



Short and medium term assessment of tillage erosion in the Uluguru Mountains, Tanzania

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Abstract

Soil translocation due to shallow tillage by manual hoeing appears to be one of the most important erosion processes in the Uluguru Mountains. In order to quantify erosion rates caused by manual hoeing in the area a tillage experiment was set up and an on-farm survey was conducted during the dry season of the years 2000 and 2001, respectively. Soil flux rates on eight slope gradients (31–67%) were monitored by measuring the tillage step characteristics using Trapezoid-step method and by collecting soil material lost in Gerlarch troughs. Soil flux rates due to medium-term (30 years) manual hoeing along contour bands with grass barrier were also monitored by measuring volumes of tillage step below and colluvium accumulation above the surface of the original slope on six slope gradients (51, 52, 55, 56, 58 and 60%). Average tillage depth for superficial tillage was 5.2 cm. The results obtained by the Trapezoid-step method ranged from 43 to 70 kg m⁻¹ per tillage pass with a mean tillage transport coefficient (*k*) of 107.5 kg m⁻¹ on the tested slopes. Mean soil flux rates obtained by Gerlarch trough method were slightly lower than those obtained by Trapezoid-step method with values ranging from 14 to 77 kg m⁻¹ per tillage pass and a tillage transport coefficient (*k*) of 83.9 kg m⁻¹ per tillage pass. The rates measured by both methods showed an increasing soil flux with slope gradient. Results on soil flux rates due to the medium-term tillage operation (step measurements) showed a negative trend with increasing slope gradient. Soil flux ranged from 148 to 42 kg m⁻¹ per year for slopes between 51 and 60%. Soil flux due to colluviation behind grass barriers showed a similar trend with values higher than those obtained by step measurements. The soil flux rates behind grass barriers ranged from 153 kg m⁻¹ per year on slope of 51% to 67 kg m⁻¹ per year on a 60% slope in approximately 30 years of cultivation. A reasonable correspondence between calculated displaced soil (area under original slope) and the accumulated colluvium (area above the original slope) was obtained indicating significant contribution of tillage erosion. Contribution due to water erosion processes ranged from 7 kg m⁻¹ per year on slopes of 51% to 25 kg m⁻¹ per year on a slope of 60%. The study demonstrated that tillage translocation rates due to manual superficial tillage are very high and could partly be held responsible for the development of

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shallow soils observed on steep slopes and the accumulation of colluvium behind grass barriers along contour bands in the Uluguru Mountains.

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1. Introduction

Tillage erosion, also referred to as “arable erosion” (Zachar, 1982) or mechanical soil erosion (Kiburys, 1995), is the process of soil movement caused by the force applied by agricultural tools and by gravity (Lindstrom et al., 1992; Govers et al., 1994; Dercon, 2001). At the level of farm plot, tillage erosion can be recognised by a less fertile tillage step at the top of the field (due to profile truncation) and the development of a soil bank with a high soil fertility status at the bottom of the field if the physical barrier is present (Turkelboom, 1999; Nyssen et al., 2000; Poesen et al., 2000). An often overlooked process contributing to soil loss is the direct effect of tillage on soil movement (Kisanga, 1992; Lindstrom et al., 1990; Turkelboom et al., 1999; Dercon, 2001). Although tillage erosion became better documented recently (Govers et al., 1994; Guiesse and Revel, 1995; Govers et al., 1996) there is still inadequate information on this process particularly in the tropical mountainous areas (Nyssen, 2001). It is also noted that research efforts on tillage erosion in these areas have rarely been directed towards this direction probably due to slow and inconspicuous nature of this process compared to more spectacular water erosion.

Tillage erosion is a relatively new research domain (Turkelboom, 1999). With respect to soil loss, most studies to-date have concentrated on tractor-plough tillage on gentle slopes (Govers et al., 1994; Guiesse and Revel, 1995; Poesen et al., 1997). Only few works that have been reported underline the importance of soil losses caused by manual tillage (Turkelboom et al., 1997, 1999; Turkelboom, 1999) which is presumably the most widespread method of land preparation in the tropical mountainous areas.

Other research works have reported the importance of using buffer strip system, grass barriers along contour and stone bands on tillage erosion (Turkelboom et al., 1999; Nyssen et al., 2000; Poesen, et al., 2000; Nyssen, 2001). A peculiar phenomenon that has

been observed in these soil conservation structures is the formation of progressive terraces (Turkelboom et al., 1999; Nyssen et al., 2000). Progressive terrace formation is commonly explained by sediment trapping and accumulation along contour bands with grass barriers or hedgerows (Poesen et al., 2000). Although trapping of water eroded sediment has been observed in the field, it is believed that this process is not the main cause for progressive terrace formation but tillage erosion can contribute significantly to the amount of sediment trapped behind these soil conservation structures (Dercon, 2001; Nyssen, 2001). Therefore, assessment of the long-term effect of tillage erosion particularly the formation of progressive terraces between permanent contour buffer strips by tillage and intra-alley erosion is of great importance, as it would form a strong base for modelling of progressive terrace formation and development of appropriate soil conservation structures. Measurement of soil translocation due to manual hoeing ought to be given priority as many farmers in many mountainous areas including Uluguru Mountains in Tanzania mostly practice manual tillage using hand hoe.

Therefore, the objectives of this study were to quantify rates of tillage translocation and erosion and deposition on farmers’ fields on the steep slopes of the Uluguru Mountains, Tanzania.

2. Materials and methods

2.1. Research background

Quantification of soil movement and redistribution by tillage using tractor drawn implements can be described by diffusion-type equation (Govers et al., 1994) as shown in Eq. (1).

$$Qt = kS \quad (1)$$

where Qt is the soil flux caused by tillage (kg m^{-1} per

tillage pass); k the diffusion coefficient and; S the slope gradient (tangent of slope angle)

The authors reported that because the soil flux is directly proportional to the slope gradient, erosion and deposition will be proportional to the slope gradient change. This means erosion occurs at the convexities, while deposition will take place at the concavities (Govers et al., 1994). Also zones with zero-influx such as hill tops and upper field boundaries face accelerated truncation of the upper soil horizons, while soil banks are commonly formed at lower field boundaries if a barrier is present (Guireesse and Revel, 1995).

Turkelboom et al. (1999) attempted to quantify soil movement by manual hoeing as a function of slope angle and slope length. The authors conducted an on-farm tillage experiment on slopes ranging from 17 to 82% in order to quantify soil translocation by manual tillage. Soil translocation was measured by monitoring tracers (rock fragments), measuring dimensions of tillage steps and by collecting soil material in a trench (Turkelboom et al., 1999). The authors observed that soil flux by manual deep tillage is quantified by linear functions for different slope gradient classes, instead of single diffusion-type of equation (often proposed for tractor derived tillage erosion) as shown in Eq. (2). It was also noted that mean tillage transport coefficient (k) for one tillage operation varied according to tillage methods applied. Table 1 presents comparison of mean tillage transport coefficients (k) for several tillage methods applied on steep slopes.

$$Qt = 77.0S + 13.3 \quad (\text{if } 3\% < S < 70\%) \quad (2)$$

where Qt is the soil flux caused by manual deep tillage (kg m^{-1} per tillage pass) and S the slope gradient of original soil surface (%).

2.2. The study area

The study area is located on the northern slopes of the Uluguru Mountains between 350295E and 354368E and 9237500N and 9243697N UTM coordinates (Fig. 1). The climate of the area is categorised as sub-humid tropical savannah of the low latitude environment (Sharma, 1987). The mean annual rainfall varies with altitude, from 900 mm at 550 m asl to 2300 mm at 1500 m asl. It is distributed into two 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 temperature varies from 25 °C at 550 m asl to 19 °C at 1500 m asl. The rocks are metasediments mainly consisting of hornblende pyroxene granulites, with plagioclase and quartz-rich veins (Sampson and Wright, 1964). The area is mountainous comprising strongly dissected mountain ridges and foothills with very steep narrow valleys.

Based on the World Reference Base for Soil Resources system of soil classification (FAO et al., 1998), the soils on the mountain ridges are dominantly *Endoskeletal* and *Leptic Cambisols* with accessory amounts of *Haplic* and *Chromic Phaeozems* and *Orthieutric Regosols*. On the foothills the dominant soils are *Chromic Lixisols* and *Profondic Acrisols* associated with *Hyperferralic Cambisols*, and *Endoleptic Cambisols* (Kimaro et al., 1999). To a great extent the Uluguru Mountains are under cultivation. The mountain ridges are mainly used for production of vegetables, beans (*Phaseolus* spp), short rain maize (*Zea mays* L.) and banana (*Musa* spp) while on the foothills long rain maize is the main crop (Kimaro et al., 1999). The cropping calendar for the major cropping system in the northern slopes of the Uluguru Mountains is presented in Fig. 2.

Table 1
Comparison of mean tillage transport coefficients (k) for one tillage operation using different tillage methods applied on steep slopes

Country	Method of tillage	Assessment method	Slope (%)	k (kg m^{-1})	Source
Rwanda	Manual hoeing	Trench	60	173	Wassmer (1981)
Spain	Duckfoot chisel, contour	Tracer	1–46	139	Poesen et al. (1997)
Spain	Duckfoot chisel, up and down	Tracer	1–46	282	Poesen et al. (1997)
Thailand	Manual hoeing	Tracer, step	17–82	107	Poesen et al. (2000)
Ethiopia	Oxen	Tracer	3–48	68	Nyssen (2001)
Ecuador	Oxen	Tracer	5–58	60–80	Dercon (2001)

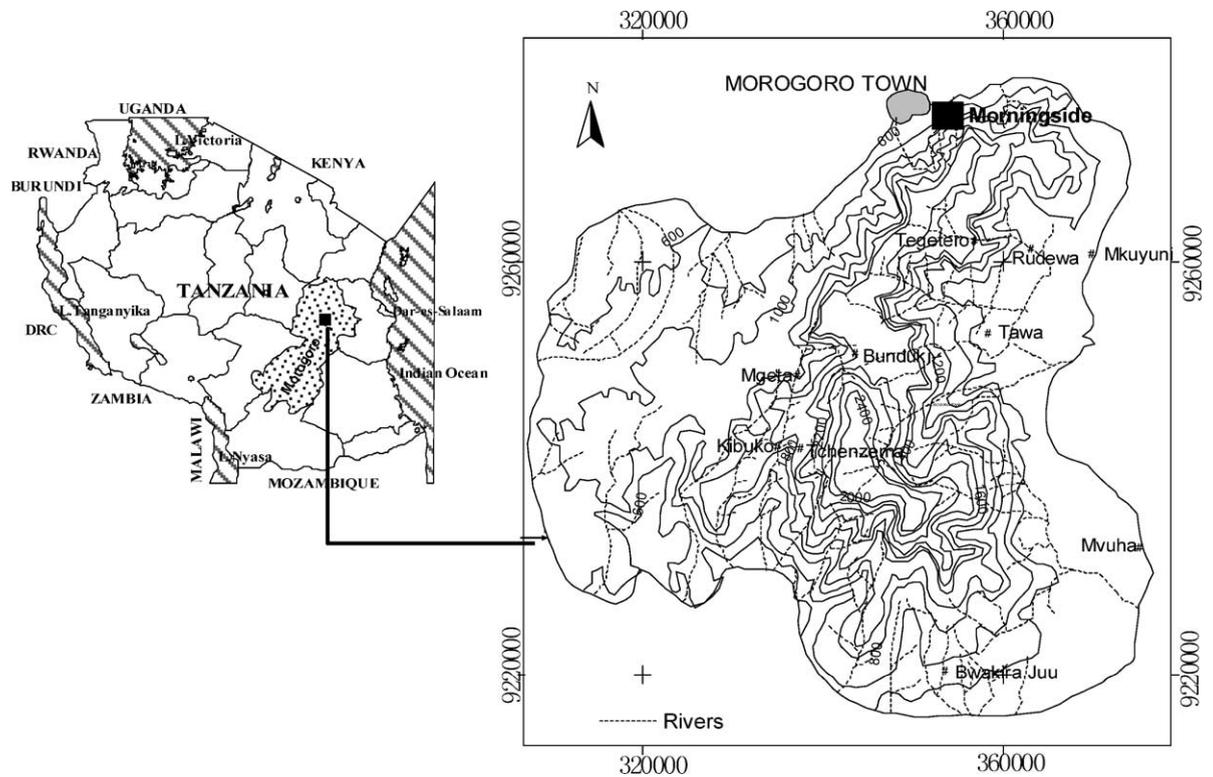


Fig. 1. Map of the Uluguru Mountains showing the location of the study area.

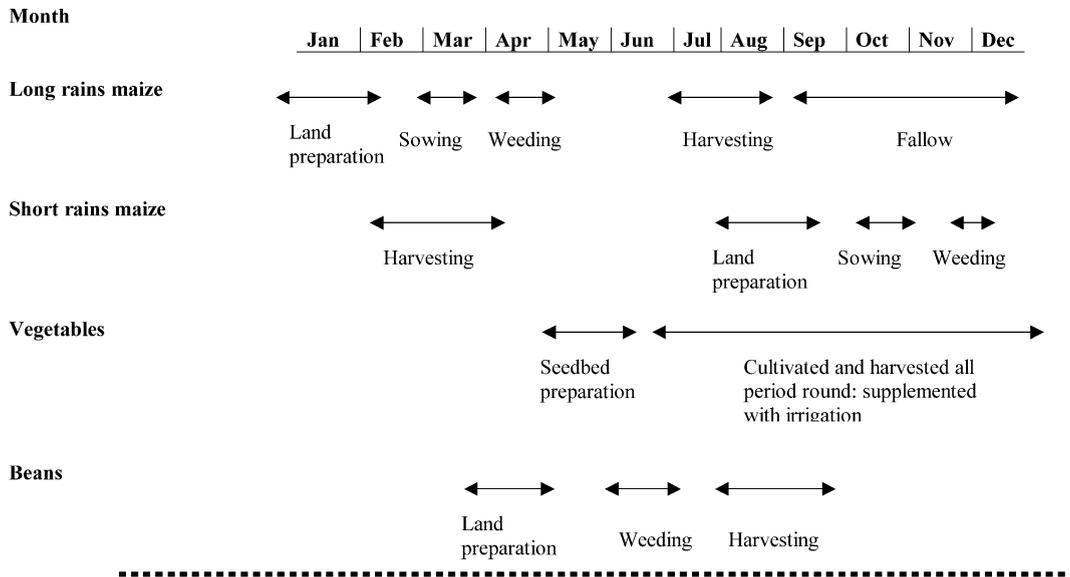
2.3. Determination of soil flux due to tillage operation by manual hoeing

2.3.1. Single tillage operation experiment

Soil movement by manual tillage was measured on the northern slopes of the Uluguru Mountains (Morningside catchment area) by means of an on-farm experiment during the dry season of the year 2000 and 2001. Twenty-four small plots (1.2 m wide) with different slopes (31, 47, 51, 54, 58, 61, 65 and 67%) were demarcated prior to seasonal land preparation. In the field, local farmers tilled the plots in the traditional way. Farmers practise superficial hand tillage without prior removal of weeds from the field plots. The plots are tilled starting from the bottom of the field and moving up on the slope. Farmers used hoes with steel blades of about 18.5 cm long and 16.5 cm wide and wooden handles of about 100 cm long. In order to measure soil translocation, two complementary methods were applied: the Trapezoid-step method (Turkelboom et al., 1999)

and the Gerlach trough method (Gerlach, 1967). These two methods provide a quick assessment of soil movement by manual tillage (Poesen et al., 2000).

2.3.1.1. Trapezoid-step method. A small step at the top of each field was the obvious indicator of soil movement by manual tillage. At this point soil is moved downwards but not replaced by any soil material from upslope (Turkelboom et al., 1999). On this spot, compacted subsoil is exposed forming a trapezoid profile shape (Fig. 3) which according to Turkelboom et al. (1999) was found to be more accurate in characterising the morphology of a tillage step profile. The trapezoid dimensions of the small tillage step at the top of each field were measured three times. The measured dimensions include: length, depth and angle of the tillage step and of the original soil surface (Fig. 3). To calculate soil translocation measured by Trapezoid-step method, Eq. (3) suggested by Turkelboom et al.



NB: short rain maize, vegetables and beans are grown alternately on higher slopes while long rains maize are only grown on lower slopes alternating with fallow period during short rains

Fig. 2. Cropping calendar for major cropping systems in the northern slopes of the Uluguru Mountains, Tanzania. Short rain maize, vegetables and beans are grown alternately on higher slopes while long rains maize are only grown on lower slopes alternating with fallow period during short rains.

(1999) was adopted.

$$T = BdD(B + 0.5X + 0.4Y) \tag{3}$$

where T is the soil flux (kg m^{-1} per tillage pass), Bd the dry bulk density of the soil (kg m^{-3}), D the tillage depth (m) measured perpendicular to the soil surface, B the bottom length of the tillage trapezoid

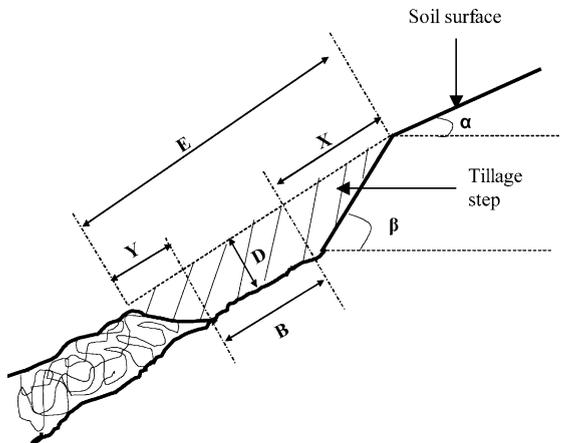


Fig. 3. Cross-section through a tillage step and the parameters needed to calculate soil flux by Trapezoid-step method.

(m), E the length of tillage trapezoid at the soil surface (m), $X = D/\beta - \alpha$ where β is the slope angle of the step and α is the slope angle of the original soil surface, $Y = E - B - X$.

2.3.1.2. Gerlarch trough method. Gerlarch troughs with hinged lid and measuring 0.6 m long, 0.4 m wide and 0.5 m high were installed in shallow trenches at the bottom of each field (Fig. 4). The troughs were left open during land preparation by manual hoeing. The soil material lost in the Gerlarch troughs during manual tillage was collected directly for weight determination under field and oven-dry conditions. Soil translocation by this method was calculated using Eq. (4) (Turkelboom et al., 1997).

$$T = MDM/W \tag{4}$$

where T is the soil flux (kg m^{-1} per tillage pass), M the mass of moist soil lost in the Gerlarch troughs (kg), DM the correction factor (soil oven dry weight as percentage of M), W the observation width (m). The length of the Gerlarch trough (0.6 m), was taken as observation width.



Fig. 4. Measurement of soil translocation due to superficial manual tillage by Gerlarch trough method.

2.3.2. *Medium-term continuous hoe cultivation experiment*

One of the medium-term (30 years of cultivation) effects of tillage erosion is the truncated soil profile at the top of the field plot, accumulation of tilled soil at

the bottom or towards the buffer strips along the contour and a progressive terrace formation. In the study area, six field plots with buried original soil surface along the contour bands were identified on six different slopes (51, 52, 55, 56, 58 and 60%) in various

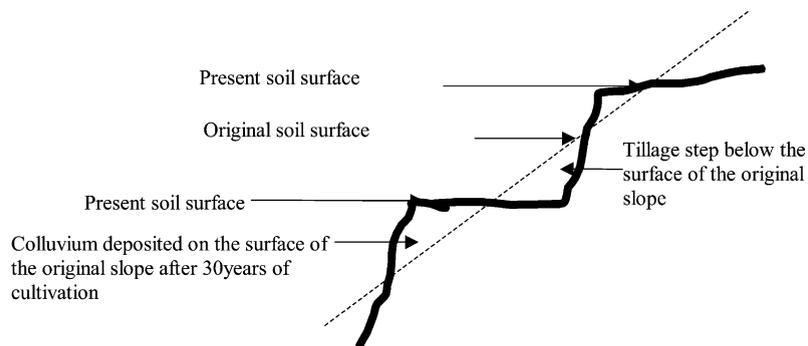


Fig. 5. Cross-section showing tillage step (below) and colluvium accumulation (above) surface of the original slope.

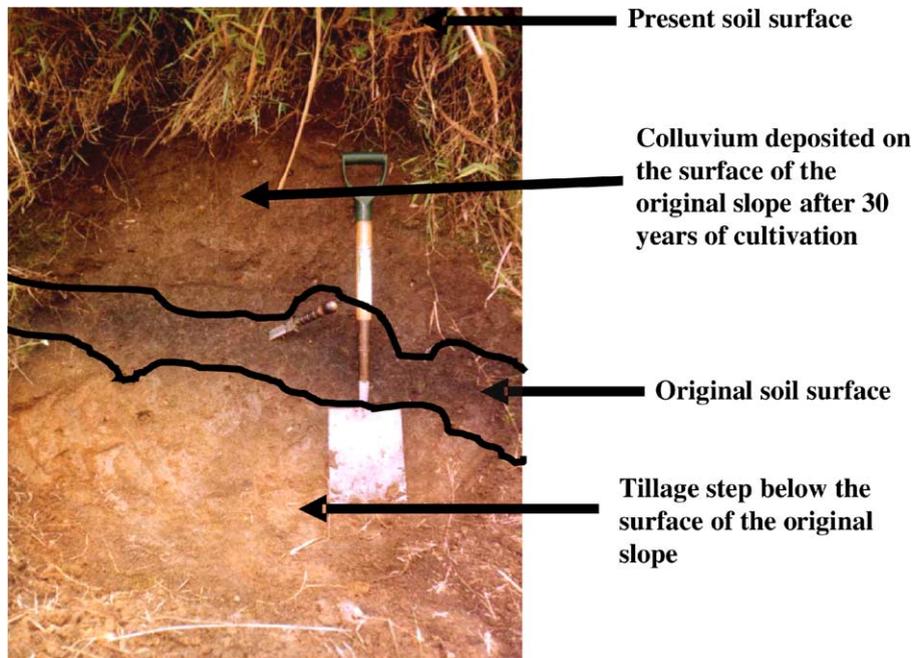


Fig. 6. Cross-section showing tillage step (below) and colluvium accumulation (above) surface of the original slope as observed in the field (length of spade = 1.2 m).

farmers' fields. The length of the identified plots ranged between 7.5 and 8.5 m. The plots had been under cultivation for about 30 years. The plots were selected in consultation with the farmers who also knew the age of the plots. In order to calculate medium-term soil translocation in the identified field plots volumes of the tillage step below the surface of the original slope and the accumulated colluvium above the surface of the original slope along the contour bands with grass barrier were measured (Figs. 5 and 6). The formula for the area of a triangle (Eq. (5)) was adopted (Michael and Murnaghan, 2001):

$$V = \frac{1}{2}DLL_b \quad (5)$$

where V the volume of truncated tillage step or soil accumulation (m^3 per metre of a contour band); D the measured depth of tillage step below the surface of the original slope or soil accumulation above the surface of the original slope; L the measured length of the truncated profile from the step into the field and perpendicular to step depth or length of the soil accumulation from the barrier into the field; L_b the 1 m length along the contour band.

Lastly the volumes obtained were converted into kg m^{-1} per year using an average soil bulk density of 1200 kg m^{-3} and 30 years as the approximate age of the contour band.

3. Results and discussion

3.1. Soil flux due to a single tillage operation by manual hoeing

3.1.1. Tillage depth

Superficial tillage (*kuparua* or *kuparaza*) is commonly practiced by most farmers on the northern slopes of the Uluguru Mountains, where the top few centimetres of the soil are cultivated. A superficial tillage step is formed as soil material is pulled backwards down slope. Mean tillage depth measured vertically in the study area varied between 4.5 and 6.0 cm with a standard deviation of 1.1 and 0.6 cm, respectively. According to Poesen et al. (2000), tillage depth is influenced by a number of factors including slope, soil texture, rock fragments content and bulk density. In the study area, a moderate correlation was

Table 2
Mean soil flux rates due to one manual superficial tillage operation assessed by Trapezoid-step method

Slope gradient (%)	kg m ⁻¹ per tillage pass				Number of observations
	Soil flux	Standard deviation	Minimum	Maximum	
31	43	5	37	47	3
47	53	8	45	61	3
51	58	10	50	69	3
54	52	6	47	58	3
58	63	15	47	78	3
61	70	6	65	76	3
65	63	7	58	71	3
67	70	13	61	85	3
			Total		24

found between superficial tillage depth and slope gradient ($R^2 = 0.3$). Average tillage depth of 5.2 cm (standard deviation = 0.8 cm, $n = 24$) perpendicular to the soil surface was calculated for use in Eq. (3). On the steep slopes of Northern Thailand, a mean tillage depth perpendicular to the soil surface of 8.2 cm for manual deep tillage was calculated (Turkelboom et al., 1999).

3.1.2. Soil flux rates measured by Trapezoid-step and Gerlarch trough methods

Soil fluxes due to a single superficial manual tillage obtained by Trapezoid-step method are given on Table 2 and Fig. 7. They ranged from 43 kg m⁻¹ per tillage operation on 31% slope to 70 kg m⁻¹ per tillage operation on a slope of 67%. The observed soil flux values by this method were slightly higher than those

obtained by Gerlarch trough method (Table 3). The flux rates of the latter ranged from 14 to 77 kg m⁻¹ per tillage operation over a slope range of 31–67%. The rates measured by Gerlarch trough method also showed an increasing soil flux with slope gradient. The tillage transport coefficient (k) of 107.5 kg m⁻¹ per tillage pass was obtained when the Trapezoid-step method was employed (Fig. 7). The tillage transport coefficient (k) by Gerlarch trough method was 83.9 kg m⁻¹ per tillage pass (Fig. 8). The tillage transport coefficient (k) obtained by Gerlarch trough method was also lower than that obtained by Trapezoid-step method.

The slightly higher rates of soil flux and k -value obtained by Trapezoid-step method compared to those obtained by Gerlarch trough method could be attributed to the tillage method practised by the farmers in the study area. Field observations indicated that superficial manual tillage produced small size clods which were partly destroyed completely over a short distance before they reached the Gerlarch trough. The k -value obtained by Trapezoid-step method compares well with the k -value for deep manual tillage calculated for Northern Thailand, i.e. $k = 107$ kg m⁻¹ per tillage pass (Turkelboom et al., 1999; Poesen et al., 2000). Although the k -value obtained by Gerlarch trough method was slightly lower, it is still acceptable when compared to those obtained by oxen ploughing elsewhere (Nyssen, 2001; Dercon, 2001). The observed soil flux values measured by the Gerlarch trough method were also much higher compared to those obtained by plastic lined trenches in Northern Thailand where soil flux values of less than 20 kg m⁻¹ per tillage pass were

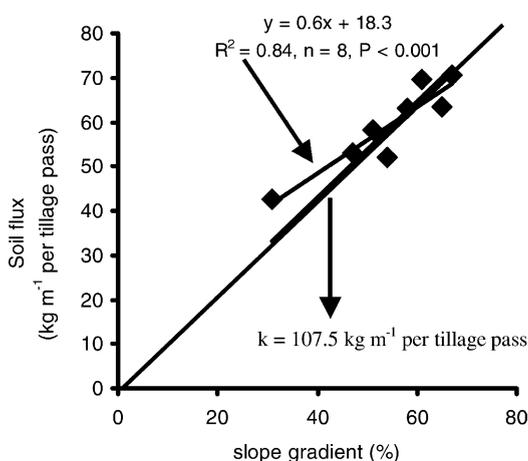


Fig. 7. Mean soil flux due to one manual superficial tillage operation and corresponding tillage transport coefficient (k) assessed by Trapezoid-step method.

Table 3
Mean soil flux rates due to one manual superficial tillage operation assessed by Gerlarch trough method

Slope gradient (%)	kg m ⁻¹ per tillage pass				Number of observations
	Soil flux	Standard deviation	Minimum	Maximum	
31	14	2	12	16	3
47	23	3	21	26	3
51	36	2	34	38	3
54	39	3	36	42	3
58	53	1	52	54	3
61	55	6	51	62	3
65	77	4	73	79	3
67	55	8	46	62	3
				Total	24

obtained from measurements done on slopes ranging from 32 to 82% (Turkelboom et al., 1997). In that study it was reported that plastic lined trenches underestimated soil fluxes because farmers probably did not use the same force when they were tilling the soil near the trench and also did not lift up the clods into the trench. In the Uluguru Mountains, farmers tilled the soil starting from the edge of the Gerlarch troughs installed in a shallow trench (Fig. 4) and all the soil clods nearby were lifted into the trough. From the results of this study it can be concluded that the Gerlarch trough method could be a quicker and more direct field method for tillage erosion assessment compared to the Trapezoid-step method which is tedious and involving relatively accurate measurement of many dimensional parameters.

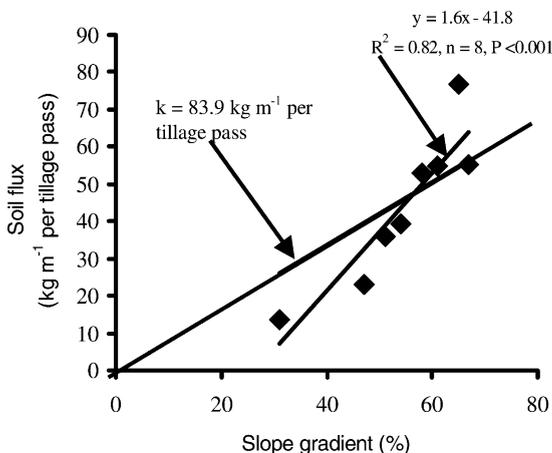


Fig. 8. Mean soil flux due to one manual superficial tillage operation and corresponding tillage transport coefficient (k) assessed by Gerlarch trough method.

3.2. Soil flux after 30 years of continuous hoe cultivation

Soil fluxes due to medium-term tillage operations by manual hoeing along contour bands with grass barriers are presented in Table 4 and Figs. 9 and 10. Soil flux rates obtained by volumetric measurements of the tillage step below the surface of the original slope (Figs. 5 and 6) showed a negative trend with increasing slope gradient (Fig. 9). The calculated soil flux rates ranged between 148 and 42 kg m⁻¹ per year for slope gradients between 51 and 60%. Soil fluxes due to colluvium accumulation behind grass barriers along the contour bands showed a similar trend with values higher than those obtained by step measurements (Fig. 10). The

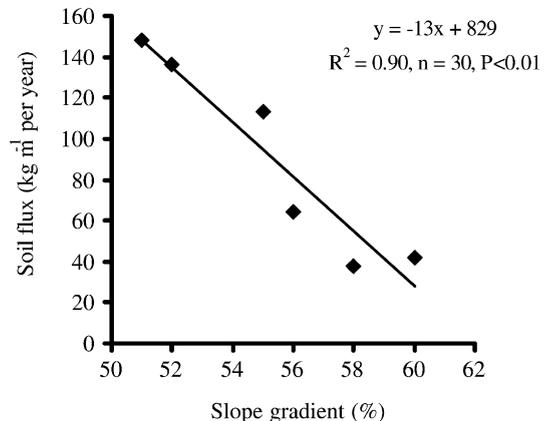


Fig. 9. Relationship between mean soil flux rates measured by the tillage step below the surface of the original soil and slope gradient.

Table 4

Mean annual soil flux rates due to tillage erosion after 30 years of cultivation along contour bands with grass barrier

Slope gradient (%)	Tillage step below the surface of the original soil (kg m ⁻¹ per year)				Colluvium deposited on the surface of the original slope (kg m ⁻¹ per year)				Net soil flux ^a	Number of observation
	Soil flux	Standard deviation	Min.	Max.	Soil flux	Standard deviation	Min.	Max.		
51	148	30	114	195	155	25	123	187	7	3
52	136	27	102	170	146	32	102	197	10	3
55	113	13	95	129	122	31	81	171	9	6
56	64	13	40	74	83	28	54	133	19	6
58	38	7	34	46	55	5	51	61	17	6
60	42	4	38	47	67	7	62	75	25	6

Min, minimum; Max, maximum.

^a Contribution from other erosion processes partly water erosion.

calculated soil flux rates of the colluvium deposited behind grass barriers along contour bands ranged from 153 kg m⁻¹ per year on a slope of 51% to 67 kg m⁻¹ per year on a 60% slope over approximately 30 years of cultivation.

The decrease in soil flux with increasing slope gradient could probably be explained by the fact that the steeper the slope, the shallower the soil profile. This would make the available volume for soil storage to decrease with an increase in slope gradient. In this case farmers till the land less deep. Nyssen et al. (2000) reported similar observations while measuring volume of sediment deposited behind stone bands in the Ethiopian Highlands. The length of contour bands in the Uluguru Mountains ranges between 7.5 and 8.5 m. Poesen et al. (2000) reported that for fields of 5 m length with well established buffer strips, tillage erosion rates can reach values of up to 170 t ha⁻¹ per

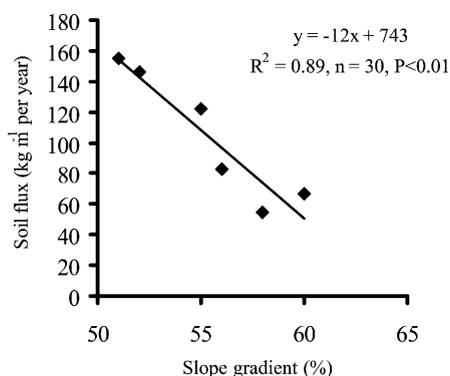


Fig. 10. Relationship between mean soil flux rates by the deposited colluvium on the surface of the original slope and slope gradient.

tillage pass whereas effect of water erosion becomes very small at this plot length. The calculated tillage erosion rates along contour bands in the Uluguru Mountains can reach values of up to 180 t ha⁻¹ per year for plots of 8.5 m length.

A reasonable correspondence between the calculated removed soil (area under original slope) and the colluvium accumulated behind grass barriers (area above the original slope) was obtained (Fig. 11). The calculated net soil flux ranged from 7 kg m⁻¹ per year on a slope of 51% to 25 kg m⁻¹ per year on slope of 60% indicating a significant contribution of tillage erosion compared to other erosion processes partly water erosion.

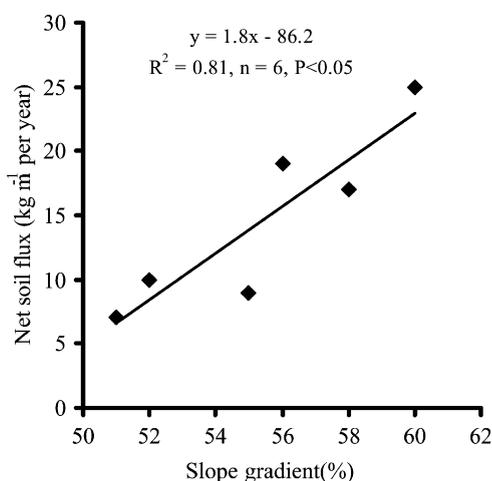


Fig. 11. Net soil flux rates due to other erosion processes, partly water erosion.

4. Conclusions

The results obtained in this study demonstrate that tillage translocation rates due to superficial manual cultivation were very high and could be responsible for the occurrence of most shallow soils observed on the steepest slopes and the accumulation of colluvium behind grass barriers along contour bands in the study area. Although it is not obvious to most farmers, tillage erosion is one of the most important processes of soil erosion that has to be taken into consideration in the overall development of soil and water conservation strategies in the Uluguru Mountains. In Tanzania, data on tillage erosion for the various agro-ecological zones are limited. Further studies are proposed including: modelling of progressive terrace formation between established contour bands with grass barrier and tillage erosion and the effect of tillage depth and displacement distance on soil flux rates due to manual superficial tillage. Assessment of the role of tillage erosion as a precursor of other types of water induced soil erosion is suggested.

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