soil conservation and management in developing countries

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Paper No. 7   STUDYING PATTERNS OF SOIL EROSION IN KENYA

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1. INTRODUCTION

Soil erosion is intense in many areas of developing countries because of
erosive climatic conditions, rugged terrain, and heavy land use, yet little quanti-
tative information is available about the patterns of erosion. This ignorance limits
an assessment of the real magnitude of erosion problems, or the ranking of priority
regions for the most urgent soil conservation programmes. When sites are chosen for
reservoir impoundment or other water resource development, a rapid assessment of
sediment transport is usually made but very few such studies are continued for a
long enough period to sample the vagaries of weather and flow which characterize the
hydrologic regimes of most developing countries, The accumulation of information on
soil erosion and sediment yields is usually too meagre and too late for adequate
design (Dunne and Ongweny, 1976).

The situation requires the training and support of a small number of field
scientists in developing nations who will be concerned with field assessment of erosion
and sediment transport. They should be able to take advantage of hydrologic records
which have sometimes been accumulated for years and have lain unanalysed in the files
of water-resource agencies. Such scientists should also be capable of setting up
networks of stations for the collection of data on erosion and sedimentation in hitherto
ungauged areas, and of carrying out field experiments on soil erosion. The cost
of such work would not be high, relative to its value, but the success of the work
requires a commitment to field work and continuity of purpose which is frequently
lacking.

In this paper, I review some work on patterns of soil erosion in Kenya and refer
to relatively inexpensive methods of studying erosion processes and patterns. It will
also indicate some of the gaps in our knowledge of soil erosion, particularly in
developing countries where physical and land use conditions differ from the more inten-
sively studied, commercial agricultural region of developed countries.

It is appropriate to stress from the outset, however, that the accumulation of
field measurements is not enough. In developed countries, large amounts of money have
been spent on monitoring programmes and the data have. lain unanalysed for long periods
of time. Developing countries cannot afford this waste, and the field scientist
must be encouraged to analyse data as they accumulate. This part of the scientific
training is as important as instruction in field methods.

Methods of Quantifying Erosion Rates

There are two basic approaches to the study of erosion patterns. The first
involves sampling the rate of sediment transport past some point on a river channel
at the outlet of a drainage basin. This method is relatively cheap, and it is easy
to monitor soil loss rates from large, representative areas by installing gauging
stations on a few rivers. Because the measurement of sediment loss is made at a
single point, however, it is not possible to interpret much about the spatial pattern

of erosion within the catchment. Nevertheless, sediment monitoring is the most widely used method of assessing soil erosion rates and many water-resource agencies collect suspended sediment records routinely. It is useful, therefore, to consider methods of extracting the maximum possible information from such records.

The second method of quantifying soil erosion involves direct measurement of soil removal by individual processes at a number of sampling sites within the drainage basin. By strategic location of plots, erosion pins, surveyed cross-sections of gullies and river channels, it is possible to define the spatial pattern of soil loss, and to study the local controls of erosion. If measurement sites are distributed so as to sample a range of hillslope gradient, soil types, land use, and conservation practices, for example, the effects of these variables on soil erosion can be isolated and quantified. This kind of information is necessary in the design of land-use and conservation strategies for developing countries. Yet very few measurements of hillslope erosion processes are presently being made in these lands. There is a need to encourage scientists in these countries to use the techniques that are now available. The most useful field methods are described in another paper (Dunne, 1976 a), which includes a bibliography of original sources.

Both of the approaches referred to above include systematic monitoring. The concept of environmental monitoring is gaining acceptance and support (U.N. Conference on the Human Environment, Stockholm, 1972) and we can reasonably look forward to an increase of erosion measurements in developing countries in the near future. In order to interpret the results from monitoring networks, however, it is usually necessary to carry out some controlled experiments of erosion under different condi-conditions of hillslope gradient, land use, conservation practice or other variables of interest. The most common type of controlled experiment involves measuring soil loss from small hillside plots under natural or artificial rainfall (Battawar and Rao, 1969; Dunne, 1976b; Fournier, 1967; Goel et al, 1968; Hudson, 1971; Vasudevaiah et al, 1965). The plots can be subjected to various treatments, such as removal of vegetation, trampling, or the growing of various crops. They are useful for previewing the soil erosion consequences of a range of management options.

Each of these approaches is presently being used to study the pattern of soil erosion in Kenya.

2. SEDIMENT YIELDS OF KENYAN RIVERS

During the period 1948-68, suspended sediment concentrations were measured by the depth-integrating method at a large number of river gauging stations throughout south and central Kenya (the only regions of the country which support perennial streams). At 63 stations, the data were adequate for constructing sediment rating curves. Daily discharge records from the same stations were then used in conjunction with the sediment rating curves to calculate suspended sediment yields for drainage basins covering a wide range of climate, topography, and land use. A map of mean annual suspended sediment yields was constructed from the data (Dunne, ms in preparation). Sediment yields range from 8 to 19 520 t/km^2/year. The results of this national survey can be used directly for estimating potential rates of sedimentation of proposed reservoir sites. They can also be used for an analysis of the major controls of basin sediment yields.

A great deal of attention has been directed toward quantifying general relationships between basin sediment yield and climate (Langbein and Schumm, 1958; Fournier, 1960; Douglas, 1967; Wilson, 1973). The climatic parameter generally used is mean annual rainfall, either obtained from direct measurements or calculated from mean annual runoff and air temperature. Each of the publications listed above proposes a different reationship between sediment yield and climate. Wilson, who analysed the most comprehensive set of data, concluded that differences in climatic regime and land use make it impossible to define a single rule relating sediment yield to rainfall or runoff.

The Kenyan data confirm the suggestion of Wilson, and of Douglas (1967) that land use is the dominant variable which confounds the establishment of general relations of sediment yield and climate. In Kenya, as in many other countries, land use depends partly upon climate but there are important differences of land use in each climatic zone.

In Figure 1, mean annual sediment yield per unit area of catchment is plotted against mean annual runoff. The dominant land use in each catchment is indicated by a symbol. In the absence of a detailed quantitative analysis of land use, the classification was confined to four classes: completely forested; forest covering more than 50 percent of the basin; agriculture covering more than 50 percent of the basin and the remainder under forest, and grazing covering more than 50 percent of the basin. A fifth class, lightly grazed scrub forest, contained only two basins. Even with such a coarse classification of land use, however, a pattern is evident.

The lines in Figure 1 are approximate envelopes for each set of land use symbols, and very few points fall outside the appropriate region of the graph. The envelopes do not separate the symbols completely because of differences in the ruggedness of topography, the degree to which the major land use dominates a basin, the duration of records, and the quality of the original data.

There are dramatic differences of sediment yield between land use types. For a fixed value of runoff in the figure, differences in sediment yields between land use types can vary over two orders of magnitude or more. The graph shows, however, that land use is not the only important variable. Agricultural catchments with heavy runoff may have sediment yields which are far greater than the driest grazing lands.

For each land use type, there is a general increase of sediment yields with annual runoff. The higher runoff yields are associated with heavier rainfalls and therefore with greater kinetic energy for hillslope erosion and stream transport of eroded sediment. Regression analysis for basins in each land use category yielded the following equations, all of which are significant at the 0.05 level:

Forest   Sed. yield = 2.67 $Runoff^{0.38}$ $r = 0.98, n = 4$

Forest > Agriculture   Sed. yield = 0.042 $Runoff^{1.18}$ $r = 0.75, n = 10$

Agriculture > Forest   Sed. yield = 0.038 $Runoff^{1.41}$ $r = 0.73, n = 39$

Grazing dominant   Sed. yield = 0.002 $Runoff^{2.74}$ $r = 0.87, n = 7$

The regressions are plotted in Figure 2.

Although only four forested basins were available for this analysis, the results are almost exactly the same over the range of the data as those from a similar analysis of sediment yields from 27 catchments in eastern Australia made by Douglas (1967). The Australian catchments were "selected to avoid as much human disturbance as possible". His results are shown in Figure 2.

For the other land use types, sediment yields are higher than under the complete forest cover. The exponents in the regression equations above also show that sediment yield increases with runoff less rapidly in regions with a forest cover than in cultivated lands, which in turn are less sensitive than rangelands.
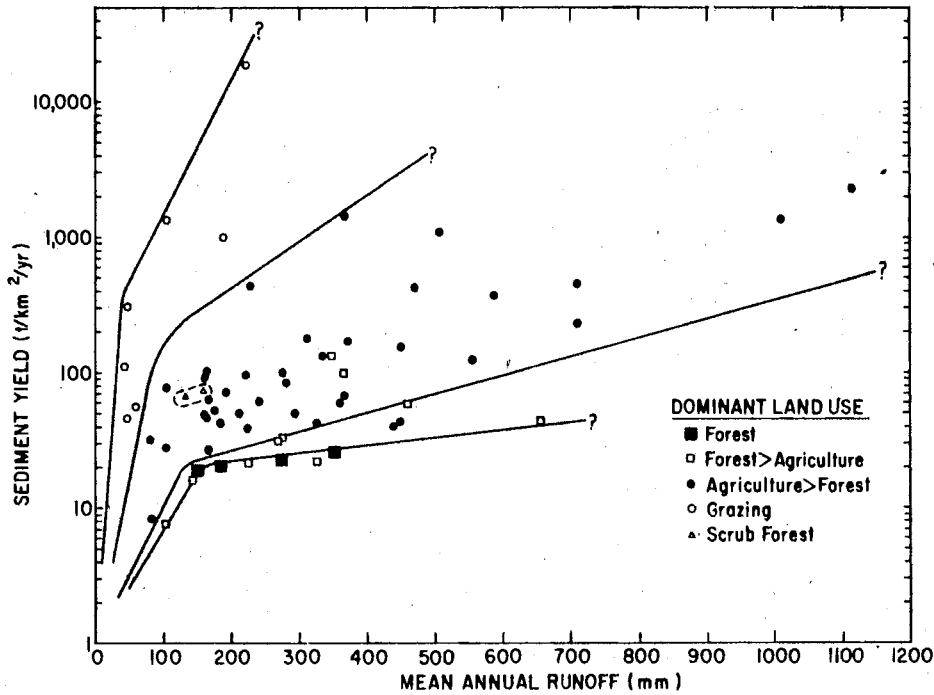
Fig. 1
Mean annual yield of
suspended sediment and
mean annual runoff for
catchments under five
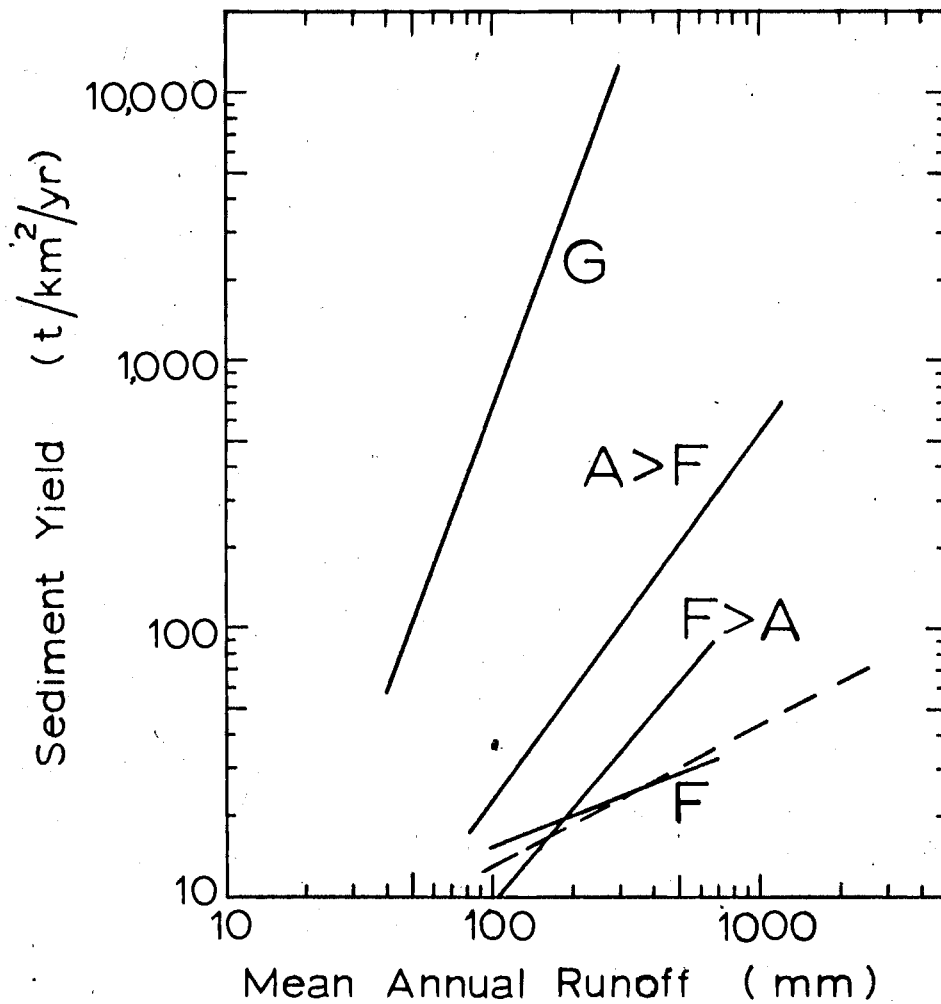dominant types of land
use

Fig. 2 Comparison of the regression lines computed for the relationship between sediment
yield and mean annual runoff for each land use type. The dashed line was computed
by Douglas (1967) for forest catchments in eastern Australia

Field observations and visual examination of the data suggested that topographic steepness is a significant factor affecting sediment yields. Measurement of the frequency distribution of hillslope angles in each drainage basin was not feasible with the resources available for this study, and a surrogate measure of basin steepness had to be used. Schumm (1955) showed that the relief·ratio of a catchment (its maximum relief divided by the length of the main stream) was positively correlated with sediment loss in Colorado.

The relief ratio was used with mean annual runoff in a stepwise multiple regression of the Kenyan sediment yields. The results were limited because most land use categories contained few points. Runoff proved to be the dominant variable in each case, but only on agricultural lands did relief ratio add significantly to the explanation of the variance in sediment yield. In the other land use classes, however, there was a positive relationship between relief ratio and sediment yield when relief ratio entered the multiple regression as a second variable, and it is likely that the effect of topography would have been demonstrated with a larger sample. The limited data also suggest that in a logarithmic multiple regression equation the exponent of relief ratio increases in the same order as that for runoff. In other words, the effect of basin steepness on sediment yield increases as the vegetation cover becomes sparser. Correction of sediment yields for the effect of catchment area by the method of Brune (1948) did not alter the general form of the results, except by increasing the sediment yields.

No bedload data are available for Kenya and so the yields referred to above underestimate the true soil loss. Field observations suggest that bedload transport is small in the volcanic uplands, where most of the eroded sediment is fine grained. The larger rivers draining the lowlands of Eastern Kenya receive considerable amounts of coarse sand from erosion of soils on schists and gneisses. Some of this material moves as bedload, but its contribution to the basin sediment yield will not be known until a programme of bedload transport measurements is undertaken.

3.   HILLSLOPE MEASUREMENTS OF EROSION

In sparsely populated dry regions, where stream flow is rare, there is little likelihood that developing nations can bear the cost of maintaining stream gauging stations for the purpose of assessing sediment yields. Under these conditions, soil erosion can be monitored directly on hillslopes. This can be done by installing plots or networks of erosion pins. Leopold et al, (1966) demonstrated how various techniques for measuring hillslope erosion processes could be used to obtain a sediment budget for a small rangeland catchment. A major problem with all field methods which involve installing even simple equipment, however, is its susceptibility to theft or disturbance.

Soil erosion rates can also be evaluated by measuring recent lowering of the surface against some dateable reference. Judson (1968) obtained rates of soil removal from the depth of exposure of Roman archaeological sites. Fence posts often show marks indicating the position of the soil surface at the time of installation. The difference between this height and the present soil surface divided by the age of the fence-line gives the soil erosion rate.

The most widespread indicators of surface lowering in some areas where erosion is intense are exposed tree roots or mounds of residual soil protected under the canopy of trees or bushes while the surrounding soil is lowered (see Fig. 3). If the tree or bush can be aged by counting growth rings (as many tropical species can, in spite of the popular misconception that tropical woody plants do not produce annual or seasonal growth rings), the height of the mound divided by the age of the plant indicates the average rate of surface lowering. In some areas the dating problem is simplified dramatically if there is evidence that soil erosion was accelerated after a period of intensive vegetation clearing. The height of the root exposure or mound can be measured simply and quickly as shown in Figure 4.

Fig. 3 An erosion mound protected by a tree canopy while the surrounding land surface
is lowered by erosion. The height of this particular mound is 60 cm
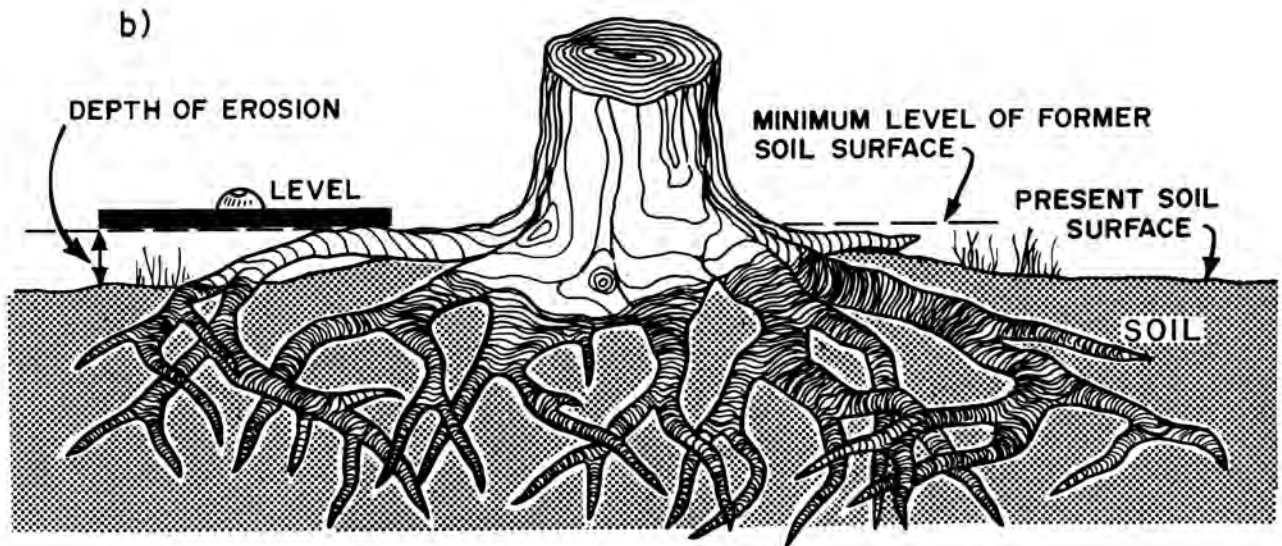

Fig. 4 Measurements of erosion rates from tree root exposures. On suitable tree
species the height of the former ground surface is located by examining the
tree for signs such as the position of the basal flare or the boundary between
trunk bark and root bark. This should be done only after examining trees in
relatively uneroded sites. A carpenter's level is then placed at the estimated
level of the former land surface and its height above the present soil surface
is measured with a ruler

Problems of interpretation arise with this method, and a great deal of care should be taken to check for potential problems in each region before the method is used there. A dateable tree species must be found and the tree-ring chronology established, or the onset of accelerated erosion must.be dated from aerial photography or other local information. Growth rings can be counted on each tree for which root exposures are measured, but this can be very time-consuming. An alternative method involves cutting down or coring only a sample of trees and constructing a graph of trunk diameter versus age for each species and region (see Figure 5). Each tree used for measuring the erosion rate can then be aged from its stem diameter.

Other sources of uncertainty arise with this method. Some trees produce their own mound by developing a wide basal flare or even by developing buttress roots above the ground surface as they grow. This problem can be avoided by choosing a species which does not have these characteristics. Careful examination of trees in sites which are not undergoing intense erosion (such as plateaux or heavily vegetated areas) should suggest the most useful tree species to use as an erosion indicator in each region. We also compare plants with a range of ages to observe how the plant, its root, and the mound or root exposure develop as the tree or bush grows.

Species, or at least individual trees, which regenerate from old stumps or root stocks should be avoided because the mound is more likely to be related to the age of the older plant than to the new stem. Termites often build mounds around trees and these must also be avoided. Recognition of this problem is not always easy, especially if the mound is no longer colonized and has been eroded. Small termite mounds can usually be recognized by their looser texture and higher organic content than surrounding eroded soils. They also lack pedogenic structures. Mounds produced by wind deposition also have a different structure and texture from the surrounding eroded area, and can be recognized through careful examination. Other sources of uncertainty are described by Eardley (1967) and by Lamarche (1968), who pioneered the method on Bristlecone pines in Utah and in the White Mountains of California.

We incorporate measurements of tree-root exposures into a general hillslope survey of topography, vegetation cover and soils, as described by Leopold and Dunne (1971). At intervals of 100 meters along the hillslope profile we measure the height of the root exposure or erosion mound under the five or ten nearest trees or bushes of the species being used in that area. The procedure illustrated in Figure 4 is carried out on opposite sides of the tree along the contour. The plant is also aged. The average erosion rate for the 5-10 plants is then computed for each site.

The data can be used for mapping the variation of erosion depth along a hillside (Dunne, 1976a, Figure 10) and therefore for computing the total amount of soil lost from a sample of hillslopes in each region. They can also be used for studying the effect of gradient on erosion, as shown for a single rock/soil complex in Figure 6. Measurements of this kind were used to quantify differences in rates of soil loss on three rock/soil complexes in Kajiado District, a heavily grazed rangeland in southern Kenya. I have quantified differences of soil erosion rates on hillslopes with differing gradients, soil types, and intensity of vegetation removal in the Maralal area of northern Kenya. The results are illustrated in Figure 7.

These field measurements show that the rate of soil erosion on even gentle gradients in Kenyan rangelands is extremely high by comparison with the rates compiled by Young (1969) for a variety of regions throughout the world. Over the last 10-20 years, soil has been lost at rates in the range of 0.1 to 0.5 cm/yr on the Athi-Kapiti plain and 0.4 to 1.2 cm/yr in Northern Kenya. These values are equivalent to yields of 1000 - 18 000 $t/km^2/yr$ depending on the bulk density of the soil. It is difficult to compare these values directly with basin sediment yields, because a portion of the soil mobilized from hillsides comes to rest in swales,
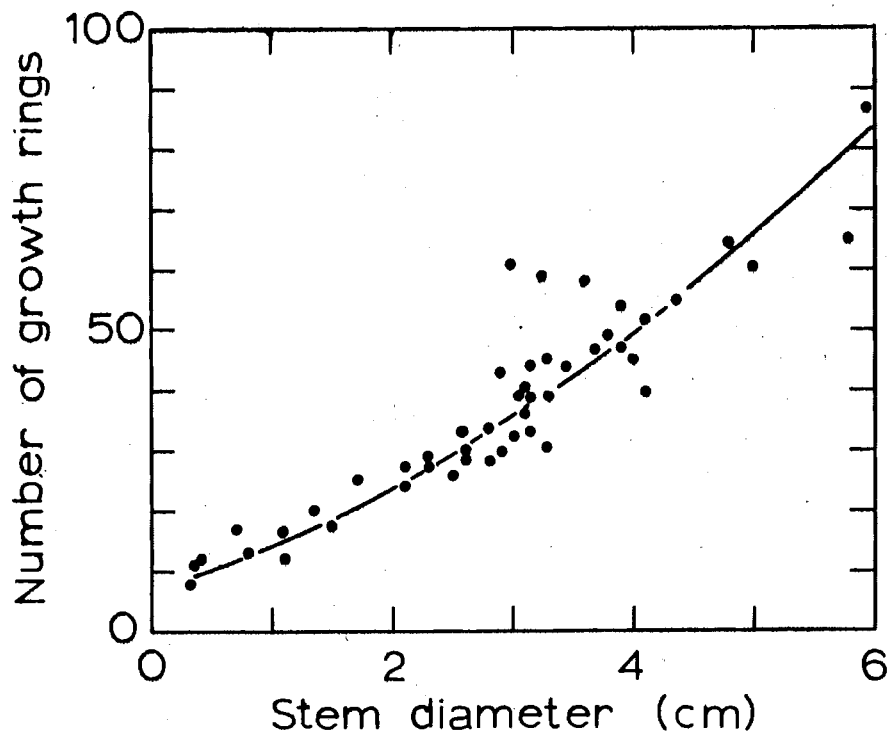
Fig. 5 Relationship between number of seasonal growth rings and trunk diameter 0.25 m above the ground surface for Acacia drepanolobium trees on the Athi-Kapiti plains of Kenya. The rings have not yet been counted under a microscope and so their numbers are still tentative. Biologists measuring plant growth in the region tell us that there are two strong growth periods in each year, even during times of low rainfall
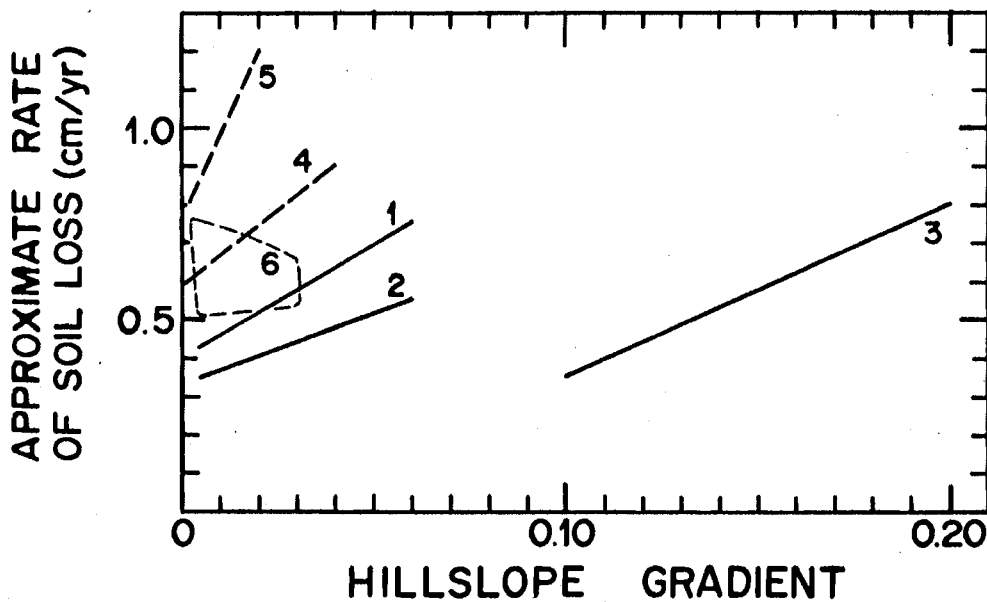
Fig. 7 Average annual rate of soil loss as a function of gradient for hill-sides on two rock types near Baringo and Maralal, N. Kenya. The granitic and gneissic Basement rocks (solid lines) weather to sandier soils than those which develop on the lavas (dashed lines). The former are more resistant than the latter to erosion
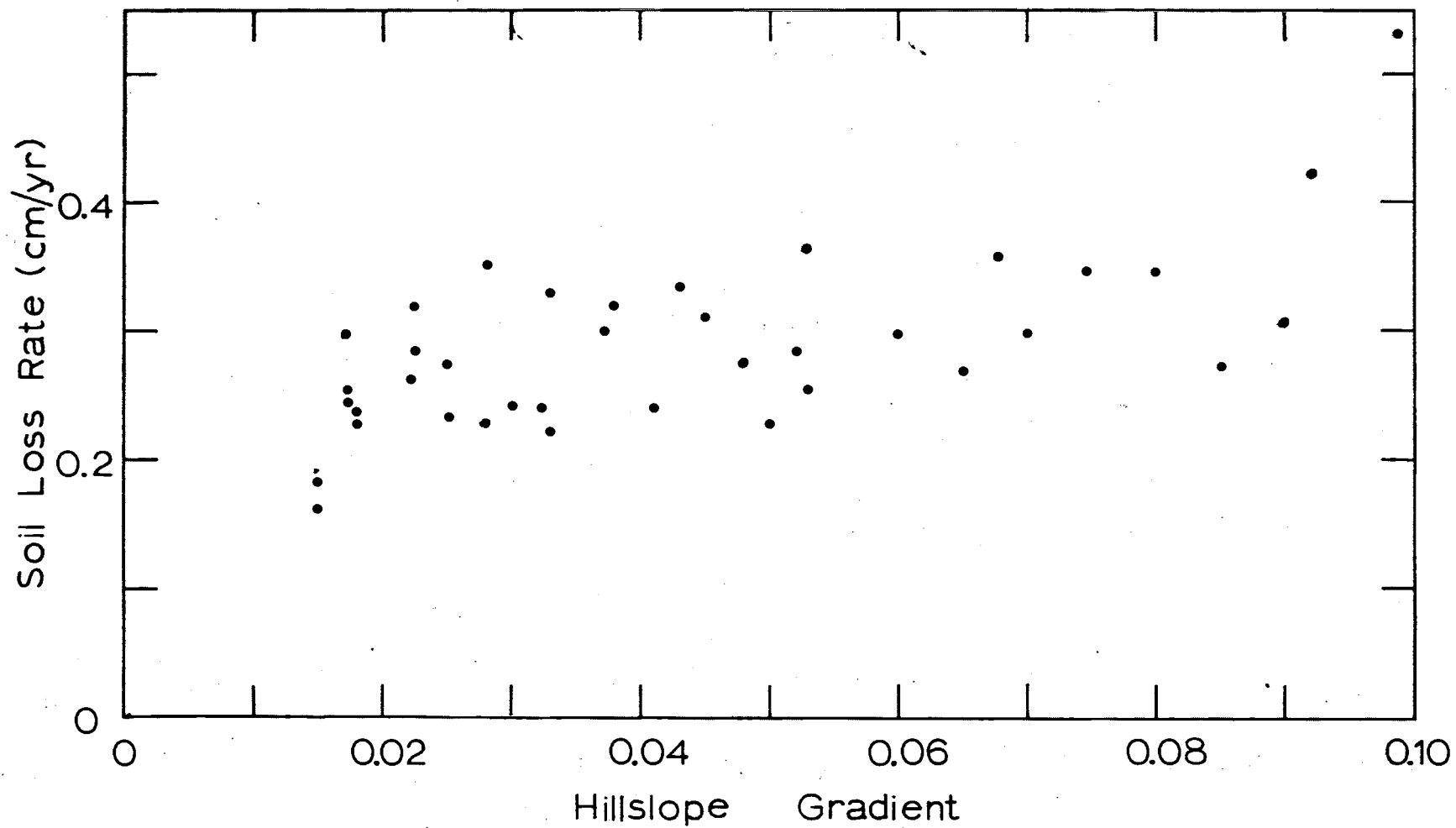
Fig. 6 Average annual rates of soil loss as a function of gradient for 38 sites on 7 grazed hillsides on the Athi-Kapiti plains of Kenya. The rates are tentative until the tree rings from which they were calculated can be checked under a high-powered microscope

floodplains, and other storage sites. The measured sediment yield per unit area for catchments usually declines, therefore, as the size of the basin increases. I know of no published information which indicates the rate at which this decline occurs for arid regions, but in moister agricultural regions of the United States, Brune (1948), Maner(1958), and Roehl (1962) have shown that sediment yield per unit area is proportional to the catchment size raised to a power of approximately - 0.15 to -0.20. Using a value of -0.20 the Kenyan rangeland sediment yields would be approximately 150-2 700 t/km²/yr at 100 km² and of 90-1 620 t/km²/year at 2 000 km². These values are in the same range as most of the basin values for the drier grazing lands in Figure 1, and confirm the evidence that soil erosion there is extreme.

This kind of simple measurement could profitably be made more widely in the rapidly eroding regions of developing countries. Two people with only a hand level, tape, carpenter's level, and rule can make an erosion survey of one to two kilometers per day, and in doing so collect a great deal of information on erosion rates and their controlling factors, In addition to costing little, the method has some other advantages over installing plots to monitor soil loss. The tree-root measurements yield data immediately, rather than the investigator having to wait three or more years to obtain usable data. Secondly the resulting calculations of erosion rate average out inter-annual fluctuations which may distort the picture over a short measurement period on a plot. Thirdly, there are no installations to be disturbed or stolen. On the other hand, monitoring of soil loss from plots or by erosion pins can yield more detailed information, such as the contribution of rainstorms of various sizes. Plots are particularly useful where the rate of erosion is less than the high values shown above, or where trees and bushes are rare. In other words, use of the two methods can be complementary.

In addition to collecting information on soil loss from hillsides we need to know more about the fate of the eroded sediment. There is very little information on this topic even in regions where soil erosion has been studied intensively and almost none for developing countries. Sediment is temporarily stored at many locations as it moves down a drainage basin after its initial release from a hillside. Such locations include footslopes, unchannelled swales, channels and floodplains, lakes and reservoirs. The amount of sediment accumulating at each of these sites is important from both an economic point of view (rates of filling of reservoirs and stock ponds) and an ecological point of view for those interested in the nutrient supply and depth of water holding sediment delivered to swales and floodplains. Our ignorance of the fate of eroded sediment is important to a full understanding of the effects of soil erosion, and could be remedied by a programme of simple, repeated topographic surveys at sites where the sediment accumulates.

4.   CONTROLLED PLOT EXPERIMENTS

To provide quantitative information on the controls of soil erosion on Kenyan rangelands, we have begun a set of controlled experiments using a portable sprinkler system which generates artificial rainstorms over a 5m by 2m plot (see Figure 8). With this system a storm of, say, one hour's duration and intensity of 7cm/hr can be applied to plots on a range of hillslope gradients on wet or dry antecedent conditions, with the grass cover in various states. With repeated irrigations of a plot to simulate a whole wet season, we can grow and cut grass to various cover densities.

But runoff and soil loss rates are monitored during the storm, and a sample of the results from one experiment are given in Figure 9. The results can be used to compare plots on the basis of infiltration capacity, total runoff, or total soil loss. Figure 10, for example, compares soil loss from three soil vegetation complexes in their typical conditions at the end of a dry season. These and similar results will be described in a set of forthcoming papers.
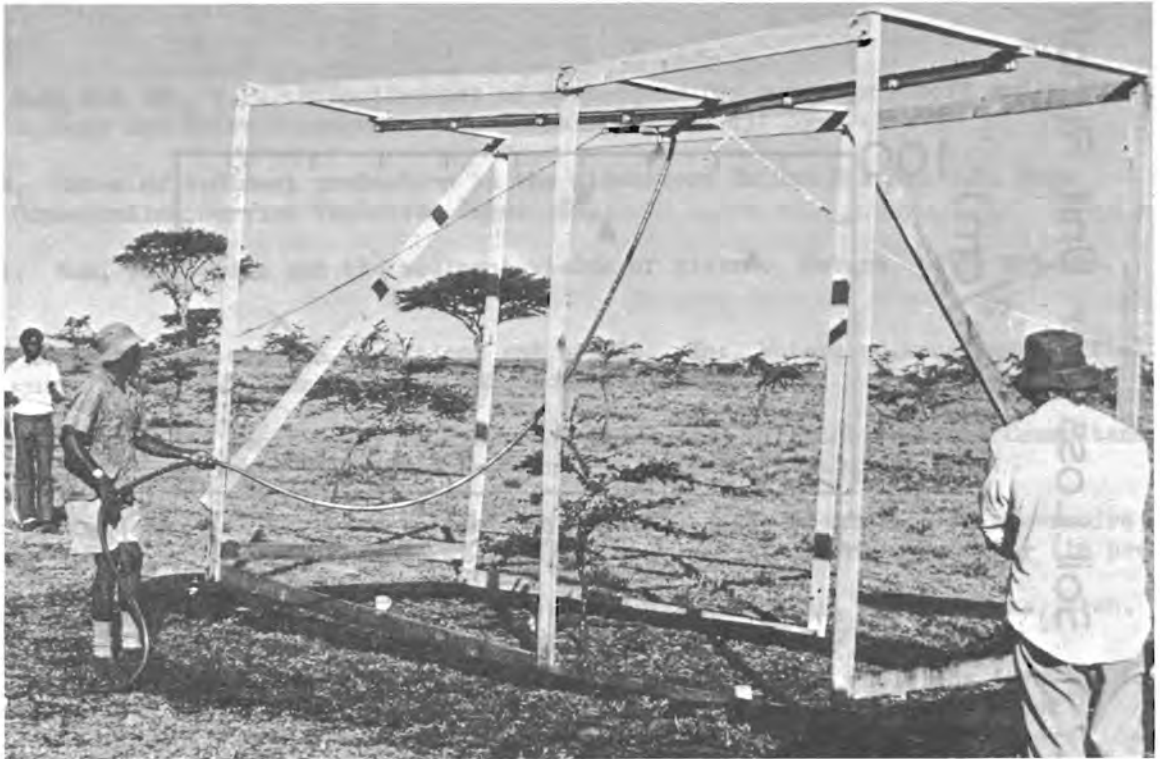
Fig. 8 The sprinkler system used for generating artificial rainstorms on hillside plots in Kajiado District, Kenya
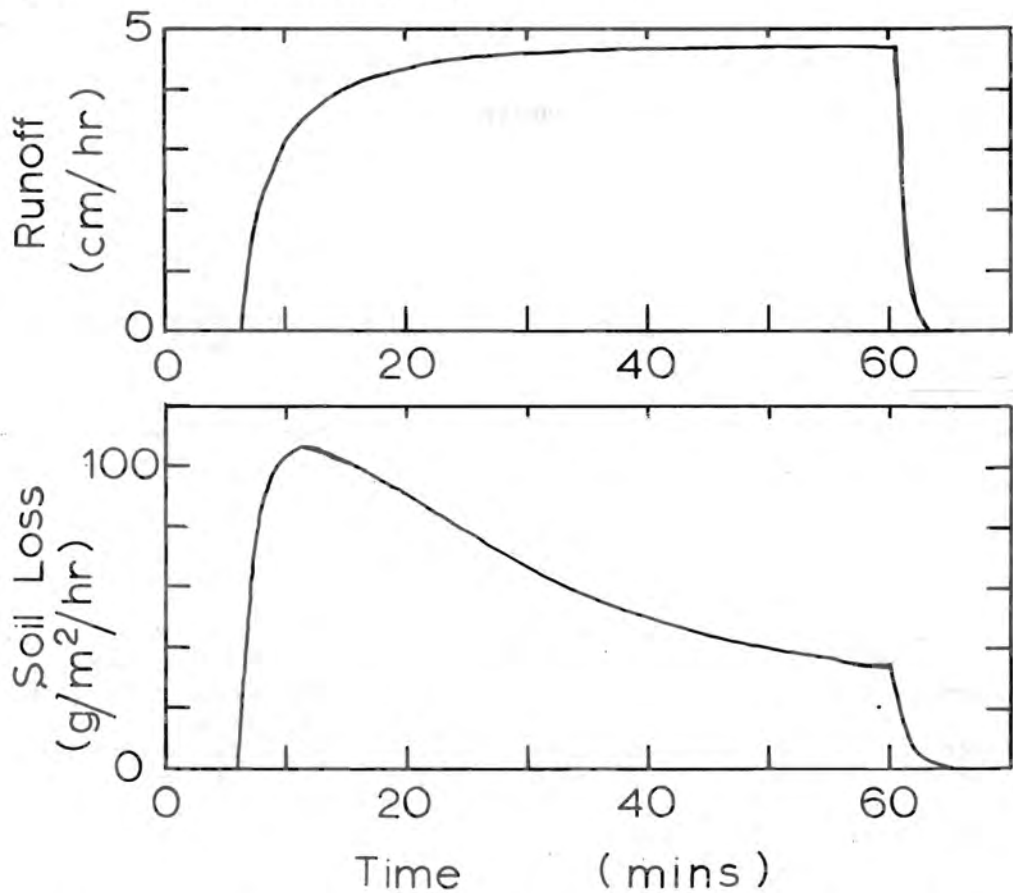

Fig. 9 Hydrographs of runoff and soil loss from a 5m x 2m plot during an artificial rainstorm. Storm duration was one hour and the intensity was 6.9 cm/hr
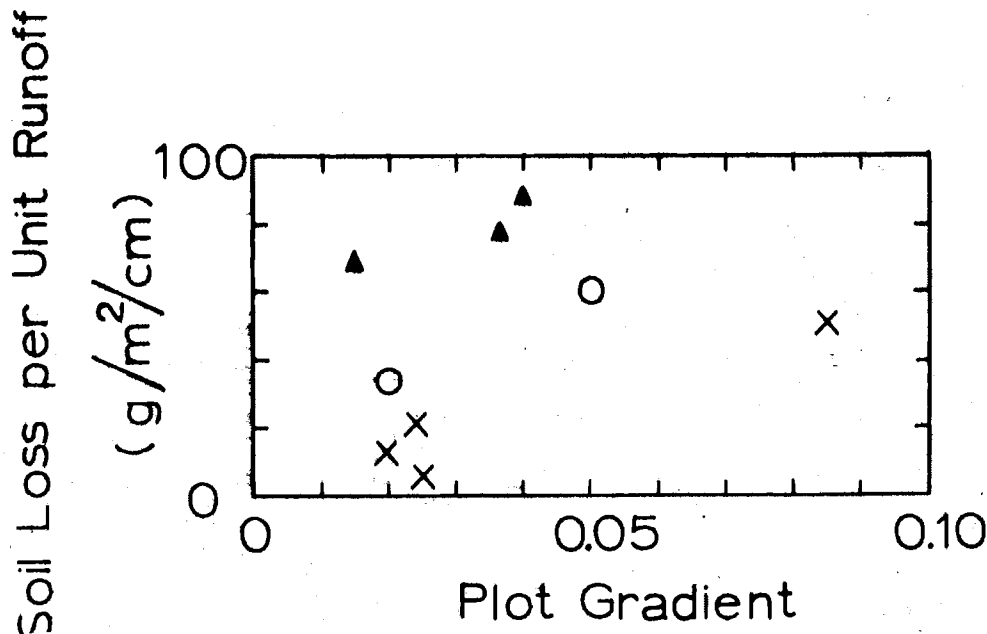
Fig. 10   Total soil loss in a one-hour rainstorm on dry conditions from plots in
their usual condition at the end of a dry season. The crosses represent
vertisolic clay soils on volcanic rocks with a ground cover averaging 65 -
85%; the circles represent sandy clay loams on schists with a ground cover
of about 10%, and the triangles indicate sandy clay loams with covers of
0 - 7% developed on volcanic rocks

SUMMARY

The purpose of the present paper is to indicate the range of approaches
available for studying soil erosion in developing countries. Most of the techniques
are simple and can be carried out by a small team of field scientists in each country.
The cost of such a programme would be small relative to its value, which was reviewed
at the beginning of this paper. There are many gaps in our knowledge of the magnitude,
distribution, and controls of soil erosion in the tropics. We do not know a great
deal about the degree to which various conservation techniques presently reduce soil
loss. In view of the present concern about "desertification" and the many pessimistic
reviews of the status of eroded lands in some developing countries, it would be
worthwhile to collect some quantitative information to form an objective basis for
decision making about soil conservation.

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