EFFECT OF WOODFUEL HARVEST ON SOIL EROSION IN KENYA

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SUMMARY OF CONCLUSIONS

(1) Systematic field observations of erosion indicators at a large number of rangeland sites demonstrate that intense erosion is widespread in the Kenya rangelands under a variety of canopy densities. Hillslope gradient and the density of ground cover (as affected by climate and grazing intensity) seem to be more important than canopy cover in influencing erosion rate. This conclusion emphasizes the fact that erosion depends critically upon the management of the herb layer, and erosion rates may be very high even under a thick canopy cover if heavy grazing reduces the ground cover.

(2) Selective removal of trees for charcoal burning alone does not radically diminish the canopy at most production sites, and therefore does not greatly increase the incidence or intensity of erosion indicators, except where a thick bushland is opened up to grazing and trampling by livestock.

(3) Much charcoal is currently being produced during the clearance of land for cultivation. Complete removal of tree canopy and undergrowth and disturbance of the soil by cultivation of marginal land leaves more indicators of intense erosion, which continues for at least several years after the site is abandoned.

(4) Empirical soil-loss equations were used to compute an index of relative erosion for 5,000 10 x 10 km blocks of rangeland. The aim was to generalize the field observations summarized above into a map of erosion status under the current canopy cover, and to examine the effect of reducing the canopy cover under a range of environmental conditions.

(5) The map illustrates the distribution of relative erosion rates for the rangeland, which are highest around the margins of forest reserves and the wetter, steeper margins of the grazing lands.

(6) Canopy reduction for charcoal can only be appreciable in those parts of the densest bushland and woodland which contain significant numbers of trees suitable for charcoal.
These cover only 7 percent of the rangelands. If the densest canopy cover is reduced by its most probable amount, erosion will increase only by about 6%. Complete removal of the canopy without reduction of the ground cover would accelerate erosion by about 20%. Both of these values refer to the years immediately after cutting, and the rate will decline during regeneration of a shrub layer, so that the average increase in soil erosion over a cutting cycle of at least 50 years will be small.

The problem can be exacerbated if canopy reduction for woodfuel occurs near a settlement or water supply, where ground cover is also reduced below the regional average. In such areas, the most probable reduction of the densest woodland canopies would increase erosion by about 10%, and complete removal would cause an increase of about 33%. The pressure of grazing and cutting at these sites is also more likely to continue for long periods of time.

At present much charcoal is being produced during the clearing of land for cultivation in the wetter portions of the rangelands. This complete removal of the canopy and the disruption of the soil by cultivation accelerates erosion sevenfold, according to the soil-loss equations. Little or no soil conservation is practiced on these fields and they are soon abandoned. Soil conservation practices could radically diminish soil loss from these clearings and should be encouraged through demonstrations, advice, and frequent supervision for they are an important source of sediment in subhumid regions.
(9) In the high-potential areas of Kenya. There are three possible sources of woodfuel: major forest reserves; small woodlots and field boundaries; and relatively unproductive areas on the margins of the agricultural lands which may be useful for large plantations.

(10) The major forest reserves can be used for wood production if operations are well-managed, if cleared areas are small, if they are replanted, and if soil- and water-conservation is practiced where necessary. Soil-loss rates, when averaged over a cutting-regeneration cycle should not increase much from their current levels of 0.2-0.3 tons/ha/yr, although erosion from new forest roads would slightly exacerbate sediment transport in mountain streams and sedimentation in reservoirs downstream.

(11) The current trend of unmanaged forest clearance for cultivation on unsuitable slopes without the use of soil- and water-conservation practices is leading to rapid erosion (upto 50 tons/ha/yr) and local crop failures on the most eroded parts of slopes. More attention should be paid to managing this forest clearance to ensure the conservation of soil and the productivity of these wet, steep lands, whether for food or woodfuel. The production of both commodities could exist on various parts of the same landscape.

(12) Trees in small woodlots and field boundaries are usually harvested without significant environmental damage if cutting occurs on small parcels of land and regeneration is assured by replanting and careful husbandry.

(13) Plantations around the margins of the high-potential regions could reduce erosion rates from their current levels of 10-20 tons/ha/yr.
EFFECT OF WOODFUEL HARVEST ON SOIL EROSION IN KENYA

STATEMENT OF THE PROBLEM

Erosion rates in Kenya are already high enough to generate concern about the thinning of soil profiles (Dunne, 1977, 1979; Dunne et al, 1978, 1979), the rate of sedimentation in reservoirs (Dunne and Ongweny, 1976; Ongweny, 1978), and the spoiling of coastal beaches (National Environmental Secretariat, 1972). The highest rates of soil loss occur in the most densely settled agricultural lands of Central and Eastern Provinces and in the wetter margins of the grazing lands, some of which are periodically cleared and cultivated on a shifting basis. The surviving vegetation covers of forest, woodland, bush, and grass in these areas reduce the soil erosion rate to varying degrees.

As the demand for fuelwood and charcoal grows, forest, woodland and bush are removed, and this trend is likely to accelerate dramatically before the end of the century. Our purpose in this report is to assess the probable effects of this activity on soil erosion.

FACTORS AFFECTING EROSION

The major controls of erosion have been studied under both experimental and uncontrolled conditions in laboratories and the field for more than half a century. It is generally acknowledged that the following controlling factors are important:-

1) Rainfall intensity and kinetic energy

Rainfall intensity determines the amount of storm runoff generated on a particular soil and vegetation cover, and therefore the amount of water available for transporting soil to and along river channels. Intensity is also correlated with the kinetic energy of rainfall, which depends on the mass and fall velocity of raindrops. A raindrop falling on bare ground
generates a splash which disperses and mobilizes soil, allowing it to be transported downslope by storm runoff. The size of the splash and the amount of soil moved are largely determined by the kinetic energy of the raindrop. Thus, the kinetic energy of rainstorms during a year has been shown to be highly correlated with the annual soil erosion rate (Smith and Wischmeier, 1958; Elwell and Stocking, 1975).

(2) **Soil Characteristics**

The infiltration capacity of a soil determines the amount of erosive runoff for a particular rainfall intensity. The erodibility of the soil expresses its resistance to dispersion and splashing by raindrops and to shearing by surface runoff. Both infiltration and erodibility have been correlated with a bewildering array of soil characteristics, but the dominant variables are the texture, structure, and organic content of the surface layer.

(3) **Hillslope Gradient**

The local gradient of the soil surface affects the velocity of runoff and the shearing force which it can apply toward mobilizing and transporting soil.

(4) **Vegetation Cover**

Vegetation cover and associated litter intercept rainfall kinetic energy and thereby decrease the mobilization of soil particles. Organic litter and shade stimulate microfaunal activity in the soil, improving soil aggregation and infiltration. It is generally agreed that soil erosion is extremely sensitive to the type and density of vegetation cover. In this report we will stress the differing roles of ground cover, canopy, and forest litter as protection against erosion.
(5) **Land-use Practices**

Land-use is commonly associated with the radical alteration of the vegetation cover, often resulting in an increased erosion rate. On the other hand, soil-conservation practices such as terracing, bunding, crop-residue management, scarification of the soil after removal of woodland or bush, and the decision to harvest woodfuel in strips along the contour may decrease soil loss. Another set of land-use effects are associated with the extension, intensity of use, and maintenance of rural roads, which appear to be major sediment sources in some parts of Kenya (Dunne, 1979).

Any attempt to assess the probable impact of woodfuel production in various parts of Kenya will have to take into account regional or institutional differences in these controlling variables.

**SUMMARY OF METHODS USED IN THIS STUDY**

Because of the short duration of this consultancy, it was not possible to use the most obvious and reliable means of assessing soil erosion, namely direct monitoring of soil loss from plots under disturbed and undisturbed vegetation over many years. Instead, three methods based on different principles have been used to provide site indices of susceptibility to erosion.

(1) Three weeks were spent travelling through the rangelands of southern and central Kenya examining erosion features and their relationship to other variables on KREMU monitoring plots and on sites of past and current woodfuel production. This work proved to be a slow method of working because many days were wasted in Nairobi waiting for vehicles or for personnel. However, it was considered necessary to make some systematic field
observations expressly for the purpose of assessing the impact of woodfuel production on soil erosion. These field observations supplemented the consultant's previous experience in studying the effects of grazing on soil erosion in Kenya (Dunne, 1977).

During this fieldwork an erosion-classification scheme was developed, based on the recognition of erosion indicators. The scheme aided systematic observations of erosion features and was applied to hillslopes under forests, woodland, and bushland and to neighbouring sites from which woodfuel had been harvested.

(2) The Universal Soil-Loss Equation, originally developed for American croplands and later modified for use in forest, woodlands, and rangeland (Wischmeier and Smith, 1978), was used to calculate an index of the susceptibility of a site to accelerated soil loss following woodfuel production. The standard procedures were modified somewhat to account for the strong seasonality of Kenya rainfall and vegetation cover and the differential effectiveness of ground and canopy cover. This last factor is of particular interest because it is manipulated through woodfuel harvest. The problems arising from the use of parameters measured in the United States and elsewhere, and the meaning of the resulting calculated soil loss values are discussed in a later section.

(3) Results of an earlier analysis of the effect of land use and other variables on the sediment yields from river drainage basins in Kenya (Dunne, 1979) were used to assess the reasonableness of the foregoing computations.
Plot experiments to determine the effect of canopy removal on runoff and soil erosion under simulated rainfall had also been planned. The experiments were to be conducted in conjunction with the Kenya Range Ecological Monitoring Unit, which was to provide a counterpart scientist, field assistance, and a water tank. Because of other calls upon KREMU resources, it proved impossible to assemble these elements at a field site during the first four months of the consultant's stay in Kenya, and the plans had to be abandoned until some future time. At the date of writing, the consultant had built the rainfall simulator, and KREMU personnel had just arrived at the site for preliminary testing of the simulator. It is hoped that during the next few months, cooperative experiments can be conducted and the results published as a KREMU report. The study would, for the first time anywhere, allow direct observation under controlled conditions of the nature of changes following woodfuel harvest.
SYSTEMATIC FIELD OBSERVATIONS

Twenty-five KREMU plots in the following districts were visited by the consultant:

(1) Narok District, including the Loita Hills;
(2) the Suswa area of Nakuru District;
(3) the Mwingi - Katumba and Kitui District;
(4) Kajiado District;
(5) the Voi area of Taita - Taveta District;
(6) the Samburu area of Kwale District.

The plots were in KREMU sampling blocks, 5, 6, 8, 12, 20, 21, 29, 30, and 31.

The visits allowed systematic comparison of erosion status and controlling variables across a range of dry environments, and they familiarized the consultant with the data collection methods of KREMU and assisted in interpreting the significance of monitoring results.

Several other locations were also visited specifically to examine sites of current or recent charcoal production. These included:

(1) the Sokoke forest and land cleared for cultivation within the past several years west of Kilifi, Coast Province;
(2) land which has been cleared and cultivated within the last decade near Sultan Hamud and Mtito Andei, Eastern Province.
(3) a rangeland site from which charcoal was produced 10 years ago in the Athi River drainage, Machakos District;
(4) a current charcoal-burning site between Voi and Samburu Village, Coast Province.
(5) a current charcoal-burning site in Langata, Nairobi.

Each site was examined for its standing crop of fuelwood and an assessment was made of the erosion status. The site was then examined carefully to judge whether a dramatic acceleration of erosion would result if the useful fuelwood species were removed. This qualitative assessment was based upon:
(1) signs of current erosion (see later);
(2) soil conditions;
(3) slope;
(4) ground cover density
(5) the role played by the present fuelwood canopy in reducing erosion (for example, whether the canopy fosters a ground cover of herbs or litter; whether soil structure is more conducive to infiltration and more resistant to erosion beneath the canopy; whether the ground is grazed or trampled beneath the canopy; and whether the tree roots trap significant amounts of soil).

This examination was made by: T. Dunne, whose area of research is hydrology and soil erosion; B. Aubry, a geologist; and E.K. Wahome, a range ecologist. The ecological expertise was occasionally supplied by D. Western, resource ecologist.

**EROSION CLASSIFICATION SCHEME**

In the absence of direct measurements of soil loss from plots, it is useful to develop some means of systematically cataloguing evidence of erosion intensity that can be compared between sites and at different times. Toward this end we have developed an ordinal-scale classification of erosion intensity based on surface morphological features and independent of the density of vegetation. The erosion-intensity scale, which is described in Table 1, yields a score between 0 and 6. It is useful to classify some sites as being intermediate between two classes by means of a score such as 1.5, 2.5, etc., though to use a more detailed scoring system would probably lead to a false sense of precision. On some hillslopes, small patches of one erosion class are interspersed with patches of another. In such cases, a notation such as 3/2 can be used, with the spatially dominant class being written first.
TABLE 1. Definition of the erosion classification scheme.

Class 0: No sign of erosion. Soil surface often rough on scale of aggregates.

Class 1: Some signs of weak erosion, such as wash marks on the soil surface, and small erosion mounds or root exposures around trees and bushes.

Class 2: Erosion mounds and tree-root exposures as in Class 1, but some signs of more intense wash and sediment transport in minor flow concentrations, which may exhibit ripples and a few millimetres of deposited sediment upslope of large stones or dams of vegetation debris.

Class 3: Well-developed root exposures, sometimes with surviving erosion mounds, and the ground vegetation shows general signs of intense washing, such as streaks or armour layers of sand and heavy minerals, ripples, and redeposited sediment. Root exposure even on some annual plants.

Class 4: General signs of intense erosion as in Class 3 but with obvious flow concentrations. The surface has a corrugated form parallel to the strike of the hillslope, and the amplitude of the ridges may be up to about 10 cm, but their wave lengths are highly variable. Although the intervening grooves show obvious signs of flow concentration their cross-sections tend to be rounded and they typically do not have channels with sharp boundaries.

Class 5: The hillslope is dissected by rills and small gullies with definite margins. The intervening surface is fairly smooth and gently sloping but shows general signs of intense wash and large erosion mounds or root exposures if suitable plants are present.
Table 1 cont'd

Class 6: The surface is intricately dissected by gullies into a badland topography. The walls of the gullies are steep and frequently rilled. They may also exhibit: erosion pedestals under stones; dry ravelling; and soil slumps after the development of tension cracks if the gully margins are nearly vertical.
Variations between the scores assigned to a site by different observers are usually small. Three of us visited 27 KREMU plots and 10 other sites including: grassland, bushed grassland, bushland, wooded bushland, thicket, and forest. Although the erosion classes of the sites ranged from 0 to 5, on only one occasion did the range of our independent estimates exceed one, and in nearly every case the three scores were identical.

In order to demonstrate that the classification scheme does reflect the intensity of soil erosion, we have correlated scores with erosion rates measured from datable tree-root exposures (Dunne, 1977) and from sediment yields in forested drainage basins (Dunne, 1979) in southern and central Kenya (Figure 1). Although the erosion rates on this graph cannot be applied to other regions considered in this report, it seems clear that our erosion classes do indicate, if only approximately, the erosion status of a site, and that the classification scheme provides a useful tool. The resulting score can, for example, be mapped to indicate the origin of most of the sediment entering a reservoir, or it can be correlated with variables that affect erosion, such as hillslope gradient, vegetation density, and land use. For the purpose of this consultancy, we have used the scheme only for systematic comparison of erosion intensity under canopy covers of different density and between uncut canopies and adjacent cleared land.

General conclusions from field observations

Instead of making a detailed description of each site, it is more useful to list the following general conclusions, which will be developed more formally in the following section on the calculation of erosion rates.

(1) Many of the rangeland sites to which the erosion classification scheme was applied showed signs of intense erosion even in the absence of woodfuel production. Figure 2 contains the data for all KREMU sites that we classified. Only eight of 27 showed no or weak signs of erosion, while 10
exhibited general signs of intense washing, frequent root exposures, and channelized erosion of various kinds. Although there is a general tendency for erosion to increase with hillslope angle for a particular canopy density, the density of the canopy does not seem to correlate strongly with erosion class for covers of $<80\%$. The influence of a thin canopy is presumably overwhelmed by the effects of rainfall erosivity and ground cover density (which could not be usefully assessed in a single visit because of the strong seasonal variation). However, the areas of dense forest and bushland thicker with canopy densities of $>80\%$ are grazed lightly or not at all. The trees provide some protection since the soil is covered by a thin layer of litter and has an aggregated structure with a relatively high infiltration capacity. Clearfelling of these canopies would accelerate erosion significantly. On most of the other sites, however, the erosion is related to intense grazing and tracking and to clearing for cultivation on plots that have since been abandoned.

(2) A large proportion of the Kenya rangelands has little or no fuelwood potential because of the sparseness of tree cover, small tree size, or the dominance of unsuitable species. Therefore the proportion of the rangelands susceptible to large-scale stripping of tree cover for woodfuel is small.

Each of the sites visited was classified by the range ecologist as having no, little to moderate, or significant standing crop of woodfuel. Of the 25 sites, 15 had no useful standing crop of woodfuel, 5 had a low standing crop that could be useful locally, and 5 had a significant potential for large-scale exploitation (disregarding transport costs to distant markets). Analysis of the available standing crop and the potential for sustained production is treated in more detail in the report by Western and Ssemakula (1981).

Obviously, there is a significant standing crop of woodfuel on the non-rangeland sites visited, since they were deliberately examined for this reason.
(3) Significant woodfuel potential, with the consequent possibility of a radical reduction of canopy cover, exists in the following types of locations:

(a) Sites with a large standing crop of trees suitable for woodfuel. These mainly include forests and woodlands of species listed in the report by Western and Ssemakula (1981);

(b) Sites that do not have important volumes of woodfuel, but which could be clearfelled and planted with high-yielding woodfuel species;

(c) Sites with a relatively thin cover of woodfuel trees among a canopy of less useful species, but which are clearfelled for permanent or temporary crop cultivation. Under these conditions, the costs of woodfuel production are charged to the need for clearing land for food production.

(4) Rangeland sites at which the canopy is exploited for charcoal production alone do not suffer a dramatic acceleration of soil erosion over the already high rates in most areas for one or more of the following reasons:

(a) Present charcoal-burning operations are localized in extent and exploit the canopy selectively. Only the largest trees of suitable species are felled, and at some sites only a few large, dead branches from the underside of the canopy are removed, leaving most of the canopy intact.

(b) Even complete removal of the trees suitable for charcoal does not radically reduce the canopy cover. Exploitation of all useful woodfuel trees would reduce the canopy density by only one-quarter to one-half of its present density in woodlands and bushlands within the range areas (Western and
Ssemakula, 1981). This point will be taken up in more detail in the later section on computations of soil loss.

(c) The vegetation component which protects soil most efficiently against erosion in the rangelands appears to be the ground cover or herb layer and the associated litter, rather than the canopy cover. Many canopies are thin, especially before leaves have developed early in the rainy season, and they allow raindrops to strike the ground surface directly. Many of the larger woodland canopies allow raindrops to fall 5-8m to the soil surface, which they reach with a considerable fraction of their original kinetic energy (Meyer, 1959).

By contrast, ground cover intercepts raindrops at the surface where they cannot regain any significant kinetic energy. Thus, in the field one often sees signs of accelerated erosion beneath tree canopies and bushes as well as between canopies. The presence of remanent mounds around the bases of some trees and bushes indicates that a canopy cover, through its effect upon ground cover, provides some protection for the soil. However, the effect is localized and far from complete. These field observations are confirmed by the calculations presented in the following section of this report.

(d) Canopy cover and ground cover are not necessarily independent of one another, and removal of canopy may alter ground cover. Figures in the report by Western and Ssemakula (1981) illustrate the nature of this relationship. Where canopy cover is sparse, there is a large difference between herb density under and between canopies. In such areas, however, the proportion of the area having a high cover density is small, and removal of the canopy could reduce the ground cover on only a small area. Even this effect is frequently not seen until several years after cutting. Also, such areas tend to be arid and have
low rainfall erosivity (see next section).

As one moves into wetter areas with denser canopies, there is relatively little influence of canopy on herb layer, and removal of the canopy again has only a minor effect. Calculations show the expected change to be only about a 10 percent reduction of the weighted average of the undercanopy and intercanopy ground cover.

However, trees are extremely (if indirectly) protective in humid forests, and these forests will be discussed separately from tree cover in the drier regions [see (6) below].

(e) The direct physical disturbance suffered by a charcoal-burning site is usually slight and not always detrimental, although the site may appear untidy. For example, we examined the physical disturbance at a burning site between Voi and Samburu village in Kwale District. Large trees of Euclea divinorum, Dyosprus africana, and Terminalia spinosa were being cut down, but because of the diversity of species in the woodland, the canopy cover was reduced only by about 10% out of an original density of approximately 50%. Small trees of the useful species were left in place as well as those species unsuitable for charcoal. The gradient of the hillslope, like that of vast areas in the Kenya rangelands was low (2 percent in this case). The bare soil around the charcoal hearths was loose and had a high infiltration capacity. The digging of the kiln had left a rough microtopography which trapped water and soil. A few tracks to the site were eroding slightly, but the total amount of accelerated erosion was very small.

(5) The major factors accelerating erosion in the semi-arid regions of Kenya appear to be the reduction of ground vegetation cover and disturbance of the soil surface promoted by intense grazing, trampling, and cultivation without soil conservation practices.

The role of vegetation removal and trampling by cattle on soil erosion in Kajiado District was documented by Dunne (1977).
Figures 3, 4, and 5 present sample results from that report indicating the sensitivity of soil loss to ground cover density and to trampling.

The results of our erosion classification reaffirmed these conclusions. Adjacent heavily-grazed sites with the same basal density of ground vegetation but radically different canopy densities differed only slightly or not at all in erosion class. The largest difference which we observed was on a 5 percent gradient at Maji ya Chumvi, Kilifi District, where the erosion class was 2.5 under a canopy cover of 40% and 3 on an adjacent slope that had been cleared of bush. The heavily-grazed basal ground cover on both sites was only 10%. On other sites, particularly those with gentler gradients and denser basal covers, the differences between heavily-grazed sites with and without canopy was not discernible by our method.

Croplands in the semi-arid region, often cultivated on a shifting basis, are particularly prone to erosion. Both canopy and ground cover are completely removed before the rainy season begins, and the soil is loosened by cultivation. The crops do not provide a significant cover against erosion until almost all of the season's raindrop energy has been expended. In the marginal agricultural lands, little soil conservation is practiced beyond loosening of the soil surface once during the rainy season to promote infiltration and reduce runoff.

Thus, at KREMU station 30/2 near Mwingi in Eastern Province a bushland thicket has been regenerating since cultivation was abandoned 5-7 years ago, as estimated from the age of the trees. The site shows signs of more intense erosion (erosion classes 1-4) than grazed stations under bush in the same area (erosion class 1-2). Bushes and trees with approximate ages of 5 years exhibit several centimetres of root exposure, although one-year-and two-year-old plants have no exposed roots, suggesting that the regeneration of bush and its associated ground cover is beginning to curtail erosion.
(6) There are important differences between the soil protection afforded by canopy cover in rangelands and that provided by forests in humid areas such as the Nguruman escarpment, the Cherangani Hills, Shimba Hills, and Aberdare Range. The effects of uncontrolled woodfuel production in these areas are quite different from those of canopy reduction in dry, heavily grazed woodlands and bushland, and although these wetter areas were not the original concern of the present consultancy, some discussion of them is necessary to suggest the magnitude of the soil erosion problem and ways of avoiding it as the forests are exploited for woodfuel.

In the humid forest, soil protection is afforded not so much by the tree canopy as by low-growing plants, where they are present, and by the litter and humus on the forest floor. Furthermore, the high organic content of the topsoil stabilizes soil aggregates, promoting infiltration and increasing the resistance to erosion.

If the forest cover is removed carefully in small patches and the hillsides promptly re-seeded, and if soil conservation practices are instituted for several years until the tree seedlings are well-established, soil erosion is accelerated slightly but only to a level which is insignificant when averaged over the rotation period of the forest. The feasibility of harvesting wood without environmental damage in the Kenyan highlands has been demonstrated (Pereira, 1962).

However, more typical is the situation which we examined in the Sokoke Forest west of Kilifi. Acacia-forested hillslopes with no sign of accelerated erosion are being settled and clearfelled. Large volumes of woodfuel are being produced on gradients of up to 30%, and the areas are being replanted with maize and beans. Where the soil is a silty sand and forest has been recently cut (1-2 years ago), the infiltration
capacity is high and some degree of soil aggregation persists. Here erosion is localized and not intense, although in some places whole fields were assigned a score of 3 on our erosion intensity scale. On finer textured soils and on the steepest slopes, however, sheetwash, rill and gully erosion (erosion classes 3 to 5) have occurred, and the maize crop was either extremely thin or had failed entirely due to rapid thinning of the soil or washing away of seed. Grass strips have been planted as a means of soil conservation on some fields but are ineffective under the conditions of intense rainfall, fine-textured soil and steep slopes. Many of the hillslopes are quite unsuitable for sustained food production, but can yield large quantities of wood fuel and timber on a continuous basis. Trees could be harvested and planted under careful supervision with attention being paid to soil and water conservation. There is a need for field studies to define the most erosion-prone sites, as a basis for promoting soil conservation practices and to aid land-use planning, which could include policies to encourage the exploitation of protective cover crops such as trees.

The same kind of unwise forest clearing without soil conservation can be observed on the forest margins in highlands such as the Aberdare Mountains and the Shimba Hills. These areas are potentially high-yielding wood-fuel localities if managed and exploited carefully. But under current land use trends, they yield only a single, large crop of charcoal and other wood products before being removed from wood-production with a consequent large increase in soil erosion (see later) that not only affects soil conditions on-site, but also contributes to the sedimentation of reservoirs, beaches and river channels downstream.
SOIL-LOSS CALCULATIONS

Purpose

It would be useful to generalize about the effects of woodfuel production elsewhere in Kenya from the systematic field observations described above. In particular, it is valuable to compute an index of the susceptibility of land to erosion as a consequence of all the main factors affecting soil loss, including woodfuel production. Such an index would allow areas and types of hillslopes most susceptible to damage to be recognized. Decisions can then be made about the wisdom of various land-use practices, their consequences can be anticipated, and the priorities for soil conservation can be ordered.

There are many empirical equations for predicting soil erosion. They are based on statistical analysis of soil loss from experimental plots, and are applied widely on the basis of the field experience of many soil scientists, agronomists, foresters, and others. The equation most relevant to this study is the Universal Soil-Loss Equation (USLE), developed in the United States and widely tested elsewhere. We have applied this method to the prediction of soil-loss resulting from woodfuel production in Kenya. We also investigated the usefulness of an equation called the Soil-Loss Estimator for Southern Africa, developed on the highveld of Zimbabwe, but the parameter values currently available for this equation do not allow a distinction to be made between the effectiveness of ground cover and canopy cover.

The USLE predicts the long-term average soil-loss rate from plots of land the size of a single field or hillslope. It does not account for the possibility of sediment being eroded and then being deposited within a field, at a field boundary, on a footslope, or along a river valley. Thus, the computed soil-loss rates cannot always be equated with the amount of sediment transported by a river.

The equation relates soil loss to its controlling variables: rainfall, soil properties, hillslope gradient, hillslope length, vegetation cover, and land-management practices.
Relevance of equations to Kenya

The Universal Soil Loss Equation was originally developed for application to agricultural lands in the east and central United States, and later extended to forests and rangelands (including dry woodlands). There has been much discussion of its relevance in countries with different rainfall regimes, soils, crops, and cultivation practices, and some writers have concluded that although the general approach may be valid the numerical values describing the role of each factor cannot be transposed from the United States. However, suitable data for modifying the input variables are not available elsewhere, with a few important exceptions such as West Africa where Lal (1975) and Roose (1975) have calibrated the equation for use on cultivated fields. Thus, it would be misleading to interpret the values of soil loss computed by the USLE and its derivatives for areas in East Africa in an exact quantitative manner. Instead the results should be seen as indices of the relative susceptibility of various sites to erosion. This is particularly true in Kenya, where there has been no field testing of soil-loss equations. Wischmeier and Smith (1978), designers of the procedure, stress that even in the United States "Soil losses computed with the USLE are best available estimates, not absolutes".

On the other hand, it has been our experience that with occasional exceptions, which can be anticipated and avoided through fieldwork, the USLE yields surprisingly useful results even where the transposition of data from the United States is necessary. The computations usually identify the most erosion-prone hillslopes in an area, as well as making clear the dominant reasons for their susceptibility. The calculation procedure also encourages systematic consideration of all of the major factors affecting erosion at a site and is a useful means of organizing discussion and planning of soil conservation needs. The approach has been used for this purpose in Kenya by Daines et al (1978) and Wenner (1980). In many instances knowing the true value of soil loss in tonnes/hectare/year is less important than being able to classify the erosion rate as slow, moderate, high or intense, and being able to assess the role of a factor such as cultivation or canopy removal.
The relevance of USLE estimates is often in the eye of the beholder. For example, Wendelaar (1978) compared soil losses measured on ten plots in Rhodesia with computed values estimated from the USLE handbook, without any modification of the values for Rhodesian conditions, and using rainfall data that were not necessarily representative of the period of erosion measurements. He concluded that the USLE was a poor predictor of soil loss in Rhodesia.

However, we look more optimistically at the same data set, which we have plotted in Figure 6. It is true that the results scatter widely about the line of equality; the highest measured value, for example, is underpredicted by 43 percent. However, it is more important that the USLE discriminates successfully between plots with high, medium and low rates of soil loss. A Spearman rank correlation test shows that the prediction ranked the plots closely enough to the order of the measured soil loss that the correlation coefficient was significant at the 0.05 level. In this light, we consider the USLE suitable for the present purpose of discriminating between areas which are susceptible or resistant to erosion as a result of particular kinds of land use, although we do not claim that the absolute values of the computed soil loss are realistic. Dunne and Professor R. Bryan, University of Toronto, recently found that USLE calculations for cultivated and grazing lands in northern Tanzania could reliably predict the relatively erosion status of hillslopes as later verified from erosion indicators and farmers' reports of intense slopewash and declining crop yields.

Below we describe the USLE procedure in greater detail than is strictly necessary for the present report for several reasons. First, we have modified the method to reflect the highly seasonal nature of erosion in Kenya. Second, we have used the USLE to calculate an index of the current erosion status of the entire area of the Kenya rangelands as a background for the discussion of the impact of woodfuel production. Third, we use the method for sample computations of the effect of woodfuel production on soil loss. Finally, our description presents the
method in a form that can be used in Kenya for future estimates of soil loss from specific hillslopes on which woodfuel production or other activity is contemplated.

**Universal Soil-Loss Equation: Method**

This procedure is described in detail by Wischmeier and Smith (1978) and in abbreviated form by Dunne and Leopold (1978, 522-531).

The equation is

\[ A = RKLSCPB \]  

(1)

Where

- \( A \) = soil loss (tons/acre), which will later be converted to tonnes/hectare (1 t/ha = 0.447 t/ac)
- \( R \) = the rainfall erosivity index
- \( K \) = the soil erodibility index
- \( L \) = the hillslope - length factor
- \( S \) = the hillslope - gradient factor
- \( C \) = the vegetation cover factor
- \( P \) = the erosion-control practice factor
- \( B \) = the proportion of the ground surface which is not covered by immobile stones or dead wood. This factor is not included in the original form of the equation.

The rainfall erosivity index is calculated from the kinetic energy of each rainstorm multiplied by the maximum 30-minute intensity of the storm. Unfortunately, there are very few calculations of \( R \) available for Kenya, and its evaluation from the original rainfall intensity records is too time-consuming to be possible within the terms of the present consultancy. Wenner (1977) has calculated \( R \) values for eleven
stations in Kenya. Moore (1979) has shown that these few data can be extrapolated throughout Kenya by means of a two-step procedure.

First, Moore computed the total annual rainstorm kinetic energy in storms with intensities greater than 25mm/hr and with durations greater than 15 minutes for thirty-five stations throughout East Africa. He used the relationship between energy and intensity developed by Hudson (1971) and Stocking and Elwell (1976) in Zimbabwe Rhodesia:

\[ ke = \left( 29.8 - \frac{127.5}{I} \right) d \]  \hspace{1cm} (2)

Where \( ke \) = kinetic energy of rainfall with an intensity greater than 25 mm/hr (Joules/M²).

\( I \) = rainfall intensity (mm/hr)

\( d \) = rainfall depth during the storm or increment thereof (mm)

The annual kinetic energy is

\[ KE_{>25} = \sum_{i=1}^{n} (ke) \]  \hspace{1cm} (3)

Where \( n \) is the number of storms in a year with an intensity greater than 25mm/hr for 15 minutes.

Moore found that if he stratified the thirty-five stations into four regions of homogeneous climatology, he could correlate the annual kinetic energy with mean annual rainfall. His results are shown in Figure 7. He then showed that the values of \( KE_{>25} \) for Wenner's eleven stations correlated well with the latter's R-values, according to

\[ R = 0.029KE - 26.0 \]  \hspace{1cm} (4)

Thus, from a map of mean annual rainfall it is possible to obtain the total annual kinetic energy for any station by using the curves shown in Figure 7, and then to employ equation (4) to compute the R-value for the station.
Because of the strong seasonality of Kenyan rainfall and ground cover, it is not useful to apply a single annual value of $R$ or of the vegetation cover factor, C. Wischmeier and Smith (1978) emphasized the need to distribute rainfall energy through the year and to make monthly computations of soil loss if there is strong seasonal variation in crop density. We have applied the same principle to the rangelands of Kenya. The variation of cover factor will be dealt with later, but first it is necessary to explain how we distributed the erosive rainfall energy as represented by $R$.

Erosive rainstorms in Kenya are usually intense and of short duration. Dunne (1977) found that heavily-grazed sandy clays and sandy clay loams in Kajiado district, which are texturally similar to soils that cover large areas of semi-arid Kenya, have infiltration capacities between 25 and 35 mm/hr, depending on the antecedent rainfall. The infiltration capacities of clay soils in Kajiado District are also high, ranging from more than 100mm/hr at the beginning of the wet season to less than 5mm/hr late in the season. Ongweny (1978) measured infiltration capacities on clays, clay loams, sandy clay loams, and sandy loams under cultivation and grazing in the Upper Tana River basin. The infiltration rates ranged from 14mm/hr for the finest soils in a wet condition to 168mm/hr for a dry soil under woodland. Comparison of these values with rainfall intensity records leads to the conclusion that only a few short rainstorms produce runoff and erosion in an average year.

It seems reasonable that the distribution of these runoff-generating rainstorms should be related to the seasonal occurrence of heavy, daily rainfalls. Therefore, we have taken the temporal distribution of days with more than 25mm of rainfall (here called "erosive days") as an index of how the total amount of kinetic energy should be distributed through a hypothetical average year. The value of 25mm/day was chosen because it is easily available from Kenya rainfall records. Larger daily totals occur so infrequently that to use them as an index would not define clearly the temporal pattern from the short records available.

Moore (1978) used records from 1959 to 1968 to tabulate the average frequency of erosive days in ten-day periods from March 1
to the end of May and from October 1 to the end of December. It is possible that erosive rains occur between these two rainy seasons, but they are exceedingly rare at most stations. We have plotted Moore's tabulated data and similar data from several other stations as the probability of an erosive rain occurring on any particular day, as shown in Figure 8. In order to smooth the data we fitted a cubic polynomial to the points for each rainy season. Then we set the sum of the integrals of these polynomials proportional to the annual R-value obtained as described above:

\[
\frac{1}{k} \int_{t=0}^{t=215} (a_0 + a_1 t + a_2 t^2 + a_3 t^3) dt + \int_{t=0}^{t=276} (b_0 + b_1 t + b_2 t^2 + b_3 t^3) dt = R (5)
\]

where \( t \) is the number of days from March 1 and the limits of integration are March 1, June 1, October 1, and December 1.

The expressions can also be integrated between the first and last days of a single month to indicate the proportion of \( R \) which should be assigned to that month. In this manner we have obtained \( R \) values for each month of the two rainy seasons at each station for which calculations are to be made. Figure 9 indicates the region of Kenya to which we have applied the seasonal distribution of erosivity from each rainfall station. It is based on a map in the Atlas of Kenya (Government of Kenya, 1970) showing the seasonal distribution of rainfall maxima. Thus, \( R \) for a particular site was obtained from the local mean annual rainfall, Figure 7, and equation (4), and its monthly distribution was estimated from Figures 8 and 9.

The soil erodibility factor, \( K \), can be estimated only approximately, since few measurements of its value have been made on tropical soils. Moore et al (1979) obtained values of 0.04 for a humic clay nitosol at Kabete and 0.4 for a sandy clay luvisol in Machakos District. In the absence of better data, we have used Figure 10 and the textural classifications of soils given on the provisional 1:1 million soils map of Kenya (provided to us by the Kenya Soil Survey), or the field descriptions of soil texture on KREMU plots made by the KREMU scientists or by us. Most
of the estimated K-values are probably within ± 0.10 of their true value, and the majority of values for Kenya rangeland soils should lie in the range 0.25 – 0.35 on the basis of their texture.

The hillslope length and gradient factors, L and S, are evaluated together from graphs provided in the texts referred to above. We obtained average slope values for large regions of Kenya from an analysis of 1: 50,000-scale topographic maps. The country was divided into regions shown in Figure 11, following a combination of Ojany's (1966) classification of physiography, an examination of topographic maps, and our field observations. The regions in Figure 11 could be subdivided and outlined more intricately, but there is little to be gained from doing this. The purpose of the present report is to outline problem areas at a regional scale. For individual site assessments this methodology or another would have to be applied to a particular measured hillslope rather than to one of average gradient.

We randomly selected 1: 50,000 - scale topographic map sheets in each of the regions in Figure 11 for the measurement of average hillslope gradient, using the Wentworth (1930) technique which involves counting the numbers of contours crossed by a large number of transects. The results are plotted in Figure 11 at the position of the map sheet used. The average slope was incorporated into the Universal Soil-Loss Equation as an index of erosion conditions, but it should be realized that in each region there is a range of hillslope gradients, and the Wentworth technique does not allow the variance to be measured reliably.

Ongweny (1978) measured hillslope gradients at 100 points in each of six regions within the Upper Tana Basin. The computed standard deviations ranged from 30 to 60 percent of the sample means. If these values are extrapolated to other regions of Kenya, one can calculate the gradients of the steepest 10, 20, 30, etc, percent of the landscape using the mean values in Figure 11 and the proportions of the normal distribution, which usually fits the frequency distribution of gradients within a topographic region.
There are no contoured topographic maps for some regions of Kenya. In these situations average gradients were transferred from nearby regions of similar topography, or were obtained from a few field measurements during previous fieldwork. These values are indicated by parentheses in Figure 11.

A characteristic hillslope length is also needed for the calculations. In spite of the great range of this parameter throughout Kenya, we used a constant length of 150m in all calculations. This is near the upper limit for which experimental results exist, and extrapolations to longer hillslopes have not yet been tested. The L-factor is proportional to the square root of hillslope length, so that for a 500-m long hillslope the factor would be 1.83 times that for the 150-m long profile if the available data can be extrapolated.

The vegetation cover factor, C, depends on both ground cover and canopy cover. Vegetation cover factors for rangeland with various densities of bush and tree cover are given in Figure 12, which has been compiled for a ground cover that consists of both grasses and broadleaved herbs from tables published by Wischmeier and Smith (1978). The data were based on laboratory experiments and theoretical computations and were compared with the small amount of field data available from rangelands and woodlands in the United States (Wischmeier and Smith, 1978). The inverse, non-linear form of the curves is in general agreement with experimental data on soil loss from plots in Kajiado District rangelands (see Figures 3 and 4, for example).

Figure 12 shows that low canopy covers, such as shrubs, provide more soil protection (lower C values) than taller canopy covers of equal density because raindrops fall a shorter distance from low trees and shrubs and strike the soil with a lower velocity. Removal of a shrub canopy would therefore accelerate erosion to a greater degree than would cutting of tall trees in the rangelands. The graphs also indicate that the C-factor is much more sensitive to ground cover variations than to changes of canopy density. Nevertheless, we need to estimate present canopy density throughout the rangelands in order to assess the current status of erosion, and also for later sample computations of the effect of woodfuel production.
Because KREMU aerial observers do not record shrub density, use of their canopy classification may lead to a significant overestimate of erosion rate. However, Figure 15 demonstrates that when total canopy cover measured on the KREMU ground stations is plotted against canopy cover >2m high, the stations fall into two groups. The majority of points cluster strongly about the line of equality, indicating that at most stations there is little or no shrub layer, so that the aerial survey data are appropriate. However, points falling along the ordinate in Figure 15 represent a group of stations at which there is a significant shrub layer but no trees. These stations and similar blocks would be recorded in class zero by the aerial observers leading to a slight overestimate of erosion. The error is not significant for the present purpose both because almost all such blocks are in dry areas where rainfall is too light to promote severe erosion, and because the shrub canopy will not be removed for woodfuel in such areas.

Under the strongly seasonal climates of Kenya, ground cover, and therefore the C-factor, varies significantly between months. At KREMU ground stations the density of the ground cover or herb layer (plants less than 0.7m high), is measured only once every two years and on most plots has been measured only once during the monitoring program. Therefore, we had to estimate the seasonal variation in ground cover density by the following method. We plotted graphs of mean monthly rainfall for the stations at which the temporal distribution of rainfall was regarded as representative of large areas of the rangelands (Figure 9). For the vicinity of each station a curve was then sketched showing the seasonal variation in density of the herb layer for a year with average rainfall. These curves were sketched by ecologists Mr. M. Olang, Mr. H. Mwendwa, and their field assistants at KREMU and by Dr. D. Western. They were defined on the basis of the extensive field experience of these scientists with repeated measurements of ground cover density in various regions of Kenya. The biologists estimated the basal cover at the end of each dry season, the peak cover density after each wet season, the timing of each condition, and the approximate rate of vegetation response to rainfall, taking into
projected canopy density for each KREMU ground plot (using Figure 13). Then we assigned each ground plot to one of the classes in the list above, and computed the median value of true canopy cover for each class. These median values, listed in the second column of Table 2 were used in the soil-loss calculations.

**TABLE 2**: Median canopy cover (%) before and after exploitation for charcoal and cultivation for the KREMU canopy density classes.

<table>
<thead>
<tr>
<th>Class</th>
<th>Present</th>
<th>After charcoal production</th>
<th>After clearing for cultivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1.5 (assumed)</td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>12</td>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>17</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>36</td>
<td>0</td>
</tr>
<tr>
<td>Forest</td>
<td>100</td>
<td>0 (probable)</td>
<td>0</td>
</tr>
</tbody>
</table>
KREMU personnel record the density of canopy cover on their biennial ground and aerial surveys of rangeland vegetation. During the ground survey, canopy cover is recorded in four height classes: 0.7–2m, 2–4m, 4–8m, and greater than 8m. However, the canopy cover contributed by each species is tabulated separately, and then the total canopy cover is computed by summing these values. Such a procedure ignores overlap that may exist between canopies, and overestimates the proportion of the ground surface that is covered with a canopy which can intercept rain-drops. Therefore, we have had to alter the KREMU canopy-density values, using the following procedure.

First, we obtained some measurements of canopy density made by Dr. P. Kuchar of KREMU using the line-intercept method (Brown, 1954). The projection of every tree onto a 100-meter transect was recorded for 40 transects. From these data we calculated the amount of overlap between trees, and therefore the true (vertically-projected) canopy cover as well as the canopy cover measured by the KREMU method. Plotting these two values of canopy cover in Figure 13, we obtained a graph which is of the expected form (the amount of overlap increasing with canopy density), and which can be used to convert KREMU canopy densities to the values required for the analysis of erosion.

Canopy cover of trees > 2m is recorded by KREMU aerial observers in the following 5 density classes:

<table>
<thead>
<tr>
<th>Class</th>
<th>Density (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1–2</td>
</tr>
<tr>
<td>3</td>
<td>2–20</td>
</tr>
<tr>
<td>4</td>
<td>20–40</td>
</tr>
<tr>
<td>5</td>
<td>40–80</td>
</tr>
</tbody>
</table>

Western and Ssemakula (1981) have mapped the average canopy cover of 10 x 10km blocks of land from the results of such a survey (Figure 14). In order to find the average vertically-projected (or true) canopy cover for each class, we computed the vertically


account the general composition of the plant community, the grazing pressure, and the rate of dessication after a rainy season. The vegetation density at each station will obviously vary from year to year as rainfall fluctuates, but the curves for the nine stations shown in Figure 16 are considered to be sufficiently well-defined for the present discussion. It is to be hoped that their presentation and use here will stimulate fieldwork to check or replace them in an effort to refine our estimates of soil erosion.

Because rainfall amounts vary considerably within each of the regions surrounding the meteorological stations shown in Figure 9, a single value for peak ground cover density (for example) could not be assigned to a whole region. Instead, the basal cover at the end of the long dry season, the peak cover at the end of the long rains, basal cover at the end of the short rains, and the peak cover at the end of the short rains, were read from Figure 16 and plotted against the mean annual rainfall at the station. The results (Figure 17) indicate strong correlations between annual rainfall and each measure of cover, and testify to the remarkable consistency of the independent estimates made by the ecologists. It should be emphasized that the original cover estimates were averages for large tracts of landscape around the meteorological stations. There are obvious local variations such as along river valleys or around settlements.

For any site in the country the four extreme points on the seasonal curve of ground cover density could then be estimated from the mean annual rainfall map. Interstation differences in the timing of maxima and minima and in the rates of recovery and decline were considered to be within level of precision of the method, and were ignored. Thus, for any station the extreme points on the ground cover density curve were assigned to March 15, May 15, October 15, and December 15. This generalization tends to set the timing of the peak a week or two late in the dry regions where ground cover is dominated by opportunistic annual plants, and a couple of weeks early in
the wetter areas where there are more perennial plants with a slower response. However, these errors are less than the uncertainties in estimating the seasonal timing of rainfall itself. A linear interpolation between each minimum and maximum was used to define the variation of ground cover during the year for any station in the rangelands. Monthly values of ground cover and the constant value of canopy density were used to obtain C-values for the USLE from Figure 12.

Agricultural crops also show a strong seasonal variation in cover density, and for the few sample calculations included in this report, advice on the seasonal trend of crops and C-values was obtained from the reports of Daines et al (1978) and Wenner (1980).

In humid forests, such as those found in the various highlands of Kenya, the soil surface is covered by an organic-rich layer of varying thickness. It is this layer which maintains high infiltration and reduces surface water erosion to extremely low rates. This condition is reflected in the USLE through the use of the very low C-values for forests given in Table 3.

**TABLE 3: C-values for undisturbed, humid forest land for use in the Universal Soil-Loss Equation (Source: Wischmeier and Smith, 1978).**

<table>
<thead>
<tr>
<th>Percent of area covered by canopy of trees and undergrowth.</th>
<th>Percent of area covered by organic surface layer at least 50mm deep.</th>
<th>C-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 - 75</td>
<td>100 - 90</td>
<td>0.0001 - 0.001</td>
</tr>
<tr>
<td>70 - 45</td>
<td>85 - 75</td>
<td>0.002 - 0.004</td>
</tr>
<tr>
<td>40 - 20</td>
<td>70 - 40</td>
<td>0.003 - 0.009</td>
</tr>
</tbody>
</table>
It will be noticed that these C-values are significantly less than those given in Figure 12 for even a 75-percent woodland canopy with a complete ground cover in the rangelands, where an organic surface layer is thin and discontinuous or absent, and where the infiltration capacity is usually low enough to allow overland flow and water erosion from time to time. These C-values were applied to areas of highland and riverine forest mapped by KREMU personnel from Landsat imagery (Doute et al 1981).

The erosion-control practice factor $P$ in equation (1) was set equal to 1.0, indicating no erosion control, on wood-fuel sites in rangelands. For the brief consideration of the effects of soil conservation on lands that are cultivated after woodfuel production, $P$-values were taken from West Africa (Wenner, 1980) although again it must be stressed that these are only crude estimates of the approximate effectiveness of conservation practices in a Kenyan context.

The B-factor in equation (1) indicates the proportion of the ground surface which is available for erosion. Reid (1981) has shown that inclusion of such a term in the USLE produced good agreement with measured soil-loss rates from gravel-surfaced roads in Washington State, U.S.A. A portion of the soil surface is covered by immobile stones and large pieces of dead wood. The mobile fraction of the surface is estimated visually by KREMU personnel in each of their 30 to 80 half-metre-square quadrats at each station. We used these values in a few sample calculations for KREMU ground stations, but since the latter are distributed to sample the range of ecological conditions in an area rather than to reflect the proportion of land of each type, it was not possible to average results from stations in a region or to combine them in any meaningful way. Therefore, we have included discussion of the B-factor in this report only to suggest that it be taken into account in future site assessments of particular hillslopes from which it is proposed to remove the canopy vegetation. The relevance of this factor can be appreciated when one uses the USLE in the Kenya rangelands. The USLE result is extremely sensitive to hillslope gradient, and although there is evidence
that slope affects erosion rate significantly (Dunne, 1977), the computed effect is unrealistically large. One compensating factor which tends to reduce erosion rates on steep slopes in the dry lands of Kenya is that many steep slopes are mantled with pebbles and gravel. The fraction of the surface covered with immobile gravel or large pieces of wood could be altered due to woodfuel harvest or by the emergence of a gravelly subsoil on severely eroded sites.

UNIVERSAL SOIL-LOSS EQUATION: RESULTS

Distribution of current erosion in the rangelands

Before discussing the particular effects of canopy reduction on soil loss in the Kenya rangelands, it is useful to review their current erosion status. Figure 18 shows the results of our USLE calculations on 10 x 10km blocks for the entire rangeland area (defined as that region which has been assigned as the KREMU study area). The values computed for each block refer to rangeland only; they do not refer to patches of cropland that may occur within the rangeland.

The computed soil-loss rates range from near zero to 473 t/ha/yr, but our previous experience with the USLE suggests that the equation tends to overpredict soil loss on steep slopes, either because the slope factor is exaggerated in the equation or because erosion on steep slopes is often reduced by the stoniness of the ground surface. In fact, the equation seems to underpredict soil loss rates and to understate differences between regions with gentle slopes and to overpredict and to exaggerate differences between steep regions. Therefore, we propose that the USLE results be viewed only as an index of soil loss and we have constructed logarithmic class boundaries in Figure 18 to counteract these effects on the portrayal of results. However, we believe that the mapped classes adequately identify the major patterns of erosion for the purposes of the
present discussion. It is possible to make some generalizations about each erosion class as follows.

The class denoted F has erosion rates of less than 2t/ha/yr, and only on some of the dry mountains of northeastern Kenya is this value approached. These areas are currently protected mainly by low-growing forest plants, litter and a humus-rich soil. However, they support a significant woodfuel resource, the uncontrolled exploitation of which would remove this surface protection and promote rapid erosion on the steep hillslopes.

Widespread clearing of cedar forest for charcoal on the steep hills north and northeast of Maralal, combined with intense grazing pressure has removed the litter and humus-rich topsoil since the late 1950's. Only 1.5% (7,800 sq. km.) of the Kenya rangelands is occupied by land in this class but other highland forest areas with very low erosion rates occur in the high-potential areas of the Shimba Hills, Mt. Kenya, the Aberdares, Mau Escarpment, and elsewhere. These will be discussed in a later section of this report.

Class 1 (2-3.9 t/ha/yr) covers 153,200 sq.km (30.3% of the rangelands) mainly in the northern and northeastern portions of the country. Here vegetation is sparse, but rainfall energy is low and hillslope gradients are extremely small, so that erosion rates are slow. The sparse vegetation and abundance of bare soil often give these regions an aspect of being intensely eroded. During intense storms, runoff may be widespread and much soil is transported, but these events are rare and their long-term average effect is small relative to erosion rates in other parts of the Kenya rangeland. This is not to say that there is no significant erosion in class-1 land; only that there is much less than in other parts of Kenya. Furthermore, because these areas are dry, they tend to have thin canopy covers (Figure 14) which therefore cannot be reduced significantly for woodfuel.

Classes 2 and 3 (4-7.9 and 8-15.9 t/ha/yr) cover approximately 294,000 sq.km. (58% of the rangelands) in the
semi-arid northern, eastern, and southern portions of the country.

Classes 4 and 5 (16-31.9 and 32 t/ha/yr) cover 54,500 sq.km. (10.8%) of the steeper and wetter margins of the rangeland. Here, erosion rates are very high, as evidenced south of Maralal town by tree-root exposures indicating erosion of 25 - 250 t/ha/yr, depending on local hillslope gradient, and by sediment contributions to the Tana River between the Kamburu dam site and Grand Falls of more than 40 t/ha/yr from an area east of Mt. Kenya that is classified as 4 and 5 in Figure 18. It is significant that adjacent to each of the remnants of highland forest in the drier regions of Kenya there exist areas of land in classes 4 and 5, indicating the probable consequences of uncontrolled stripping of these wood reserves.

Effect of reducing canopy cover for charcoal production

We will now use sample calculations to examine the specific effects of reducing canopy cover on erosion. The earlier discussion and calculations imply that the effect at a site will vary according to the local combination of rainfall erosivity, hillslope gradient and ground cover. However, the general conclusion will be that reduction of the canopy for woodfuel alone should cause a relatively small acceleration of the already high erosion rates in the Kenya rangelands. Two important exceptions are the removal of forests for woodfuel and the production of charcoal from trees and shrubs cleared from marginal agricultural areas within the rangelands.

First, it is necessary to assess the probable magnitude of tree cover reduction in the various canopy density classes mapped by KREMU. Western and Ssemakula (1981, Table 5) have listed the amount of wood utilizable for charcoal at each KREMU ground station. They have also calculated the resultant reduction in total canopy cover (as measured by the KREMU method, which includes overlap). We have converted their measurements to vertically projected canopy cover, as used previously, and have listed the median cover reduction for each canopy class in Table 2. The values indicate that charcoal production alone will reduce canopy cover only by one-quarter to one-half of its present density, except in forest land,
where essentially all of the canopy could be removed in areas such as the hills northeast of Maralal. Clearfelling of bushland and woodland for cultivation would, of course, reduce the tree canopy to zero.

To illustrate the effects of charcoal production alone on erosion rate we have made a set of soil-loss calculations for class 5 woodland before and after charcoal production for a range of hillslope gradients in an area with a mean annual rainfall of 600mm and a seasonal distribution of erosivity like that at Narok. The computations yield the lower two solid curves in Figure 19, which indicate that a reduction of canopy density from 50% would accelerate soil loss by only six percent, although on a gradient of 10 percent this would amount to 3t/ha/yr. The graph also shows that removing the entire canopy in such a grazing land, but maintaining the ground cover in its current state, would result in an approximately twenty-percent increase in soil loss (or about 10 t/ha/yr on the steepest slopes considered). Exploitation of the other canopy density classes in Table 2 would result in even smaller increases in erosion.

In these calculations, the ground cover density is set by the mean annual rainfall, according to Figure 17, which portrays the effects of interactions of rainfall and current regional average stocking densities. However, there may exist significant local variations in grazing pressure, where herds are concentrated near a water supply or settlement. In such areas, the ground cover density may range only between 0 and 10% through the year. Also in such areas, woodfuel utilization is often most intense. The dashed curves in Figure 19 illustrate that the resulting soil loss would be much higher than previously calculated and that the reduction in canopy cover from 50% to 36% would accelerate erosion by about 9 percent and complete canopy removal, if all trees were utilizable, would cause a 33 percent increase in soil loss.

Our conclusion from these computations is that canopy removal for charcoal production alone will not accelerate soil erosion catastrophically, although there will be significant increases (5-20%) and these rise to important amounts in absolute terms on the steeper slopes of a region. If the shrubs, bush, and
tree vegetation is allowed to recover after cutting, the erosion rate will decline quickly with the spread of a low canopy. Thus the temporarily elevated rates of soil loss should become even less important when averaged over the duration of a cutting-regeneration - cutting cycle. The probable time-trend of erosion on a bushland site that has been exploited rapidly for charcoal and then allowed to regenerate is illustrated by the solid curve in Figure 20. A rapid increase in erosion is followed by a decline as the trees, from which raindrops fell several meters and under which animals could graze, are replaced by more protective shrubs. If the shrubs are prolific, the decline may persist to levels below the long-term average undisturbed rate, but erosion will revert to the long-term average as the canopy rises.

If, on the other hand, charcoal burning is accompanied by the immigration of livestock and people who burn deliberately to remove bush and improve grazing, the initial acceleration of erosion may be sustained to a higher long-term average level (dashed line in Figure 20). This appears to have happened south of Maralal since the late 1950's for example.

In the forested mountains within the Kenya rangelands the effects of woodfuel production would be far more significant than in the more open canopies of the, drier areas referred to above. Under a dense forest canopy the soil is protected against erosion by plants, litter, and humus of the forest floor. Removal of the forest canopy leads to a rapid deterioration of the forest floor, especially if it is grazed. Because these forests are in the wetter, steeper portions of the rangelands, erosion is accelerated dramatically. Figure 21 shows a typical set of USLE predictions for the conversion of a closed forest canopy to a grazing land under 800mm of rainfall. Removal of forest in the highlands should therefore result in the blocks of F-class land in Figure 18 being transformed into grassland and eroded at the rate of several millimetres per year. This process can be seen around the margins of the hills north and east of Maralal, where hillslope gradients range from 10 to 25 percent.
Effect of producing charcoal during clearance of land for cultivation

At present much charcoal is produced during the clearance of bushland and woodland for cultivation in the wetter margins of the rangelands, where mean annual rainfall exceeds 450-500mm. This trend will continue until the end of the century in some parts of Kenya, according to the projections of Western and Ssemakula (1980). Figure 21 illustrates the current distribution of cultivated land, which is concentrated in the wetter and steeper portions of the rangelands.

Watson (1970) has documented clearing and regeneration cycles of more than 40 years in northern, eastern, and southern divisions of Kitui District where mean annual rainfall is 400-500mm. After clearance of the bush, fields are cultivated first to maize and then to bullrush millet for 7-9 years. Then they are abandoned to bush regeneration and are grazed by livestock from 5-10 years after abandonment. Thus, at any time only 17-23% of the total culturable land is producing crops, the remainder being in various stages of regeneration. New bush clearance is required every few years to replace land that goes out of production. Increasing population pressure and government policies may soon discourage such shifting cultivation, thereby decreasing this source of woodfuel and aggravating erosion unless soil conservation is also encouraged.

The effect of this land clearance on erosion is more extreme than that of selective cutting for charcoal alone. All woody vegetation is removed, the soil surface is disrupted and loosened by digging or ploughing. This change may sustain or even increase the rate at which soil can absorb rainfall, but it exposes loose, highly erodible soil and increases the amount of soil lost per unit of runoff. At the beginning of each wet season the soil is bare, and the crops only provide a significant cover after most of the erosive rainfall has occurred. If two crops can be grown in a year, the soil surface is disrupted and cleared a second time. Finally, the regeneration of woody vegetation is prevented until the field is abandoned.
The general magnitude of erosion following bush clearing for cultivation can also be examined with the USLE although predictions are complicated by the variety of crops and tillage practices that are possible. If the class 5 canopy (50% cover) referred to in Figure 19 were replaced by maize cultivation, the erosion rate would rise to 3-4 times that with the present ground cover and 1.6-2.4 times that with the ground cover severely reduced by local heavy grazing pressure. The range of values arises from using C-values for maize in Kenya given by Daines et al (1978) and Wenner (1980). Substitution of C-values for sorghum, millet, and beans gives slightly different soil-loss rates, but they are all significantly greater than those for rangelands if no soil conservation practices are used on the cleared croplands.

Soil conservation practices can radically reduce the erosion rate, and sustain both food and fuel production with less damage to soil and water resources. For example, Wenner (1980) lists management practice factors [P in equation (1)] for the USLE, which predict that channel terraces and tied ridges would reduce soil loss to 10-20% of the values without conservation practices; stone terraces to 10% of that value; and heavy mulches to 1%. In view of the potential savings of soil and of storage capacity in both local and major reservoirs, it seems worthwhile to mount a vigorous programme of soil conservation in these marginal lands. Technical advice, demonstrations, and other incentives are necessary, and could promote not only more intensive agricultural production but the growing of high-yielding fuelwood trees as part of an overall plan for resource conservation and enhancement.
EROSION DUE TO WOODFUEL PRODUCTION IN HIGH-POTENTIAL AREAS

Statement of the Problem

In their assessment of woodfuel potential in the Kenya rangelands, Western and Ssemakula (1981) concluded that the remaining stock of wood and the sustainable production in accessible areas are too small to satisfy the projected demand for fuel. Thus, large-scale extraction will be necessary from (mainly forested) lands into which agriculture will expand and from managed woodlots within or adjacent to arable lands. This raises the question of whether catastrophic erosion will result from woodfuel production in the high-potential regions of Kenya. Many of these lands are steep and receive heavy rainfall. Furthermore, they drain into the major rivers of the country, particularly the Tana River on which most of the country's hydroelectricity is generated. Thus, the danger exists that intensive production of wood energy could accelerate the already high rate of sedimentation in the reservoirs on this river, reducing their capacity to store water for power generation and irrigation.

Although the original terms of the consultancy dealt only with the rangelands, we also report here on the brief consideration that we have given to the problem of erosion potential associated with woodfuel production in the humid regions of Kenya. The following is based on previous analyses of erosion rates by one of us, some field observations during the current consultancy, and some illustrative USLE computations.

Current erosion status of the high-potential areas

Erosion rates in the high-potential zones of Kenya have been studied through the analysis of sediment loads in perennial rivers. In steep lands such as most of upland Kenya, with narrow, steep and rocky river channels, most of the sediment eroded from hillsides is transported quickly to the basin outlet and there is little evidence of significant accumulation of sediment in most basins. Under those conditions, the sediment yield from the basin (expressed in tons/ha/yr) is an accurate
reflection of hillslope erosion, although the former will be somewhat lower than the latter because some sediment must be trapped at field boundaries and other obstructions.

Dunne (1974) compiled sediment concentration records, collected by the Ministry of Water Development from 1948-1968 into a form that could be used for estimating basin sediment yields (Dunne and Ongweny, 1976; Dunne, 1979). Ongweny (1978) re-established and extended part of the Ministry network of sediment sampling stations and documented the flux of sediment from various subcatchments of the Upper Tana river. Each of these studies has documented the overwhelming importance of land use on erosion, although the amount of runoff (and therefore rainfall) and the steepness of the land are important factors.

Dunne's (1979) study of sediment yields from 61 gaging stations can be summarized by Figure 23, in which the lines separate points from basins with various dominant land uses, and by the following equations:

**Forest**

\[ SY = 0.0267 Q^{0.38} \quad R^2=0.98, \ n=4 \]

**Forest covering more than 50% of a basin that is otherwise cultivated**

\[ SY = 0.0010 Q^{1.28} H^{0.47} \quad R^2=0.76, \ n=9 \]

**Agriculture covering more than 50% of a basin that is otherwise forested**

\[ SY = 0.0014 Q^{1.48} H^{0.51} \quad R^2=0.74, \ n=28 \]

**Rangeland (with some agriculture)**

\[ SY = 0.0426 Q^{2.17} H^{1.12} \quad R^2=0.87, \ n=5 \]

In these equations \( SY \) = basin sediment yield \( (t/ha/yr) \), \( Q \) = mean annual runoff \( (mm/yr) \), and \( H \) is the basin relief divided by its length \( (m/m) \). The symbols \( R^2 \) and \( n \) indicate the multiple correlation coefficient and the sample size respectively.

The limitations of the data and analytical techniques are reviewed in the original report, where it is emphasized that the regression equations are not sufficiently well-defined for the
prediction of sediment yield from a single basin, but they can be used for making regional generalizations such as the following:

(i) Forested catchments lose sediment at the rate of 0.2–0.3 t/ha/yr.

(ii) The sediment yields of agricultural lands vary enormously with runoff, topography, and probably the type of cultivation (although no data are available on this last factor). At one end of the scale, a basin with flat topography developed on permeable soils and with sparse rainfall loses approximately 0.1 t/ha/yr. In the wettest, steepest cultivated basins such as the Mathioya basin, and those tributary to the Tana River on the eastern side of Mt. Kenya) soil loss ranges between 20 and 40 t/ha/yr.

(iii) Sediment yields from rangeland catchments are also variable, ranging from 1 t/ha/yr in the driest catchments (where there is considerable deposition and storage of eroded sediment) to 200 t/ha/yr on the wettest, steepest grazed catchments, which are also partially cultivated.

(iv) Removal of forest and its conversion to agricultural land can have highly variable results depending on rainfall, topography, and soil, but around the steep, wet margins of the remaining highland forests on the Aberdares and Mt. Kenya, the spread of maize and vegetable cultivation is likely to raise the erosion rate between tenfold and one hundredfold, unless soil conservation is adopted with greater enthusiasm than at present.

Field observations of stream sediment concentrations during the heavy April rains of 1981 indicated that steep, lightly-grazed land covered with pasture and small woodlots in the upper portions of catchments draining the Aberdares do not release much sediment compared with the arable land further downvalley. However, where cultivation is spreading into the forest, the fields show signs of intense sheetwash erosion.
Much of the sediment eroded from cultivated catchments appears to be entering stream channels from roads and tracks. Extension of settlement into forests would increase this influx also.

The study by Ongweny (1978) confirmed these conclusions.

**Potential sites for woodfuel harvest**

In the high-potential areas the following types of localities offer opportunities for woodfuel production:

1. The major forest reserves, such as on the Aberdare Range, Mt. Kenya, the Mau, Mt. Elgon, and smaller remnants such as the Cherangani Hills, Shimba Hills, Sokoke forest, and other remnants along the coastal lowland;

2. Small woodlots, often on rocky or eroded sites, along field boundaries, or within settlement enclosures;

3. Areas on the margins of the agricultural region which are less suitable for arable crops than for tree crops. These areas may be useful for the establishment of large plantations of fuelwood. At present some of these lands are occupied by abandoned sisal plantations, and poor-quality pasture.

We will now examine the erosion status of each type of site in its present condition and if exploited for woodfuel.

**Erosion resulting from woodfuel harvest**

1. As indicated in Figure 24, the erosion rate under undisturbed forest is exceedingly slow. The calculated values for steep gradients are in general agreement with the basin sediment yields of 0.14-0.30/ha/yr measured for the Mt. Kenya forests by Ongweny (1978) and Dunne (1979).
Experiments conducted in the Kenya Highlands indicate that it was possible to harvest wood from these forests without significant erosion if the exploitation is strictly controlled and involves replanting with rapidly growing trees. The system that was examined works as follows (Oland, 1962). After cutting of the trees, two food crops are planted during the first year. During the second year the ground is cleaned and weeded, and another food crop is planted. Tree seedlings are planted among the food crops and are weeded and cultivated. During the third year, crop cultivation continues until the trees grow tall enough to shade out lower vegetation.

Dagg and Pratt (1962) showed that such a system did not increase storm runoff, presumably because the high infiltration capacity and resistance to erosion of the organic-rich, structurally stable forest soil persist through the agricultural interlude. Poreira et al (1962) found that average sediment concentrations in streamflow were elevated several-fold during the cultivation period, especially during the third year of clean weeding. In the early part of the third year, the cultivated area was losing nearly 2.5 t/ha/yr, but late in the same year the sediment concentrations declined to pre-cutting levels as the tree canopy became closed.

It is possible, therefore to support wood production and some food production on the forested portions of the highlands without significantly accelerating erosion. However, it is important that planting occurs promptly and that the land does not suffer crop cultivation for long. In extremely sensitive areas such as on particularly steep slopes, erodible soils, or river banks, cutting may have to be avoided altogether or may require simple techniques of soil-conservation. Roads and tracks should be minimized and laid out along gentle gradients with careful attention paid to the control of road drainage.
Forest roads are likely to be the main source of sediment if the cutting and replanting are done effectively. Careful exploitation of the forest in this manner requires supervisory personnel with a training in forest engineering and soil conservation.

However, there is a significant erosion problem on the margins of the forest reserves because of uncontrolled forest clearance and cultivation of food crops without any significant soil conservation. Long steep hillslopes are being cleared of a dense tree cover and the surface is burnt, diminishing the important forest litter. Within several years of clearing, one can see rills or light streaks of sandy sediment tens of meters long extending downslope, indicating accelerated erosion. Fans of sediment line the base of the fields and the rills cross them, conveying sediment to stream channels. Many recently-cleared hillslopes on the eastern backslope of the Rift Valley escarpment between Nairobi and Nyahururu exhibit a transition form dense crop covers on flat ridgetops through progressively poorer crops as the gradient of the field increases downslope until there is complete crop failure on the steeper gradients. Large areas on the lower eastern slopes of Mt. Kenya show even more extreme examples of erosion on hillslopes that have yielded much charcoal during the process of clearing for cultivation.

A sample calculation with the USLE indicates the appropriate magnitude of the erosion due to clearance for cultivation. Figure 24 indicates the result of soil-loss calculations for a region receiving 1500mm of rainfall with a seasonal distribution similar to that of Embu. A soil erodibility index of 0.05 was used for these areas, as suggested by the work of Hennemann and Kaufman (1975) and Moore et al (1979) on well-aggregated, clay-rich soils in the Kenya highlands. Vegetation cover factors for various periods in the cropping cycle were taken from Wenner (1980), who also proposed a typical field length of 50m.
The results indicate that cultivation of maize and beans for a period long enough to degrade the litter, high organic content and other characteristics of the forest floor would result in a several-hundredfold increase in the rate of erosion. In agreement with the previously-mentioned field observations, the predictions are particularly severe on hillslopes with gradients of 20 percent or greater. Figure 24 also includes soil-loss calculations for fields with various kinds of terraces, tied ridges, and bunds which according to West African data quoted by Wenner (1980) should be reflected by P-values of 0.1-0.3 in the USLE. Even with such practices, the erosion rate is high on the steep slopes around the forest margins. The dense network of roads and tracks that evolves as permanent cultivation and settlement spread into a forested region would also aggravate the sedimentation problem in streams and reservoirs.

(2) At present trees are cut from small woodlots, field boundaries, and similar sites without significant acceleration of soil loss. After cutting, the ground surface beneath these trees retains its permeability and resistance to erosion long enough for a shrub cover to become established in the early stages of regeneration. In other cases the ground cover beneath the open stands of trees is grazed by goats and cattle, and although this practice accelerates erosion there are no signs of widespread intense erosion under the canopy or after it has been removed (except for a few concentrations of flow and soil wash where logs have been dragged downslope, or animal tracking has been concentrated, or where a sparse bush canopy has been heavily browsed on extremely steep slopes).

The erosion problem could be reduced still further if landowners were given advice and incentives to plant faster-regenerating tree species which would promote a better ground cover and greater soil protection than do the eucalypts and wattle trees that are now widespread. Extension of woodlots onto the unproductive, steeper, rapidly eroding sites referred to in the previous section would reduce soil loss and produce woodfuel. However, such promotion would require the provision of good advice in the field, demonstrations, seed, and economic incentive.
Around the margins of the high-potential areas there are some lowland regions, such as those in the upper Athi and upper Tana river valleys, which support only low-yielding agriculture, abandoned sisal plantations or pasture. Often the constraint is partly edaphic, because the soils are heavy, swelling clays developed from volcanic rocks on the dry margins of the highlands. It is possible that some of these lowlands could be used for large-scale plantations of fuelwood if silvicultural problems associated with the soils are overcome.

The steeper and drier parts of these lands, such as the upper Tana valley between Sagana, Thika, and the Masinga reservoir are currently losing soil at the rate of 10t/ha/yr (Ongweny, 1978). In the Kitengela grazing area of the Athi Basin, south of Nairobi, tree-root exposures indicate recent erosion rates of about 20t/ha/yr, although the long-term value is probably less (Dunne et al, 1979). On the cracking clay soils of this region, runoff is abundant once the soils become wet enough to close the shrinkage cracks. After that time, infiltration of rainwater is limited by the dense, fine-textured clay which has a poor structure (evidence from field experiments by Dunne, 1977). Introduction of trees onto these soils would improve their structure and promote infiltration. Thus it is to be expected that plantations of fuelwood would decrease erosion, in these areas, the effect being greatest in the Upper Tana basin, where there would be some amelioration of the sedimentation rate in the Tana reservoirs. Although there would be a short-lived acceleration of erosion at the time of cutting, it would be insignificant when averaged over the length of a harvest cycle.
REFERENCES


Dunne, T. and Ongweny,G.S. (1976). A new estimate of sediment yields in the upper Tana catchment; The Kenya Geographer, 2, 20-


FIGURE CAPTIONS

Figure 1: Correlation between erosion-intensity class and measured recent rates of erosion in Kenya. The crosses represent measurements made on tree-root exposures (Dunne, 1977), and the circle indicates estimates based on the sediment yields from forested drainage basins in central Kenya (Dunne, 1979).

Figure 2: Relations between erosion class and hillslope angle for various canopy densities. The reasons for the anomalous nature of the data from Kajiado District are unknown.

Figure 3: Relationship between average erosion rate measured from tree-root exposures and ground cover density at sites in Kajiado District. The solid circles and curve refer to the ground cover in the August-September period of 1976, and the open circles and dashed line refer to basal cover density at that time. (Source: Dunne, 1977).

Figure 4: Relationship of soil loss per unit of runoff to ground cover density for two hillslope gradients during artificial rainstorms on experimental plots in Kajiado District. See Dunne (1977) for methodological details and discussions.

Figure 5: Soil loss from plots during experiments under simulated rainstorms at Amboseli. The plots were trampled with varying intensities to simulate the trampling effects (but not the ground cover) associated with a range of stocking densities. See Dunne (1977) for methodological details and discussion.

Figure 6: Relation between measured soil loss and that predicted by the Universal soil-loss equation for plots in Zimbabwe (Source: Wendelaar, 1978).
Figure 7: Relation between mean annual rainfall and annual kinetic energy in storms with intensities greater than 25mm/hr for various regions of East Africa (Source: Moore, 1979).

Figure 8: Seasonal variation in the probability of 25mm or more rainfall occurring in one day for various stations in Kenya.

Figure 9: Regions of Kenya for which the relative seasonal distribution of rainfall erosivity was taken to be identical to that at the indicated meteorological station.

Figure 10: Variation of the soil-erodibility index, K in the Universal Soil-loss Equation, with texture for soils in the mid-western United States. Compiled from data given by Wischmeier and Smith (1978).

Figure 11: Average hillslope gradients for regions of Kenya. See text for explanation of data sources.

Figure 12: Vegetation-cover index, C in the Universal Soil-loss Equation, as a function of ground cover and canopy cover in rangelands. Numbers on the curves represent the canopy cover density (%). Compiled from data given by Wischmeier and Smith (1978).

Figure 13: Relation between canopy cover density as measured by KREMU and the true (vertically-projected) canopy cover used in erosion calculations. Compiled from line-intercept measurements of canopy density originally collected by Dr. P. Kuchar, KREMU.

Figure 14: Canopy density of trees taller than 2m for the Kenya rangelands. The data were recorded by KREMU aerial observers and compiled by Western and Ssemakula (1981).

Figure 15: Relationship between the total canopy cover and that for trees taller than 2m on KREMU ground plots.
Figure 16: Seasonal variation of mean monthly rainfall (solid lines) and the estimated average ground cover density (dashed lines) for various stations in Kenya. See the text for a description of the method of constructing the vegetation density curves.

Figure 17: Relationships between mean annual rainfall and the estimated seasonal maximum and minimum ground cover for stations in Figure 16. On the upper graph the crosses refer to the minimum ground cover density before the long rainy season and the circles represent peak ground cover at the end of that season. The lower graph indicates the minimum vegetation density before the short rains and the ensuing peak density. The solid curves were fitted by polynomial regression, and the dashed extensions are extrapolations beyond the range of available estimates.

Figure 18: Map of the erosion index computed with the Universal Soil-loss Equation for 10 x 10 km blocks of the Kenya rangelands.

Figure 19: Soil loss computed with the USLE, for hillslopes with a range of gradients under various cover densities in the vicinity of Narok. The numbers on the curves indicate canopy density. See text for details.

Figure 20: Schematic representation of the temporal variation of erosion that would result from clearing of a dense woodland canopy for fuel. The numbers on the axes are entirely hypothetical, but the general form of the curves agrees with our field observations and calculations.

Figure 21: Map of the percentage of land under cultivation for 10 x 10 km blocks of the Kenya rangelands. The data were recorded by KREMU aerial observers and compiled by Western and Ssemakula.

Figure 22: Soil loss, computed with the USLE, for forested land and for cleared and grazed land with a range of gradients under 800 mm of annual rainfall with a
seasonal distribution typical of Narok. The range of values for the forest reflects the range of C-values in Table 3.

Figure 23: Mean annual sediment yield and mean annual runoff for catchments in Kenya with indicated dominant land uses. The curves are envelopes separating the land-use categories. (Source: Dunne, 1979).

Figure 24: Soil loss, computed with the USLE, for forested and cultivated land with a well-aggregated, clay-rich soil under 1500mm of annual rainfall with a seasonal distribution typical of Embu. Parameter values obtained from sources indicated in the text.
Figure 1.
Figure 2.
Figure 3.
Figure 5
Figure 8b

- MOYALE
- NAKURU AIRFIELD
- NAIROBI AIRPORT
- NAROK
- VDI

Probability of 25 mm or more rainfall in one day.
Figure 10
Low bush. Average drop fall height 0.5 m.

Bush. Average drop fall height 2 m.

Trees with no appreciable low bush. Average drop fall height 4 m.

Figure 12
Figure 15
Figure 16a

Mean Monthly Rainfall (mm) and Average Ground Cover Density (%)

Lodwar

Mombasa Airport

Garissa

Makindu
Figure 16b
Figure 19

Cutting with increased grazing pressure.

Cutting with current grazing pressure.
Figure 20

- Increased grazing and burning.
- Regeneration
- Erosion lowered by growth of shrubs.

Graph showing the ratio of erosion to long-term average rate without cutting over time since cutting for woodfuel (year).