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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

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[1] In 1877, G. K. Gilbert reasoned that bedrock erosion is maximized under an intermediate soil thickness and declines as soils become thinner or thicker. Subsequent analyses of this "humped" functional relationship proposed that thin soils are unstable and that perturbations in soil thickness would lead to runaway thinning or thickening of the soil. To explore this issue, we developed a numerical model that simulates the physical weathering of bedrock by root fracture and tree throw. The coupled biogeomorphic model combines data on conifer population dynamics, rootwad volumes, tree throw frequency, and soil creep from the Pacific Northwest (USA). Although not hardwired into the model, a humped relationship emerges between bedrock erosion and soil thickness. The magnitudes of the predicted bedrock erosion rates and their functional dependency on soil thickness are consistent with independent field measurements from a coniferous landscape in the region. Imposed perturbations of soil erosion during model runs demonstrate that where bedrock weathering is episodic and localized, hillslope soils do not exhibit runaway thinning or thickening. The pit-and-mound topography created by tree throw produces an uneven distribution of soil thicknesses across a hillslope; thus, although episodes of increased erosion can lead to temporary soil thinning and even the exposure of bedrock patches, local areas of thick soils remain. These soil patches provide habitat for trees and serve as nucleation points for renewed bedrock erosion and soil production. Model results also suggest that where tree throw is a dominant weathering process, the initial mantling of bedrock is not only a vertical process but also a lateral process: soil mounds created by tree throw flatten over time, spreading soil over bedrock surfaces.

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1. Introduction

[2] In 1877, G.K. Gilbert put forth the first significant hypothesis regarding bedrock weathering and the production of soil. He posited a "humped" functional relationship between the rate of bedrock erosion and soil thickness whereby bedrock erosion is maximized at some critical (nonzero) soil thickness [*Gilbert*, 1877]. Working in the Henry Mountains of Utah, Gilbert identified dissolution and frost as the primary weathering agents and reasoned that a certain thickness of soil was required to store the water necessary to drive these processes. Although this hypothesis was stated in its entirety in only four sentences, it established the theoretical foundation for the soil production studies that followed (see *Humphreys and Wilkinson* [2007] for a lucid history of the topic).

[3] Nearly 100 years later, *Carson and Kirkby* [1972] proposed that under the humped Gilbert function, thin soils should be only metastable (Figure 1a). At steady state, soil erosion is balanced by bedrock erosion; however, they argued that because of a positive feedback between soil thickness and bedrock erosion described by the left-hand side of the curve representing the Gilbert function, a perturbation in the erosion rate should inevitably lead to runaway soil thinning or thickening (Figure 1b). Thus, *Carson and Kirkby* [1972] concluded that where soils are thin, a temporary increase in erosion will ultimately result in the complete and permanent loss of soil and that a temporary decrease in erosion will eventually cause the soil to thicken dramatically. They reasoned that the Gilbert function would produce landscapes with either no soil or thick soil and that soil thicknesses between these two states could not exist, except transiently. Although *Carson and Kirkby*'s analysis [1972] was essentially qualitative, their conclusions have been supported by

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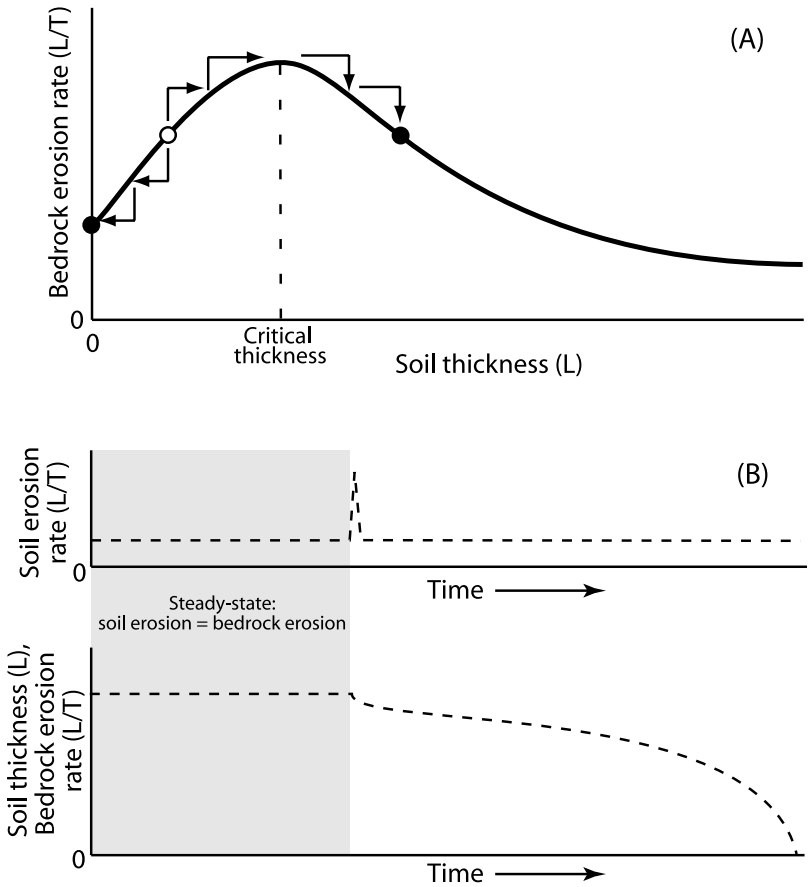

Figure 1. (a) Hypothesized relationship between soil thickness and the rate of bedrock erosion (*Carson and Kirkby* [1972]). Open circle represents initial soil depth, and filled circles represent both possible final soil depths after a perturbation in the soil erosion rate. (b) Illustration of "runaway" soil thinning.

more quantitative approaches [*D'Odorico*, 2000; *Furbish and Fagherazzi*, 2001]. For example, model results from *D'Odorico* [2000] suggest that when the range of perturbations is sufficiently high to include the removal of the entire soil column in one erosional event, the distribution of soil depths approaches the bimodal condition proposed by *Carson and Kirkby* [1972].

[4] Interestingly, the spatial distribution of soil thicknesses predicted by Carson and Kirkby's analysis of the humped function is not readily borne out by observation. Most hillslopes support a range of soil depths [e.g., *Gerrard*, 1990; *Graham et al.*, 1990], thus raising doubts about whether the humped function accurately represents the relationship between soil thickness and bedrock erosion [*Dietrich et al.*, 1995]. This alleged flaw in the Gilbert function has led to an alternative hypothesis whereby the rate of bedrock erosion is at a maximum on bare bedrock and decreases exponentially with increasing soil depth [*Dietrich et al.*, 1995]. The exponential function is attractive on theoretical grounds because it has no inherent positive feedback that might amplify perturbations and lead to runaway soil thinning or thickening. Interpretations of measured bedrock erosion rates have been equivocal, supporting both the exponential function [*Heimsath et al.*, 2000; *Heimsath et al.*, 1997] and the humped function [*Bierman and Nichols*, 2004; *Small et al.*, 1999; *Wilkinson et al.*, 2005].

[5] Because convincing evidence exists to support the humped function, the issue of its stability needs to be revisited. *Carson and Kirkby's* [1972] analysis assumes that bedrock erosion is a steady and continuous process, but most mechanisms of bedrock erosion (e.g., frost cracking [*Anderson*, 2002] and burrowing mammals [*Heimsath et al.*, 2000; *Heimsath et al.*, 2001]) are episodic, occurring in events that are discrete in time and space. In forested regions, for example, the mechanical weathering of bedrock is dependent on the life cycle of individual trees. Exerting axial and radial pressures as high as 1.45 and 0.91 MPa [*Bennie*, 1991], respectively, a tree's roots can penetrate bedrock and split it apart. Breaking the bedrock into smaller pieces accelerates its conversion to soil by creating more surface area vulnerable to chemical attack and by creating space for water and other weathering agents. If the tree topples over and is uprooted, often by strong winds [e.g., *Kotarba*, 1970], the root mass is torn out of the ground, carrying with it rock and soil, and leaving behind a pit. As the roots decay, the rock and soil fall to the ground, creating a mound. The ability of this process to disrupt and remove bedrock is considerable: *Lutz* [1960] documented boulders weighing nearly 4 tons being lifted

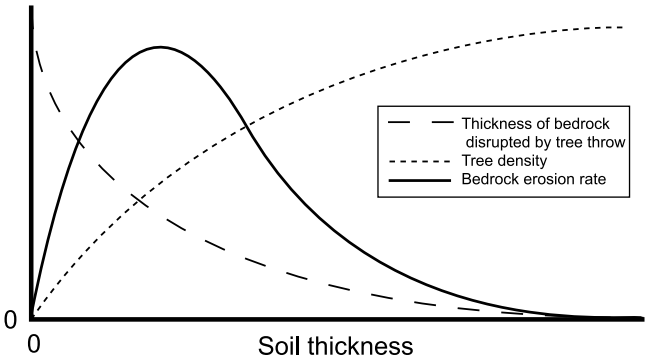

Figure 2. As soil thickness increases, the amount of bedrock disrupted by tree roots decreases because of their limited vertical extent. Conversely, thicker soils support higher tree densities. The combination of these two opposing trends is posited to produce a humped bedrock erosion function.

up into the air by uprooted trees. The surface expression of tree-throw, pairs of pits and mounds, is also remarkable. In some instances, pit-and-mound pairs can cover >40% of the land surface and create a local microrelief of up to 2 m ([*Schaetzl et al.*, 1989b] and references therein). Because similar paired features could not be created by purely physical processes, tree throw leaves an unmistakable topographic imprint of biological activity on the Earth's surface (see counterargument by *Dietrich and Perron* [2006]).

[6] To investigate the stability of the humped function under more realistic conditions of bedrock erosion than those assumed by *Carson and Kirkby* [1972], we created a numerical model to simulate the physical weathering of bedrock by root growth and tree throw. The numerical model incorporates published measurements of population dynamics of trees in relevant forested ecosystems, tree mortality and tree throw frequency, and the efficacy of tree-throw events in uprooting and transporting material. With this model, we explore two questions. First, does a humped bedrock erosion function emerge as a consequence of coupling biological imperatives with geological processes? *Dietrich et al.* [1995] proposed that where bioturbation is an important physical weathering process, the necessity for soil by most biological agents at the Earth's surface would produce a humped bedrock erosion function. For example, gophers are efficient diggers; however, they need a minimum amount of soil to provide shelter; thus the amount of bedrock disrupted by gophers is low in thin soils, increases to a maximum as soils thicken, and declines as soils become thicker than the mean depth of burrows [e.g., *Yoo et al.*, 2005]. Note that although biological imperatives may lead to a humped bedrock erosion function, a bedrock weathering model based on the purely physical process of frost-shattering also yields a humped relationship [*Anderson*, 2002], thus supporting Gilbert's initial intuition from the Henry Mountains [*Gilbert*, 1877]. The second goal of this study is to determine whether a realistic treatment of bedrock erosion (i.e., episodic in time and space) damps instabilities attributed to the humped function [*Carson and Kirkby*, 1972]. Finally, we adopt the maxim, attributed to *George Box* [1987], that "all models are wrong, some are useful." We have highlighted data gaps that prevent us from accurately parameterizing the model and noted the ways that the model simplifies a more complex reality. Nevertheless, we present this model as a useful heuristic tool for exploring relationships between biotic and geomorphic processes.

2. The Model

2.1. General Approach

[7] For the purposes of this investigation, we broadly define *soil* as that portion of the regolith which is physically disturbed, and we include both saprolite and unweathered bedrock within the term *bedrock* [*Yoo and Mudd*, 2008]. In addition, we use the terms *bedrock erosion* and *soil mantling* to describe two distinct processes that are often combined in the term *soil production*. Although *bedrock erosion* and *soil production* are often used synonymously [e.g., *Heimsath et al.*, 2001], erosion of bedrock does not necessarily result in the production of soil. For example, material weathered from a steep bedrock slope may ravel down the hill into a lake: bedrock has been eroded, but no soil has been produced. Furthermore, soil (*sensu lato*) produced at one location may be simultaneously translocated laterally (e.g., by tree throw), thereby spatially decoupling the processes of bedrock erosion and soil thickening. We adopt the term *soil mantling* to refer to the suite of processes, local and nonlocal, that result in a cover of soil overlying bedrock.

[8] Our model incorporates the biological aspects of seed recruitment and tree growth with the physical aspects of bedrock erosion by root fracture and tree throw. As suggested by *Gabet et al*. [2003], the combination of these two sets of processes may produce a humped bedrock erosion function in which the rates of bedrock erosion are low when soils are thin, reach a peak at an intermediate soil thickness, and then decline as soils continue to thicken (Figure 2). The envisioned natural analogue for the model is a temperate forest in the Pacific Northwest (a region encompassing the U.S. states of Washington and Oregon and the Canadian Province of British Columbia), dominated by Douglas fir and underlain by sandstone. This landscape was chosen because of the wealth of information regarding biological and geomorphological processes for the region. Nevertheless, because of data gaps, some parameter values needed for the model were approximated on the basis of measurements from similar, but not identical, environments. The model, then, should be viewed as a composite model rather than one strictly applicable to a specific region.

[9] We believe that the use of Douglas fir in this bedrock erosion model is acceptable if not entirely accurate. Douglas firs are initial colonizers in forests cleared by fire [*Stewart*, 1986; *Winter et al.*, 2002]; however, alders typically colonize geomorphically disturbed surfaces (e.g., landslide scars) [*Geertsema and Pojar*, 2007]. Over time, alders on disturbed surfaces are succeeded by conifers, such as Douglas fir [*Geertsema and Pojar*, 2007]. Thus, the adoption of Douglas fir may lead to errors in bedrock erosion rates in the early stages of soil mantling due to differences in rootwad geometry between firs and alders. Note that firs are able to grow in soils as thin as 4 cm, indicating that they can survive on nearly bare bedrock surfaces provided the saprolite is sufficiently weathered [*Meyer et al.*, 2007].

[10] Finally, the model focuses solely on physical weathering. *Anderson and Dietrich* [2001] report a chemical weathering rate of 1.4×10^{-2} mm yr^{-1} for a forested mountainous watershed in the Oregon Coast Range. This rate is

~10% of the total erosion rate for hillslopes in the region [*Heimsath et al.*, 2001; *Roering et al.*, 1999]. In landscapes where the chemical weathering rate is small relative to physical erosion rates, chemical processes will have minimal impact on the morphologic evolution of the hillslope [*Mudd and Furbish*, 2004].

2.2. Model Space

[11] The initial 100-m-long hillslope profile is a bedrock surface with four equally distributed, 50-cm-long patches of thin soil (4 cm thick). The condition of an essentially soil-less surface could be due to a massive, short-term erosional event such as a landslide or could be the result of a millennial scale disturbance such as glaciation. The small patches of soil are necessary for trees to gain an initial foothold in the model space (see section 4). Physical analogues for these patches include joints and veins that weather more quickly than the surrounding bedrock to create suitable growing conditions and topographic discontinuities, such as rock ledges, that accumulate loose mineral and organic debris [*Matthes-Sears and Larson*, 1995; *Phillips et al.*, 2008; *Zwieniecki and Newton*, 1994; *Zwieniecki and Newton*, 1995].

[12] Because the response time scales of hillslope topography are long (e.g., hundreds of thousands to millions of years) relative to millennial scale disturbances [*Mudd and Furbish*, 2007], these perturbations will strongly affect soil thickness but not underlying bedrock topography. We therefore approximate long-term steady-state conditions by imposing a predetermined hillslope curvature assuming that the profile is a result of sediment transport processes that are proportional to the hillslope gradient (i.e., linear diffusion). Whereas it has been found that many hillslope sediment transport processes are nonlinearly related to slope [*Gabet*, 2000; *Gabet*, 2003; *Gabet et al.*, 2003; *Roering and Gerber*, 2005; *Roering et al.*, 1999], the nonlinearities of the relationships are typically observed at only the steepest slopes. (A similar argument for the use of linear diffusion was made by *Roering et al.* [2002].) Note also that although *Gabet et al.* [2003] determined that sediment transport by tree-throw is proportional to the sine of the hillslope angle, the net rate of downslope transport by tree-throw is much lower than the other soil creep processes (see later) and therefore will have a negligible effect on the steady-state relationship between process and form imposed here.

[13] The assumption that the rate of sediment transport is linearly proportional to slope allows a simple steady-state relationship between curvature, soil erosion rate (E, LT^{-1}; variables are henceforth presented with their dimensions in [M]ass, [L]ength, and [T]ime unless the units are explicitly declared), and diffusivity (D, LT^{-2}), which is a measure of the efficiency of transport processes:

$$\frac{\partial^2 z}{\partial x^2} = \frac{E}{D} \tag{1}$$

where x is the distance from the divide and z is elevation [*Fernandes and Dietrich*, 1997]. Integrating equation (1) twice yields an equation for a steady-state profile:

$$z = z_{\max} - \frac{E}{D}\frac{x^2}{2} \tag{2}$$

where $z_{\max}$ is the elevation at the divide. Studies from hilly forested catchments underlain by sandstone in the Oregon Coast Range report long-term erosion rates in the range of 0.05–0.15 mm y^{-1} [*Heimsath et al.*, 2001; *Roering et al.*, 1999]. To avoid creating a hillslope with steep slopes that could, in reality, be prone to landsliding, the lowest long-term erosion rate (0.05 mm y^{-1}) is chosen. This value incorporates all erosional processes, including fire-driven erosion and shallow landslides. To isolate erosion by tree-throw and small-scale soil creep processes, we assume an erosion rate that is a fraction of the total rate. *Roering and Gerber* [2005] estimated that in the region, fire-driven erosion accounts for 25–80% of the total sediment flux. Thus, we set E equal to 0.025 mm y^{-1}, (i.e., 50% of the total rate) and the diffusivity to 2.5×10^{-3} m^2 y^{-1} (see section 2.6). With these values, a steady-state hillslope profile can be defined with equation (2). The nodes are spaced at 10-cm intervals to allow for sufficient resolution of the pit-and-mound topography while maximizing processing speed and minimizing numerical instabilities.

2.3. Seed Recruitment, Tree Growth, and Stand Density

[14] Studies support the intuition that bare bedrock surfaces support fewer trees than thick soils. Because thin soils have a more limited capacity to store water [*Meyer et al.*, 2007], they provide a less hospitable environment for seed recruitment and tree growth [*Childs*, 1981; *Helgerson*, 1981]. Indeed, *Meyer et al.* [2007] documented a positive relationship between basal area (the sum of the cross-sectional areas of all trees in a plot and thus a rough proxy for stand density) and soil thickness. Converting stand density to an average distance between trees allows the specification of a threshold intertree distance such that trees need a minimum amount of space to grow. The threshold intertree distance (d_t) at each node in the model is determined as a function of soil thickness with

$$d_t = d_1 + (d_2 - d_1)e^{-k_d h} \tag{3}$$

where d_1, d_2, and k_d are empirically determined constants and h is the soil thickness at that node. A negative exponential form of the relationship is proposed because of its asymptotic approach to a minimum intertree distance (or an asymptotic approach to a maximum stand density). To our knowledge, no studies have been published that quantitatively define a relationship between intertree distance (or stand density) and soil thickness; nevertheless, there are sufficient data to estimate plausible values for the parameters in equation (3). From a regression presented by *Meyer et al.* [2007], the basal area of a mixed conifer forest would be ~12 m^2 ha^{-1} on soils 4 cm thick. Old-growth Douglas fir have trunk diameters (measured at the standard breast height) of approximately 1 m [*USGS*, 2003]; converting this value to a basal area and combining it with the data from *Meyer et al.* [2007] results in a minimum stand density of 10 trees ha^{-1}, or an intertree distance of 32 m. We note that the *Meyer et al.* [2007] data come from a mixed conifer forest under a drier and colder climate; although their results may not be strictly

applicable to our model, we are primarily interested in their general relationship between soil thickness and tree density. At the other extreme, *Shaw et al*. [2004] report a stand density of ~430 trees ha^{-1} (or an intertree distance of 5 m) in an old-growth Douglas fir forest in soils that are 2–3 m deep. Parameterizing equation (3) to match these two end members produces the following values: $d_1 = 5$ m, $d_2 = 32$ m, and $k_d = 5\ m^{-1}$.

[15] At every annual time step, a seed is dispersed to each treeless node. A minimum of 4 cm of soil is required for the seed to have the potential to grow [*Meyer et al.*, 2007]. If there is enough soil and if there are no trees within the critical distance, the seed is successfully recruited and begins to grow. The model therefore simulates seed recruitment, sapling survival, and competition between trees that leads to self-thinning. There are, of course, more sophisticated models that simulate seed dispersal, seedling survival [*Greene and Johnson*, 2000], and tree growth that take into account factors such as competition for nutrients and light [e.g., *Kohyama*, 1992]. However, because we are only interested in the role of root fracture and tree throw in weathering bedrock, we do not include additional biological factors in our model. We emphasize that the focus of this work is not to rigorously simulate biological processes but to explore the role of the biota in setting the relationship between soil thickness and bedrock erosion.

2.4. Tree Mortality and Toppling

[16] Douglas fir trees in old-growth stands of the Oregon Coast Range have an average age of 330 years [*Spies and Franklin*, 1991]. To arrive at this stand age in the model, a random number is chosen for each tree at each annual time step, and that number is compared to that tree's probability of dying (i.e., 1/330). This mortality rate includes all the different ways that a tree can die, such as trunk snap, disease, fire, and tree throw. Of these different outcomes, tree throw is treated differently in the model because it displaces rock and soil laterally. *Sinton et al*. [2000] determined that tree throws affected 3.1% of an old-growth Douglas fir forest over a period of 68 years (before logging). Combining these values with the average stand age suggests that topples are responsible for 15% of tree deaths. This probability is applied stochastically at each annual time step to trees older than 80 years that have been selected to expire. In an inventory of toppled trees presented by *Reid* [1981], 80 years appears to be the threshold age for trees to topple over. This value is supported by *Schaetzl et al*. [1989b], who found that tree throws are uncommon in trees younger than 100 years old. Younger trees have weaker trunks and are more likely to snap than to be uprooted [*Schelhaas et al.*, 2007].

[17] Whereas an individual tree in a forest may be toppled by the wind, entire swaths of forest may be toppled in catastrophic blowdowns associated with tornadoes, hurricanes, and microbursts [e.g., *Peterson*, 2000]. Fires may also force the temporal clustering of tree throw events [*Gallaway et al.*, 2009]. With *Sinton et al*.'s [2000] data, a recurrence interval of 2200 years can be calculated for a catastrophic blowdown that would topple all of the trees in the model space. Because insufficient data exist to determine the relative proportion of individual tree topples versus catastrophic blowdowns, we model both as end-member scenarios. In the catastrophic blowdown scenario, tree throws only occur when all the trees topple every 2200 years (on average).

[18] Note that we assume that each tree older than 80 years has an identical probability of being toppled, regardless of local soil thickness. *Mills* [1984] observed, however, that trees may be more firmly anchored in thin soils. In contrast, *Lutz* [1960] concluded that trees are more likely to be uprooted on rocky soils. In addition, potential decreases in tree-throw rate from firmer anchoring may be offset by the higher wind stresses suffered by trees in less dense forests [*Harcombe et al.*, 2004; *Sinton et al.*, 2000]. Indeed, by explicitly modeling wind speeds, resistance to uprooting, and the spatial distribution of Douglas fir stands, *Schelhaas et al*. [2007] found that individual trees in thinner stands are more vulnerable to being blown down. The ambiguity in the relationship between soil thickness and uprooting rates [*Schaetzl et al.*, 1989b] prevents us from confidently parameterizing this portion of the model. Importantly, divergence of the model from reality on this point only matters with respect to the lateral transfers of soil from the pits to the mounds and does not affect the modeled bedrock erosion rates.

2.5. Pit Excavation and Mound Building

[19] Local conditions (e.g., the amount of light penetrating the canopy) within a forest play an important role in determining tree size, and thus the size of a tree and its rootwad are not necessarily correlated with its age [*Kuiper*, 1988]. Because tree age and rootwad dimensions are decoupled, pit size is randomly chosen from a probability distribution. Data from Douglas fir rootwads [*Mort*, 2003; *Schooten*, 1985] suggest that pit volumes are normally distributed with a mean of $3 \pm 1.3\ m^3$. The shape of a pit can be approximated as half of an ellipsoid in which the length and width are the same (i.e., the pit can be approximated as a circle in plan view) [*Norman et al.*, 1995]. The volume of half of such an ellipsoid is

$$V = \frac{2\pi}{3} r^2 h_p, \tag{4}$$

where r [L] is the radius of the pit and h_p [L] is its depth. The depth of the pit is approximately one half of its radius [*Mort*, 2003; *Schooten*, 1985], such that the volume can be simply related to its radius with $r = (3V/\pi)^{1/3}$. The normal distribution of volumes can then be converted to a normal distribution of radii from which values are randomly selected. A semi-elliptical pit (with the chosen radius) is then excavated in the soil and, if the pit is deep enough, into the bedrock (Figure 3). Note that the data used to derive the distribution of rootwad volumes comes from a variety of sites, including forests that had been previously logged (although not recently). It is possible, then, that the rootwad volumes may be biased toward younger and smaller trees, thus depressing the modeled bedrock erosion rates.

[20] Observations suggest that rootwads in thin soils are thinner, and pits shallower, because bedrock can impede the growth of roots. In addition, trees growing in thin soils are unlikely to grow as quickly as those in deeper soils and thus should have smaller rootwads [*Thies and Cunningham*, 1996]. To account for these effects in the model, the ratio between rootwad thickness and radius decreases linearly from

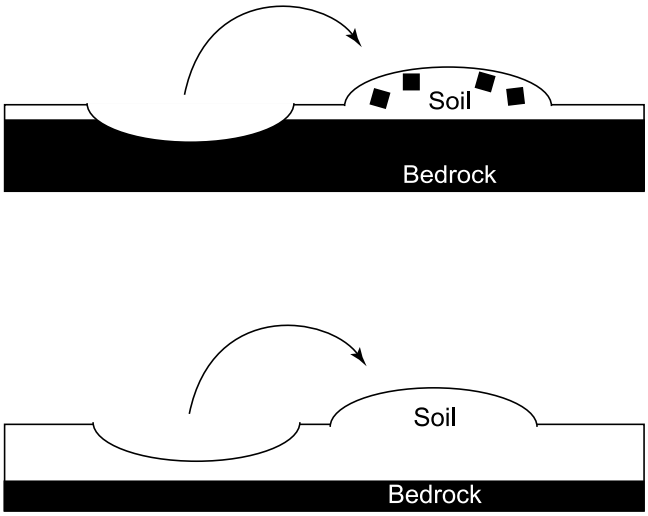

Figure 3. Illustration of bedrock and soil excavation in model. Top: Tree throw pits that are sufficiently deep to excavate bedrock; bedrock clasts are represented by black squares. Bottom: No bedrock is disrupted if the pit does not extend into the bedrock. Bedrock is broken but left in place for standing dead trees.

one half to one fourth as soils thin from 0.5 m to 0 m; in soils thicker than 0.5 m, the ratio is constant at one half [*Mort*, 2003; *Schooten*, 1985]. We emphasize that our modeled change in rootwad geometry in thin soils is not derived from any quantitative data and is simply a reasoned guess based on informal observations. Finally, note that the volume of a rootwad includes only soil and rock. Root growth will dilate the soil and bulge up the soil surface around the tree, whereas root decay will cause it to collapse. Over time, these two processes cancel each other locally, and thus the model does not keep track of the cyclical changes in soil surface elevation due to root growth and decay.

[21] Because of the one-dimensional nature of the model, a tree may only fall directly uphill or downhill. From our observations, trees are more likely to fall downhill as slopes steepen. Although we do not have sufficient data to accurately formalize a relationship between fall direction and slope, we assume that the probability of a downhill fall increases linearly from 50% on a horizontal surface to 90% on a 45° slope. Note that we are modeling the most general situation possible as trees may preferentially fall in the direction of the dominant winds, even uphill [*Gallaway et al.*, 2009]. In any case, tree-fall direction is irrelevant with respect to bedrock erosion rates and only affects the modeled sediment transport rates by tree throw.

[22] Depending on the randomly chosen tree fall direction, a mound is built uphill or downhill of the pit. *Gabet et al.* [2003] demonstrated that the emplacement of the mound relative to the pit is dependent on slope such that, for a tree falling uphill, the distance separating the pit and mound centroids, x_u, is determined with

$$x_u = \frac{r}{2}(\cos\theta - \sin\theta) - \frac{h_p}{2}(\cos\theta + \sin\theta) \tag{5a}$$

and for a tree falling downhill, the distance (x_d) is

$$x_u = \frac{r}{2}(\cos\theta + \sin\theta) + \frac{h_p}{2}(\cos\theta - \sin\theta) \tag{5b}$$

where θ is hillslope angle (°). In the model, the mound is built at the same moment that the pit is created. In reality, the mound forms gradually as the tree decays and the rock and soil are released from the roots' grip. This process takes 5–10 years [*Schaetzl and Follmer*, 1990], a relatively instantaneous event considering the slow rates of bedrock erosion. For trees that die but do not topple, the extent of bedrock broken up by root growth is assumed to be similar to the dimensions of uprooted root wads; because there is no lateral displacement, the disrupted material remains in place.

[23] The shape of the mound mirrors the pit and the model keeps track of the amount of bedrock and soil contained within it. We assume that the bedrock is fractured by the roots into 25-cm cubic clasts. The choice of 25-cm-diameter clasts is an approximation based on our general observations and, of course, does not represent the full range of clast sizes created by tree-throw; importantly, the clast size does not affect the results. At each annual time step, the surface of each clast is weathered, and the weathering products are incorporated into the soil. *Rapp* [1960] measured a maximum disintegration rate of 0.5 mm y^{-1} for sandstone surfaces in a cool, wet environment. Because the model's physical analogue in the Oregon Coast Range is wet and underlain by weak sandstone [*Mort*, 2003], use of Rapp's maximum rate seems justified. As the clasts weather to smaller fragments, the bulk density of the mound decreases and the soil surface dilates. The bulk densities of the sandstone bedrock and soil are set to 2300 kg m^{-3} and 740 kg m^{-3}, respectively, according to regional measurements [*Anderson et al.*, 2002].

[24] The bedrock erosion rate is calculated at each annual time step by subtracting the previous year's bedrock elevation from the present bedrock elevation and dividing the difference by the hillslope length. To avoid problems at the boundaries, tree-throws were not allowed within 1-m buffers at both ends of the hillslope. The bedrock lowering rate in the buffers was specified to be the average bedrock lowering rate for the rest of the model space.

2.6. Soil Creep

[25] While tree throw creates the large-scale topography on the soil surface, other processes (e.g., rainsplash, raveling) fill in the pits and flatten the mounds. The sediment flux from these soil-creep processes is typically slope-dependent; thus they are represented in the model with the following simple linear diffusion equation:

$$q_{sc} = D\,S \tag{6}$$

where q_{sc} ($m^2\ y^{-1}$) is the sediment flux, D ($m^2\ y^{-1}$) is the diffusivity, and S ($m\ m^{-1}$) is the local slope. Equation (6) is implemented in the model with a finite-difference scheme. In a forested watershed in the Oregon Coast Range, *Reneau and Dietrich* [1991] found a value of 5×10^{-3} $m^2\ y^{-1}$ for D. As described earlier, *Roering et al.* [2005] estimated that fire-driven erosion accounts for 25–80% of the total sediment flux; thus, to focus exclusively on tree-throw and soil creep,

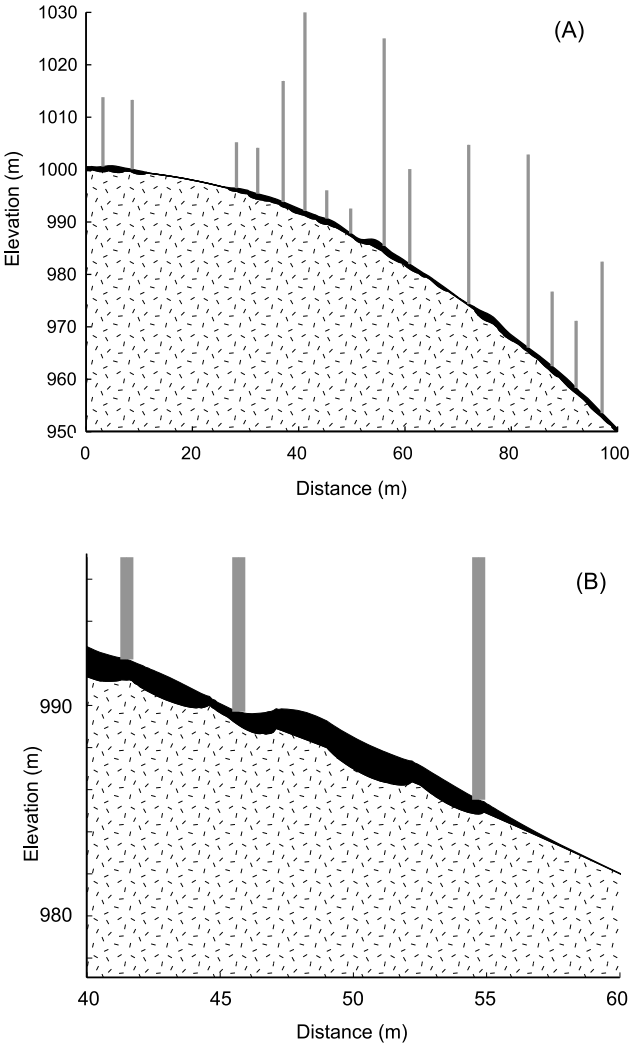

Figure 4. Modeled soil thicknesses and surfaces after 5000 years of model time. Vertical lines = trees, black area = soil, dotted area = bedrock. Tree height is proportional to tree age. (a) The model recreates the distinctive topography typical of forested hillslopes. (b) A pit-and-mound pair and the irregular bedrock surface are visible at this resolution.

we assume a value of 2.5×10^{-3} m^2 y^{-1} for D (i.e., 50% of the landscape-scale value reported by *Reneau and Dietrich* [1991]).

[26] The value for D can be evaluated by modeling the longevity of tree-throw topography. In a northern Michigan forest, *Schaetzl and Follmer* [1990] found that the oldest still-recognizable mound was 2420 years old (on a 14° slope). With a value of 2.5×10^{-3} m^2 y^{-1} for D, model results demonstrate that a mound on a 14° slope will be flattened after 2500 years, a result consistent with these observations. This analysis suggests that the hillslope-scale value of D used here may also be appropriate at the microtopography scale. We recognize, however, that pit-and-mound topography in the wet Oregon Coast Range may be shorter-lived than in Michigan [*Putz*, 1983]. Finally, there is no reason to assume that soil creep rates are steady in time; driving factors such as rainfall change annually. Therefore, to simulate annual variations in transport rates, a value of D is randomly chosen every year from a normal probability distribution with a standard deviation of 50%.

3. Results

3.1. Microrelief

[27] The model produces the distinctive pit-and-mound topography commonly observed in forested landscapes [*Gabet et al.*, 2003], as well as the rough and uneven bedrock surface [*Mort*, 2003; *Phillips et al.*, 2005] (Figure 4). True bedrock surfaces in forested landscapes, however, likely do not have the sharp asperities seen in the model results; chemical weathering and fracture dynamics may smooth sharp edges.

3.2. Stand Evolution and Soil Thickness

[28] As mentioned earlier, the initial condition for the model runs was a bare bedrock surface with four small soil patches. The coupled evolution of stand density and soil thickness as the bedrock surface is converted into a soil mantle can be seen in Figure 5. In the early years of the run, the thin soils can only maintain a low tree density. However, as trees mature, their roots break up bedrock and soil is created. The formation of soil allows for a greater tree density which, in a positive feedback, leads to the formation of more soil [*Phillips and Marion*, 2004]. Both the soil thickness and tree density remain low in the first few thousand years, then increase quickly and begin to level off when the soil becomes thicker than the rooting depth. In most model runs, steady-state soil thickness and tree density were reached in 7000–10,000 years. From 200 model runs, soils attained a steady-state thickness of 103 ± 40 cm. For comparison, *Anderson et al*. [2000] measured average soil thicknesses of 70 ± 40 cm in a steep, forested (albeit recently logged) catchment in the Oregon Coast Range. The model's overprediction of average soil thickness is expected considering that the slopes in the catchment averaged 43°, considerably steeper than those modeled here. Importantly, the similarity of the measured and predicted variance in soil thickness suggests that the model effectively represents the microrelief of the natural soil surface and the uneven distribution of soil.

3.3. Rates of Bedrock Erosion vs. Soil Depth

[29] Averaging the results from 200 model runs, a humped relationship emerges between the rate of bedrock erosion and soil thickness (Figure 6). It is important to emphasize that this humped relationship is not hardwired into the model but arises dynamically from two considerations: (1) tree density increases with soil thickness, whereas (2) the amount of bedrock incorporated into a rootwad decreases with soil thickness (Figure 2).

[30] The model can be tested by comparing its results to bedrock erosion rates measured with cosmogenic radionuclides in a Douglas fir forest underlain by sandstone in the Oregon Coast Range [*Heimsath et al.*, 2001]. Both sets of model results, individual tree throws and catastrophic blowdowns, (Figure 7) correspond well with measured bedrock erosion rates, although the catastrophic blowdown results are closer in magnitude to the measured rates. Considering that the model does not contain any tunable parameters (albeit some parameter values are estimates) and that the governing

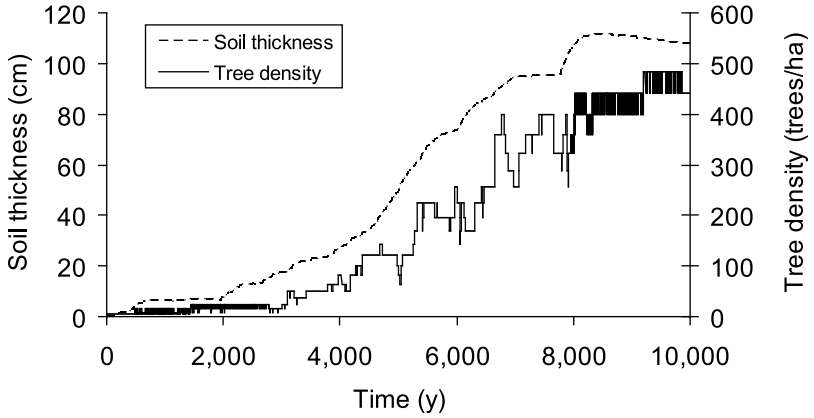

Figure 5. Coupled evolution of stand density and hillslope-averaged soil thickness. Multiple model runs suggest that both stand density and soil depth reach approximately steady-state conditions after 7000–10,000 years.

equations were based on processes and relationships entirely independent of *Heimsath et al.*'s [2001] approach, the close correspondence is encouraging. There are two main differences between the modeled and the measured rates. First, the model predicts no bedrock erosion on a soil-less surface, whereas the Oregon Coast Range data indicates that some soil is produced. The difference is due to the rule in the model that stipulates a minimum soil cover of 4 cm for tree growth. However, in the Oregon Coast Range, the near-surface sandstone bedrock is mechanically weak [*Mort*, 2003] and is likely to have high porosity from chemical weathering enhanced by the wet climate [*Graham et al.*, 2010]. These two factors suggest that trees could root directly into the bedrock and thus produce soil even in the absence of an initial soil mantle. The second difference between the model and the data is that the model predicts a peak in bedrock erosion rates in soils that are 30–40 cm thick, whereas the field data show a peak in soils that are 20–30 cm thick. The difference, if real and significant, may be due to an error in the parameterization of the tree density-soil thickness function (equation (3)), the least constrained of the governing equations; a steeper increase in tree density with increasing soil depth would push the peak bedrock erosion rate toward thinner soils. The difference may also be due to our parameterization of rootwad geometry: allowing deeper root penetration in shallower soils would push the modeled peak to the left. Nevertheless, we consider the similarity in the trends and the magnitudes between the modeled rates and the measured rates to be satisfactory.

[31] Results from the model emphasize the spatial decoupling of bedrock erosion and soil thickness where root fracture and tree throw is an important weathering process. Tracking the soil thickness and bedrock erosion rate at a single node (located 50 m below the divide) illustrates the absence of a relationship between the two at a specific location (Figure 8). A tree-throw event excavates a pit into the

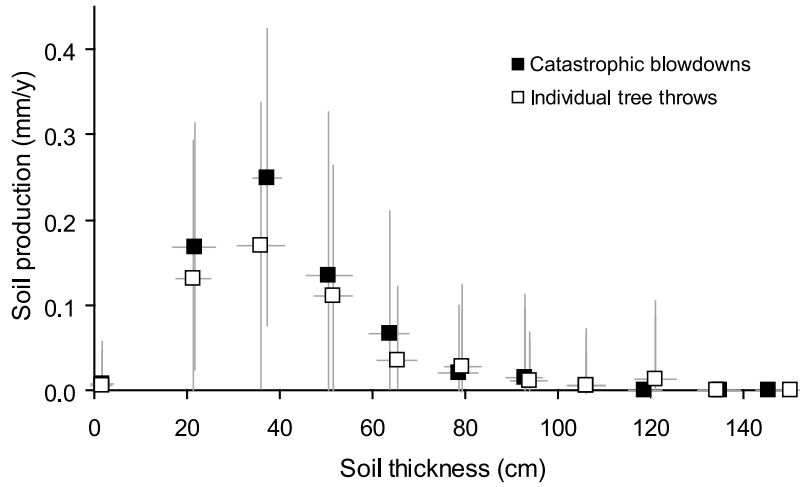

Figure 6. Bedrock erosion rate versus soil thickness from model runs. A humped relationship, with a peak where soil thickness is ~35 cm, emerges from the binned and averaged results (error bars = 1σ). Model results suggest that peak soil production rates may be higher in forests where tree throw occurs primarily during large blowdown events.

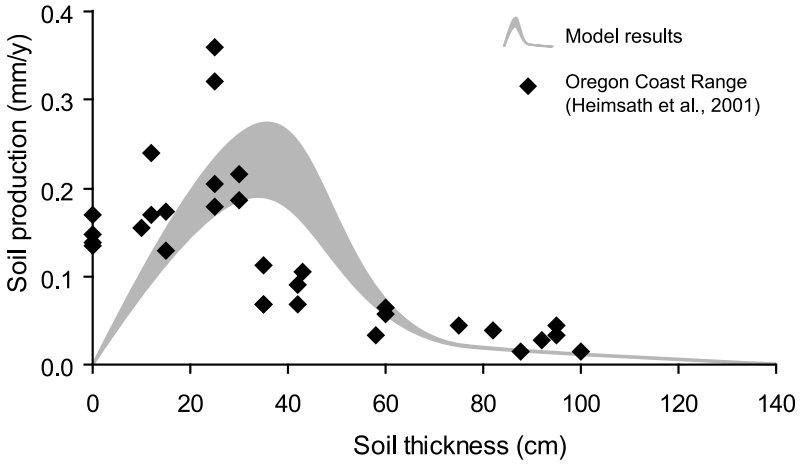

Figure 7. Model results compared to bedrock erosion rates measured in a Douglas fir forest in the Oregon Coast Range. The results from Figure 6 bracket the shaded area. Both the data and the model results reveal a humped relationship between bedrock erosion rates and soil thickness.

bedrock in Year 2183, and the pit becomes partially filled with mound material; the bedrock at that node then remains undisturbed for the following 3000 years. The soil thickness, in contrast, varies considerably over the duration of the model run and is independent of the bedrock erosion rate at that node. The first bedrock erosion event thickens the soil to ~40 cm, and subsequent diffusion of the mound material back into the pit continues to thicken the soil. After this initial event, the soil thickness at that node undergoes several rapid and significant changes associated with either the instantaneous removal or the deposition of soil from tree-throw events. These abrupt changes are followed by gradual changes as soil creep slowly redistributes soil from mounds and into pits. Importantly, after Year 2183, none of the variations in soil thickness are associated with the erosion of bedrock. Therefore, the model results suggest that bedrock erosion rate and soil thickness are decoupled at any specific location in a landscape where tree-throw is a dominant physical weathering process. The decoupling of these two processes as well as the unsteady nature of soil thickness in a forested landscape raises questions about how best to interpret cosmogenic radionuclide data to measure bedrock erosion rates where bedrock erosion occurs during low-frequency, high-magnitude events; this issue is currently under investigation.

3.4. Testing the Stability of the Humped Function

[32] The model presented here can be used to test *Carson and Kirkby*'s [1972] hypothesis that the humped function yields a soil mantle that is only metastable when soils are thinner than the critical soil thickness. Steady-state soils thinner than the critical thickness (~35 cm), a necessary condition for testing Carson and Kirkby's instability hypothesis, were forced by increasing the soil erosion rate by 0.1 mm y^{-1}. To simulate an intense erosional perturbation, the erosion rate was then increased 40-fold for a period of 10 years at a randomly selected point in time. The increase results in an instantaneous thinning of the soil but does not lead to runaway soil thinning (Figure 9), and therefore we conclude that Carson and Kirkby's analysis of the humped function does not apply where root fracture and tree throw are dominant soil-forming processes.

4. Discussion

4.1. Initial Colonization of the Bedrock Surface and Development of the Soil Mantle

[33] Observations of multiple model runs suggests the following sequence in the colonization of the bedrock surface by soil and trees (see also *Phillips and Marion* [2004] for a similar conceptual model). Initially, the tree cover is limited to the small, thin patches of soil because of the inhospitability of the bare bedrock surface. The roots of trees established in the initial soil patches burrow into the bedrock and fracture it, accelerating weathering at the spot. Trees that tip over create mounds that diffuse laterally, widening the initial soil patch. Over time, root fracture and tree throw expand these initial patches into islands of soil scattered across the bedrock slope. The soil patches serve as attractors for more trees, a process

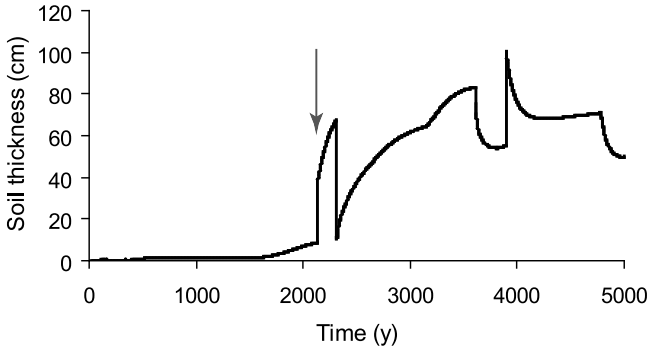

Figure 8. Changes in soil thickness at a single node. A bedrock erosion event by tree throw occurs only in Year 2183 (shown with arrow). The nonsteady nature of bedrock erosion and the instantaneous lateral transfers of soil from tree-throw decouple bedrock erosion rate and soil thickness when considered at a point.

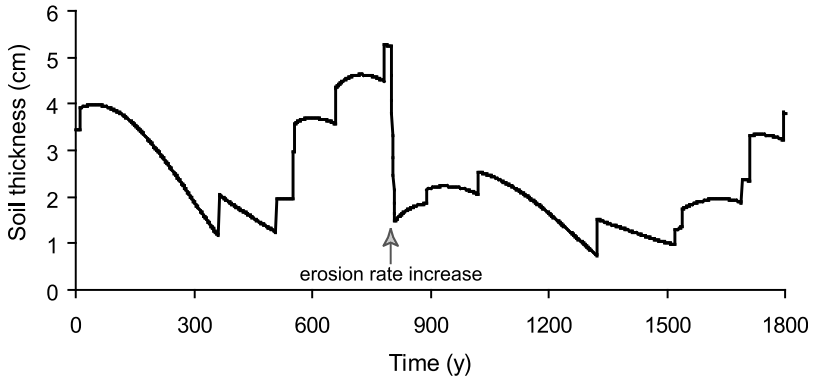

Figure 9. Response of soil thickness, averaged over the entire hillslope, to a temporary increase in erosion. With soil thickness having reached an approximate steady-state value below the critical soil depth (~35 cm), the erosion rate was increased 40-fold for 10 years (indicated by arrow). Despite the increase in erosion and subsequent soil thinning, the perturbation did not lead to permanent soil loss.

dictated by equation (3), which simulates the role of a soil cover in harboring seeds and providing a nurturing environment by trapping water. The storage of water is important for seedling survival, and it also helps accelerate chemical weathering processes by lengthening the water-rock contact time [*Clow and Drever*, 1996; *Gabet et al.*, 2006; *Lohse and Dietrich*, 2005], which increases the bioavailability of mineral-derived nutrients. Because the mounds are local topographic highs, they spread out quickly by soil creep processes. Lateral diffusion of the mounds adds soil cover to adjacent bedrock surfaces that have not yet been disrupted by physical weathering, thereby increasing the size of the soil patch and increasing the area amenable to tree growth. Over time, the patches of soil coalesce to form a complete soil cover.

[34] The conceptual model described above is somewhat different from the commonly envisioned process in which a soil mantle emerges more or less uniformly and vertically via the downward propagation of the weathering front (Figure 10). Instead, our model suggests that an exposed bedrock surface becomes mantled with soil by vertical weathering and by the lateral advection of soil from mounds. It is important to note that this model only explicitly considers root fracture and tree throw because of the relatively large database from which to extract parameter values; however, because trees can affect weathering and transport processes in other ways [*Phillips and Marion*, 2005], the results discussed here may be broadly applicable to the general role that trees have in the weathering of bedrock and perhaps even to other landscapes where biological activity is an important agent of bedrock

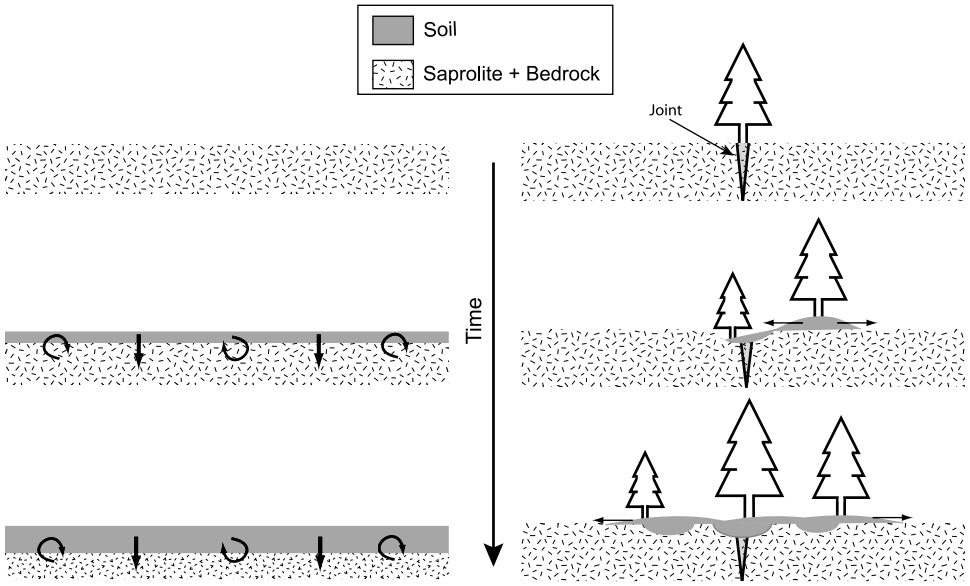

Figure 10. Left: The three descending images on the left illustrate a commonly described process by which a bedrock surface becomes mantled with soil. The weathering front moves down uniformly with soil incorporating saprolite and bedrock via small-scale mixing. Right: Illustration of how a bedrock surface may become mantled by soil in a landscape dominated by tree-root disturbance. In this model, the mantling of the bedrock surface by soil is a lateral process as well as a vertical one.

erosion. In addition, although we focus on the role of trees in physical weathering, trees and their fungal symbionts can also accelerate rates of chemical weathering [*Bonneville et al.*, 2009; *Moulton et al.*, 2000].

[35] According to our conceptual model, heterogeneities of the bedrock surface may confer small but significant advantages for seed capture and seedling survival and thus serve as nucleation sites for the soil mantle. Rock joints and fractures are well-known examples of bedrock heterogeneities that promote the growth of vegetation [e.g., *Phillips et al.*, 2008; *Zwieniecki and Newton*, 1994; *Zwieniecki and Newton*, 1995]. The topography of the bedrock surface may also provide hospitable microhabitats. Rock ledges and depressions in bedrock surfaces may inhibit the erosion of seeds by wind and runoff and may collect stray lithological and biological detritus, as well as rainwater, and thus serve as natural potting containers. In the recently deglaciated landscapes of the Sierra Nevada (California), we have observed countless examples where isolated soil patches supporting trees have formed along ledge-forming joints.

[36] The initial exploitation of a bedrock microsite by a tree triggers a powerful positive feedback between tree growth and soil creation [*Phillips and Marion*, 2004]. Several studies have found enhanced seedling survivorship on tree-throw mounds [*Denny and Goodlett*, 1956; *Lyford and MacLean*, 1966; *Mort*, 2003; *Ulanova*, 2000]. Mounds provide favorable conditions by retaining moisture yet not remaining saturated [*Ulanova*, 2000] and by being warmer during the summer months [*Schaetzl et al.*, 1989a]. In addition, when a tree topples over, the mound that is subsequently created is exposed to greater amounts of rainfall and solar radiation than nearby soil [*Millikin and Drew*, 1996]. Because weathering reactions increase with water supply and temperature [*White and Blum*, 1995], holes in the forest canopy may accelerate local rates of mineral weathering and nutrient release. Furthermore, when a mound is created, the soil surface and ground vegetation on the deposition site become buried, thus mixing the nutrient-rich A horizon deep into the soil [*Bormann et al.*, 1995] and entombing established plants that could compete against the tree seedlings [*Ulanova*, 2000]. The delivery of fractured bedrock and fresh mineral surfaces to the soil may also provide an important source of nutrients for saplings. The mounds therefore serve as attractors for other trees that may eventually topple over, rip up bedrock, create new mounds, and distribute soil laterally.

4.2. Resiliency of the Soil Mantle to Perturbations

[37] Contrary to what had been previously postulated, a thin soil mantle in a rapidly eroding landscape proved resistant to a temporary increase in erosion rate (Figure 9). However, for that particular simulation, the average thickness of ~3 cm across the modeled hillslope belies a large variance. It describes a landscape composed of large patches of bare bedrock punctuated by thick mounds of soil. The model suggests that these patches of soil and bedrock can coexist for extended periods of time and are neither forced by changes in climate [e.g., *Strudley et al.*, 2006] nor indicative of a landscape where the volume of soil is monotonically declining and fated to be completely removed from the landscape [*Carson and Kirkby*, 1972; *Furbish and Fagherazzi*, 2001]. Our model instead predicts that the expansion and contraction of soil and rock patches can achieve an equilibrium condition that maintains a constant soil volume on the hillslope and is resilient to perturbation. The long-term viability of patchy soil, despite temporary increases in regional erosion rates (e.g., high rates of sheetwash by large storms), is a property of the lumpy and uneven soil distribution. Increased erosion reduces the average soil thickness and may even expose bedrock where soils are locally thin, but the mounds may be sufficiently thick to preserve some soil. These remnant soil patches then serve as nucleation sites for renewed bedrock erosion and soil mantling.

4.3. Effect of Disturbance Size on Initial Bedrock Erosion Rates

[38] Whether bare bedrock weathers slowly or quickly is the critical difference between the humped and exponential bedrock erosion functions. An important consideration, however, that has generally gone unexamined in discussions of bedrock erosion on a soil-free surface is the lateral extent of bedrock patches and the processes that create them. Ecological studies have shown that ecosystem recovery time increases with the spatial scale of the disturbance [*Dobson et al.*, 1997]. Similarly, in landscapes where physical weathering by biotic agents is important, the size of a bedrock patch should limit the rate at which the surface can be recolonized and subjected to further weathering. The disappearance of soil therefore should be understood as a disturbance with specific dimensions. For example, in the case of tree-throw, the vast majority of seeds dispersed from a tree travel distances no greater than four or five tree heights [*Greene and Johnson*, 1989]; thus, the edges of a large bedrock surface should be recolonized quicker (and bedrock erosion will begin sooner) than the middle. Indeed, in a study of soil formation, *Phillips et al.* [2008] reasoned that rapid rates of bedrock weathering were associated with close proximity to a seed source. It follows that the bedrock erosion rate on a bedrock surface should be influenced by its distance from the nearest colonizer. Therefore, all else being equal, the initial weathering rate in the center of a small bedrock patch exposed by a landslide should be higher than in the middle of a rocky landscape exposed by the retreat of an ice cap (Figure 11).

[39] In the model presented here, it was assumed that the initial extent of the bedrock surface was small relative to its proximity to the forest edge (i.e., the seed source) such that each node had an equal probability of being seeded. In the Oregon Coast Range during the Holocene, bedrock was likely only exposed in small patches by landslides or from postfire erosion [*Roering and Gerber*, 2005; Roering and Jackson, 2008], thus explaining, perhaps, the relatively high bedrock erosion rates measured on bedrock surfaces by *Heimsath et al.* [2001] (Figure 7). For larger bedrock surfaces (e.g., lava flows, deglaciated terrain) in regions where root disturbance by trees is an important process, the initial rate of bedrock weathering may be determined by how quickly trees can colonize the surface. This colonization rate, in turn, should depend on seed dispersal distance [*Greene and Johnson*, 1989], tree growth rates, and the degree to which chemical weathering and small-scale physical weathering has prepared a surface suitable for seed recruitment and seedling survival. In landscapes where the lateral extent of bare bedrock is large relative to the advance rate of colonizing vegetation, we propose that soil initiation and mantling is a

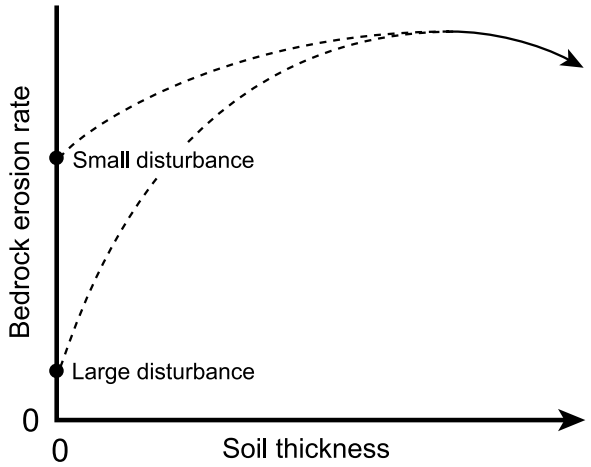

Figure 11. In the case of tree-throw, the initial rate of bedrock erosion in the center of a bedrock patch should be dependent on the size of the disturbance that exposed it. (Only the left-hand side of the humped bedrock erosion function is shown here.)

function of the lateral distance to the nearest extant soil rather than a simple function of local soil thickness. Indeed, intact patches of glacial polish exposed >10 ky by receding glaciers in the Sierra Nevada of California testify to negligible rates of weathering on vast bedrock surfaces. The point in time at which soil begins to mantle a large bedrock surface is an important milestone for landscape evolution because most geomorphic transport processes are only able to move gravel-size material and smaller. This initial period of soil mantling also starts the clock for the development of terrestrial ecosystems by providing habitat, nutrients, and moisture for plants and animals.

4.4. The Potential Role of Trees in the Evolution of Terrestrial Life

[40] Recent research dates the emergence of *Archaeopteris*, the first modern tree, to the Devonian at 370 mya [*Meyer-Berthaud et al.*, 1999]. By the end of the Permian, coniferous trees had moved into drier upland areas and were growing in mineral soils [*Behrensmeyer et al.*, 1992]. Since then, trees have mounted a successful invasion, presently covering 30% of the Earth's land surface [*FAO*, 2005]. We propose that trees may have altered hilly and mountainous landscapes where erosion rates are elevated. Prior to trees, bedrock erosion rates, largely driven by chemical weathering processes and small-scale physical disturbances, may have been unable to keep pace with transport rates, leaving slopes glazed by only a thin cover of weathered material. The arrival of trees, however, would have accelerated rates of physical and chemical bedrock weathering [*Moulton et al.*, 2000] in these rocky upland surfaces to generate a thick soil cover that, in turn, may have provided new niches and habitats to be exploited by new species of plants and animals.

5. Conclusions

[41] Soil serves as the substrate for most terrestrial ecosystems. Predictions of its long term viability in the face of changing erosion rates depend on constraining both the rate at which soil is produced from bedrock and its resistance to disturbance. To examine the relationship between soil thickness and bedrock weathering rates, we developed a model that simulates bedrock erosion by root fracture and tree throw. The model incorporates published data on tree-throw rates, rootwad volumes, and conifer population dynamics. A humped relationship between bedrock erosion rate and soil thickness emerges independently from this coupled biogeomorphic system. In addition, the model predicts rates of bedrock erosion similar to independently measured bedrock erosion rates from the Oregon Coast Range. We find that the stochastic nature of bedrock erosion by trees and the spatial heterogeneity of soil thickness protect the soil against perturbations in erosion rate. Thus we conclude that the oft-used short-cut of assuming steady and uniform bedrock erosion in numerical models, although computationally efficient, is inappropriate in forested landscapes and that explicitly accounting for natural mechanisms of bedrock erosion that are discrete in space and time is crucial for understanding the long-term stability and viability of hillslope soils.

[42] Finally, the model illustrates that soil mantling is not solely a vertical process, as is often depicted, but also a lateral process. Local areas of thick soils can support more trees, leading to greater bedrock erosion. The soil produced in these more densely vegetated zones can then spread outward through soil creep processes. Although our results demonstrate the importance of lateral processes in affecting soil mantling, we also note that the relative effect of lateral processes will be scale-dependent. The rate at which a bare bedrock surface becomes mantled with soil will depend on the size of that surface as well as its distance to colonizing organisms that promote bedrock erosion; small landslide scars may become quickly remantled, whereas the establishment of a soil cover on large bedrock landscapes exposed by glaciers may take thousands of years. This key scale dependence is often observed in nature but not predicted by traditional theories of bedrock erosion.

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