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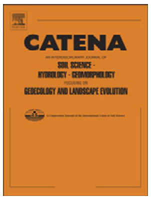

Magnitude of soil erosion on the northern slope of the Uluguru Mountains, Tanzania: Interrill and rill erosion

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ABSTRACT

The magnitude of interrill and rill erosion was determined on the northern slopes of the Uluguru Mountains, Tanzania which is representative for larger areas of East African Arch Mountains, where population pressure is high and land degradation is severe. The aim of the study was to develop a database to support soil conservation in the area. The study was done on two distinct geomorphic units with respect to altitude and hence rainfall distribution pattern: mountain ridges with an altitude ranging from 1000 to 1500 masl and mean annual rainfall of 2300 mm and mountain foothills whose altitude and mean annual rainfall are 550 to 900 masl and 900 mm, respectively. Total soil loss was measured on 36 individual bounded plots measuring 1.2 m × 20 m using Gerlarch troughs on each day with rain from July 2000 to June 2001. The plots were located on six different geopedologic units, nine on mountain ridges and the rest on the mountain foothills. The slope gradient on the terrain ranged from 30% to 70%. The plots were put under maize cultivation as the main crop. Soil loss through rill erosion was estimated by volumetric measurements of rills on each soil erosion plot. The soil loss due to interrill erosion was obtained by subtracting soil loss through rill erosion from the total soil loss measured in the Gerlarch troughs. The results indicate that soil loss due to both interrill and rill erosion was very high with mean soil loss of 69 and 163 t/ha/year, respectively. Rill erosion accounted for about 58% of the total soil loss while interrill erosion contributed to the remaining 42%. Both interrill and rill erosion were higher in the mountain ridges with mean soil loss of 88 t/ha/year and 210 t/ha/year compared to 49 and 116 t/ha/year in the mountain foothills, respectively. Rill erosion was significantly higher ($P \leq 0.001$) in all geopedologic units with slope gradient above 40% (mean soil loss ranged between 91 and 258 t/ha/year) compared to interrill erosion with mean soil loss varying from 41 to 115 t/ha/year. In geopedologic units with slope gradient above 60% both interrill and rill erosion were highly active while in geopedologic units with slope gradient below 40% the two processes were less active. The results demonstrate that rill erosion is more important than interrill erosion in the study area particularly where the slope gradient exceeds 40%. The results further show that the major part of the studied area has moderate interrill erosion (10–50 t/ha/year) and severe to very severe (>100 t/ha/year) rill erosion. This study clarifies the magnitude of interrill and rill erosion which is important for designing soil conservation on agricultural fields.

1. Introduction

Highlands of East Africa suffer severely from soil degradation since the deforestation of the natural mountain forests and the cultivation of large areas. High amounts of soil losses due to severe soil erosion are reported from arable lands in the mountainous areas of East Africa (Oldeman et al., 1990). In these areas, past studies showed that rates of soil loss by combined processes of interrill and rill erosion are very high, i.e. in excess of 50 t/ha/year which exceeds the tolerable values generally recommended to be 10 to 12 t/ha/year (Milliman and Meade, 1983). Although interrill and rill erosion are recognised to be the most important forms of soil erosion in the mountainous areas of East Africa, their relative contribution to overall soil loss is not known due to lack of such detailed quantitative information.

In the mountainous areas of Tanzania, soil degradation caused by water erosion is rampant and the magnitude of soil loss is increasing at an alarming rate (Lundgren and Rapp, 1974; Mboya et al., 1998; Westerberg and Christiansson, 1999). Soil loss rates recorded in different mountainous areas of Tanzania (Temple and Murray-Rust, 1972; Rapp et al., 1973) exceed the tolerable values generally assumed to be 0.02 to 1.0 mm/year compared to the mean rate of soil formation of 0.01 to 0.02 mm/year (Morgan, 1995). In the Usambara Mountains soil erosion is estimated to vary from 72 t/ha/year to 120 t/ha/year (Lundgren, 1980; Pfeifer, 1990)

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while a soil loss of 28 to 72 t/ha/year was observed in the arable lands on the slopes of Mount Kilimanjaro (Temple, 1972). Based on studies by Rapp et al. (1973) very high amounts of soil loss were reported from the arable lands of Morogoro catchment in the Uluguru Mountains. The calculated average sediment yield in the year 1966 to 1970 was estimated to be 312 t/ha/year. Sheet wash (interrill erosion) from the cultivated land constituting about 10% of the catchment is thought to supply the main flow of the sediments. Sheet wash (interrill erosion) measurements on erosion plots from cultivated land at Mfumbwe in the Uluguru Mountains showed a soil loss of 336 t/ha/year (Temple and Murray-Rust, 1972).

In the Uluguru Mountains, farmers tend to pay more attention to landslides neglecting other forms of soil erosion (Temple and Rapp 1972; Kilasara and Rutatora, 1993; Lulandala et al., 1993; Westerberg and Christiansson, 1999; Verbesselt and Mertens, 2000). However the erosion process in these areas is complex and the importance of other forms of soil erosion leading to denudation has widely been reported. Accordingly, interrill erosion (Temple and Murray-Rust, 1972), rill and gully erosion (Lundgren, 1978; Sorensen and Kaaya, 1998) and episodic landslides (Westerberg, 1999; Westerberg and Christiansson, 1999) are extremely important forms of soil erosion in the Uluguru Mountains. The alarming rate of soil erosion in the Uluguru Mountains and other mountainous areas in East Africa has raised a lot of ecological, environmental and economic concerns. However, efforts to arrest soil erosion in these areas have progressed very slowly due to lack of adequate data and link between specific soil erosion processes and their control measures. The way forward to combat soil erosion in the Highlands of East Africa has to be supported with information on the contribution of the various processes of soil erosion while taking into account both their spatial distribution and the degree of severity. This kind of information will assist in developing appropriate soil conservation strategies in the Uluguru Mountains, Tanzania and in similar areas in East Africa.

The objective of this study was to determine the magnitude and severity of interrill and rill erosion in different geomorphic units on the northern slopes of the Uluguru Mountains, Tanzania with the aim to develop a database to support soil conservation in the area and in similar environment of the East African Highlands.

2. Study area

The study area is located on the northern slopes of the Uluguru Mountains between 350,295E and 354,368E and 9,237,500N and 92,436,97N UTM coordinates (Fig. 1). The climate of the area is classified as sub-humid tropical savannah of the low latitude environment (Sharma, 1987). The mean annual rainfall varies with altitude, from 900 mm at around 550 masl to 2300 mm at 1500 masl. It is distributed into 2 distinct periods, a long rainy season (*masika*) which lasts from March to May and short rains (*vuli*) which extend from October to January. The mean annual air temperature varies from 25 °C around 550 masl to 19 °C at 1500 masl.

The area is mountainous with strongly dissected mountain ridges and foothills with very steep narrow valleys. The rocks are metasediments mainly consisting of hornblende pyroxene granulites, with plagioclase and quartz rich veins (Sampson and Wright, 1964).

Based on the World Reference Base for Soil Resources system of soil classification (FAO, 1998), the soils on the mountain ridges are *Endoskeletic* and *Leptic Cambisols* while *Haplic* and *Chromic Phaeozems* and *Orthieutric Regosols* are subsidiary. On the foothills, the dominant soils are *Chromic Lixisols* and *Profondic Acrisols* associated with *Hyperferralic Cambisols* and *Endoleptic Cambisols* (Kimaro et al., 1999). Over 70% of the Uluguru Mountains is under cultivation. The study area is mainly cultivated with maize (*Zea mays* L.), vegetables, beans (*Phaseolus* spp) and bananas (*Musa* spp) as main crops. In Fig. 2, the

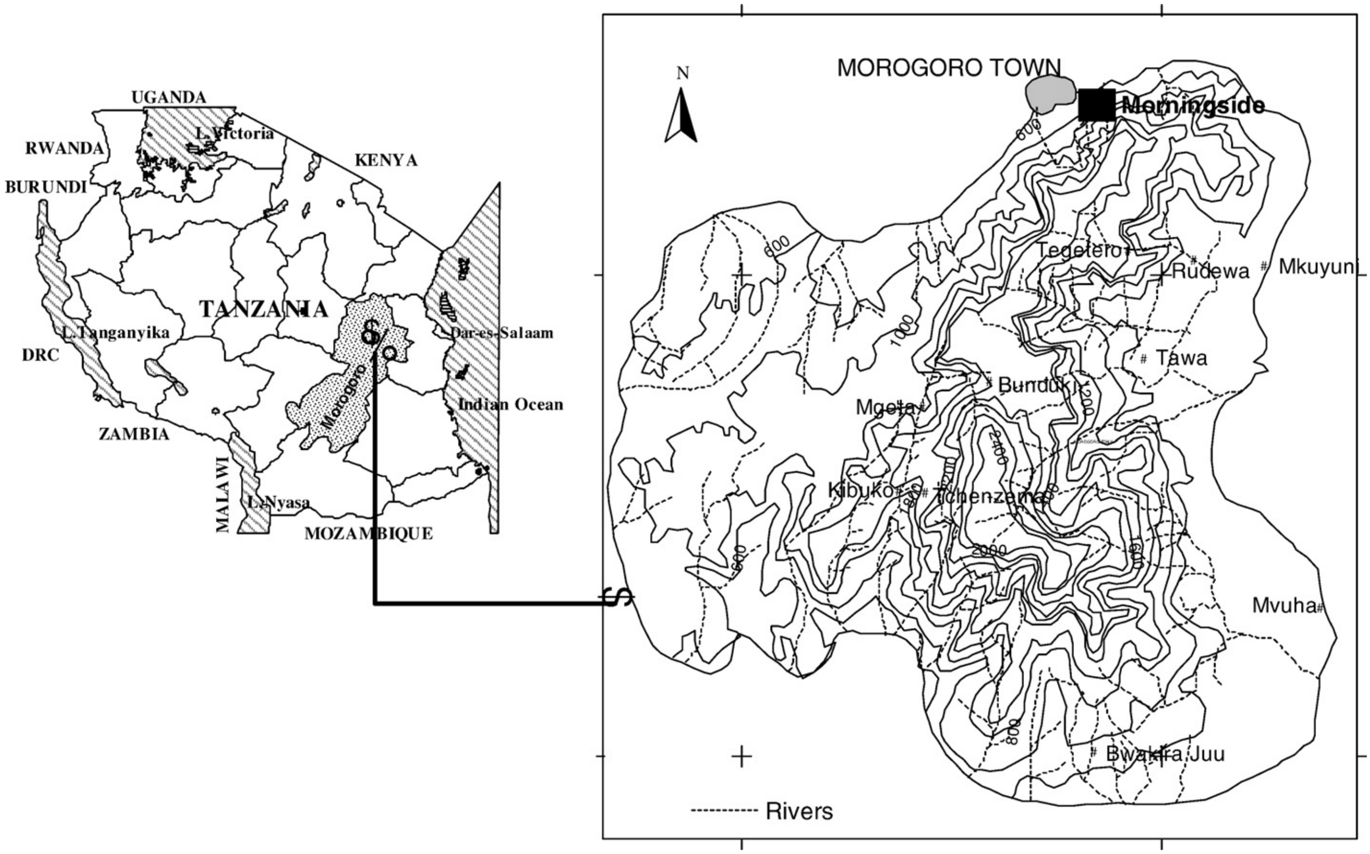
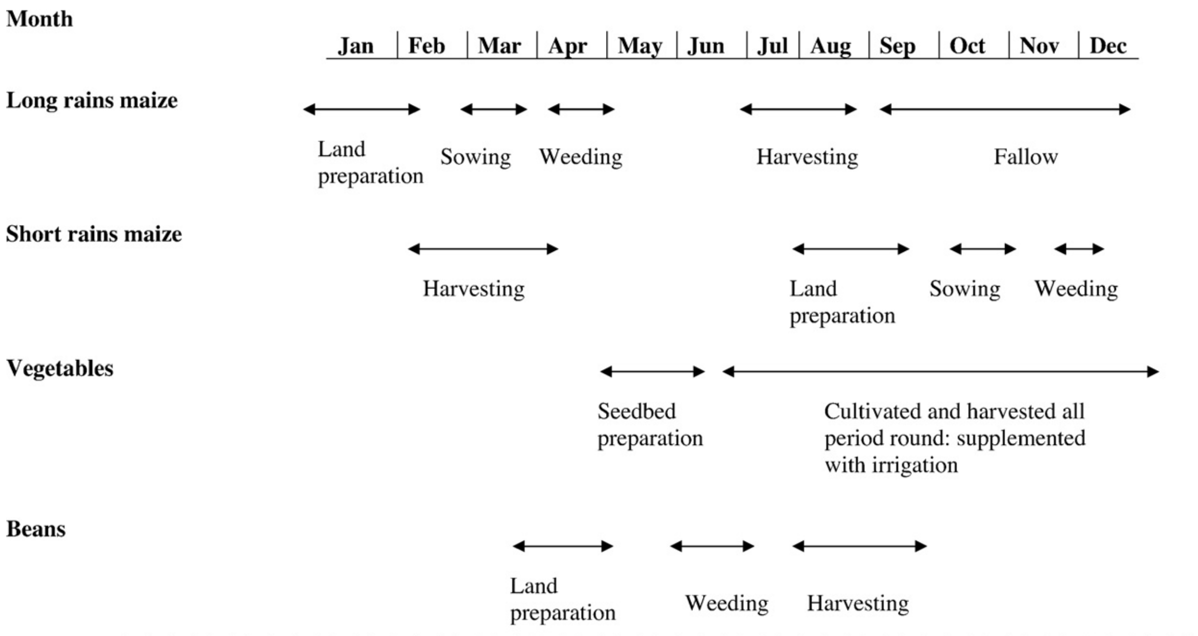


Fig. 1. Location map of the study area.



NB: short rain maize, vegetables and beans are grown alternately on the mountain ridges while long rains maize is grown on mountain foothills alternating with fallow period during short rains

Fig. 2. Cropping calendar of major farming systems in the study area (Kimaro et al., 2005).

cropping calendar for the major cropping system on the northern slopes of the Uluguru Mountains is presented (Kimaro et al., 2005).

3. Materials and methods

The rate of interrill and rill erosion was determined on two distinct geomorphic units: mountain ridges and mountain foothills. The selection of these units was mainly based on geopedologic characteristics presented in Table 1.

Total soil loss was measured on 36 individual bounded plots each measuring approximately 1.2 m×20 m (Fig. 3) and equipped with Gerlarch troughs (Sutherland and Bryan, 1989; Prasuhn, 1992) each with a capacity of 120 l. The erosion plots were located on six different geopedologic units, nine on mountain ridges and the rest on the mountain foothills (Fig. 4). The slope gradient of the terrain ranged from 30% to 70%. The plots were bounded by compacted bunds of soil (30 cm high) on the upper and lateral sides sandwiching polythene sheet in order to lead only the runoff of the bounded area into the Gerlarch troughs. Land husbandry activities such as land preparation, planting and weeding on these erosion plots were strictly done in accordance with the usual farmers' practice. Sediments and runoff water were collected on each day with rain from July 2000 to June 2001. Both the volume of runoff and mass of sediments were determined. The volume of the runoff was estimated by multiplying height of its level in the Gerlarch trough with the cross-sectional area of the trough. Daily soil loss was determined on a 5 l sub-sample after thoroughly stirring the contents in the Gerlarch trough from a given plot. Where the volume of runoff was less than 5 l, the entire volume was taken as a sample. Each sample was left to settle and the sediments were obtained by decantation followed by oven drying. The sediments were weighed and the cumulative weights were expressed on the basis of oven dry mass.

Soil loss through rill erosion was estimated daily using the volumetric method (Mtakwa et al., 1987; Govers and Poesen, 1988;

Table 1
Selected geopedologic characteristics of the geomorphic units used for the determination of interrill and rill erosion in the study area

Geopedologic units	Slope	Topsoil/subsoil	Vf.sand %	Silt %	Clay %	Rfrag.	si/c	BD kg/m^3	OM %	WSA %
Mountain ridges (1000–1500 masl)										
Hyperferralic Cambisols	>60	Topsoil	31	17	28	38	0.61	1200	2.1	3
		Subsoil	29	17	28	32	0.61	1400	2.4	
Leptic Cambisols	50–60	Topsoil	25	7	27	32	0.26	1200	1.6	5
		Subsoil	22	7	27	28	0.26	1400	0.3	
Mountain foothills (550–900 masl)										
Hyperferralic Cambisols	>60	Topsoil	16	9	54	35	0.17	1200	2.8	7
		Subsoil	17	11	58	48	0.19	1200	1.6	
Endoleptic Cambisols	50–60	Topsoil	21	5	36	14	0.14	1300	2.8	9
		Subsoil	21	3	37	27	0.08	1300	1.7	
Chromic Lixisols	40–50	Topsoil	12	13	38	30	0.34	1200	1.4	13
		Subsoil	9	9	70	27	0.13	1200	1.2	
Profondic Acrisols	30–40	Topsoil	10	7	56	19	0.12	1200	2.1	15
		Subsoil	8	3	66	12	0.05	1200	0.9	

Rfrag. = rock fragments, si/c = silt/clay ratio, BD = bulk density, OM, = organic matter, Vf.sand = very fine sand WSA = water stable aggregate (>4 mm).
Source: Kimaro et al., (1999).

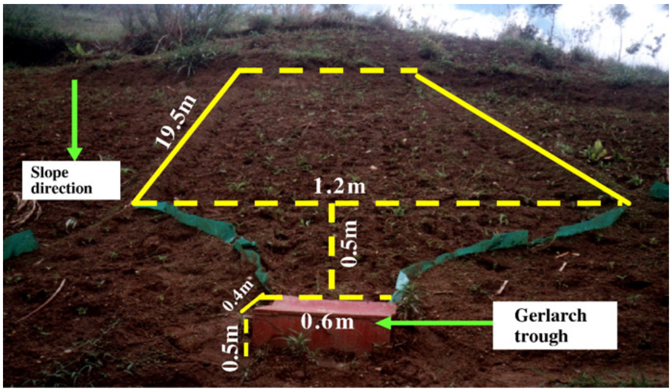


Fig. 3. Bounded plot for determination of interrill and rill erosion using Gerlarch troughs on farmers' field.

Morgan, 1995). The procedure involved determining the dimensions of each individual rill in a demarcated erosion plot. In this case the same area in which the interrill erosion was measured was used for estimating the volume of rills. The average width, depth and length of each rill were measured using a metre rule with an accuracy of ±1 mm. In this study, a channel was considered to be a rill when the concentrated flow channel has incised into the plough layer to a depth and width ranging from 2 to 15 cm and 3 to 50 cm, respectively (Turkelboom, 1999). The volume of each rill was calculated as a product of its length, width and depth. Summation of the volume of all rills in a particular plot gave the volume of soil lost from the plot. Weight of soil loss from each plot was estimated using the following equation:

$$A = V^{*}D_{\mathrm{b}} \tag{1}$$

where:

A estimated rill erosion (kg/ha/year),
V volume of soil loss (m^3/ha) and
D_b dry bulk density (kg/m^3).

Bulk density of the soils affected by rills were determined on undisturbed soil samples following the procedures after Blake and Hartage (1986). The results of soil bulk density for each soil unit are given in Table 1. The difference between the measured total soil loss and estimated soil loss by rill erosion was taken to represent soil loss through interrill erosion. The rates of soil loss obtained for both interrill and rill erosion were expressed in t/ha/year. The estimated soil erosion rates by both interrill and rill were categorised into five different soil erosion severity classes following the criterion established by Turkelboom (1999). These are:

Class 1	Mild erosion (0–10 t/ha/year)
Class 2	Moderate erosion (10–50 t/ha/year)
Class 3	Moderately severe erosion (50–100 t/ha/year)
Class 4	Severe erosion (100–150 t/ha/year)
Class 5	Very severe erosion (>150 t/ha/year).

4. Results and discussion

4.1. Magnitude of interrill and rill erosion in the study area

The mean soil loss due to interrill and rill erosion in the study area is presented in Table 2. Interrill and rill erosion accounted for 69 and 163 t/ha/year of soil loss, respectively. Rill erosion was therefore more aggressive, accounting for an average of 70% of the total soil loss while interrill erosion contributed to the remaining 30%. These results agree with many studies (Zachar, 1982; Govers and Poesen, 1988; Herweg, 1992; Smolska, 1999) which have reported that on fields where interrill and rill erosion are active, the contribution of rill erosion becomes dominant. According to these authors, the contribution of rill erosion assessed in many arable fields was observed to vary from 54% to 78% of the total soil loss by interrill and rill erosion. These ratios were mainly obtained from soil erosion assessment on the fields located on more gentle slopes with slope gradient ranging from 15% to 33%. For mountainous areas with slope gradients steeper than 30% more soil loss due to rill erosion is expected because rilling and channel sidewall processes become more active with increase in slope gradient as the latter increases beyond 30% (Govers and Poesen, 1988). Interrill and rill erosion are mainly influenced by rain, slope, soil characteristics and cropping systems. These characteristics are better assessed at meso- and micro-scale levels when assessing interrill and rill erosion (Lal, 1990; Turkelboom, 1999). Furthermore, interrill and rill erosion processes generally evolve very fast and hence short duration observations which can be easily done using field plot scale approach.

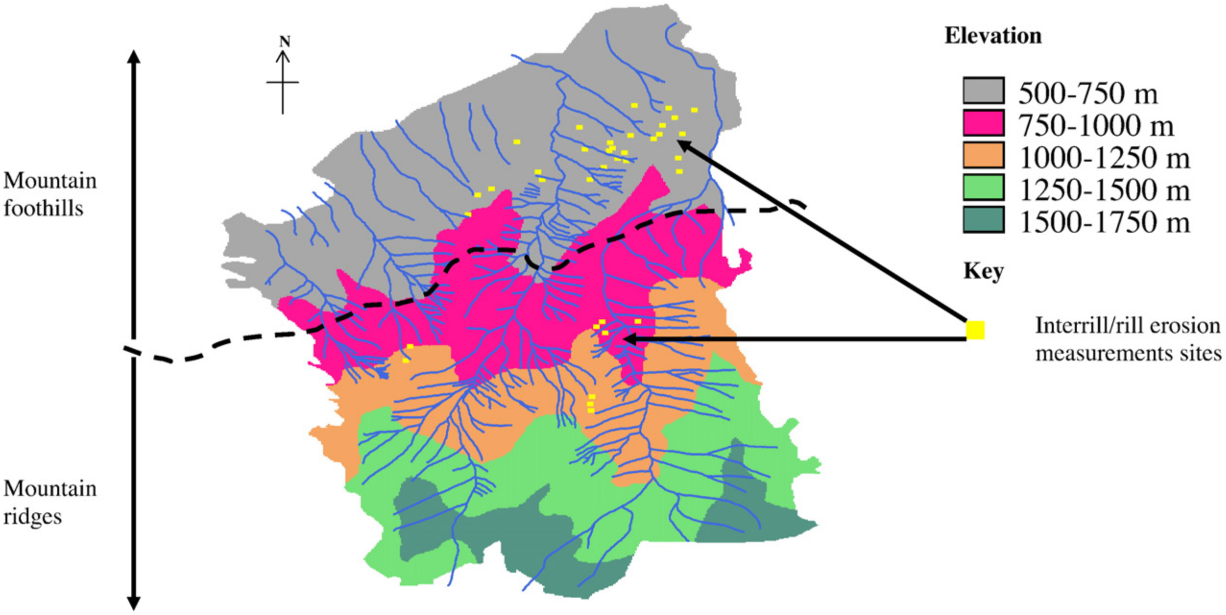


Fig. 4. Elevation map of the study area showing location of interrill and rill erosion measurement sites.

Table 2
Soil loss rates due to interrill and rill erosion in the study area

Type of soil erosion	Soil loss (t/ha/year)				
	Mean	Standard deviation	Minimum	Maximum	Number of erosion plots
Interrill	69	15	7	143	36
Rill	163	12	24	275	36

Therefore, results obtained from field plot scale assessment of interrill and rill erosion processes can assist in recommending better soil conservation measures and evaluation of alternative crop management on agricultural fields. However, as observed by Turkelboom (1999) results obtained at this scale, should only be used as complementary to higher scale levels i.e. at catchment or landscape levels.

4.2. Interrill and rill erosion on the mountain ridges and foothills

Mean soil losses due to interrill and rill erosion in the mountain ridges and foothills of the study area are presented in Table 3. Both interrill and rill erosion were higher on the mountain ridges than on the mountain foothills. The corresponding values were 88 and 210 t/ha/year in the mountain ridges compared to 49 and 116 t/ha/year in the mountain foothills.

The results clearly show that both interrill and rill erosion vary significantly between the two major geomorphic units. The higher erosion rates observed in the mountain ridges could be attributed to the characteristics of this geomorphic unit, particularly high rainfall (Rapp et al., 1972), very steep slopes (Table 1) (Georges et al., 1992) and the continuous shallow and fine cultivation being practised by the farmers. Fine tilled soil surface layer on steep slopes and under high rainfall can, upon saturation, be transported very easily down slope by concentrated water flow and by widening of rills (Turkelboom, 1999). The slightly lower rates of both interrill and rill erosion observed in the mountain foothills could be explained by the physical properties of the soils such as high aggregate stability (Table 1) which reduces soil detachment rates (Prasuhn, 1992) and the nature of cultivation practices such as fallow cultivation (Fig. 2) resulting on more stable aggregates held together by a mesh of fine roots which results into limited soil erosion as observed by Turkelboom (1999).

4.3. Interrill and rill erosion in the selected geopedologic units

The magnitude and variation of interrill and rill erosion in the selected geopedologic units of the study area are presented in Table 4. The data indicate that rill erosion was significantly higher than interrill erosion ($P \leq 0.01$) in all geopedologic units with slope gradient above 40%. The mean soil loss due to rill erosion ranged between 91 and 258 t/ha/year) while that of interrill erosion varied from 41 to 115 t/ha/year. In geopedologic units with slope gradients above 60% both interrill and rill erosion were highly active while in geopedologic units with slope gradient below 40% both processes were less active.

Table 3
Soil loss rates due to interrill and rill erosion on the mountain ridges and foothills of the study area

Geomorphic units/type of erosion	Soil loss (t/ha/year)				Number of observations
	Mean	Standard deviation	Minimum	Maximum	
Mountain ridges					
Interrill	88	25	45	143	9
Rill	210	15	141	275	9
Mountain foothills					
Interrill	49	9	7	110	27
Rill	116	10	24	254	27

Table 4
Soil loss rates due to interrill and rill erosion on different geopedologic units of the study area

Geopedologic units	Slope (%)	Soil loss (t/ha/year)								N
		Interrill				Rill				
		Mean	s.d	Min	Max	Mean	s.d	Min	Max	
Mountain ridges										
Hyperferralic Cambisols	>60	115***	35	70	143	258***	15	240	275	5
Leptic Cambisols	50–60	61**	15	45	79	161***	15	141	175	4
Mountain foothills										
Hyperferralic Cambisols	>60	98***	12	81	110	235***	11	222	254	6
Endoleptic Cambisols	50–60	44**	6	37	49	111***	9	96	121	5
Chromic Lixisols	40–50	41**	15	21	60	91***	14	68	107	9
Profondic Acrisols	30–40	13^{NS}	4	7	24	28*	5	24	35	7

s.e = 11; NS = not significant, * = $P<0.05$, ** = $P<0.01$, *** = $P<0.001$.
s.d = standard deviation, s.e = standard error, Min = minimum, Max = maximum, N = number of observations.

These results are slightly different from those of Turkelboom (1999) who observed that in the highlands of northern Thailand rill erosion was dominant over the slope gradient range of 31 to 71%. Following Turkelboom's method it can be observed that differences in the absolute measured soil loss rates could be explained by the semi-quantitative nature of observations, subjectivity and field heterogeneity. Some authors (e.g. Meyer et al., 1985; McCool et al., 1987) have also reported that at a slope gradient of around 10% there is a switch from interrill to rill erosion. The higher slope gradient threshold of 40% observed in the Uluguru Mountains cannot be sufficiently explained on the basis of the available information. Studies conducted elsewhere (e.g. Turkelboom, 1999), have shown that on slope gradients above 47% rills tend to widen and become more frequent. This would hence correspond with a relative domination of rill erosion over interrill erosion as slope gradient increases. The results presented in both Tables 3 and 4 illustrate the importance of subdividing the landscape into homogenous units when studying soil erosion as this could form the basis for setting out conservation priorities.

4.4. Interrill and rill erosion severity levels and their spatial distribution

The measured average interrill and rill erosion rates in the study area vary from 12 to 115 and 28 to 258 t/ha/year, respectively (Table 4). This is in agreement with soil erosion rates measured elsewhere with similar environmental conditions e.g. in northern Thailand

Table 5
Interrill and rill erosion severity classes on different geopedologic units

Geopedologic units	Slope (%)	Interrill soil loss (t/ha/yr)	Severity class	Rill soil loss (t/ha/yr)	Severity class
Mountain ridges					
Hyperferralic Cambisols	>60	115	4	258	5
Leptic Cambisols	50–60	61	3	161	5
Mountain foothills					
Hyperferralic Cambisols	>60	98	3	235	5
Endoleptic Cambisols	50–60	44	2	111	4
Chromic Lixisols	40–50	41	2	91	3
Profondic Acrisols	30–40	12	2	28	2

2 = Moderate erosion (10–50 t/ha/year), 3 = Moderately severe erosion (50–100 t/ha/year), 4 = Severe erosion (100–150 t/ha/year), 5 = Very severe erosion (>150 t/ha/year).

(Anecksamphant and Boonchee, 1992; Anecksamphant et al., 1995; Turkelboom, 1999). However, the rates of interrill and rill erosion from these results are much higher when compared to previous results (Temple, 1972; Lundgren, 1980; Pfeifer, 1990) from Tanzanian highlands. This could be explained by the fact that many of the reported previous studies are based on the extrapolated measurement of total soil loss (Mulengera, 1996; Magunda et al., 1999) from few on-station observations using Wischmeier standard runoff plots (Wischmeier and Smith, 1978) and erosion pins.

On the basis of the soil erosion severity criterion established by Turkelboom (1999) the interrill and rill erosion under this study fall into the following severity classes: (2) moderate, (3) moderately severe, (4) severe and (5) very severe erosion (Table 5).

The spatial distribution of the individual interrill erosion severity classes indicate that class 2 is the most dominant affecting 3 out of the 6 major geopedologic units of the study area while class 4 is the least in terms of its spatial coverage. Class 3 is intermediate affecting only 2 geopedologic units.

The spatial distribution of the individual rill erosion severity classes indicate that class 5 is the most dominant one affecting 3 major geopedologic units occupying the steepest slopes of the mountain ridges and foothills while class 4 is the least occupying only one geopedologic unit in terms of its spatial coverage. Classes 2 and 3 are intermediate affecting only two geopedologic units in the mountain foothills. The severity of rill erosion in the study area could be attributed to the steep slope gradient of most geopedologic units which are >40% (McCool et al., 1982; Govers and Poesen, 1988; Morgan, 1995; Turkelboom, 1999). The most severe rill erosion occurs in the geopedologic units with slope gradient >50%. Similar observations were made elsewhere (Moeyersons, 1991; Turkelboom, 1999). The spatial distribution of the studied soil erosion processes has clearly identified areas mostly dominated by the individual interrill and rill erosion and the degree of their severity. It is clear that the land units of the study area are not uniformly affected by these processes. Therefore, the spatial information presented here forms an important tool in understanding the behaviour and occurrence of interrill and rill erosion in a complex mountainous environment. The information will guide the setting of soil conservation priorities in the study area which will eventually minimize costs by concentrating efforts on priority areas in East African Highlands.

5. Conclusions

Interrill and rill erosion rates in the northern slopes of the Uluguru Mountains vary spatially along the landscape both in terms of the type of process and the degree of severity. The rates of interrill and rill erosion observed in this study are much higher when compared to total soil loss by interrill and rill erosion measurements seen from previously reported rates. The results of this study demonstrate that interrill and rill erosion are among the soil erosion processes highly active in the study area. Interrill and rill erosion affect all the studied geopedologic units. Rill erosion is more aggressive than interrill erosion in terms of its spatial coverage and degree of severity, accounting for an average of 58% of the total soil loss while interrill erosion contributes to the remaining 42%. Rill erosion dominates on the geopedologic units occupying the steepest slopes of both the mountain ridges and mountain foothills, affecting 66% of the studied area. It is more severe on the mountain ridges and foothills where the slope gradient is >50%. About 50% of the rill-affected geopedologic units is categorised as very severely eroded. Interrill erosion is active mostly on the mountain ridges where it is moderately severe affecting 30% of the studied geopedologic units. The study has provided an opportunity to identify active spots for interrill and rill erosion on different geopedologic units. It is clear that the land units of the northern slopes of the Uluguru Mountains are not uniformly affected by these processes. Therefore, the spatial information presented here forms an important tool in understanding the behaviour and occurrence of interrill and rill erosion in the study area. This could serve as a guide for setting soil conservation strategies and plans in the northern slopes of the Uluguru Mountains.

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