, 2000). The transition from soil-mantled to bedrock-dominated landscapes occurs when transport rates are greater than production rates (Anderson and Humphrey, 1989), and two transport functions are typically used to model landscape evolution (Dietrich et al., 2003). The slope-dependent transport law has its basis in the characteristic form of convex, soil-mantled landscapes assumed to be in equilibrium, and has some field support (e.g., McKean et al., 1993; Roering et al., 2002). A nonlinear, slope-dependent transport law also has its roots in morphometric observations, and has recent support with the veracity of assuming landscape equilibrium (Roering et al., 1999), experimental constraints (Roering et al., 2001), or postfire ravel (Gabet, 2003; Roering and Gerber, 2005).

Disturbances due to freeze-thaw (e.g., Anderson, 2002; Matsuoka and Moriwaki, 1992), shrink-swell (e.g., Fleming and Johnson, 1975), viscous or plastic flow (e.g., Ahnert, 1976), and biological activity (e.g., Gabet, 2000) cause soil transport, and the disturbances decline with depth, typically exponentially (e.g., Roering, 2004). Disturbance penetration distance sets the mobile soil thickness. In thin soils, the penetration is limited by underlying bedrock or saprolite, but can result in mechanical soil production from the rock. In thick soils, the disturbance-driven depth can be less than the thickness of the total deposit. This disturbance depth influence suggests that soil transport should depend on local gradient and mobile depth, and while depth-slope dependency has long been postulated (e.g. Ahnert, 1967), field data have been lacking.

Recently, two theories have been proposed (Furbish, 2003; Roering, 2004) that explicitly model transport due to biotic disturbance. Here we test the simpler of the two, as we lack data on the velocity profiles that would inform the Roering (2004) model. Furbish (2003) argues that the dilational effects of biotic activity cause the vertically averaged volumetric flux density (i.e., vertically averaged velocity), \( q_v(L^{-1}) \), to be proportional to land surface, \( z \), gradient. The depth-integrated flux per unit contour distance is then the product of mobile soil thickness, \( H \), and this flux density:

\[
Hq_v = -K_h H v_z.
\]

The coefficient \( K_h \) (L t\(^{-1}\)) characterizes the magnitude and frequency of downslope soil-
produced cosmogenic nuclides, $^{10}$Be and $^{26}$Al, from exposed bedrock or stream sediments, underlying the soil mantle, and erosion rates at the Nunnock River and Tennessee Valley sites. We also observe that biogenic processes are dominant at the Nunnock River site. It is outside historical agriculture and stream sediments to determine soil production rates from parent material, detrital cosmogenic nuclide concentrations from each site. C: Topographic map, 2 m contour intervals by laser total station survey, showing soil pit locations for PR. Creek drains right to left at page bottom and elevation of crest is 195 m.

FIELD SITES AND METHODS
Each field site is a soil-mantled upland landscape with the characteristic convex form used to infer a slope-dependent transport law. The Nunnock River (NR), southeastern Australia, field site is at the base of the passive continental margin escarpment (Heimsath et al., 2000). Underlying bedrock is Late Silurian to Early Devonian granodiorite, rainfall is ~900 mm yr$^{-1}$ distributed equally across seasons, and vegetation is a dry sclerophyll forest. We also use the well-studied region of Tennessee Valley, northern California, with a Mediterranean climate, active tectonic setting, and metasedimentary bedrock typical of the Franciscan Formation (e.g., Dietrich et al., 1995). Our third site is on the relatively steep slopes of Mount Vision, in Point Reyes, California, is underlain entirely by granitic rocks, mostly quartz diorite and granodiorite (Galloway, 1977), and is ~30 km north of the Tennessee Valley site. It is outside historical agricultural impacts and supports a native forest of Bishop pine trees that burns periodically and is replaced by grassland and scrub understory. Tree throw contributes to soil production and transport, which are also observed to be due to burrowing gophers, mountain beavers, and invertebrates, with overland flow potentially following fires. Biogenic processes are also observed to be dominant at the Nunnock River and Tennessee Valley sites.

Soil production rates from parent material underlying the soil mantle, and erosion rates from exposed bedrock or stream sediments, can be quantified by measuring the in situ-produced cosmogenic nuclides, $^{10}$Be and $^{26}$Al. Measured concentrations of either nuclide depend on the nuclide production rate and half-life as well as the erosion or soil production rate of the target material. We use $^{10}$Be and $^{26}$Al concentrations from saprolite, bedrock, and stream sediments to determine soil production, erosion and average erosion rates for each site, and report the new Point Reyes results here. Site-specific nuclide-derived soil production rates and detailed soil depth measurements are used to determine the depth-integrated flux for each site. Soil thickness is measured by digging soil pits to the soil-bedrock boundary at ~10 m intervals across the sites. We assume that on convex portions of the landscape, soil production and transport is much faster than the rate of change in topography. In this case, the rate of soil thickness change is sufficiently small that we determine soil flux by integrating soil production within flow tubes mapped from ridge crest to base (see Data Repository).
and reduced to a tenth by 115 cm, which is roughly the maximum soil depth found on ridges. Soil depth varies across the study sites, with thinnest soils on the narrow ridge crests, and thicker soils bordering unchanneled valleys (e.g., Heimsath et al., 1997, 2000). The soil production functions (Fig. 1B) imply that ground surface lowering is highest on ridge crests. This apparent topographic disequilibrium may be counteracted by periodic evacuation of the adjacent colluvial fills, setting up a transient upslope thinning of soils (Dietrich et al., 1995).

DEPTH-DEPENDENT TRANSPORT

Soil depths vary spatially across the divergent areas of the Point Reyes landscape such that topographic curvature declines exponentially with increasing soil thickness (Fig. 2A), although a linear decline similar to the other field sites cannot be ruled out (Fig. 2B). In the case of a simple slope-dependency of transport, curvature is a proxy for soil production (Heimsath et al., 1999), and the exponential decline of curvature with depth would support the soil production function defined by equation 2, assuming an independently documented (Reneau, 1988) linear diffusivity of 30 cm² yr⁻¹. The clear linear (versus exponential) decline of curvature with increasing soil depths at Nunnock River suggested, however, that a linear slope-dependent transport model did not adequately capture the transport mechanisms, prompting modeling (Braun et al., 2001) and optically stimulated luminescence (Heimsath et al., 2002) studies highlighting the role of soil thickness in sediment transport.

Here we plot depth-integrated flux, determined by integrating soil production rates downslope (Data Repository; see footnote 1), against the depth-slope product across all field areas to test equation 1 (Fig. 3A). We observe strong linear increases of soil flux with increasing depth-slope product for both Nunnock River (NR) and Tennessee Valley (TV), but no such relationship at Point Reyes (PR), where a purely slope-dependent relationship is a better fit. Two observations might explain the failure of the depth-slope model at PR. First, the significantly greater soil depths for any given curvature value suggest that the frequency and magnitude of biotic penetration into the soil might be mediated differently than at NR and TV, and not be captured by a constant \( K_h \). Second, the higher gradients on the lower slopes of PR suggest that shallow landsliding might be a dominant process.

Data from Nunnock River support equation 1 with a transport coefficient, \( K_h \), equal to 0.55 cm yr⁻¹. Roughly equating this coefficient to the linear diffusivity with an average soil thickness for Nunnock River of 50 cm yields a coefficient of 28 cm² yr⁻¹, compared to the 40 cm² yr⁻¹ reported by Heimsath et al. (2000). Reversing the process for the Tennessee Valley data, which have independently determined linear diffusivities of 50 and 30 cm² yr⁻¹ (Reneau, 1988) and average soil thicknesses of 40 cm and 60 cm, yields depth-dependent transport coefficients, \( K_h \), of 1.25 and 0.5 cm yr⁻¹, respectively. Using the data from Tennessee Valley and Point Reyes (Fig. 3A), \( K_h \) values of 1.2 and 0.4 cm yr⁻¹ are determined.

This comparison of transport coefficients places the depth-dependent transport flux within the context of the more familiar slope-dependent transport framework and supports the applicability of a linear transport law for low-gradient convex landscapes. Plotting flux against gradient shows, however, that a linear relationship does not reflect all the data (Data Repository; see footnote 1). Our test for depth-dependent transport thus involves two sets of complementary plots: \( H^\prime q \) vs. \( HS \) (Fig. 3A) and \( H^\prime q (HS)^{-1} \) versus downslope distance.

![Figure 2](image2.png)

**Figure 2.** Negative curvature vs. vertical soil depth. Curvature calculated as in Heimsath et al. (1996) and is proxy for soil production if local soil depth is constant with time. A: Black circles from individual soil pits at Point Reyes with exponential negative curvature axis. B: Black circles (as in A) with open gray diamonds are from Nunnock River (Heimsath et al., 2000). Tennessee Valley data from Heimsath et al. (1997, 1999) overlay Nunnock River data values and range and are not included here for plot clarity. Black dashed line separates divergent from convergent topography. C: Curvature map for Point Reyes: blue represents convex and red represents concave topography.

![Figure 3](image3.png)

**Figure 3.** A: Depth-integrated soil flux (calculated as per Appendix 1; see footnote 1) per unit contour length (m² yr⁻¹) vs. the depth-slope product (cm) for all field sites. B: Depth-integrated flux divided by depth-slope product vs. downslope distance. Kₕ value, determined by fitting data shown in A, is dashed line. NR—Nunnock River; TV—Tennessee Valley; PR—Point Reyes.
stance, $X$ (Fig. 3B). If equation 1 is correct, the first plots (Fig. 3A) should show a linear increase, with slope equal to $K_b$ and zero origin—in the absence of covariance of $H$ or $S$ with distance $X$. However, because $H_q$, must, by definition, increase with $X$, these plots might exhibit spurious covariance with the depth-slope product. Thus, the importance plots might exhibit spurious covariance with $X$, with slope equal to $H$ origin—in the absence of covariance of $H$ with distance $X$.

Couple spatial variations in soil depth with soil evolution modeling efforts more completely. We consider the depth-dependent transport law at Nunnock River site; the National Park Service for access to Point Reyes, and the Golden Gate National Recreation Area for access to Tennessee Valley. M. Borosund helped with flow tube analyses. M Jungers, J. Roering, and an anonymous reviewer helped improve the paper. We were funded through the National Science Foundation. Nuclide measurements were partially performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract W-7405-Eng-48.

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