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Rapid evaluation of soil erosion and soil lifespan in the grazing lands of Kenya

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Abstract. Recent soil erosion rates on heavily-grazed rangelands can be mapped by measuring the exposure of datable tree roots. The technique allows the rapid definition of sediment production over decades and over large areas with a variety of soil types, gradient, and vegetation cover. Temporal variations in erosion can also be recognized in some cases. When projected into the future under various scenarios of land use and weather, the relationships between erosion rates and their controls can be used to predict the rate of thinning and eventual removal of soil along a hillslope profile.

Evaluation rapide de l'érosion et de la durée de vie des sols dans les savanes du Kenya

Résumé. On peut évaluer les taux récents d'érosion dans les savanes intensivement pâturées d'après les racines d'arbre mise à découvert pour lesquelles on peut donner un âge. Cette technique peut-être rapidement utilisée pour définir la production de sédiment pendant quelques décennies et sur de vastes territoires caractérisés par la diversité de leur sol, de leur pente, et de leur couverture végétale. Il est possible d'identifier aussi les fluctuations temporelles d'érosion en quelques cas. Les résultats peuvent servir à prédire la durée de vie des sols pour diverses conditions atmosphériques et d'aménagement des sols.

INTRODUCTION

Rates of erosion and sediment production should be defined for a variety of purposes, such as predicting the infilling of reservoirs, examining factors that affect soil erosion, and predicting the future rates of soil removal. Numerous monitoring techniques exist (e.g. Leopold, 1967; Dunne, 1976), but their usefulness is diminished by spatial and temporal sampling problems, vandalism, and the need in some cases to provide answers for design purposes in a single field season.

The measurement of rates of ground lowering against a datable reference, although less precise than continuous monitoring, has many advantages. The measurements are made quickly along with surveys of the controlling factors. By an appropriate sampling scheme, areal averages of sediment production can be defined and the effects of individual variables can be isolated more easily than is the case with sediment production measured just at the basin outlet. It is possible to compute average rates over at least several decades and to recognize fluctuations in the rate of soil loss under some circumstances. We have used the degree of exposure of datable tree roots to document and predict erosion rates for the purposes of range management, and as an aid in designing a set of plot experiments for the controlled study of variables affecting runoff and erosion (Dunne, 1977).

The measurement of long-term rates of hillslope erosion against datable exposed tree roots was pioneered by Eardley (1967) and Lamarche (1968), who reviewed some of the uncertainties in the estimation of erosion through the use of bristlecone pine trees that were several thousand years old. In heavily grazed regions of Kenya, high rates of erosion expose the roots of quite young trees and bushes or produce remnants of undisturbed soil beneath each canopy. Rapp *et al.* (1972) noticed that such mounds in Tanzania indicated erosion rates of about 10 mm/year. We have measured mounds and root exposures along hillslope transects on three rock types in southern Kenya.

STUDY AREA

Tree-root exposures were mapped in semarid lowlands of Kajiado district, Kenya, which are intensively grazed by wild game and the cattle, sheep, and goat herds of nomadic pastoralists. The study area consists of three physiographic regions, each developed on a different rock type. The Athi-Kapiti Plains consist of dissected plateaux developed on Cenozoic tuffs and lavas within a radius of 50 km south and east of Nairobi. Mean annual rainfall varies from 500 to 700 mm, and the vegetation consists of grasses that cover 40 to 90 per cent of the ground below a sparse (less that five per cent) canopy cover. The soils are swelling clays that vary in depth and degree of cracking along each hillslope profile from planosols on the ridges through phaeozems to vertisols on the footslopes.

One hundred and eighty kilometres southeast of Nairobi, Quaternary lavas extend northwards as stepped plateaux from the proximal slopes of Mt Kilimanjaro into an area with a mean annual precipitation of about 450 mm. The soils are 10–200 cm thick sandy clays. Ground cover is generally less than 10 per cent and large areas are bare except for a sparse (mostly 10–30 per cent) canopy cover of dry woodland and bush.

Between the two volcanic plateaux lies a belt of Precambrian basement schists north of the Amboseli basin. This region receives 300 mm of rainfall per year and has a vegetation cover of grassland (ground cover of 10–40 per cent) and bush, with patches of bush (with a canopy cover of up to 40 per cent) on the higher, steeper hillsides. The soils are sandy clays mostly between 50 and 150 cm deep. In all three regions, the majority of hillslopes have lengths greater than 500 m and only a small proportion of the landscape has gradients greater than 0.10.

MEASUREMENT TECHNIQUE

The erosion measurement is illustrated in Fig. 1. The former position of the ground surface can be recognized (on useful plant species) from certain aspects of the form, an abrupt change in the colour and texture of the bark, or from tracing the development of the plant through a sequence of individuals on slowly eroding sites. On

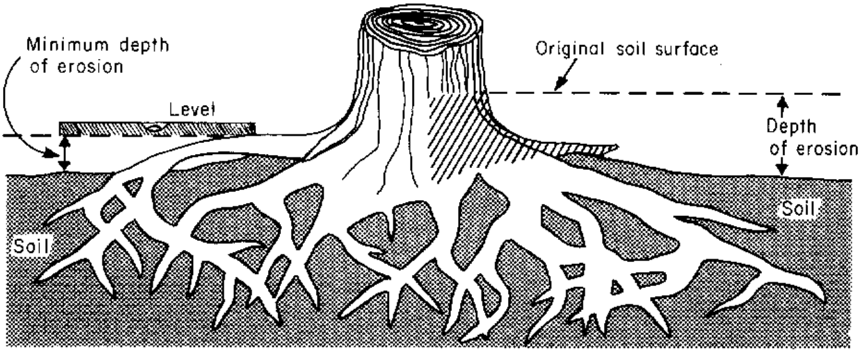

FIGURE 1. Measurement technique. On the left, the top of the root (on appropriate species) indicates the minimum elevation of the original soil surface. On some plants, a morphological feature or a change in bark texture or colour indicates the original ground elevation (right-hand side). The carpenter's level is set on a survey rod to extend measurement beyond a wide canopy.

some species it is only possible to obtain a minimum depth of erosion from the uppermost surface of roots that are known to remain underground on uneroded sites. The duration of erosion is obtained either by incorporating independent knowledge about the onset of rapid erosion (e.g. from aerial photographic records of land use), or by estimating the age of the tree from the number of growth rings or its diameter (Fig. 2). Detailed considerations concerning aging of the trees, the choice of species, recognition of erosion mounds and mounds of other origin, and ways to reduce measurement errors are described by Dunne *et al.* (1978). Here we present only some results to illustrate the value of the technique.

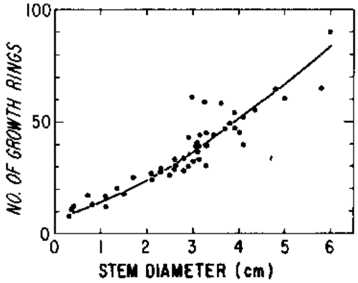

FIGURE 2. Number of semi-annual growth rings *versus* stem diameter for *A. drepanolobium* in the 500–700 mm rainfall zone.

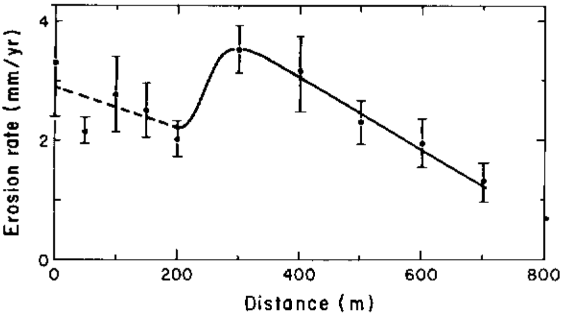

FIGURE 3. Average erosion rate and standard error (bars) along a hillslope.

On each hillside transect, topography was measured with a hand level and a tape. At intervals of 50 or 100 m the heights of the root exposures or erosion mounds were measured on the five or 10 nearest trees of the indicator species. The average erosion rate was then computed for each site. The standard error of the mean for a site was generally less than 25 per cent of the mean. Near Maralal in northern Kenya, 10 measurements at each site yielded standard errors of 10 per cent or less for means of approximately 5 mm year^{-1}.

HILLSLOPE PROFILES OF EROSION

Figure 3 indicates the mean erosion rate obtained by measuring erosion mounds under *Acacia drepanolobium* trees, 12–50 years old, along a hillslope transect on the Athi-Kapiti Plains. Error bars indicate the standard error of the mean at each station. The profiles typically had a maximum erosion rate on the central, steepest part of the hillslope, although in Fig. 3 a secondary maximum at the top of the hill is probably related to the low infiltration capacity on the planosol there. The frequency and width of soil cracks, and therefore the infiltration capacity (according to our measurements with a sprinkling infiltrometer) generally increased downhill on the Athi-Kapiti Plains.

The annual sediment yield of the hillslope can be determined by integration along the profile. For the hillslope shown in Fig. 3, the distance-weighted average erosion rate was 2.5 mm year^{-1}, which with the measured topsoil bulk density of 1.05 g cm^{-3}, implies a sediment yield of 2500 t km^{-2} year^{-1}. Other hillsides with the same rock and soil characteristics had an average erosion rate of 3.0 mm year^{-1} (3150 t km^{-2} year^{-1}). In order to estimate basin yields of sediment, we correlated erosion rate with local gradient and tried to construct maps of soil erosion from isotangent maps based on the 1:50 000 topographic series. However, the topographic base maps at this scale were not sufficiently accurate for the purpose. As an alternative the results of erosion surveys along a number of hillslope transects were combined to compute the average basin sediment yield.

When basin-average erosion rates are applied to the calculation of downstream effects, such as reservoir sedimentation, it is necessary to evaluate the sediment delivery ratio as basin area increases downstream (Agricultural Research Service, 1975). We mapped the volume of alluvium per kilometre of valley floor along several reaches of stream, and found that on the Athi-Kapiti Plains less than the equivalent of two years of sediment yield from the contributing basin was stored there. Measurements of root exposures indicated that erosion extended to the edge of the channel. Sediment is carried from these hillsides mainly as silt and sand-sized aggregates of clay. Soon after entering the stream they are dispersed and transported far downstream as wash load, so that the sediment delivery ratio is close to 1.0.

On the basement rocks, the average erosion rate during the past 10–15 years was 8 mm year^{-1} (11 300 t km^{-2} year^{-1}) and on the Kilimanjaro lavas it was 14.7 mm year^{-1} (17 600 t km^{-2} year^{-1}). The measurements were made on *Sericomopsis* bushes 2–12 years old. Erosion extends over the whole slope, and only small amounts of sediment are stored in the alluvium of first and second-order valleys. However, large amounts of sandy sediment are accumulating along the channels and flood plains of third and higher-order channels, and vast amounts of sediment are deposited on the large alluvial fans to which the region is drained. The sediment delivery ratio of the area below the fans is close to zero, so that suspended sediment records on major streams would not reflect the intensity of erosion in Kajiado district.

TEMPORAL VARIATIONS OF EROSION

Temporal fluctuations in the erosion rate can be recognized by plotting the exposure of roots of trees of various ages from one site. This is illustrated in Fig. 4 for *Acacia*

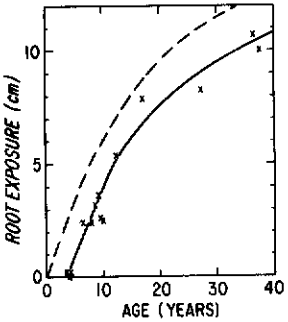

FIGURE 4. Root exposures of *A. drepanolobium* on a nine per cent gradient on the Athi-Kapiti Plains. The dashed line indicates the position of the curve through the points if 20 mm are added to each root-exposure measurement to correct for the original depth of burial of the root.

drepanolobium. One interesting result in the graph is that four-year-old trees indicate no root exposure, yet young *Sericomopsis* bushes (2–12 years old) in other areas of Kajiado district, and two to six-year-old plants in northern Kenya indicate that erosion has been rapid during that time. The most likely explanation for the discrepancy is that the root exposures, measured as shown on the left-hand side of Fig. 1, are minimum values because the root was initially some distance below the soil surface. In order that the solid curve in Fig. 4 go through the origin, and the rate of exposure indicated by the five to 15-year-old trees be preserved, the curve must be shifted to the position of the dashed line. The change indicates that the exposure was underestimated by about 2 cm, and provides a check on the accuracy of the method.

The change of slope along the curve in Fig. 4 indicates an acceleration of erosion rate around 1961 (15 years before the measurement). Before that time, the rate of exposure on this nine per cent slope averaged about 1.9 mm year^{-1}, while the mean rate over the last 15 years has been approximately 5.5 mm year^{-1}. In late 1961, a long drought was broken by catastrophic rainstorms. Heavy rainfall and high streamflow generally persisted until 1968 when a succession of drought years again depleted the vegetation cover. We do not yet have enough data to state whether such a large difference occurred on slopes less than nine per cent, and so the effect has been temporarily ignored when presenting average data in this report. However, Fig. 4 indicates that when used carefully the technique can define subtle fluctuations that warn of the occurrence of temporal fluctuations in the erosion rate even in regions without long records of sediment load. Such information can be extremely useful when one is judging the representativeness of short hydrological records which may not reflect periods of accelerated erosion and sedimentation (Dunne and Ongweny, 1976).

GEOLOGIC EROSION RATE

Average rates of erosion over the last 65 million years give an order-of-magnitude estimate of the rate to which soil erosion could be controlled if the natural vegetation

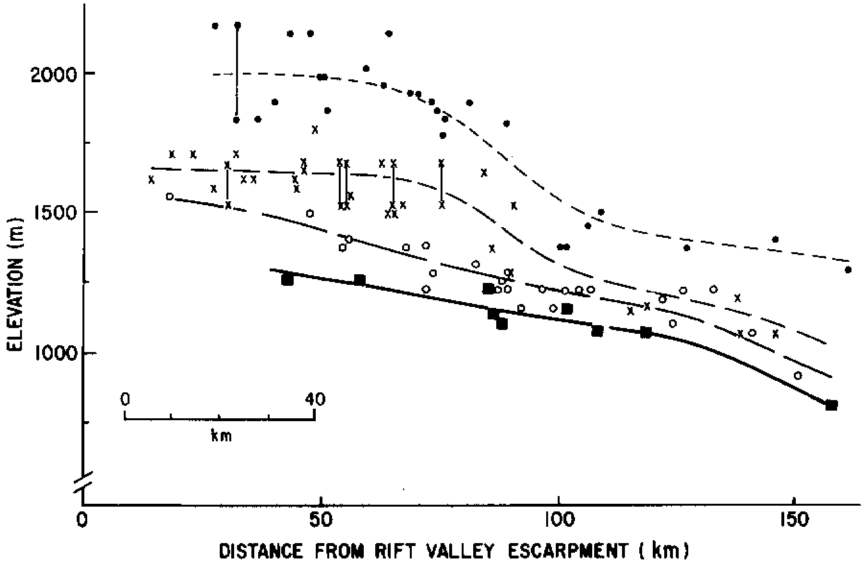

FIGURE 5. Composite profiles of erosion surface remnants along a line running southeastward from the escarpment of the Great African Rift Valley near Nairobi. Symbols represent remnants that are respectively 65 million years old (•), 24 million (x), four million (○) and the last several thousand years (■).

were allowed to re-establish itself. They also indicate the approximate rate of soil formation. In Kajiado district, geologic rates of denudation can be estimated from the differences in elevation of dated erosion surfaces that were mapped and dated by Saggerson and Baker (1965 and other authors referred to therein). We have projected these remnants onto a profile (Fig. 5) running southeastwards from a point 40 km southwest of Nairobi, and they define erosion surfaces that have been uplifted and dissected during the evolution of the Great African Rift Valley which runs north–south at zero distance on the profile. The ages of the surfaces are approximately 65 million, 24 million, four million years, and the present. Our sites on the Athi-Kapiti Plains lie at 15–35 km along the profile, while the Amboseli basement and Kilimanjaro lava sites lie opposite 120 and 150 km respectively.

The surfaces indicate an average erosion rate of about 0.0084 mm year^{-1} during most of the Tertiary period (65 million to four million years ago) when the climate was moister than at present and the region probably had a woodland cover (Hamilton, 1973). This denudation rate is equivalent to 22 t km^{-2} year^{-1} of sediment and solutes from a rock with a density of 2.65 t m^{-3}, which is similar to present yields from forested basins with about 100 mm year^{-1} of runoff (Dunne, 1978, 1979) and 750 mm year^{-1} of rainfall.

In the late Pliocene the regional climate is thought to have become drier and since then to have fluctuated between conditions slightly wetter and slightly drier than the present (Hamilton, 1973; Bonnefille, 1976). During the late Tertiary and Quaternary periods the vegetation became more sparse and the denudation rate increased to about 0.029 mm year^{-1}, which is equivalent to the removal of 77 t km^{-2} year^{-1}. This rate is in the range of current sediment and solute yields (50–140 t km^{-2} year^{-1}) from lightly-grazed, semiarid drainage basins with high sediment delivery ratios (Dunne, 1978, 1979). During the Quaternary period the denudation rate probably varied as the vegetation fluctuated between the relatively dry glacial periods and relatively wet interglacials, and current erosion is occurring in deep clay-rich subsoil or saprolite that was probably developed during a moist interflacial period.

The transport of solutes by rivers in the semiarid regions of Kenya is so low (approximately 1–5 t km^{-2} year^{-1}) that the rate of chemical weathering and soil formation must be very low. Over the past 65 million years the average rate of soil formation must have equalled the average erosion rate which was of the order of 0.01 mm year^{-1}. The rate in the present semiarid climate must be of the same order, and is therefore insignificant by comparison with current erosion rates.

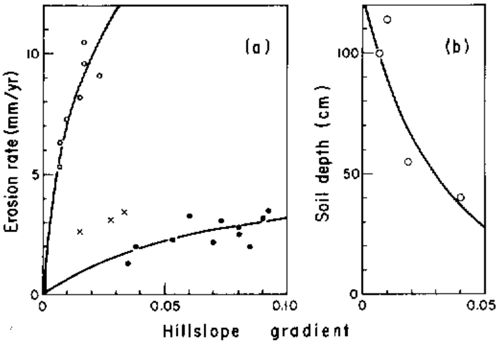

FIGURE 6. (a) Erosion rate *versus* local gradient for three hillslopes. ●: tuff soil, average ground cover of 75 per cent. x: tuff, 50 per cent cover. ○: basement soil, 11 per cent cover. (b) Variation of soil depth with hillslopes gradient on basement schist, Amboseli.

LIFESPAN OF THE SOIL

If erosion greatly exceeds the rate of soil formation the soil profile will soon be exhausted, and weathered bedrock will emerge at the surface. Variation in the rate of soil erosion as a function of gradient (Fig. 6a) will lead to differences in the timing of such emergence. These differences may be accentuated if soil depth is inversely related to gradient.

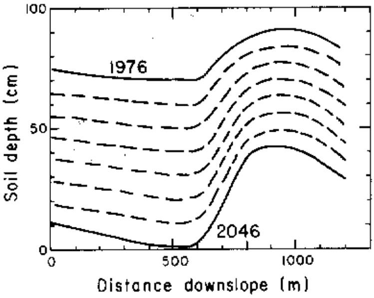

FIGURE 7. Predicted soil depths for successive 10-year intervals along a typical hillslope on the Amboseli basement. The calculation was made under the assumption that erosion rates during the past 12 years will continue.

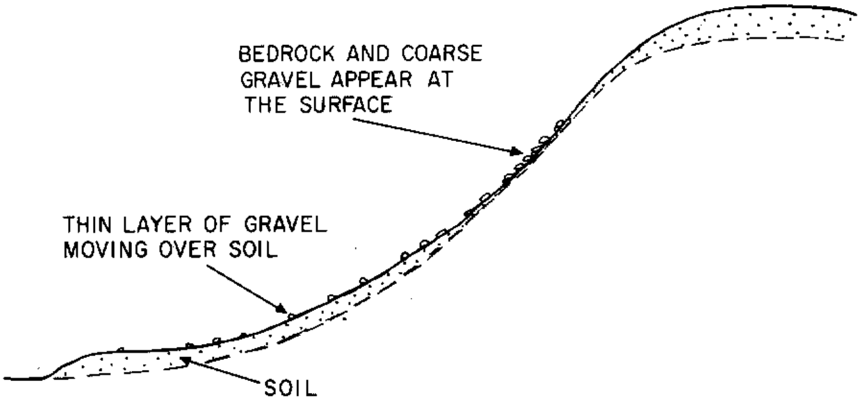

FIGURE 8. Earliest stages of soil stripping from a hillside.

To illustrate the effects of continued high rates of erosion we present a calculation for a typical hillslope on the Amboseli basement. The only available root exposure data (Fig. 6a) are for the last 12 years and, as discussed above, can be considered 'worst case' rates of erosion. The rate of soil formation should be subtracted from erosion rate, but because formation is so slow at Amboseli (see above) it can be ignored. We defined the variation of soil depth with gradient (Fig. 6b) from a few pits along or near the hillslope profile. A regional relationship between depth and gradient could be developed as illustrated for a different climate by Dietrich and Dunne (1978, Fig. 1), although in semiarid grasslands, local differences in rock structure, grazing intensity and other factors can have an extreme effect on soil depth. Figure 7 shows the projected soil depth along a typical hillslope profile. Because local differences in erosion cause changes in local gradient we recomputed slope along 400 m intervals after each 10 years of erosion. The effect is negligible in the case illustrated, but becomes important on hillslopes that are strongly convexo-concave.

Within 75 years from the initial measurements the steepest section in the middle of the hillslope will be eroded to the broken upper surface of the underlying bedrock, and gravel will appear at the ground surface and will be spread downslope by overland flow and creep, as illustrated in Fig. 8. Western and Dunné (1979, Fig. 3) illustrate the effects for a steeper and more intensively grazed hillside 10 km west of the example in Fig. 7. The increased runoff on the exposed bedrock will tend to increase the magnitude of erosion downslope. However, this will be offset by armouring of the surface. We have not yet determined the relative importance of these counteractive processes and so we have not computed soil loss beyond the first emergence of weathered bedrock.

A more approximate method for predicting soil removal involves computing the proportions of a region that have specified values of gradient and calculating the life span in each category. A 'best case' estimation using average erosion rates over the past 50 years suggests that 50 per cent of the Amboseli and Kilimanjaro lava will be stripped of soil in about 120 years, but that soil will remain on at least one half of the Athi-Kapiti Plains for at least 400 years (Dunne *et al.*, 1978, Fig. 8).

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