Chapter 3

Sediment Sources in Tropical Drainage Basins

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SEDIMENT SOURCES AND SEDIMENT BUDGETS

During the past decade, considerable activity has been devoted to the study and prediction of erosion and sedimentation in tropical regions. The emphasis of the work has followed American research in these fields in the sense that efforts have concentrated heavily on monitoring sediment loss from plots and to a lesser extent on measuring suspended loads, especially in large rivers scheduled for development. However, Wolman (1977) has pointed out that the vast literature on such studies in the United States often proves to be inadequate for answering important questions about the impact of land management or of water-resource development on sedimentation processes. He stressed, among other issues, the need for analysis of the modes of transport and storage of sediments as they move through a drainage basin.

We have elsewhere (Dietrich and Dunne, 1978; Dietrich et al., In press; Reid, 1981) discussed the methodological aspects of the construction of sediment budgets for drainage basins as a means of addressing some of the issues raised by Wolman for disturbed and undisturbed catchments. A sediment budget is a quantitative statement of the rates of production, transport, and discharge of detritus within a catchment. The first step in the construction of such a budget involves the identification of sediment sources, which allows the investigator to isolate the relative importance of different erosion processes contributing sediment to a

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channel. It also enables one to isolate major controlling variables, including particular aspects of land use which should be the focus of attention in programs of soil conservation. Other steps in definition of a sediment budget (not dealt with in this paper) are (a) identification of linkages between sediment transport processes, (b) definition of recurrence interval for each transport process, and (c) quantification of the volume and residence time of sediment in storage elements such as alluvial fans and floodplains.

The sediment budget is a useful tool because it deals with problems of soil erosion and sediment delivery that are not addressed by standard agronomic plot studies. Such problems include the influence of climatic fluctuations over longer time scales than the duration of plot studies, the influence of the large-scale geologic character of a region, and the importance of storage and breakdown of debris as it is transported through a catchment. The sediment budget technique is particularly valuable for predicting downstream consequences of soil erosion such as the filling of reservoirs, sedimentation on floodplains, and channel changes (Madej, In press; Trimble, In press).

Many sedimentation problems in tropical regions are currently addressed on the basis of inadequate instrumental records of streamflow and sediment transport. In one Kenyan example, a simple sediment budget demonstrated gross errors in previous estimates of the rate of reservoir siltation. The budget was based on measured tributary inputs, estimation of characteristic soil erosion rates under various land uses in Kenya, a field check for depositional sites, and taking into account large weather fluctuations that complicate hydrologic records in many tropical regions (Dunne and Ongweny, 1976). Many other planning problems in developing countries require rapid identification and quantification of sediment sources, transport, and patterns of deposition. Agronomic plot studies should be augmented with basin-wide studies of the sediment budget that incorporate hydrologic and geomorphic field observations. These skills should be taught in developing countries.

We have studied soil erosion in Kenya and Panama and are at various stages in our investigation of sediment budgets and sources. Our initial studies have been at the catchment scale, but we have made field observations and measurements that allow some interpretations about sediment sources within catchments. These interpretations suggest where future emphasis should be placed as we continue our monitoring and experimental studies.

In this paper we will review various sources of sediment in tropical catchments and discuss the relative importance of different erosive processes under a range of land use. The general state of quantitative knowledge about sediment sources in tropical catchments is extremely weak, however, and a range of field studies are needed.

BASIN-SCALE ANALYSIS

We have analyzed suspended sediment yields from 61 catchments with a range of climate, topography, and land use in the southern half of Kenya. The physical geography of these catchments and the length and quality of records are described by Dunne (1979). Because of the lack of an appropriate agricultural census, it was possible only to classify the dominant land use of each catchment into one of four categories: (1) forest, (2) forest covers 51 to 100% of a basin and the remainder is cultivated, (3) agriculture occupies more than half of a basin and the remainder is forested, and (4) rangeland. Most of the agriculture involves smallholder cultivation of maize, pyrethrum [*Chrysanthemum cinerariifolium* (Trevir.) Vis], vegetables, coffee (*Coffea arabica* L.), tea [*Camellia sinensis* (L.) Ktze.], and bananas (*Musa* × *paradisiaca* L.). The gradients of smallholdings vary from horizontal on narrow ridgetops and valley bottoms to about 70% on hillsides, although most fields have slopes of less than 50%. There is very little soil conservation apart from strip cropping. A few large estates, producing tea, coffee, wheat (*Triticum aestivum* L.), sisal (*Agave sisalana* Perr.), and sugar occupy the gentlest slopes. Most of the rangelands consist of grasslands and bushed grasslands occupied by nomadic pastoralists, who rear cattle, sheep, and goats in the presence of large herds of wild herbivores.

The sediment yields are summarized in Fig. 1, which shows that undisturbed forest catchments lose sediment at a rate of 20 to 30 metric tons/km^2/year. The yield of agricultural basins range between 10 and several thousand metric tons/km^2/year, depending on runoff, topography, and the proportion of the basin that is cultivated. Rangelands have similar variability, but sediment yields are generally high.

Forty-six of the 61 basins were independent in the sense that none was a tributary of any other. Data from these 46 were subjected to a step-

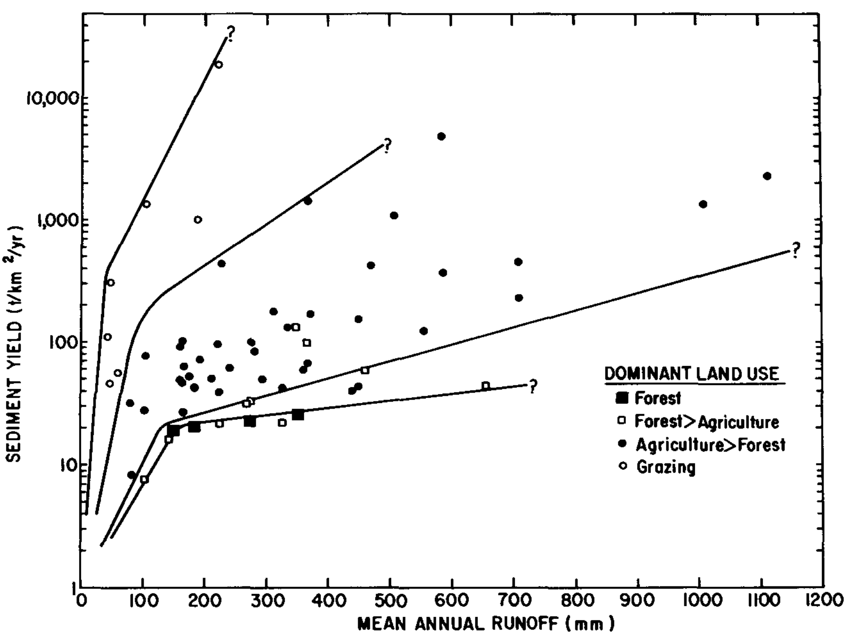

Fig. 1. Mean annual sediment yield and mean annual runoff for catchments with indicated dominant land uses. (After Dunne, 1979.)

wise multiple regression analysis (with rejection of a variable when the t-statistic was less than $|1|$) using the model

$$SY = U\,Q^{a}S^{b} \qquad [1]$$

where SY = mean annual sediment yield (metric tons/km^2/year) and Q = mean annual runoff (mm), as in Fig. 1. The latter is strongly correlated with mean annual rainfall throughout Kenya. Relief ratio (basin relief/mainstream length) was used as a dimensionless index of topographic steepness, S. Landuse was expressed by means of a dummy variable, U (Rao and Miller, 1971), the logarithm of which takes on values of zero and one in the logarithmic form of Eq. [1] according to the four categories defined above (See Dunne, 1979, for details of the method).

Land use proved to be the most important controlling variable, although it has been omitted from other regional analyses of sediment yields (Langbein and Schumm, 1958; Fournier, 1960; Jansen and Painter, 1974; Dendy and Bolton, 1976), presumably for lack of data. The full multiple regression equation which is given in an earlier paper (Dunne, 1979) illustrates the interaction between the general thinning of vegetation density from forest to rangeland and the effects of increasing both runoff and steepness. Here the separate equations for the various land-use types will be used for clarity.

The stepwise multiple regression equations for the various land-use types were:

Forest (n = 4)

$$SY = 2.67\,Q^{0.38} \qquad R^2 = 0.98 \qquad [2]$$

Forest > agriculture (n = 9)

$$SY = 0.10\,Q^{1.28}S^{0.47} \qquad R^2 = 0.76 \qquad [3]$$

Agriculture > forest (n = 28)

$$SY = 0.14\,Q^{1.48}S^{0.51} \qquad R^2 = 0.74 \qquad [4]$$

Rangeland (n = 5)

$$SY = 4.26\,Q^{2.17}S^{1.12} \qquad R^2 = 0.87 \qquad [5]$$

Although the sample sizes (n) for forests and rangelands approach the number of independent variables and produce misleadingly high correlation coefficients (R^2), the increase from Eq. [2] to [5] of the exponents on Q and S indicates that as the density of cover decreases the effects of increasing runoff and topographic steepness are enhanced.

Catchment-scale analysis allows one to quantify the effects of the major controls on sediment production, and thereby to make gross projections about the consequences of land-use changes. For example, it is possible to predict that if the current encroachment of cultivation into the wet, steep uplands of Kenya continues, the sediment yield of a typical forested basin, for which Q = 1,000 mm and S = 0.04, will increase from about

30 to 40 metric tons/km^2/year to about 850 metric tons/km^2/year by the time agriculture dominates the land use. The standard errors of estimate for any regional multiple regression analysis are too large for useful predictions within a single catchment, but they are adequate for such an order-of-magnitude estimate for a region. The analysis is useful for general planning purposes such as computing the probable rate of reservoir sedimentation or predicting in general terms the down stream consequences of land-use trends. There is much to be learned, however, about the sources and movement of sediment within catchments, and in the remainder of this paper we will concern ourselves with what needs to be known about these issues in tropical catchments.

SEDIMENT SOURCES IN TROPICAL FORESTS

Tropical forests represent a wide range of conditions from dry, deciduous forest to seasonally wet, semideciduous forest to evergreen and continually wet forests. Some are undisturbed while others are managed for the production of rubber, charcoal or timber; still others are disrupted by mining.

Erosion processes in these environments are strongly controlled by hydrology, but only recently have studies been undertaken to define the processes of runoff generation in tropical forests (Roose, 1980; Leigh, 1978; Bonell and Gilmour, 1978; Northcliff et al., 1979). These studies suggest that subsurface flow and saturation overland flow (Dunne, 1978) are major runoff processes in tropical forested catchments. It is not yet clear whether Horton overland flow occurs, although Ruxton (1967) has argued for its occurrence in the forests of New Guinea. There is a need to combine experimental studies of runoff in tropical forests with a thorough investigation of hillslope erosion processes in order that results from a few measured sites might be generalized and transposed to other localities through field recognition of controlling factors and through mathematical modeling.

At present, little is known about the erosion processes which contribute to the sediment budgets of tropical forested catchments. There have been quantitative studies of individual processes which transport sediment from hillslopes in tropical forests. These include: landslides (Sheng, 1966; Simonett, 1967; Starkel, 1972); soil creep (Eyles and Ho, 1970; Lewis, 1976) and sheetwash (Rougerie, 1960; Roose, 1976; Leigh, 1978). Yet there have been no quantitative comparisons of the rates of each process within a catchment, nor has there been an examination of how the processes are linked (for example, at what rate and for how long sheetwash erodes sediment from a landslide scar), and what factors control the magnitude of each. Further, and equally important, no investigations have been undertaken of the passage of sediment downstream.

Changes in rates of erosion and discharge of sediment into streams due to deforestation have been observed in a general manner by examining the increase of landsliding (e.g., Sternberg, 1948; Starkel, 1972) and sheetwash erosion (Rougiere, 1960; Roose, 1976; Daubenmire, 1972; Bell, 1973; Chim, 1974) in cleared areas. A factor which has not been examined in the tropics is the erosion of rural roads. In the temperate zone it is well established that roads are a major source of sediment in disturbed forests and they continue to lose sediment after reforestation of cutover hillslides (Anderson, 1974). Studies of the sediment budget of disturbed catchments would be useful for planning purposes in view of the rapid exploitation of tropical forests for timber and agricultural land.

Our fieldwork in forested catchments of Kenya and Panama indicates dramatically different sediment budgets. In the former region, hillslope runoff is predominantly by subsurface flow with some narrow saturated areas developed during the wet season on footslopes and drainage depressions (Dunne, 1978). As a result, downslope transport of soil occurs only by creep and very rare landslides. Consequently, the streams draining these forests carry small sediment loads, typically about 20 to 30 metric tons/km^2/year (Dunne, 1979; K. A. Edwards, personal communication). The streams flow on bedrock or over a thin veneer of cobbles in steep, narrow valleys such that little sediment is placed in storage. The sediment budget for such a system is relatively simple and appears to be similar to one that we constructed for a rainforest-covered basin in the Oregon Coast Range (Dietrich and Dunne, 1978). Introduction of roads for timber management in the Kenyan forests has increased the basin sediment yield to at least 45 metric tons/km^2/year (K. A. Edwards, personal communication), although at present we have not studied the processes by which this occurs.

On Barro Colorado Island, created by flooding for the Panama Canal, we have begun studies of runoff and erosion on a 10-ha catchment (Dietrich et al., In press, b). This basin (Fig. 2a) is developed in volcanoclastic sediment and basaltic lavas and has a rugged topography with narrow ridges and slopes that average roughly 20 degrees. The hillsides are covered by a mature, second-growth semideciduous forest which annually receives about 2,600 mm of rainfall. In the dry season the shallow, clay-rich soils develop wide, deep shrinkage cracks which at the onset of the wet season prevent surface runoff. As the wet season continues large areas of the watershed contribute saturation overland flow from soils which remain near saturation between rains.

In this environment, several process transport debris to river channels. The presence of rainsplash pedestals and the abundance of root exposure indicate that surface erosion processes are active, but the magnitudes of rainsplash and sheetwash erosion cannot be defined until measurements using erosion pins, splash cans, and runoff plots are completed. Associated with wetting of the cracked clay soils there appears to be a shallow, swelling-induced creep similar in style to that reported by Fleming and Johnson (1974).

In contrast to these surface processes, deep rotational landslides have disrupted about 5% of the catchment (Fig. 2b). Backwall scarps on the slides range from 2 to 8 m in height, and the slides form distinct steps in the topography. Two of the slides appear to have been active within the last 20 years. In December 1959, after 5 days of nearly continuous rain, several landslides occurred on Barro Colorado Island (Moynihan, 1960).

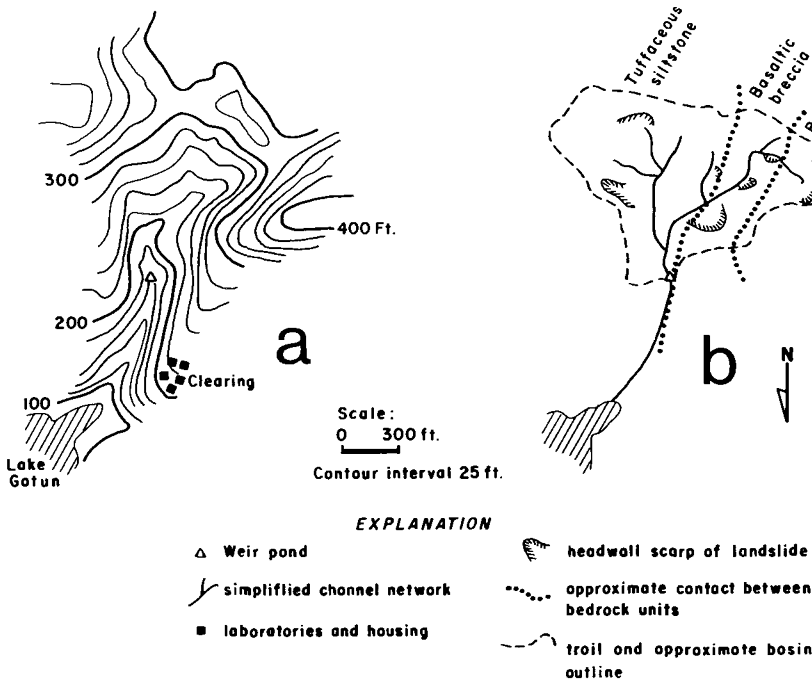

Fig. 2. (a) Topographic map and (b) geologic sketch map showing location of major rotational landslides in the 10-ha Lutz Creek basin, Barro Colorado Island.

Vegetation characteristics on two slides in the Lutz Creek basin suggest that the slides moved during this event (R. Foster, personal communication). Although they form pronounced topographic steps, these features are not obvious on aerial photographs or by direct observation from the air because of the tall, dense forest. The toe of each slide intersects a deeply incised (2 to 4 m) drainage channel and significant amounts of weathered bedrock enter the channels as thin bank spalls from these slide boundaries. The gravel-size fragments contributed from the weathered bedrock quickly break down to sand, silt, and clay and the sediment discharged from the hillslopes is rapidly transported out of the basin in suspension. There is little sediment in storage along the valley floor.

Preliminary data from two wet seasons of suspended sampling and 4 years of runoff record indicate that this set of processes contribute 600 metric tons/km^2/year, a value which greatly exceeds the erosion rates from the forested catchments of Kenya and tropical Australia and Malaya (Douglas, 1967, 1968). The high erosion rate in the Panama basin is due to the occurrence of sheetwash on extensive portions of hillsides and erosion of weathered bedrock from the distal margins of large landslides that appear to be failing slowly into stream channels. Thus, transposition of data on sediment yields between tropical forested sites depends on the recognition of major runoff and erosion processes.

SEDIMENT SOURCES IN TROPICAL AGRICULTURAL REGIONS

In the previously-mentioned analysis of basin sediment yields in Kenya, we estimated the sediment contribution from the agricultural portion of each catchment by subtracting the sediment yield of the forested land from that of the whole basin. The median yield from agricultural regions was only 90 metric tons/km^2/year, but the highest decile of the distribution included yields in the range 1,000 to 5,000 metric tons/km^2/year from the steepest and wettest regions.

Although a knowledge of these yields is useful for downstream planning, little is known about the sources of the sediment, which need to be identified before a program of watershed management can be designed. In agricultural regions, much attention is correctly focused on cultivated fields as a source of sediment. Rates of soil loss from these sources have been documented and subjected to statistical analysis as a means of prediction. Hudson and Jackson (1959) for example, measured soil loss rates of several hundred to several thousand metric tons/km^2/year from beneath crops in Rhodesia. Rapp et al. (1972a) and Temple (1972) summarized early plot experiments in East Africa which yielded the same sort of results. Roose (1976) and Aina et al. (1976) have reviewed the results of many years of experiments on soil erosion and conservation on agricultural lands in West Africa. These agronomic plot studies are concerned with testing and demonstrating the influence of various crops and management practices on the rate of soil loss. They do not deal with the important question of how much of the eroded soil leaves the hillside, enters a river channel, and is transported downstream. Thus, little is known about the contribution of these cultivated lands to the sediment budget, or about the downstream impact of soil conservation programs. These issues could be addressed through a program to sample runoff and sediment concentrations at various points along ditches or other small drainage channels on cultivated hillsides, and to trace and map sediments as they move from fields. By these methods, one could examine the effectiveness of various field layouts in trapping sediment, as well as the feasibility of returning trapped sediment to the fields.

In the Kenyan agricultural regions there are two obvious sources of sediment: cultivated fields and a dense network of roads and footpaths. On the fields, soils are deep and moderately to highly permeable; infiltration capacities of wet bare soils generally exceed 25 mm/hour (Ongweny, 1978; Barber et al., 1979), and the soil surfaces are roughened by hand cultivation. Horton overland flow from these soils occurs only during several major storms per year. Fields are small and much of the sediment is trapped in hedgerows, but the amount leaving a hillside still needs to be quantified. By contrast, rural roads frequently expose saprolite which is dense and has a low infiltration capacity; Horton overland flow occurs in almost every rainstorm. Roadside banks are steep and are usually bare, cultivated, or grazed. The roadbed is disturbed frequently by vehicles, pedestrians, and animals, and the loosened sediment often moves as a thin slurry to roadside ditches which convey it directly to stream channels.

No measurements of soil loss from rural roads have yet been made in the tropics. A few results are available from logging roads, building sites, and road cuts in North America (Diseker and Richardson, 1961, 1962; Hornbeck and Reinhart, 1964; Wolman and Schick, 1967; Swanson and Dyrness, 1975; Reid, 1981). These and the calculation procedure outlined by Farmer and Fletcher (1976), suggest that soil loss rates from rural roads in regions of Kenya with similar rainfall erosivity probably lie in the range of 10,000 to 20,000 metric tons/year per square kilometer of road. We have made a conservative estimate of the area of roads in several Kenyan catchments by measuring only those roads shown on 1:50,000-scale maps, which comprise about 0.5 to 1.2% of the basin area. Application of the sediment yields given above to these areas conservatively suggested contributions of 118 to 236 metric tons/year per square kilometer of a steep, wet agricultural region in Central Kenya with a total suspended sediment yield of 720 metric tons/km^2/year. Footpaths cover at least another 1% of the land surface and traverse steeper gradients (up to at least 25%). Their sediment contribution is probably of the same order of magnitude as that from roads. Thus, in a densely-settled, subsistence agricultural area the sediment contribution from roads is conservatively estimated to be 25 to 50% of basin yields. In a drier, flatter area of commercial grain farming in western Kenya, similar calculations indicate that the few roads and footpaths contribute approximately 50 metric tons/year per km^2 of drainage basin, while basin sediment yields in the region vary between 23 metric tons/km^2/year and 80 metric tons/km^2/year.

These rough calculations suggest that more attention should be paid to defining the importance of rural roads as sediment sources in tropical catchments. Although they do not reflect a lowering of land productivity, such losses have important downstream consequences that cannot be alleviated by better agronomy alone. Research is needed on soil and water management techniques that are appropriate for such thoroughfares which are used more intensively and in more varied ways than the highway road cuts, building sites, and logging roads for which conservation technologies have been developed in North America. Careful consideration also needs to be given to local attitudes to such conservation strategies in regions where land pressure forces people to cultivate roadsides and to use them for grazing areas.

SEDIMENT SOURCES IN TROPICAL RANGELANDS

In spite of widespread expressions of concern about soil degradation in tropical rangelands, and the downstream damage caused by soil erosion, little research effort has been focused on definition and understanding of the sediment budget in the manner demonstrated by Leopold et al. (1966) for the rangelands of the southwestern United States. In tropical grazing lands, erosion rates are high and extremely variable in space and time. Yet catchment-scale records of sediment yield are not the best indicators of the problem. There are few such records and they are generally too short for adequate definition of the long-term average yield.

Large amounts of sediment can be eroded from hillsides and deposited in alluvial fans or floodplains without being recorded at the basin outlet. They may remain in these storage elements for long periods of time or be scoured out occasionally to contribute very high sediment yields in rare storms. In either case, such storage is an important factor that complicates the interpretation of basin sediment yields.

For many purposes, such as predicting downstream sedimentation rates, quantifying the effects of variables that control soil erosion, or predicting the future lifespan of the soil profile, it is necessary to have information on the distribution of erosion and deposition along hillslope profiles, and to study the fate of sediment after it leaves the hillside. It is not easy to monitor soil movement in tropical rangelands. Plots, stakes, and similar devices are prone to vandalism and require a discouragingly long period of record to obtain reliable results under a variable climate. Such studies are needed, however, and more effort needs to be expended on them, including the development of vandal-proof instrumentation.

Monitoring of erosion by means of stakes and plots requires the accumulation of at least several years of data before results can be extrapolated meaningfully. Even before such methods yield results, erosion rates can be mapped along hillslope transects by measuring the lowering of the ground surface against datable references, such as tree roots and fence posts. The method is illustrated in Fig. 3 and the necessary precautions are reviewed by Dunne et al. (1978, 1979). Figure 4 consists of a sample set of erosion rates along a hillslope profile in northern Kenya. In this case the erosion rates were obtained by measuring the heights of exposed roots on *Juniperus procera* trees and divided by the time (13 years) since 1962 when a fire killed most of the trees and the slope was subsequently grazed heavily and exploited for firewood. Under adjacent undisturbed *J. procera* woodland the tree roots were not exposed. Carrara and Carroll (1979) have also shown how the morphology of exposed tree roots can be used to construct a 400-year record of erosion rates in a rangeland in Colorado.

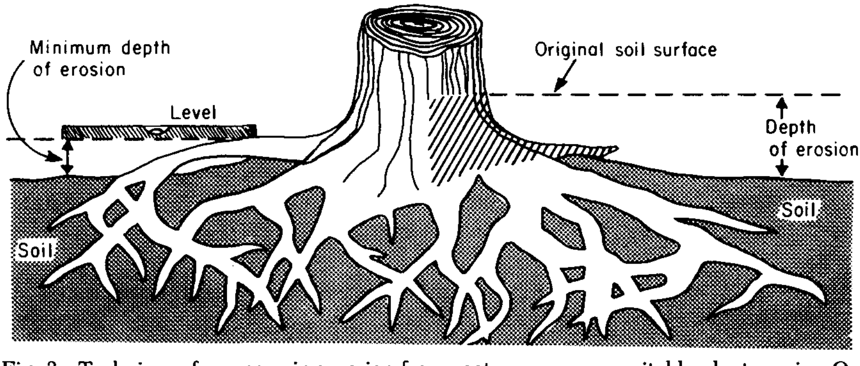

Fig. 3. Techniques for measuring erosion from root exposures on suitable plant species. On the left, the top of the root indicates a minimum elevation of the original soil surface. On some plants, a morphological feature or a change in bark texture or color indicates the original ground surface (right-hand side). The carpenter's level is set on a survey rod to extend measurements beyond a wide canopy.

The method allows rapid coverage of large areas, stratified sampling to isolate the influence of controlling variables, and the averaging of erosion rates over several years or decades. From the spatial distribution of erosion rates (Fig. 4), it is possible to compute total soil loss and the rate of thinning of the soil profile along a hillside (see Dunne et al., 1978, 1979 for different examples of such calculations).

In the Kenyan rangelands, almost all soil loss results from rainsplash and sheetwash erosion; gully erosion is rare, although it occurred in some regions during a rare period of heavy rainfall in 1961–1962. On sandy clay loam Luvisols near Maralal in northern Kenya, this rainfall (which generated the highest floods in records of more than 30 years duration) initiated gullies on heavily grazed rangelands where land surface gradients exceeded 0.035 and hillslope lengths exceeded 600 to 1,800 m, and on gradients of 0.10 to 0.15 at hillslope lengths of 80 to 180 m. Thus, only a small proportion of the landscape has the critical combination of drainage area and gradient required to produce the erosive conditions necessary for gullying. Similar analyses could be conducted in other regions to define zones that are sensitive to gullying, as Patton and Schumm (1975) have suggested.

When the total amount of soil leaving a hillside has been defined, it is necessary for many purposes to consider what portion is transported various distances downstream. We have obtained some measure of the

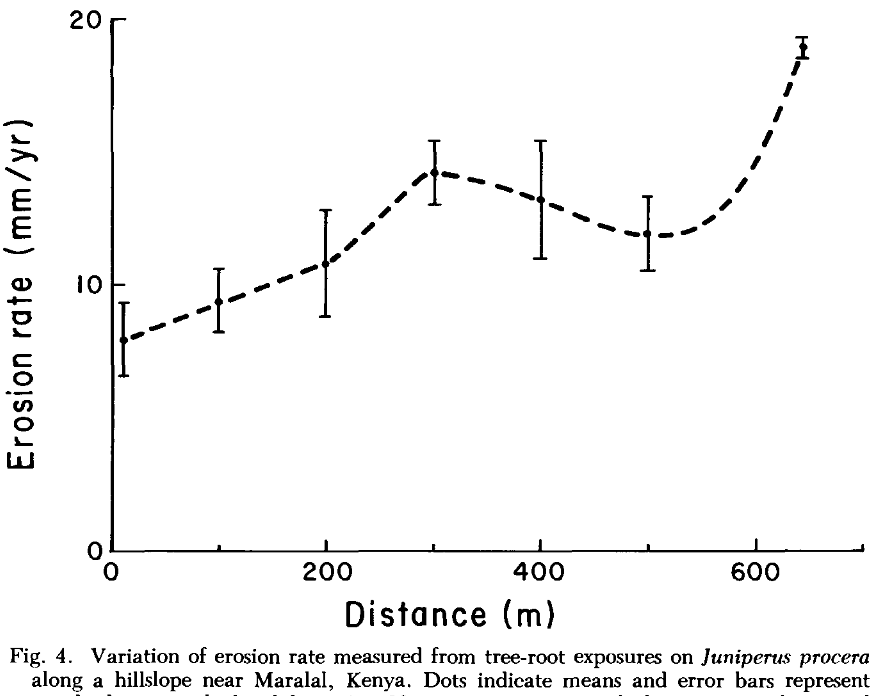

Fig. 4. Variation of erosion rate measured from tree-root exposures on *Juniperus procera* along a hillslope near Maralal, Kenya. Dots indicate means and error bars represent standard errors calculated from 5 to 10 root exposures at each distance. For the period 1962–1975 the average rate of soil loss along the hillslope profile is 11.8 mm/year, and the overall gradient is 0.19.

fate of eroded sediment in Kenyan rangelands by mapping the volume of alluvium per kilometer of valley floor. Close to Nairobi, in an area with a rainfall of 750 mm/year, the equivalent of 2 years of sediment from a contributing area of clay soils was stored as alluvium over the bedrock of the valley floor. Such a small volume of sediment stored in the valley floor indicates that very little of the soil removed from hillslopes is retained near its source, and thus the sediment delivery ratio is very high for these fine-textured soils. In a drier and flatter region north of Amboseli in southern Kenya, sediments are almost entirely stored in swales, fans, and floodplains, and do not reach a major stream channel. There are a variety of intermediate circumstances under which the amount of sediment deposited in these storage elements can be recognized and dated by means of various stratigraphic tools (American Society of Civil Engineers, 1970). The volume and current rate of sediment accumulation on footslopes, alluvial fans, and valley floors can be monitored by repeated survey of monumented cross-sections. Recent rates of accumulation can be measured by locating buried soil surfaces and datable markers such as bridge and building foundations, fence posts, and benchmarks (Trimble, in press). Ritchie et al. (1975) have demonstrated how recent rates of sediment accumulation on valley floors can be reconstructed by measuring the burial depth of peak concentrations of radioactive Cesium-137 from the 1963 peak of fallout from nuclear bomb testing. These methods need to be used more widely to quantify the role of storage in the construction of sediment budgets for tropical drainage basins.

CONSTRUCTION OF SEDIMENT BUDGETS FOR TROPICAL CATCHMENTS

There are four basic requirements in the construction of a sediment budget for a drainage basin: (1) identification and quantification of major processes which generate and transport sediment, (2) identification of linkages between processes, (3) definition of recurrence interval of each transport process, and (4) quantification of the volume and residence time of sediment in storage elements in the landscape which modulate major sediment discharge events.

In tropical catchments some progress has been made in the first and fourth requirements. We have stressed the need to expand the types of processes examined, such as road erosion in both forested and agricultural basins. Experimental plot studies relying on natural rainfall yield useful information on local rates of erosion, but the results are not easily extrapolated to basin-wide processes where the effects of requirements (2), (3), and (4) are felt. Monitoring of erosion and transport processes should be done in the context of integrated experiments that allow one to define the sediment source, storage elements, and transport mechanisms that control the sediment budget. Such programs of research would augment the monitoring of plot erosion and basin sediment yields with studies that involve the tracing, mapping, and dating of sediment as it moves through a catchment. The predictive value of the slow accumulation of plot and catchment results would be greatly enhanced if such techniques were practiced and taught in tropical countries.

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