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GOPHER BIOTURBATION: FIELD EVIDENCE FOR NON-LINEAR HILLSLOPE DIFFUSION

EMMANUEL J. GABET*
Department of Geological Sciences, University of California Santa Barbara, Santa Barbara, California 93106, USA

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ABSTRACT

It has generally been assumed that diffusive sediment transport on soil-mantled hillslopes is linearly dependent on hillslope gradient. Fieldwork was done near Santa Barbara, California, to develop a sediment transport equation for bioturbation by the pocket gopher (*Thomomys bottae*) and to determine whether it supports linear diffusion. The route taken by the sediment is divided into two parts, a subsurface path followed by a surface path. The first is the transport of soil through the burrow to the burrow opening. The second is the discharge of sediment from the burrow opening onto the hillslope surface. The total volumetric sediment flux, as a function of hillslope gradient, is found to be: q_s ($\mathrm{cm^3\ cm^{-1}\ a^{-1}}$) = $176(\mathrm{d}z/\mathrm{d}x)^3 - 189(\mathrm{d}z/\mathrm{d}x)^2 + 68(\mathrm{d}z/\mathrm{d}x) + 34(\mathrm{d}z/\mathrm{d}x)^{0.4}$. This result does not support the use of linear diffusion for hillslopes where gopher bioturbation is the dominant mode of sediment transport. A one-dimensional hillslope evolution program was used to evolve hillslope profiles according to non-linear and linear diffusion and to compare them to a typical hillslope. The non-linear case more closely resembles the actual profile with a convex cap at the divide leading into a straight midslope section. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: non-linear diffusion; hillslope evolution; bioturbation; gopher

INTRODUCTION

Hillslope diffusion

As early as 1892, W.M. Davis (1892) hypothesized that soil creep created convex hilltops. This idea was subsequently expanded upon by G.K. Gilbert (1909) who reasoned that sediment flux by creep processes on a ‘mature’ (i.e. steady-state) hillslope must increase with increasing distance from the divide so that a convex hillslope will develop if sediment transport is proportional to hillslope gradient. This theory was later formalized by others (Culling, 1960, 1965; Kirkby, 1971) and, presently, the most commonly used model for erosion on transport-limited hillslopes is based on a one-dimensional sediment transport equation that assumes that flux is linearly dependent on gradient:

$$q_s = -D\frac{\mathrm{d}z}{\mathrm{d}x} \tag{1}$$

where q_s is volumetric sediment flux ($\mathrm{L^3\ L^{-1}\ T^{-1}}$), D is the diffusion coefficient ($\mathrm{L^3\ L^{-1}\ T^{-1}}$), and $\mathrm{d}z/\mathrm{d}x$ is the hillslope gradient. Equation 1, when combined with the continuity equation:

$$-\frac{\mathrm{d}z}{\mathrm{d}t} = \frac{\mathrm{d}q_s}{\mathrm{d}x} \tag{2}$$

yields the one-dimensional diffusion equation:

$$\frac{\mathrm{d}z}{\mathrm{d}t} = D\frac{\mathrm{d}^2z}{\mathrm{d}x^2} \tag{3}$$

* Correspondence to: E.J. Gabet, Department of Geological Sciences, University of California Santa Barbara, Santa Barbara California 93106, USA. E-mail: egabet@bren.ucsb.edu
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where dz/dt (L T^{-1}) is the landscape lowering rate and d^2z/dx^2 is hillslope curvature. This final equation establishes a linear relationship between landscape lowering and hillslope curvature. Note that, in this paper, diffusivities that encompass the whole of the diffusive processes will be distinguished from a diffusivity caused by a single process so that the *aggregate* diffusivity is the sum of each individual *process* diffusivity.

Linear diffusion has been used to model the evolution of hillslopes over a wide range of scales, from simple hillslope profiles (Ahnert, 1987; Fernandes and Dietrich, 1997) to drainage basins (Armstrong, 1980) to entire mountain ranges (Koons, 1995). Despite the widespread use of linear diffusion in modelling hillslope evolution, few studies have provided evidence that support the fundamental assumption that the rate of sediment flux is linearly dependent on hillslope gradient. Schumm (1967) found that the transport rate of coarse surface cover by frost heave was linearly related to the sine of the slope angle, which approximates the hillslope gradient at low angles. Additionally, McKean *et al.* (1993) confirmed a linear relationship for aggregate diffusion using cosmogenic ^{10}Be, although the range of hillslope gradients did not exceed 0·22.

However, in his development of hillslope diffusion theory, Culling (1960) wrote that it was ‘extremely unlikely’ that the functional relationship between sediment transport and hillslope gradient was strictly linear. On the basis of simple geometrical relationships, Scheidegger (1961) developed a non-linear diffusion equation and determined through computer simulations that non-linear diffusion produced more realistic hillslope profiles than linear diffusion. Increasingly, the limitation of a linear transport assumption is being recognized because the main prediction of linear diffusion, that hillslope profiles will evolve towards a constant curvature at steady state, is not borne out by actual hillslope profiles (Andrews and Bucknam, 1987; Roering *et al.*, 1999). In fact, soil-mantled hillslopes only tend towards constant curvature near their divide while the midslope sections are generally straight (Strahler, 1950). To address this limitation, several studies (Kirkby, 1985; Anderson, 1994) have suggested that straight slopes are threshold slopes where landsliding is the dominant transport process.

While flux by creep processes has often been assumed to increase linearly with slope, this has been more a matter of convenience rather than observation. Moreover, for the aggregate diffusivity to be linear, each of the process diffusivities must also be linear. In fact, several studies have shown that sediment transport may be non-linearly dependent on gradient. DePloey and Savat (1968) developed a theoretical model for rainsplash transport and found that it had a non-linear dependence on hillslope gradient. Moeyersons and DePloey (1976) established a non-linear transport equation for rainsplash on the basis of laboratory experiments. Andrews and Bucknam (1987) back-calculated a non-linear sediment transport rate from hillslope profiles and Roering *et al.* (1999) developed a non-linear transport equation on the basis of gravitational and frictional forces. Whereas these studies strongly suggest a non-linear transport law for hillslope diffusion, there still are no actual field measurements of processes to support this.

Gopher bioturbation

The importance of gopher bioturbation as a sediment transport process in certain environments has been recognized for many years (Ellison, 1946) and several studies have sought to determine the magnitude of gopher bioturbation in a variety of environments, from the coastal ranges of northern California (Black and Montgomery, 1991) to the alpine zone of Colorado (Ellison, 1946; Thorn, 1978, 1982). Two of these studies (Black and Montgomery, 1991; Thorn, 1978) concluded that gopher bioturbation was locally the dominant mechanism for sediment transport. Pocket gophers (*Thomomys bottae*) dig burrows parallel to the ground surface while foraging for below-ground plant parts (Vleck, 1981). The sediment excavated from the burrow is then pushed up onto the ground surface, creating mounds of loose soil. The mound continues to grow until the burrow opening becomes plugged with sediment (Figure 1), heretofore referred to as the ‘terminal’ state.

Approach

This study began with the observation that the displacement of soil due to gopher burrowing is a function of hillslope gradient (also noted by Ellison (1946)). To develop a diffusion-type transport equation for gopher bioturbation, the route taken by the sediment is divided into two sections (Figure 1): a subsurface path (A) and

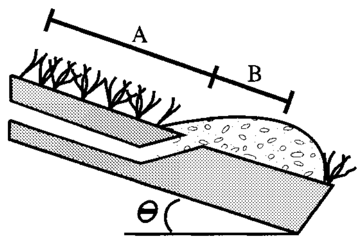

Figure 1. Profile view of gopher tunnel and mound illustrating the sediment transport path. A is the distance from the centroid of the tunnel to the burrow opening, B is the distance from the burrow opening to the mound centroid, and θ is the hillslope gradient. The tunnel is partially backfilled by displaced soil, indicating that this mound is 'terminal.' Note that the tunnel is parallel to the ground surface

a surface path (B). Section A is the transport distance from within the burrow to the burrow opening and is determined by calculating the length of tunnel necessary to produce the volume of soil in the mound. This assumes that the soil in the mound is derived from the proximal portion of the associated tunnel and is, therefore, a minimum transport distance. A' is the x-component of the net downslope transport from the tunnel centroid to the burrow entrance:

$$A' = A \cos\alpha \cos\theta \tag{4}$$

where the burrowing angle, α, is the angle between ∇Z (the direction of steepest slope) and the tunnel (Figure 2), and θ is the hillslope gradient. This presupposes that α, which is a function of burrowing strategy, varies according to hillslope gradient. This is reasonable considering that pushing soil uphill, downhill or along a contour will have different bioenergetic costs (Vleck, 1981).

Section B is the distance from the burrow entrance to the visually estimated mound centroid. B' is the x-component of the downhill transport:

$$B' = B \cos\theta \tag{5}$$

The total x-component of the downslope transport distance is then equal to the sum of A' and B'. The general

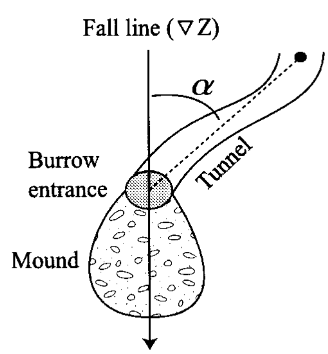

Figure 2. Planform view of gopher tunnel and mound illustrating the effect of burrowing angle, α, on the downslope subsurface transport distance. For example, there is no net downslope subsurface transport if α is 90°

diffusion equation used to calculate the volumetric rate of sediment transport is:

$$q_s\left(\frac{L^3}{LT}\right) = \text{MPR} \times \text{ave.mound volume} \times (A' + B') \tag{6}$$

where MPR is the mound production rate (number of mounds $L^{-2}\ T^{-1}$).

MATERIALS AND METHODS

Field site

The fieldwork for this study was carried out at Sedgwick Ranch, a University of California Natural Reserve, in the tectonically active Transverse Ranges near Santa Barbara, California. The climate is semi-arid mediterranean and the lithology is weakly consolidated Plio-Pliestocene fanglomerate of the Paso Robles Formation (Dibblee, 1993). The fanglomerate has been incised into a series of unpaired, step-like strath terraces. The channel that cut the terraces is no longer present and fill has been accumulating in the valley, presumably since the end of the Pliestocene. The terrace scarps are mantled by coarse loamy soils to a depth of approximately 1 m and are primarily vegetated by coast live oak (*Quercus agrifolia*) with patches of exotic, annual grasses (*Avena* and *Bromus*).

Mound selection

Sixty-five gopher mounds were selected for measurement according to two criteria. The first was that the mound was a solitary mound. Compound mounds were avoided to reduce any ambiguity about the source of the displaced soil. Secondly, only terminal mounds were considered. Because burrow entrances are buried under terminal mounds and hidden from view (Figure 1), this requirement prevented any sampling bias in the choice of mounds. Furthermore, terminal mounds represent the total volume of sediment brought up to the surface.

Surface transport distance

Before measuring the volume of each mound, a flag was placed at the visually estimated centre of mass. After the mound was removed, the entrance to the burrow was located and the distance between the flag and the entrance was measured.

A subset (30) of these mounds was randomly chosen to gauge the accuracy of the visual estimation of the centre of mass. After the flag was emplaced, the volumes of the sediment uphill of the flag and downhill of the flag were measured separately. The difference between the two volumes was divided by the total volume to give a percentage error for each mound. The average error was 1 per cent, indicating a small but systematic overestimation of surface transport distance.

Volume and bulk density

The volume of each mound was measured by scooping the mound material into a 400 ml container and counting the number of filled containers. The average mound volume was calculated to be 4290 ± 356 (s.e.) cm^3. Bulk densities of loose mound material and undisturbed soil taken from 10–30 cm beneath the surface were measured using the resin-coated clod technique (Buol *et al.*, 1997) and found to be $1{\cdot}08 \pm 0{\cdot}02$ (s.e.) $g\ cm^{-3}$ and $1{\cdot}19 \pm 0{\cdot}02$ (s.e.) $g\ cm^{-3}$, respectively.

Subsurface transport distance and burrowing angle

With the average mound volume, an average tunnel length necessary to produce that volume was calculated using the measured bulk densities and an average measured tunnel diameter, $5{\cdot}8 \pm 0{\cdot}2$ (s.e.) cm. This length was calculated to be 147 cm, which is similar to the mean tunnel length, $133 \pm 0{\cdot}03$ (s.e.) cm, measured by Vleck (1981) in a desert scrub environment. The subsurface transport distance is defined as the distance from the midpoint of the tunnel to the burrow opening, therefore A equals 73·5 cm.

Starting from the burrow entrance, 56 tunnels were then excavated a distance of approximately 150 cm. The burrowing angle, α, was measured between the 'fall line' (∇Z) and a line from the burrow entrance to the end of the excavated portion of the tunnel (Figure 2).

Mound production rate

Mounds were counted along five 50 m long transects that were laid out perpendicular to the hillslope contours. Only mounds that did not have any vegetation growing on them were tallied because it was reasoned that these had been created after the end of the seasonal rains. This is important because it isolates the sole sediment transport process as gopher bioturbation and it constrains the estimate for the rate of mound production. Approximately four months had passed since the last rainstorm so it was assumed that any mounds without vegetation had been created since then. From this initial density, mound production was assumed to be steady in time and a yearly rate was estimated.

The mound density along the transects was found to be 0·375 mounds m^{-2} which results in a mound production rate (MPR) of 1·13 mounds m^{-2} a^{-1}. This agrees well with a range of MPRs calculated from other studies. Miller (1948) and Bandoli (1981) both found that one gopher produces, on average, 110 mounds a^{-1}. This rate, combined with a range of gopher population densities of 47–153 gophers ha^{-1} (Miller, 1964; Miller and Bond, 1960; Reichman *et al.*, 1982; Reichman and Smith, 1990; Stromberg and Griffin, 1996), yields a MPR of 0·52 –1·31 mounds m^{-2} a^{-1}. Finally, to a first order approximation, mound density did not appear to vary by gradient.

RESULTS

There is a large amount of scatter in the burrowing angle data (Figure 3a) and this scatter is propagated into the subsurface transport distance (A') calculations. To compensate for this, the data were binned into slope classes. Subsurface transport distances were calculated according to Equation 4. A power-law regression for A' is (Figure 3b):

$$A'(\mathrm{cm}) = 70\frac{\mathrm{d}z^{0\cdot 4}}{\mathrm{d}x} \tag{7}$$

Given the scatter in the burrowing angle data, it could be argued that A' is essentially constant at all gradients. The power-law regression, however, fulfills the requirement of zero flux at a gradient of zero, which is a necessary condition for diffusive transport.

The data for the surface transport distance were transformed to reflect the x-component of transport using

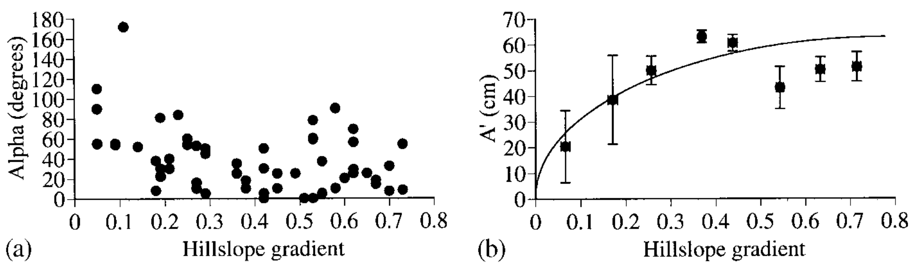

Figure 3. (a) Burrowing angle, α, versus hillslope gradient. (b) Subsurface transport distance, A', versus hillslope gradient. Data for this graph have been binned into hillslope gradient intervals of 0·1. The regression equation is A' (cm) = $70(\mathrm{d}z/\mathrm{d}x)^{0\cdot 4}$ and $R^2 = 0{\cdot}66$. Error bars represent one standard error

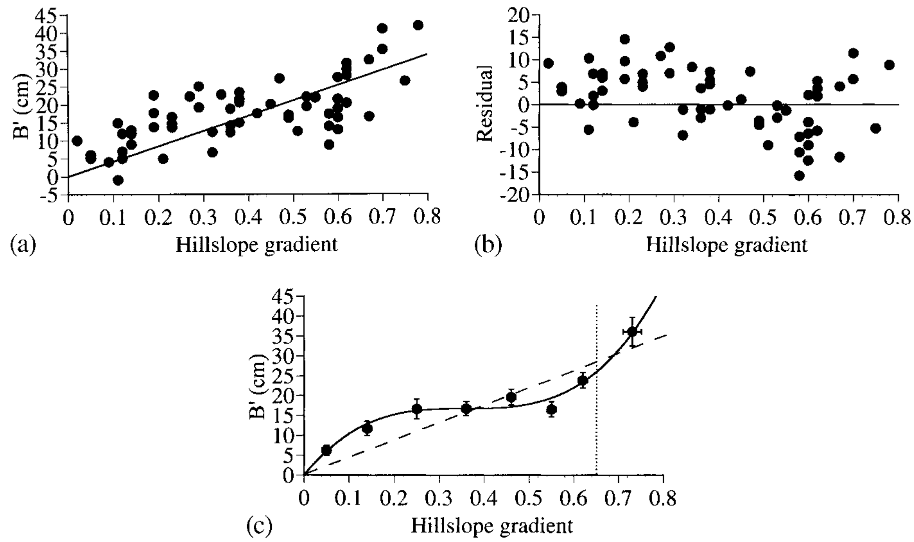

Figure 4. (a) Surface transport distance, B', versus hillslope gradient. A best-fit linear regression yields the equation: B' (cm) = 42·2 (dz/dx) and R^2 = 0·42. (b) Residuals from the linear regression plotted against gradient. The uneven distribution of residuals along the abscissa indicates that a linear regression is inadequate. (c) Binned surface transport distance, B', versus hillslope gradient. Data from (a) have been binned into hillslope gradient intervals of 0·1. The solid line is a third-order polynomial regression and, for comparison, the dashed line is a linear regression. The polynomial regression describes B' as a function of hillslope gradient (dz/dx) so that B' (cm) = $364(\mathrm{dz}/\mathrm{d}x)^3 - 390(\mathrm{dz}/\mathrm{d}x)^2 + 140(\mathrm{dz}/\mathrm{d}x)$ and R^2 = 0·97. The linear relationship is B' (cm) = 43(dz/dx) and R^2 = 0·80. Error bars represent one standard error. The dotted vertical line indicates the gradient of the measured angle of repose

Equation 5. An initial regression on this data was done to determine whether a linear fit was adequate (Figure 4a). A visual analysis of the residuals from the linear regression plotted against gradient (Figure 4b) shows a pattern that indicates non-linearity (Montgomery and Peck, 1992). Because a regression on the data would have skewed the regression line towards the gradients that had more data, the data were binned into slope classes. Different bin sizes of 0·05, 0·10 and 0·15 were evaluated to determine which would have the optimal balance of reducing scatter while preserving the shape of the function. While all three bin sizes produced regressions of similar shapes, the bin size of 0·10 was chosen as the most appropriate. From Figure 4c, the third-order polynomial regression equation for the surface path distance, B', is:

$$B'(\mathrm{cm}) = 364\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right)^3 - 390\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right)^2 + 140\frac{\mathrm{d}z}{\mathrm{d}x} \tag{8}$$

Substituting the mound production rate, the average mound volume, and Equations 7 and 8 into Equation 6 yields the following transport equation:

$$q_s\left(\frac{\mathrm{cm}^3}{\mathrm{cm\ a}}\right) = 34\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right)^{0\cdot4} + 176\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right)^3 - 189\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right)^2 + 68\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right) \tag{9}$$

DISCUSSION

To compare the sediment flux measured here to the flux measured by Black and Montgomery (1991), an average hillslope gradient of 0·36 was estimated from the topographic map of their field site in Marin County, northern California. At a gradient of 0·36, Equation 9 predicts a flux of 30·8 $\mathrm{cm}^3\ \mathrm{cm}^{-1}\ \mathrm{a}^{-1}$, while Black and

Montgomery (1991) estimated a range of rates from 0·48 to 6·31 $cm^3\ cm^{-1}\ a^{-1}$. This difference can be attributed to a larger average mound volume and a greater mound concentration at Sedgwick Ranch.

Although the diffusion equation calculated here is non-linear, a linear approximation facilitates comparison with aggregate diffusion coefficients (D in Equation 1) estimated by others. This produces a coefficient of 74 $cm^3\ cm^{-1}\ a^{-1}$, which is within the range of published estimated aggregate diffusivities, 4·4 to 360 $cm^3\ cm^{-1}\ a^{-1}$, compiled by Fernandes and Dietrich (1997).

The results show that the subsurface transport and the surface transport are two distinct processes. The subsurface transport is dependent on the bioenergetic costs of shearing and pushing soil (Vleck, 1981) and it has been shown that mammals adapt their behaviour to minimize energy expenditure on hillslopes (Reichman and Aitchinson, 1981). Surprisingly, there is only a weak dependence of the subsurface transport data on hillslope gradient. In a more detailed analysis of burrow geometry, Seabloom *et al.* (in press) concluded that the independence of movement patterns from hillslope gradient was a unique feature of subterranean animals. The surface transport, however, is clearly dependent on hillslope gradient, albeit non-linearly.

Figure 4c indicates that sediment flux at the surface increases quickly at lower gradients, suggesting that the gophers are very sensitive to slope and adjust their digging behaviour to prevent the loose soil from tumbling back down into the tunnel. At intermediate gradients (0·22–0·54) transport increases very little with slope. Field observations indicate that this is due to the roughness of the hillslope caused by microtopography and vegetation that inhibits the downslope movement of soil particles. At slopes steeper than 0·6, gravity overcomes these retarding forces and the curve rises sharply again. To determine whether this rapid increase in flux is related to the angle of repose, a series of measurements was made with 0·08 m^3 of loose soil. The soil was poured into a pile from a low height until the material ceased to accumulate and began tumbling down. The average gradient of the slope face was $0{\cdot}65 \pm 0{\cdot}05$ (s.d.; $n = 32$) which is a typical value for uncohesive materials (Statham, 1977). This suggests that sediment flux increases non-linearly at hillslope gradients near the angle of repose. An investigation of post-fire dry raveling in the same region found a similar non-linear increase in sediment flux (Gabet, manuscript in preparation).

Although Equation 9 does not describe all diffusive sediment transport processes, I suggest that the general form of the equation, in particular the terms that represent the surface transport component:

$$q_s\left(\frac{\mathrm{cm}^3}{\mathrm{cm\ a}}\right) = 176\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right)^3 - 189\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right)^2 + 68\left(\frac{\mathrm{d}z}{\mathrm{d}x}\right) \tag{10}$$

may approximate other diffusive hillslope processes. The non-linear form of the equation is consistent with the theoretical prediction that there is a rapid increase in the sediment flux as the slopes approach a critical gradient (Andrews and Bucknam, 1987; Roering *et al.*, 1999).

SIMULATION OF HILLSLOPE EVOLUTION AT SEDGWICK RANCH

With the assumption that Equation 10 approximates the aggregate diffusion equation, a hillslope evolution computer program was used to compare non-linear and linear diffusion. In this model, hillslope profiles were determined by solving Equations 1 and 2 under conditions that are thought to have occurred at the field site. Three assumptions were made for the simulations. First of all, since the hillslopes in the study area are scarps of strath terraces, the initial condition was taken to be a flat surface. Secondly, assuming that channel incision was able to keep pace with uplift, the right boundary was then lowered at the rate of 0·5 mm a^{-1}, which is in the range of uplift rates found by Rockwell *et al.* (1984) in this region of the Transverse Ranges. The third assumption relates to a change of geomorphic processes. The present valley no longer has a channel and is filling with colluvium. This suggests that, at some point in time, rainfall diminished so that the channel no longer had the capacity to remove sediment brought down from the hillslopes. This change in rainfall regime may have happened 16 500 years BP, when the Santa Barbara region emerged from the latest glacial maximum (Kennett and Ingram, 1995). To summarize, the model boundary conditions are as follows: (1)

begin with an initially flat profile; (2) lower the right boundary at 0·5 mm a^{-1} until the present relief is reached (25 000 years); (3) stop incision and then run the model for another 16 500 years.

To compare the differences in hillslope evolution according to non-linear and linear diffusion, two separate profiles were evolved. Equation 10 was the transport equation used for the non-linear case. Although it is impossible to determine whether the gopher population has remained steady over time, the magnitude of the diffusion is within the range of estimated aggregate diffusivities (Fernandes and Dietrich, 1997) so it may be reasonable to assume that Equation 10 would account for other processes that might have been transporting sediment. For the linear case, a linear regression was fitted to the surface transport data (Figure 4c) and a new flux equation was calculated. The resulting linear diffusion equation is:

$$q_s\left(\frac{\mathrm{cm}^3}{\mathrm{cm\ a}}\right) = 21\frac{\mathrm{d}z}{\mathrm{d}x} \qquad (11)$$

Several observations can be made from Figure 5a, which shows the results from the model simulations and a typical hillslope profile. The first is that the simulated hillslopes do not accurately match the actual hillslope. This may be caused by incorrect boundary conditions or by an insufficient sediment flux. Although maximum transient hillslope gradients during the simulations approached 1·0, landsliding was not accounted for in the model. The second observation is that the simulated hillslopes look very similar to each other. This should be expected since the magnitudes of the linear and non-linear diffusion equations were derived from the same data set. With these caveats, the simulation of the non-linear case does reproduce the general shape of the surveyed profile: both have a convex cap followed by a distinct break in slope leading to a straight midslope. In contrast, the linear model run is more rounded. A plot of the gradients (Figure 5b) further illustrates this point. Whereas the gradients in the linear model run increase nearly monotonically beyond the midpoint of the profile, both the non-linear case and the surveyed profile reach a maximum gradient and then remain essentially constant. The non-linear case also simulates well the rapid increase in slope where the convex cap meets the midslope section. The important difference between the non-linear and linear transport equations is in their behaviour at steep slopes (Figure 4c). In the non-linear case, sediment flux increases at a higher rate at steeper slopes, thereby rapidly relaxing high-gradient slopes until they reach a more stable angle. This difference in flux at steep slopes also accounts for the greater removal of material in the non-linear simulation. Finally, these simulations suggest that straight slopes may form by processes other than landsliding.

CONCLUSION

On the basis of field measurements, a diffusion equation was determined for the sediment flux due to gopher burrowing. This equation suggests a non-linear relationship between hillslope gradient and sediment flux and the general form of the equation was found to be similar to theoretical predictions. To compare the effects of non-linear and linear diffusion on hillslope evolution, hillslope profiles were evolved using a simple finite difference model and the profile evolved according to non-linear diffusion was more similar to an actual hillslope. This simple modelling exercise highlights the importance of determining valid sediment transport equations for hillslope processes. While the magnitude of the diffusion controls the rate of hillslope evolution, the functional relationship between diffusive sediment flux and hillslope gradient determines the direction of hillslope evolution.

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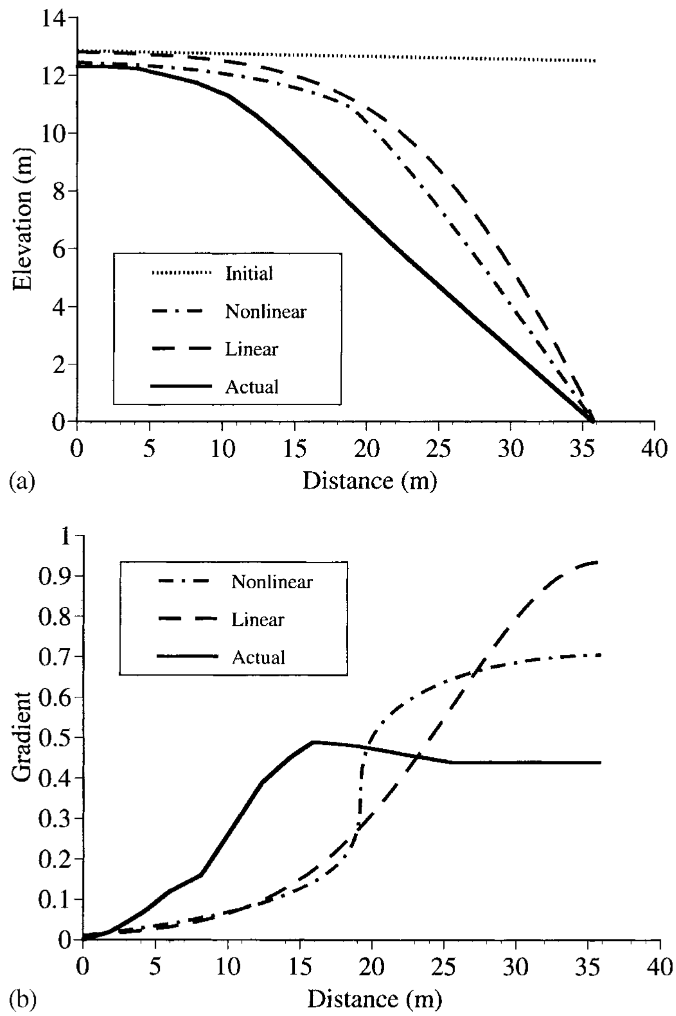

Figure 5. (a) Model runs according to non-linear and linear diffusion compared to a typical profile surveyed in the field. Both the non-linear simulation and the surveyed profile have convex caps leading into a straight midslope section, suggesting that the form of the non-linear diffusion equation approximates the form of the aggregate diffusion. The dotted line is the initial condition for the model runs and was given a slight slope for reasons of model stability. Note 2 × vertical exaggeration. (b) Gradients from profiles in (a) showing the similarity in hillslope form between the non-linear simulation and the surveyed profile

behaviour of gophers. M. Kirkby and D. Montgomery are gratefully acknowledged for their thoughtful reviews of the manuscript. This work was supported by NSF-SGER DEB9813669.

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