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Recent and past erosion rates in semi-arid Kenya

by

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with 8 figures

Zusammenfassung. Man kann die geologische Erosionsgeschwindigkeit im semiariden Kenia von känozoischen Abtragungsflächen und von der rezenten Größe des Sedimenttransports in gering beweideten Abflußgebieten berechnen. Während des größten Teiles des Tertiärs war die durchschnittliche Erosionsrate $8 \cdot 10^{-6}$ m/Jahr und hat sich während des Pliozäns und des Quartärs auf $29 \cdot 10^{-6}$ m/Jahr vergrößert. Die erstere Geschwindigkeit ist heute typisch für die feuchten Gebiete in Kenia, und der größere Betrag wird in wenig beweideten trockenen Regionen beobachtet. Aus Meßwerten für die chemische Abtragung kann eine Obergrenze von 10^{-5}/m/Jahr als heutige Rate der Bodenbildung angegeben werden, und selbst in wenig beweideten Gebieten ist der derzeitige Erosionsbetrag sehr viel größer. Man kann den erhöhten Bodenabtrag verursacht durch intensive Beweidung durch Messung aus dem gesamten Einzugsgebiet erfassen. Aber bessere Angaben kann man erhalten, wenn die Hangabtragung durch Baumwurzelentblößung gemessen wird. Mit diesen Messungen ist es möglich, die Effekte der Pflanzendichte und der Hangneigung zu quantifizieren. Wir haben eine rezente Vergrößerung der Abtragung über eine weite Region beobachtet. Die gemessenen Erosionsraten erlauben eine Vorhersage der Geschwindigkeit, mit der das Bodenprofil gekappt und schließlich ganz entfernt wird.

Summary. The geologic background rate of erosion in semi-arid Kenya can be calculated from Cenozoic erosion surfaces and from the current sediment yields of lightly grazed catchments. Throughout most of the Tertiary the rate averaged 8×10^{-6}m y^{-1}, and accelerated to 29×10^{-6} m y^{-1} during the Pliocene and the Quaternary. The former rate is typical of moist regions of Kenya today, while the higher rate is observed in lightly grazed dry regions. From measurements of chemical denudation, an upper limit of 10^{-5} m y^{-1} can be placed upon the present rate of soil formation, and even in lightly grazed areas this value is greatly exceeded by the present rate of erosion. The accelerated soil loss due to heavy grazing can be documented from catchment studies, but more information can be obtained through measuring hillslope erosion by means of tree-root exposures. With these measurements it is possible to quantify the effect of cover density and hillslope gradient on erosion. We have also recognized a recent acceleration of erosion over a wide area. The measured erosion rates can be used for predicting the rate of soil profile thinning and ultimate removal.

Résumé. Dans les régions semi-arides du Kenya, on peut obtenir quelques données de base sur le taux géologique d'érosion d'après quelques superficies d'érosion cenozoïques et d'après le transport de sédiment des bassins versants peu dérangés. Pendant la plupart de la période tertiaire, le taux moyen était 8×10^{-6} m/ann et celui-ci est monté jusqu'à 29×10^{-6} m/ann pendant la Pliocène avancée et la Quaternaire. Le premier taux est actuellement celui des régions humides du Kenya, et on peut mesurer le taux le plus haut dans les régions semi-arides et boisées. D'après quelques données concernant la dénudation chimique on peut mettre une limite supérieure de 10^{-5} m/ann au taux actuel de la formation du sol. Même dans les régions peu dérangées le taux d'érosion est beaucoup plus rapide que ce chiffre. On peut définir l'augmentation de l'érosion due a l'élevage intensif en étudiant des bassins versants. Cependant, on peut obtenir plus d'informations en mesurant l'érosion des pentes à partir des racines d'arbres hors du sol. D'après ces mesures il est possible de quantifier les effets de la couverture végétale et la déclivité sur l'érosion. Nous avons aussi constaté une augmentation récente de l'érosion dans une vaste région. On peut aussi utiliser les taux mesurés pour prédire la durée de vie du sol.

Because of their generally thin vegetation cover semi-arid regions experience high rates of erosion, even without the influence of man. With human activity the rate of soil loss is greatly accelerated and leads to the current concern for the future of vast areas of the semi-arid tropical world. In this paper we present some data on the geologic background rate of erosion in the drier regions of Kenya, and then document the acceleration of soil loss under a range of controlling variables. For this documentation, commonly-used data on catchment yields of sediment are not very useful and it is necessary to measure soil erosion on individual hillsides. We discuss the potential and the limitations of making such measurements from tree-root exposures. Finally, we consider the possibility of predicting the lifespan of soils.

Physical geography of Kenyan rangelands

The grazing lands of Kenya occupy the lowland regions of the country and receive less than about 700 mm of rainfall per year (100 mm of runoff). This study refers to the southern part of Kenya, shown in fig. 1. The rainfall occurs in

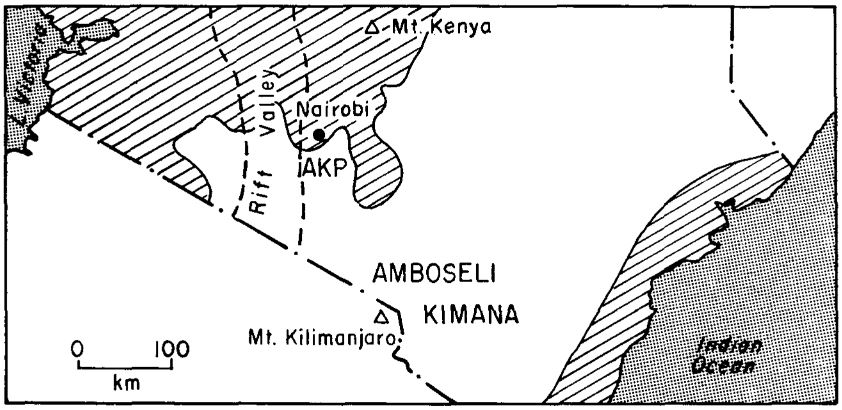

Fig. 1. Map of southern Kenya showing the three localities at which tree-root exposures were measured. AKP represents the Athi-Kapiti Plains. The unshaded areas are the rangelands in areas with less than 700 mm of rainfall per year.

two wet seasons with intervening severe droughts. Vegetation cover consists of grassland, bush and dry woodland depending upon rainfall and the type and intensity of grazing. Canopy cover ranges from zero to 50 percent. Basal ground cover (measured after the ground cover has been heavily grazed or clipped varies with rainfall from 10 to 40 percent.

The soils have developed on Cenozoic volcanic rocks and on schists of the Precambrian Basement Complex. In regions with 300—500 mm of rainfall the soils are sandy clay ultisols containing little organic matter (generally less than 0.5% by weight in the upper 10 cm) and have a poorly developed structure. Their infiltration capacity, measured under a rainfall simulator, averages 2 to 2.8 cm/hr and their depths range from 0.1 to 2.0 m, but are mostly in the range 0.5—1.0 m.

In regions which currently receive more than 500 mm of rainfall the soils are swelling clays which vary in degree of cracking and depth of soil according to their positions on hillslopes. The depth and degree of cracking increase downslope as the soils grade from planosols through rendzinas or phaeozems into vertisols, which can absorb large amounts of water at the onset of rain. Their infiltration capacity in the early part of a rainy season exceeds 5 cm/hr. The cracks close gradually through the wet season and the soils become essentially impermeable after the accumulation of about 400 mm of rain during a particularly wet season, but during most years these cracking clay soils shed less runoff than the ultisols.

Most hillslopes are 0.5 to 2.0 km long, and while limited areas have gradients exceeding 0.10, most gradients are less than 0.05.

Geologic background rate of erosion

The geologic erosion rate can be estimated from differences in elevation of dated Cenozoic erosion surfaces, and from the solute and sediment yields of a few catchments that are grazed only lightly. The results, which will be published in detail elsewhere, indicate that through most of the Tertiary when the climate was moister than at present the denudation rate averaged 0.0084 mm y^{-1}, equivalent to a yield of 22 t km^{-2} y^{-1} of sediment and solutes from a rock with a density of 2.65 t m^{-3}. Such a yield is similar to those of forested Kenyan catchments receiving 750 mm of rainfall today. During the late Pliocene and Quaternary, as the climate became generally more arid and the vegetation cover became thinner (HAMILTON 1973; ANDREWS & VAN COUVERING 1975; BONNEFILLE 1976), the denudation rate accelerated to 0.029 mm yr^{-1}, (77 t km^{-2} y^{-1}), as FAIRBRIDGE (1964, 1969) has hypothesized. The rate may have been as high as 0.075 mm yr^{-1} (200 t km^{-2} y^{-1}) during the drier glacial periods. Current yields of solutes and sediment from lightly grazed, semi-arid catchments range from 50 to 140 t km^{-2} y^{-1}, close to the Quaternary values.

Catchment studies of erosion rates

Suspended sediment yields from six semi-arid catchments, subject to heavy grazing, range from 108 to 20,000 t km^{-2} y^{-1} and are extremely sensitive to variations of both mean annual runoff and catchment steepness.

There are limitations, however, in the use of basin sediment yields for studying erosion. First, the calculations are limited to the period of hydrologic record, which is usually too short to sample the vagaries of rainfall and runoff. Second, few rivers in semi-arid regions are gauged. Large amounts of sediment can be eroded from hillsides and deposited in swales, floodplains and fans without being recorded at a station on a major river. Furthermore, one has a measurement at a single point, and from that measurement inferences are drawn about an area. The types and the spatial variation of erosion within the catchment cannot be determined by this method. Yet these aspects of erosion are often the most important ones for a study of either hillslope development or the effects of land use on erosion under various combinations of hillslope length and gradient, soil type and vegetation cover.

Hillslope measurements of erosion rates

The two most commonly used methods for developing a spatial view of erosion are the entrapment of soil washed from small plots and the repeated measurement of ground surface elevation against stakes. The techniques work well and give useful answers when practiced for many years. They are, however, subject to vandalism, and the observer must wait for a discouragingly long time to obtain results.

Erosion rates can also be obtained by measuring the lowering of the ground surface against a datable reference. The main advantage of such a method is the length of the record that becomes quickly available. Eardley (1967) and Lamarche (1968) showed that where erosion rates are high enough they can be measured from the degree of root exposure on datable trees. Some of the uncertainties in the method are reviewed by Lamarche.

In the rangelands of Kenya, erosion rates are so high that roots become exposed during the lifetimes of quite young trees and even small bushes, which grow with their roots underground on flat areas but which show obvious root exposures on hillslopes with a poor ground cover and signs of intense erosion. Other trees are surrounded by a mound of undisturbed soil which has the same diameter and general outline as the tree canopy. These root exposures and mounds are expressions of the minimum amount of erosion that has occurred during the life of the tree. Rapp et al. (1972) have noted this in Tanzania, where mounds indicate erosion rates of about 1 cm y^{-1}. As with any approximate field technique, this method of obtaining erosion rates is subject to several problems of interpretation and of measurement error, but with care these problems can be reduced.

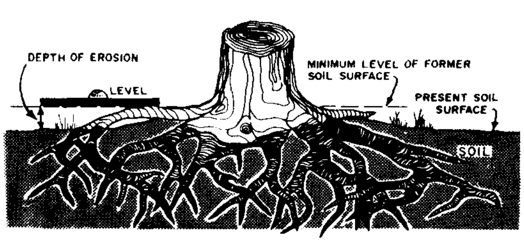

Fig. 2. Method of measuring the minimum depth of soil erosion from tree roots. Some species indicate the former position of the ground surface by a change in bark texture or some other morphological feature higher on the trunk.

The technique of measurement is illustrated in fig. 2. A careful choice of plant species is vital to success. The first step should be a careful examination of the chosen species on flat or heavily vegetated, uneroded sites to avoid plants whose roots eventually grow above the surface even without erosion, or which produce their own mounds by lifting the soil around them as they grow. If uneroded sites are not available, the investigator can examine a series of plants with different ages to observe the change in the ground surface elevation relative to some easily recognized part of the plant as erosion proceeds.

After examining a number of plant species in southern Kenya, we chose: *Acacia drepanolobium*, a small tree with ages ranging up to 50 y; *Acacia tortilis*, a larger tree up to 80 y old; and *Sericomopsis pallida*, a shrub with ages up to 12 y. Near Maralal in northern Kenya we have also used *Olea africana* and *Acocanthera* sp.

Some plants (e.g. *A. drepanolobium*) regenerate from old stumps or root stocks. The height of the erosion mound, therefore, may be related to the age of an older plant. Each individual must be carefully examined and discarded if it grows from stump.

It is also important to recognize mounds which may be produced by other agencies. Termites often build mounds around trees and shrubs. Deposition of sediment by wind or water around low shrubs produces mounds in some areas. These mounds can be recognized by their loose texture, their lack of pedogenic structures, and the fact that they often bury low branches or the bark of stems.

Mounds in compressible, clay-rich soils could also be produced by animals trampling the soil around each plant. Our measurements of mound height were made soon after a wet season, during which the clay surface layer had expanded and was no longer compacted.

Another agency producing mounds on poorly-drained clay soils seems to be the process of vertisol formation itself. On the best developed vertisols, mounds surround *A. drepanolobium* as well as other shrubs and forbs. The diameters of these mounds are not related to the size of the canopy and their sides are steeper than those of erosion remnants. These mounds were avoided in measuring erosion.

The ages of some trees and shrubs can be determined by counting the number of growth rings in the main stem if it is known how many growth rings develop per year. Dr. D. WESTERN (pers. comm.), who has been measuring plant production in southern Kenya for many years, informs us that even in dry years trees and shrubs manifest two flushes of foliage growth per year. Each flush should be accompanied by the fixation of a ring of woody tissue. In the aging of trees, therefore, we have assumed that two growth rings represent one year. This assumption is not likely to be grossly inaccurate, and minor errors would not alter our general conclusions.

We measured tree-root exposures and the heights of erosion mounds on 14 hillslope profiles in southern Kenya. Ten lay on volcanic and metamorphic rocks of the Athi-Kapiti Plains, 20—40 km south of Nairobi (see fig. 1); three were measured on the lavas at Kimana, and one on the Basement rocks near Amboseli.

Each erosion survey involved measuring a topographic profile of the hillside. At intervals of 100 meters along each profile the heights of root exposures or erosion mounds were measured under the five nearest plants of the indicator species. The average erosion rate for the five plants was then computed for each site.

The results can be used first of all to map erosion for each hillside, as shown in fig. 3. The erosion rate is greatest at the steepest, central part of the hill, but is also substantial even on the gentle footslope near the channel[1]. Soil removed from the upper slopes, therefore, is not deposited on the footslopes. The eroded material (70% clay) is fine enough to stay in motion until it reaches a channel.

Integration under the curve in fig. 3 gives the sediment yield from one hillside. In this case the distance-weighted average erosion rate is 2.5 mm y^{-1}, and

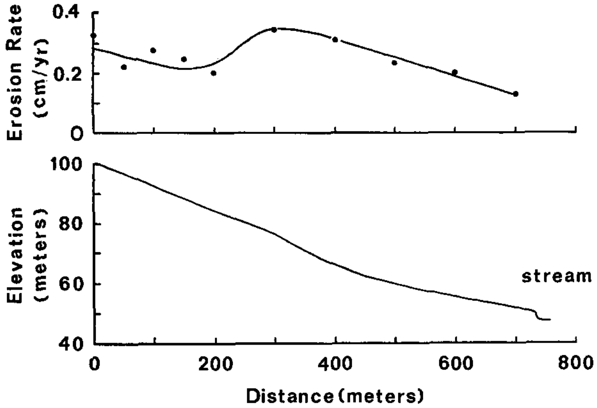

Fig. 3. Topographic profile (lower diagram) and the average soil erosion rate measured on 5 *A. drepanolobium* trees at each of 10 stations along a hillside. The age of each tree was obtained from a graph relating diameter to age for a sample of 48 trees in the area (see DUNNE 1977b).

using a typical average soil bulk density of 1 g cm^{-3} this rate is equivalent to a sediment yield of 2,500 t km^{-2} y^{-1}. The average for all hillsides (fig. 4) on the cracking clay soils was 3 mm y^{-1} (3000 t km^{-2} y^{-1}).

On the Amboseli Basement ultisols the shrub *Sericomopsis* indicated erosion

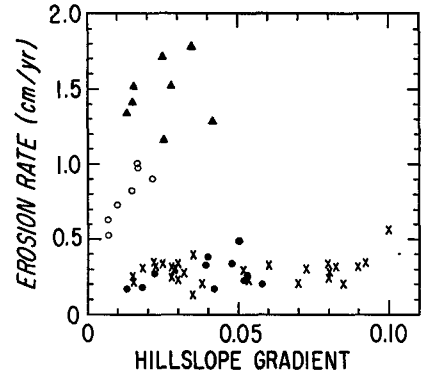

Fig. 4. Relationship between average erosion rates and hillslope gradients for various rock/soil complexes. The crosses represent clay planosols, phaeozems and vertisols on the volcanic rocks of the Athi-Kapiti Plains and the solid circles represent similar soils on the Basement schist in the same area. The open circles indicate sandy clay loams on the Basement schist near Amboseli, and the triangles relate to silty clay loams and sandy clay loams on the Kilimanjaro lavas at Kimana.

[1] Vertisolic mounds referred to earlier were not present on the footslope shown in fig. 3.

rates of 5.3—10.5 mm y^{-1}, depending upon the gradient of the measurement site, as shown in fig. 4. The distance-weighted average erosion rate is 8.0 mm y^{-1} (8,000 t km^{-2} y^{-1}). On Kilimanjaro lavas at Kimana, east of Amboseli, erosion rates measured on *Sericomopsis* bushes averaged 14.7 mm y^{-1} and ranged from 11.6 mm y^{-1} on a hillside gradient of 0.015 to 17.8 mm y^{-1} on a gradient of 0.036.

The first striking result portrayed in fig. 4 is the magnitude of the erosion rates. They are of the same magnitude as rates from much steeper rangelands in other parts of the world (Lusby 1965; Leopold et al. 1966; Rapp et al. 1972).

The averages for the three rock/soil complexes are strikingly different and the data show almost no overlap. The most important variable affecting erosion rate was found to be cover density, as shown in fig. 5, where we have plotted data from different soil types and gradients together. We also conducted plot experiments during which we measured soil loss under simulated rainstorms with a variety of runoff rates, hillslope gradient and cover density (Dunne 1977). When corrections were made for these factors, the results indicated the same pattern as that shown in fig. 5. Erosion rates accelerated dramatically as ground cover decreased below 20 to 30 percent. The relationship in fig. 5 is very close to that predicted for the effect of cover density in recent developments of the Universal Soil Loss Equation (US Soil Conservation Service 1975).

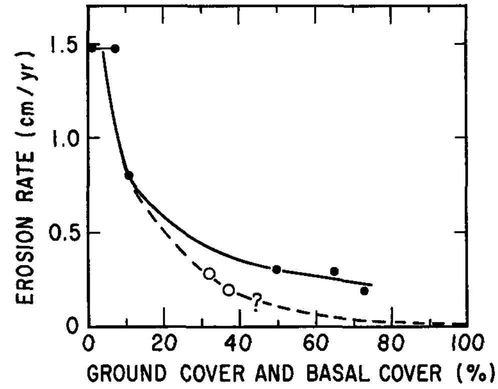

Fig. 5. Relationship between average erosion rate and ground cover in August—September, 1976 (solid circles and solid line). The open circles and the dashed line show how the relationship changes if basal cover is used for the points from the Athi-Kapiti Plains. In August and September, 1976, the ground cover at Amboseli and Kimana was already grazed down to its basal condition.

Temporal variations of recent erosion rates

Erosion rates vary from year to year as rainfall and vegetation cover fluctuate. More significant are variations over periods of a decade or longer. Such variations raise the question of whether current rates of erosion should be extrapolated into the future.

We have measured root exposures on trees of different ages at a few sites where all other conditions are equal. At all of these sites in both northern and southern Kenya we have obtained results, such as those shown in figs. 6 and 7, which indicate a significant acceleration in the rate of soil loss.

There seems to have been a three- to four-fold increase in the erosion rate which began approximately 10 to 15 years before 1976. Throughout Kenya the sediment loads of rivers increased dramatically in late 1961 and remained high during a sequence of wet years until 1968, after which there was a decrease (Dunne & Ongweny 1976).

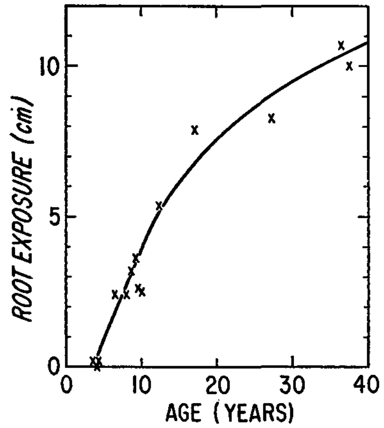

Fig. 6. Root exposures measured in 1976 on *A. drepanolobium* trees with different ages on a single gradient (0.09) and under a single cover density on the Athi-Kapiti Plains.

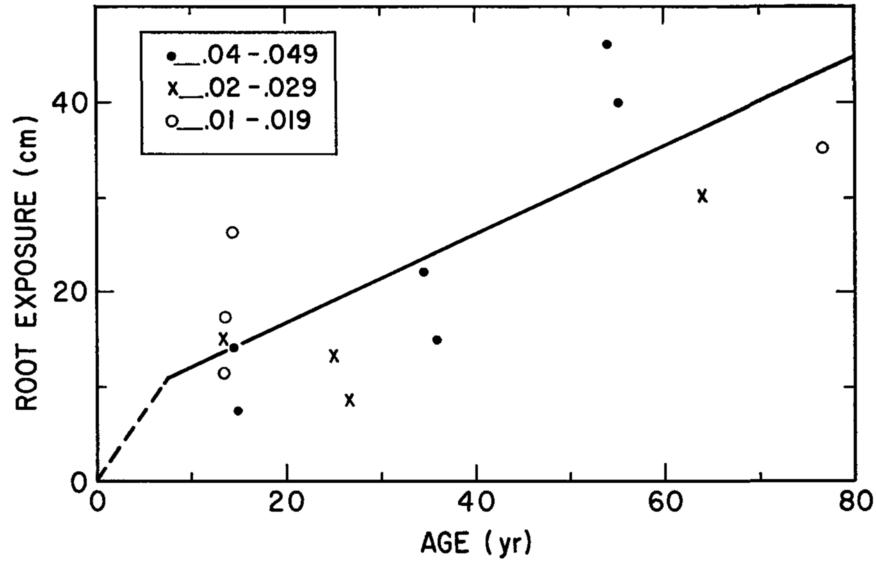

Fig. 7. Root exposure measured under *A. tortilis* trees with different estimated ages on gradients of 0.013 to 0.042 on three hillslopes near Kimana. The average rate of erosion obtained from 2 to 8-year old *Sericomopsis pallida* bushes on the same hillside is added as a dashed line for comparison. The ages of the *A. tortilis* trees are approximate because they were based on a growth rate calculated from only two measurements. The *Sericomopsis* bushes were dated by counting growth rings on each individual used for an erosion measurement. The symbols indicate the local hillslope gradients on which the measurements were made.

Rates of soil formation

Rates of dissolution in semi-arid Kenya are low (Dunne, in press). The yield of rock components dissolved in streamwater varies from 1.5 t km^{-2} y^{-1} under 300 mm of rainfall to 5.5 t km^{-2} y^{-1} under 700 mm. The rate of chemical weathering, therefore, must be low.

Under forest cover in the moist highlands of the country the soil erosion rate varies between 18 and 30 t km^{-2} y^{-1} and has remained in this range for millions of years, as indicated by the rates of erosion measured from erosion surfaces under thick vegetation. Since the soil profiles in those regions are only one to several meters thick, the soil formation rate must be approximately the same as the soil erosion rate, namely 0.014 to 0.024 mm y^{-1} (using a soil bulk density of 1.25 g cm^{-3}).

Because the rates of chemical denudation in the forested regions are 5 to 10 times greater than those of the semi-arid zone, it seems safe to conclude that the rate of soil formation in lowland Kenya is less than 0.01 mm y^{-1}. Therefore the soils of this region, which are now 0.5 to 2.0 m deep clays and sandy clays, must have been formed under a climate significantly wetter than the present one, probably during the last interglacial period. Even under light grazing pressure, where the catchment sediment yields are 50 to 140 t km^{-2} y^{-1}, these soil profiles are not stable under the present climate. Finally, soil erosion under heavy grazing pressure is so intense that the rates of soil formation are insignificant, and the soil profiles are being rapidly thinned, raising the question of how soon profiles will be stripped completely from hillsides.

Lifespan of the soil

The lifespan of a soil profile that is being eroded without significant replacement will depend upon the profile depth and the erosion rate, which under the conditions of cover and soil type found in each of the three areas studied, is controlled mainly by hillslope gradient.

Because of the recent acceleration of erosion, it is not clear which rate should be extrapolated into the future. It is possible that the recent succession of weather patterns (several years of drought alternating with several years of heavy rainfall) could continue because of some recent, subtle fluctuation of the global atmospheric circulation (Lamb 1966). In such a case the most recent rate should be extrapolated. Alternatively, the weather conditions extant before 1960 could be reestablished and punctuated occasionally by more erosive intervals. The weather records of the past 80 years suggest that this might have happened, and that average erosion rates over the past 50—80 years should be used for the prediction of future conditions. In view of this uncertainty, we have used both sets of figures to show upper and lower bounds on the life of the soil profile.

For each rock/soil complex in southern Kenya, we measured in the field and from maps the proportion of the landscape having gradients less than certain values. Knowing the average erosion rate and soil depth for each gradient, we then calculated the length of time required for removal of the profile over the measured proportion of the landscape, as shown in fig. 8, which predicts the rate

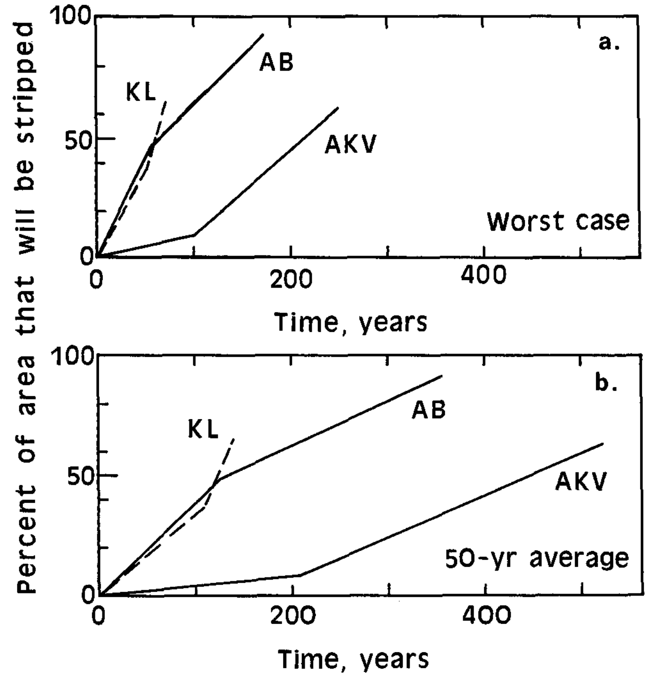

Fig. 8. Amounts of land which will have their soil cover removed completely within various periods of time in the three study areas; (a) assumes the "worst case" conditions of erosion rates from the past 15 years continuing into the future; (b) assumes the continuation of the average erosion rate from the past 50 years. AKV represents the area of volcanic rocks on the Athi-Kapiti Plains; AB indicates the Basement schists and gneisses around Amboseli; KL stands for hillslopes on the Kilimanjaro lavas.

of spreading of bare rock which today covers less than one percent of the landscape.

If the lines in fig. 8b are projected, they indicate that except for the flat ridgetops and drainage swales there will be little or no soil on the Kilimanjaro lavas within 200 y, on the Amboseli Basement schists within 400 years, and that even on the more thickly vegetated Athi-Kapiti Plains 50 percent of the landscape will be bare within 500 y.

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