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Dynamics of surface runoff and soil loss from a toposequence under varied land use practices in Rwizi catchment, Lake Victoria Basin

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Abstract: In this study, we quantified surface runoff and soil loss along a toposequence considering four land use systems and three topographic segment positions in Rwizi catchment, Lake Victoria Basin (LVB). The land use systems were grassland dominated by a local species known as "Omugugu" (*Cyperus* spp.), tree plantation of pine (*Pinus sabiniana*) and eucalyptus (*Eucalyptus globus*), mulched banana (*Musa Paradisiaca*), and unmulched banana, topographically located on the foot slope, midslope, and summit. Runoff and soil loss magnitude and trends under varied rainfall regimes were measured using closed runoff plots measuring 2×20 m (40 m^2). A split plot experimental design was adopted for the study. In total, 36 runoff plots were installed considering the land use and topographic factors with three replications. Observed monthly rainfall values varied from 9.3 to 167 mm (75 ± 54 mm). Annually, the registered rainfall depth was 680 mm. The annual rainfall depth was below the long-term annual mean for the area. Nearly all rainfall events with a depth greater than 10 mm contributed relatively heavy runoff, while rainfall events less than 10 mm in general caused minor surface runoff at the sites. Annual runoff within the catchment at the studied sites varied from 42 to 411 m^3 ha^{-1} y^{-1}. The average observed cross-site annual runoff was 151 ± 95 m^3 ha^{-1} y^{-1}. Results show that annual runoff was in the order of tree plantation > unmulched banana sites > grassland = mulched banana. Soil losses were greatest (1.5 t ha^{-1} y^{-1}) and lowest (0.8 t ha^{-1} y^{-1}) on unmulched banana and mulched banana sites, respectively. Annual soil loss showed an increase with topographic slope segment position. Average annual soil loss on the upper slope position facets (1.7 t ha^{-1} y^{-1}) were 2.4 folds higher than those observed on the footslope position facets (0.7 t ha^{-1} y^{-1}), giving a percentage difference of 83%. We did not detect a statistical difference in runoff ($p > 0.05$) due to either land use system or toposequence position. However, statistical differences were observed in soil loss ($p < 0.05$) for land use system and toposequence position. While the observed annual soil loss magnitude is within the tolerable thresholds, a sustained maintenance of best land use practices is still critical in maintaining the delicate balance on the fragile hillslopes in the study area.

Key words: Lake Victoria Basin—land use system—runoff—soil loss—toposequence

The magnitude and extent of soil erosion processes continue to occupy a fundamental position in the sustainability debate of the coupled tropical Africa landscapes and the attendant livelihoods, especially in the Lake Victoria Basin (LVB). Soil erosion has increasingly become an issue of significant societal and environmental concern due to its adverse effects (Fungo et al. 2011; Lal et al. 2007). The current premise based on anecdotal and some scattered studies avers that land degradation significantly linked to the intensity of soil erosion and sediment loading pervades the LVB (Ntiba et al. 2001; Ryken et al. 2015) and will worsen unless timely and considerate interventions are implemented. A significant proportion of the population subsists from harnessing landscape and ecosystem resources through a continuum of agricultural practices (Valipour 2014, 2015a; Valipour et al. 2015). Consequently, recent development programs in LVB countries exemplified by the National Development Plan (NDP I and NDP II) of Uganda (2014 to 2018), Uganda Vision 2040, and the Green Growth Strategy of Rwanda have given more attention to soil erosion control.

The LVB with an area of 184,000 km^2 is transboundary and geographically significant in terms of biogeochemistry. The LVB is rapidly urbanizing, and with a rate of 3% to 6% per annum, it has the fastest growing population in sub-Saharan Africa (SSA) (Kayombo and Jorgensen 2006; Swallow et al. 2009). The gross economic product of LVB is in the order of US$4 to US$6 billion annually (Muyodi et al. 2010). The LVB is an important ecosystem, not only for the over 30 million inhabitant population, but also for the larger Nile River system community (Swallow et al. 2009). Consequently, degradative landscape processes not only have intra proximate implications, but also have global ecological implications.

A significant proportion of the livelihoods in tropical SSA and LVB in particular are intricately linked to the quality of the soils, and soil erosion has been implicated as the fundamental factor that accentuates nutrient depletion. The (un)sustainability issues linked to soil erosion rates particularly amplified on topography by human activities are widely addressed in literature (Meshesha et al. 2012; Niu et al. 2015; Wickama et al. 2015; Yaalon 2007) and mirrored through a compendium of in situ and ex situ impacts. Soil erosion leads to reduction of soil productivity through on-site loss of the fertile topsoil, while off-site, sedimentation and pollution loading of stream and water bodies is a common phenomenon (Wei et al. 2007; Zang et al. 2015). Quantitative data from empirical research on soil erosion implications are scanty, but Lal (1995) projected yield reduc-

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tions due to soil erosion to the tune of 15% by the year 2020 for SSA, while in Uganda it is estimated (UNDP 2007) that US$600 million is lost annually, of which human-induced soil erosion accounts for 85%.

A critical component on topographic landscapes under intense human activities, therefore, is to keep soil erosion rates within the soil threshold of tolerance (*T* value) through a range of robust soil and water management interventions that substantially sustain and replenish a significant proportion of the inherent soil ecological properties. Soil loss tolerance signifies soil erosion rates below the rate of soil formation and is directly correlated with fundamental problems of soil erosion (Bamutaze 2015; Li et al. 2009). Empirically derived *T* values for tropical SSA soils are lacking, but a guiding tolerance limit of 5 t ha^{-1} y^{-1} (Lufafa et al. 2003) is often invoked. The geopedological realization of this sustainability niche on steep and fragile slopes requires delayed in situ surface runoff and enhanced soil and water infiltration.

Conspicuous from previous isolated and scattered studies on soil erosion in the LVB (De Meyer et al. 2011; Lufafa et al. 2003; Majaliwa 2005; Mulebeke 2004; Nadhomi et al. 2006) are the alarmingly high rates beyond the tolerable levels (Hancock et al. 2015; Lufafa et al. 2003; Verheijen et al. 2009). Notwithstanding the methodological, spatial, and temporal limitations, these studies elicit some insights on the soil erosion risk, potential sources, hotspot sites, and extent. While a growing body of knowledge now broadly questions the reported rates from tropical SSA (Bamutaze 2015; Kiage 2013; Stocking 1995), substantial gaps exist in our understanding of erosion dynamics in the complex and heterogeneous LVB landscape where (1) terrain, rainfall, soil, and agronomic and socioeconomic conditions are highly diverse; and (2) geographically explicit data and information on soil erosion dynamics are crucial for policy options and practical landscape management measures.

Rainfall driven soil erosion in tropical systems is a function of a concert of geo-ecological factors such as lithology, topography, and climatology (García-Ruiz 2010). However, evidence is gaining weight that terrain factors and land use practices are proportionally overwhelming in altering the dynamic of soil erosion and require more attention. Land use practices influence the speed and extent of horizontal and vertical geomorphic processes, which in turn influence runoff efficiency, biogeochemistry, and overall surface soil-water retention capacities (Montgomery et al. 2014; Niu et al. 2015; Schiettecatte et al. 2008; Valipour 2015b).

Rwizi catchment in the LVB is considered a land degradation hotspot purportedly conveying huge quantities of sediment through numerous streams to the lake (Ryken et al. 2015; Wanyama 2012). Anecdotally, the high lake and stream sediment is quite often linked to upstream land use activities, particularly agriculture as source and export areas. This notion is, however, simplistic and debatable considering (1) the paucity of experimental quantitative studies, (2) a limited scope of previous studies with a concentration on annual-perennial agricultural fields, and (3) limitations of the Revised Universal Soil Loss Equation (RUSLE model), which is often applied in erosion assessment in the LVB. These general limitations notwithstanding, there are no empirical studies to the best of our knowledge that have been conducted on soil erosion dynamics in Rwizi catchment, in spite of its categorization as a degradation hotspot, which could probably be called a flawed premise. Rwizi catchment is geomorphologically and geologically quite unique in the LVB with its undulating terrain residing in a tectonically reversed region. The purpose of this study was therefore to assess the dynamics of runoff and soil loss on the coupled interactive toposequences under diverse land uses with a view of gaining greater insights on landscape sustainability and resilience niches.

Materials and Methods

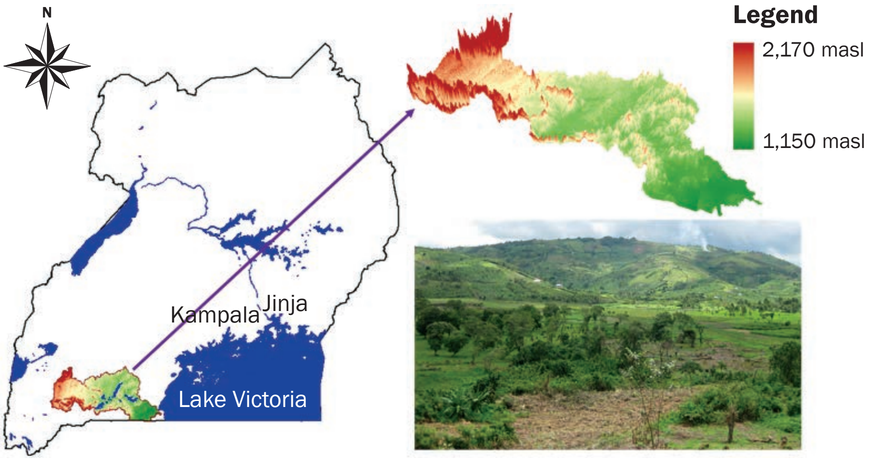
Study Area. The study was conducted in the Rwizi catchment, Lake Victoria Basin, which is situated between 0°50´ S to 0°35´S and 30°15´ E to 30°35´ E (figure 1). The catchment is dominated by rugged and undulating landscape topography (Ryken et al. 2015). This makes it highly prone to soil erosion processes. Altitude ranges between 1,150 and 2,170 m above sea level (masl), with a mean elevation of 1,729 masl according to Wanyama (2012). The landscape can therefore be described as highlands (1,500 to 2,000 masl) on the basis of the elevation (Bamutaze 2010) and are highly fragile from the terrain perspective. The area consists of the Precambrian geological materials, which are inclusive of the partly granitized materials that occurred mostly in southern Uganda. The underlying rocks of upper Rwizi catchment mainly include sandstones from the premetamorphosed products and later intrusions of schists, gneisses, and granites, which underlie the sedimentaries (Atim 2012; Wanyama 2012). The dominant soils are Plinthosols, Leptosols, and Gleysols on the plateaus, uplands, and valleys, respectively. Mean annual temperature ranges between 15°C and 27°C, while average annual rainfall is 1,000 mm. The received annual rainfall amounts are characteristically distributed in a bi-modal structure, constituting two seasons. The first rainfall season spans from March to June, while the second season is spread between August and November. An analysis done by Ryken et al. (2015) shows that rainfall is spatially homogenous, but depicts strong seasonal contrasts. The population density is quite high, ranging from 97 to 324 persons km^{-2}. Agriculture is the major livelihood source encompassing both crop growing and livestock keeping. The Rwizi catchment generally lies in the banana (*Musa Paradisiaca*)-livestock agroecological zonation of Uganda.

Site Characterization. Topographic data with respect to the experimental sites bearing runoff and soil loss plots were recorded for purposes of site characterization. The data included slope angle, slope aspect, altitude (m), and geographical position. Slope angle was measured using a Suunto clinometer calibrated in degrees. Slope aspect was measured using a compass, while elevation together with location data were captured using a high resolution Global Positioning System (GPS), Trimble GEOXT model (Trimble, Sunnyvale, California).

Experimental Design and Layout. The runoff plot approach was used in a design incorporating three slope facets on a toposequence, four land use systems, and three replications. These were implemented in a split plot design with the runoff plots installed on farmers' fields. The implemented layout schema of the study plots is shown in figure 2. In total, 36 geo-referenced runoff plots were installed for monitoring runoff and soil loss. The land use systems included (1) mulched banana, (2) unmulched banana, (3) grassland, and (4) tree plantation. These land use systems were selected after an inventory undertaken in the catchment to identify the signature representative land use systems on the hillslope of Rwizi catchment. A

Figure 1

Location and topographic impression of the Rwizi catchment, Lake Victoria Basin area from which the study was undertaken.



characterization of the practices under these land use systems is given in the Results and Discussion section. Some annual crops are also grown, but these are intercrops within largely banana (and to some extent coffee [*Coffea* L.]) dominated systems. To better understand the underlying purposes, farmers at the 36 experimental sites were interviewed throughout the experimental period to determine aspects of land use practices. The slope facets were selected along the toposequence in tripartite arrangement and positioned in a north-south direction. The slope facets included the summit representing the most northern segment along the toposequence; midslope, which was intermediate; and the footslope segment, the most southern and in relative proximity to valley.

Instrumentation and Data Collection Protocol. The experiments for data collection were conducted from January of 2014 to December of 2014. Measurement of runoff and soil loss was conducted using bounded runoff plots, which were intended to minimize runon as well as leakage. All runoff plots were under farmers' management practices, which included land preparation, seed planting, weeding, thinning or pruning, and harvesting of crops. The runoff plots were installed on sites having different slope aspects and soil types, but almost uniform land slope. The plots were bounded with strips of zinc (Zn) iron (Fe) sheets inserted in the ground to about 0.1 m depth. The runoff plots measure 20 m long by 2 m wide, giving an area of 40 m^2. The plot width was sufficient for the land use types in the study area allowing free development of runoff. The length was considered adequate to minimize storage and allow collection of entire plot runoff and soil lost from each storm event. The runoff plot experiments were equipped with a set of precalibrated divisors connected to a jerry can of 5 L capacity. The calibration of the plots was repeated in the second season to ensure consistence in the coefficients for determining the magnitude of runoff and soil loss. Runoff plots were laid in a downslope direction with a collection system at the lower end for sediment and runoff. At the lower end of the plot, a divisor was attached and proportional runoff collected was directed into a jerry can attached to the divisor using tubes. The runoff plot infrastructure was continuously maintained mutually between the farmers and the scientists. All management activities, especially tillage and weeding within the runoff plots, were documented to facilitate potential explanation of observed changes in the magnitude and intensity of runoff and soil losses.

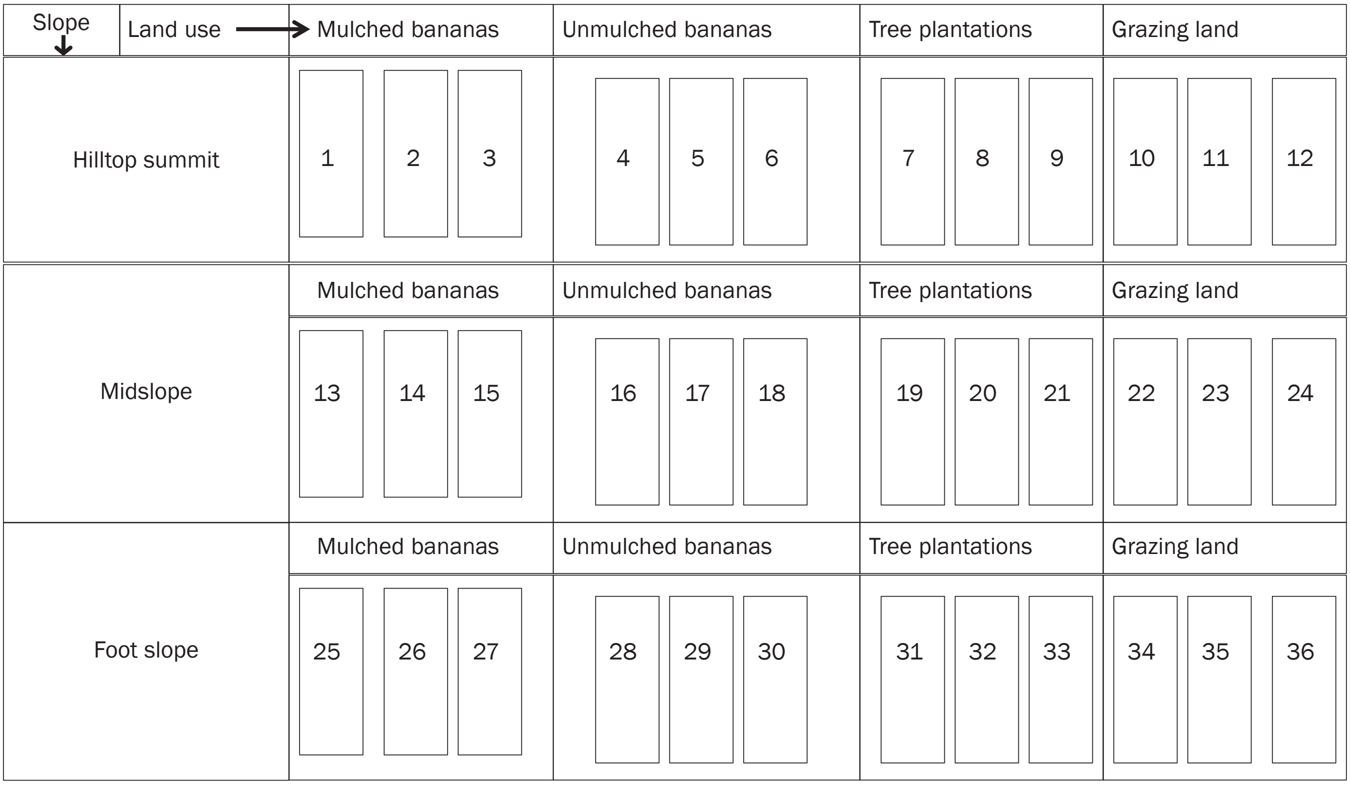
Rainfall depth (mm) was measured after each rainfall event by means of a manual rain gauge installed at the site and an automatic weather station (Davis 6250 Vantage Vue; Davis Instruments, Vernon Hills, Illinois). Recorded rainfall was categorized into daily, monthly, seasonal, and annual totals (mm) and number of rainy days. Individual storms were arranged in terms of rainfall intervals of light rainfall (less than 10 mm), moderate rainfall (10 to 24 mm), heavy rainfall (25 to 49 mm), and extreme rainfall (more than 50 mm) according to Kwarteng et al. (2009).

Determination of Runoff and Soil Loss. Runoff (mm) measurements at each plot were taken after every erosive rainfall event. Runoff composite samples were weighed and taken for laboratory analysis of the sediment concentration. Standard laboratory methods described by Okalebo et al. (2003) were used for determination of the sediment concentration, which was undertaken at the Makerere University Soil Science Laboratory. Using the plot calibration coefficients, the magnitude of runoff and soil losses were determined and extrapolated to the size of a hectare (t ha^{-1}) for each erosive event recorded. For each rainfall regime, we computed the features of runoff and soil loss as (1) runoff: accumulated (mm), runoff coefficient (%), and mean and standard deviation of both runoff and runoff coefficient; and (2) soil loss: accumulated total loss (t ha^{-1}) and mean and standard deviation of total loss (t ha^{-1}).

Statistical Data Analysis. A range of statistical techniques were used for data analysis. Descriptive statistical analyses were used to numerically summarize the data. Descriptive analysis entailed measures of central tendency such as the mean ($\bar{x}$), statistical dispersion measures such as the percentage distribution (%), minimum, maximum, standard deviation, and coefficient of variation (%). Rainfall, runoff, and soil loss relationships were tested using linear correlation and regression procedures. Correlation matrices between runoff, soil loss, and rainfall event variables were performed using the linear correlation procedures available in Genstat programme (VSN International Ltd., Hemel Hempstead, United Kingdom). Differences in runoff and soil loss with land use and slope position were tested using the analysis of variance (ANOVA) signifying repeated measures over space. Prior to the ANOVA test, the data were first subjected to a normality test. For runoff analysis, rainfall regimes were the independent variable while runoff was the dependent variable. The main factors in the statistical analysis were land use and slope position. Cover evolution was captured in the land use component. The statistical separation of means among treatments was obtained where applicable using the least significant difference (LSD) test at the 0.05 significance level.

Figure 2

Layout schema of the plots in the study area. Numbers signify plot codes.



Slope ↓ / Land use →	Mulched bananas	Unmulched bananas	Tree plantations	Grazing land
Hilltop summit	1, 2, 3	4, 5, 6	7, 8, 9	10, 11, 12
Midslope	13, 14, 15	16, 17, 18	19, 20, 21	22, 23, 24
Foot slope	25, 26, 27	28, 29, 30	31, 32, 33	34, 35, 36

Results and Discussion

Land Use Characteristics and Implications to Sustainability. The major land uses considered in the experimentation include mulched bananas, tree plantations, grassland, and unmulched bananas. Mulched bananas is a management practice where farmers mulch their banana–coffee plantations with dead papyrus grass (*Cyperus papyrus* L.), foliage of weeds, annual crop residues, and banana fiber. The applied mulch thickness is approximately 5 cm, and it is spread laterally across the field. Mulch application obviously promotes more infiltration and reduces runoff and soil loss. However, the primary role of mulch according to the farmers is to improve soil fertility and control weed growth. Ninety percent of the farmers apply mulch once a year, while 10% apply mulch twice a year. There also exist unmulched banana as a dominating land use activity. It is basically a farmer practice of managing banana gardens without use of mulching. Farmers also intercrop annual crops in banana gardens during the rainy season. The common intercrops include banana/beans (*Phaseolus vulgaris*)/maize (*Zea mays* L.) with coverage of 70:30 perennial to annual combination. The tree plantations consisted of pine (*Pinus sabiniana*) and eucalyptus (*Eucalyptus globus*). These are planted largely for commercial purposes (80%), while 20% are for domestic use. It is explicitly clear that commercial interests for tree plantation override ecological management or benefit. There have been concerns with eucalyptus pertaining to site soil-water retention, but it remains a popular tree due to its market. The grassland consists of species locally known as "Omugugu" (*Cyperus* spp.). This is natural grass, which is used for grazing, but is also used as garden mulch. Most of it exists in the upper section of the hillslopes. The land use systems and associated activities are shown in table 1.

Temporal Characteristic of Rainfall Depth. Results on daily and monthly rainfall depth are shown in figure 3 and figure 4, respectively. The onset of the rains occurred in March. Forty-five rainfall events were annually received within the period of analysis. Those events ranged from 1.2 to 52 mm and had an average of 15 mm. Overall, a coefficient of variation of 74% in the daily rainfall events was computed. Our inspection of the data revealed an intermittent rainfall pattern with breaks in the rainfall occurrence. Out of the 45 rain days, repeated rainfall events on subsequent days occurred only on seven occasions (16%) and were largely observed between November and December. This result implies that the significance of antecedent moisture due to recurring precipitation on runoff and soil loss magnitude and patterns in the study area is likely to be limited.

Monthly rainfall values varied from 9.3 to 167 mm (75 ± 54 mm). The months of high rainfall amounts (above 100 mm) were October and November. With the exception of the dry months, which were January and February, the lowest monthly rainfall depths were observed in March and May. Overall, the proportion between wet and dry months was about 50% using the critical rain depth threshold of 50 mm. In terms of seasonality, this region has two rainy seasons just like most parts of central Uganda. The rainfall phenomenon is controlled largely by two factors, i.e., the Inter Tropical Convergence Zone (ITCZ) global positioning (Mubiru et al. 2012) and the proximity to Lake Victoria.

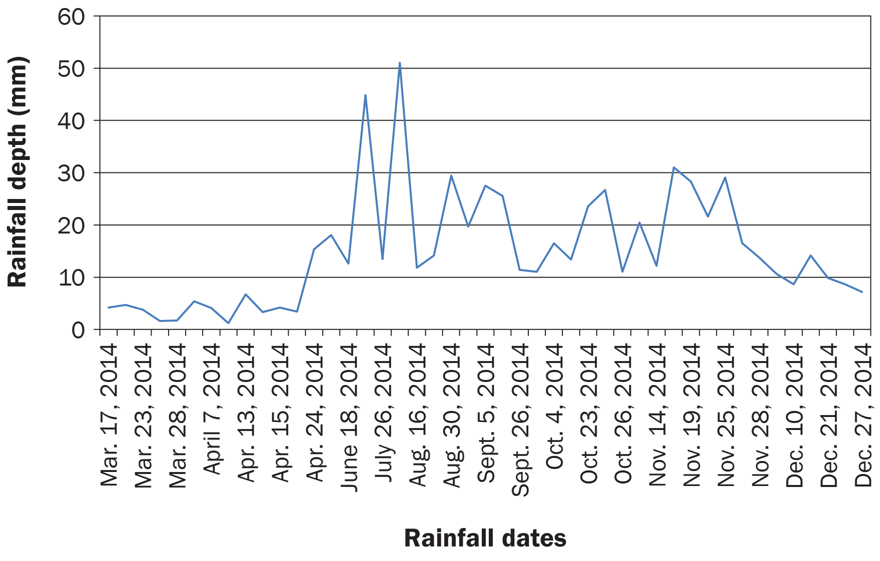
Table 1
Land use systems and associated activities.

Land use system	Intercrop	Activities	Remarks
Grassland	None	Grazing	Livestock in enclosures
Tree plantation	None	Pruning, thinning, tillage, and slashing	Some grass on the surface
Unmulched banana	Occasionally	Tillage, pruning, and crop harvesting	Weed growth and removal
Mulched banana	Occasionally	Tillage, pruning, mulching, and crop harvesting	Mulch added one to two times a year

The data indicate that rainfall received in the second season was four-fold greater than the first season. In the first season, only 20% (135 mm; 16 events) of the total annual rainfall was obtained, while 80% (538 mm; 39 events) was obtained in the second season. While conclusions cannot be drawn with only one year of data, the observed pattern has implications for farmers' planning, especially the crop calendar where diverse crops are grown in each season. A significant feature of the rainfall distribution was the continuity across all months from the onset in March. This configuration can create antecedent soil moisture conditions, which can alter the runoff and soil loss dynamic even in the midst of low rainfall events (Wei et al. 2007; Ziadat and Taimeh 2013).

Annually, the registered rainfall depth was 680 mm. The annual rainfall received was about 200 mm below the long-term rainfall average of 800 to 1,000 mm, according to Wanyama (2012). This reflects a strong temporal contrast in the area, which was alluded to by Ryken et al. (2015).

Figure 3
Daily rainfall depth recorded at the sites.



Statistical Features of Rainfall Regimes. Boardman (2006) underscored the significance of distilling and accounting for extreme rainfall events in overall total erosion. To have insights on the contribution of different rainfall regimes on the overall runoff and soil loss magnitude, we adopted rainfall thresholds given by Kwarteng et al. (2009), namely, light rainfall (under 10 mm), moderate rainfall (10 to 24 mm), heavy rainfall (25 to 49 mm), and extreme rainfall (over 50 mm). Results on categorical distribution of rainfall regimes show that light and moderate rainfall events were more frequent (80%) in the area as shown in figure 5. In total, the light and moderate rainfall events occurred 36 times out of the 45 rain days recorded. Outstandingly, moderate rainfall events are not only the most frequent, but also contributed greatly to the annual totals. The total annual rainfall depths were 79 mm (12%), 301 mm (45%), 242 mm (36%), and 51 mm (8%) for light, moderate, heavy, and extreme regimes, respectively. It is generally well established that extreme rainfall events are quite rare and have a longer return period (low frequency-high magnitude). Thus, the registration of only one extreme event (51 mm) in our study conforms to the expected phenomenon.

Surface Runoff Dynamics in Relation to Land Use and Slope Facet. The magnitude of observed annual runoff and the site characteristics from which measurements were conducted are given in table 2. Annual runoff within the catchment at the studied sites varied from 42 to 411 m^3 ha^{-1} y^{-1}. The average observed cross-site annual runoff was 151 ± 95 m^3 ha^{-1} y^{-1}. The coefficient of variation in the runoff magnitude was 63%. This indicates relatively high variation, but understandable in respect of the site soil, terrain, and vegetative conditions.

Annual runoff by land use was in the order of tree plantation (166 m^3 ha^{-1} y^{-1}) > unmulched banana (156 m^3 ha^{-1} y^{-1}) > mulched banana (142 m^3 ha^{-1} y^{-1}) > grassland (139 m^3 ha^{-1} y^{-1}). Clearly, the difference in registered annual surface runoff between the highest and lowest is quite small (27 m^3; 19%) among the land use systems and was found to be statistically insignificant ($p > 0.05$) when subjected to ANOVA. In Uganda, the general thesis and campaign is to promote tree plantation as the harbinger for landscape sustainability. While this is a laudable campaign and efforts should be commended, the results here allude to a precautionary aspect that borders on the typology of trees promoted as well as the landscape ecology.

Surface runoff characteristics from a temporal perspective give varying patterns in the studied land use systems. In the mulched banana plantations, the amount of runoff was different across the rainfall season. High surface runoff was recorded during the onset of the first rainy season. The magnitude of surface runoff in the second season more than doubled that of the first season with a peak at 11 m^3 ha^{-1} in October. In the unmulched banana system, highest surface runoff (10.37 m^3 ha^{-1}) was recorded in March and the lowest in September. In grass-

Figure 4
Monthly rainfall depth and mass curve for the monitored climatological period.

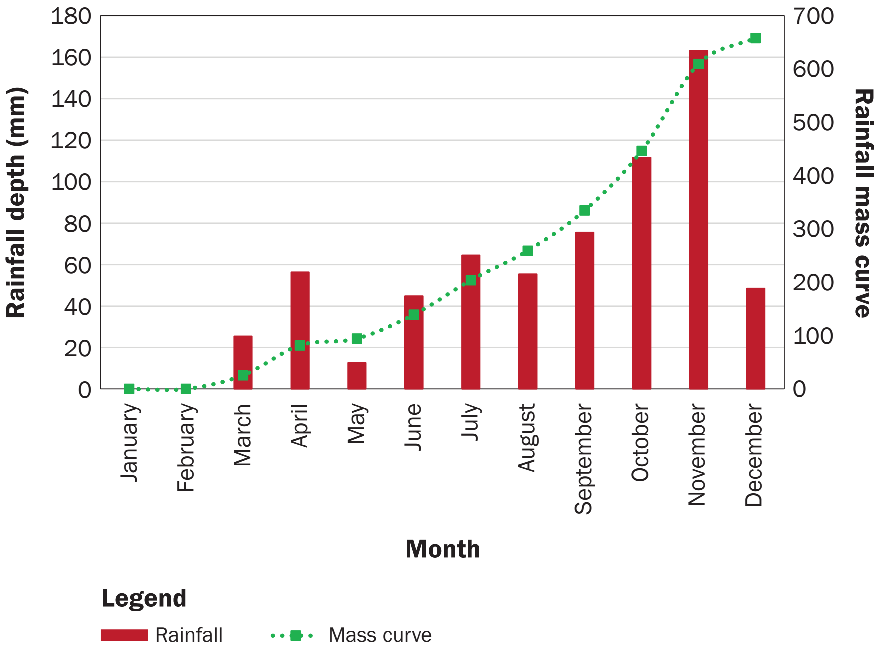
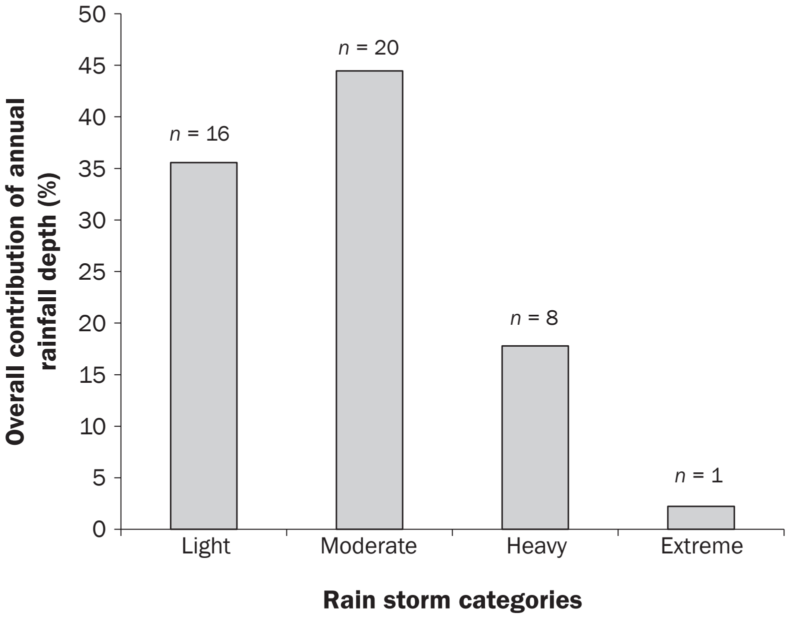


Figure 5
Intensity of rainfall regimes and their overall contribution (as a percentage) of the annual rainfall depth.



land, surface runoff generally increased with rainfall season, whereby low surface runoff amounts were recorded during the onset of rainy season and increased towards the end of the rainy season. In the tree plantations, the amount of surface runoff increased with rainfall season, whereby high surface runoff was recorded during the onset of rainy season and decreased towards the end of the rainy season; however, peak surface runoff was recorded in July.

Average runoff generally shows a spatially increasing trend with slope facet from foot slope, midslope, and summit as shown in figure 6. The observed site variations in runoff did not reveal a statistically significant difference ($p > 0.05$), signifying that across the foot slope, midslope, and upper slope facets, the annual runoff magnitude is uniform. The mulched banana sites registered more runoff on the midslope facets as opposed to both the lower and upper slope segments. The tree plantation and unmulched banana sites registered lower runoff on the on the midslope facets as opposed to both the lower and upper slope segments.

The runoff on the grassland sites shows a spatially increasing trend from foot slope, midslope, and summit. Considering slope facet, average runoff shows no uniform trend for land use categories. At the summit slope facet, grasslands registered the highest runoff (201 $m^3\ ha^{-1}\ y^{-1}$), followed by tree plantation (194 $m^3\ ha^{-1}\ y^{-1}$), unmulched banana (171 $m^3\ ha^{-1}\ y^{-1}$), and mulched bananas (73 $m^3\ ha^{-1}\ y^{-1}$). At the midslope facet, mulched bananas had the highest runoff (279 $m^3\ ha^{-1}\ y^{-1}$), followed by unmulched and grassland (129 $m^3\ ha^{-1}\ y^{-1}$), and tree plantation (116 $m^3\ ha^{-1}\ y^{-1}$). At the foot slope facet, the tree plantation registered the highest runoff (186 $m^3\ ha^{-1}\ y^{-1}$), followed by unmulched bananas (169 $m^3\ ha^{-1}\ y^{-1}$), grassland (88 $m^3\ ha^{-1}\ y^{-1}$), and mulched bananas (73 $m^3\ ha^{-1}\ y^{-1}$). The absence of a clear trend shows that runoff cannot be explained by land use and slope facet in isolation but rather the interaction with plot specific land use management practices by farmers across the cropping season. Some of the unmulched plots were intercropped by farmers with beans forming a different spatial pattern of soil cover, which affects the runoff. The observed variation in the runoff trend across the sites in our study corroborate with the findings of Boix-Fayos et al. (2007) and Boix-Fayos et al. (2006).

Table 2

Topographic and land use attributes of the experimental sites where annual runoff and soil loss were measured.

Site	Location	Land use system	Slope facet	Aspect	Slope (°)	Altitude (m)	Runoff events (n; %)	Runoff ($\mathrm{m^3\,ha^{-1}\,y^{-1}}$)	Soil loss ($\mathrm{t\,ha^{-1}\,y^{-1}}$)
1	0°45′02″ S, 30°24′32″ E	Mulched banana	Foot slope	344 Northwest	10	1,474	24 (53%)	60	0.2
2	0°45′02″ S, 30°24′32″ E	Mulched banana	Foot slope	338 Northwest	10	1,475	23 (51%)	58	0.4
3	0°45′02″ S, 30°24′32″ E	Mulched banana	Foot slope	336 Northwest	11	1,477	23 (51%)	101	0.7
4	0°45′02″ S, 30°24′31″ E	Mulched banana	Midslope	344 Northwest	13	1,482	21 (47%)	59	0.2
5	0°45′04″ S, 30°24′31″ E	Mulched banana	Midslope	328 Northwest	12	1,486	32 (71%)	366	1.8
6	0°45′04″ S, 30°24′31″ E	Mulched banana	Midslope	348 Northwest	13	1,482	26 (58%)	411	1.1
7	0°45′14″ S, 30°24′37″ E	Mulched banana	Summit	190 South	12	1,494	25 (56%)	42	0.3
8	0°45′14″ S, 30°24′37″ E	Mulched banana	Summit	162 South	13	1,490	21 (47%)	71	0.3
9	0°45′14″ S, 30°24′37″ E	Mulched banana	Summit	158 South	12	1,474	38 (84%)	107	0.8
10	0°45′02″ S, 30°24′31″ E	Unmulched banana	Foot slope	344 Northwest	13	1,476	20 (44%)	210	1.1
11	0°45′02″ S, 30°24′31″ E	Unmulched banana	Foot slope	338 Northwest	12	1,474	24 (53%)	84	0.3
12	0°45′03″ S, 30°24′31″ E	Unmulched banana	Foot slope	344 Northwest	11	1,475	25 (56%)	212	1.1
13	0°45′16″ S, 30°24′38″ E	Unmulched banana	Midslope	134 Southeast	10	1,466	25 (56%)	187	2.4
14	0°45′16″ S, 30°24′38″ E	Unmulched banana	Midslope	146 Southeast	12	1,473	21 (47%)	68	0.7
15	0°45′15″ S, 30°24′38″ E	Unmulched banana	Midslope	144 Southeast	11	1,470	38 (84%)	131	1.4
16	0°45′10″ S, 30°24′30″ E	Unmulched banana	Summit	220 Southwest	19	1,490	20 (44%)	117	1.8
17	0°45′10″ S, 30°24′31″ E	Unmulched banana	Summit	222 Southwest	18	1,487	27 (60%)	174	2.6
18	0°45′10″ S, 30°24′31″ E	Unmulched banana	Summit	206 South	16	1,489	28 (62%)	223	2.8
19	0°45′08″ S, 30°24′26″ E	Grassland	Foot slope	254 West	20	1,498	33 (73%)	127	1.2
20	0°45′08″ S, 30°24′26″ E	Grassland	Foot slope	240 West	21	1,499	32 (71%)	63	0.5
21	0°45′08″ S, 30°24′28″ E	Grassland	Midslope	278 West	14	1,479	31 (69%)	67	0.4
22	0°45′09″ S, 30°24′28″ E	Grassland	Foot slope	256 West	20	1,502	25 (56%)	76	0.4
23	0°45′08″ S, 30°24′28″ E	Grassland	Midslope	290 North	13	1,478	28 (62%)	226	1.0
24	0°45′08″ S, 30°24′28″ E	Grassland	Midslope	274 West	12	1,481	27 (60%)	93	0.6
25	0°45′08″ S, 30°24′31″ E	Grassland	Summit	310 Northwest	11	1,496	32 (71%)	142	1.0
26	0°45′08″ S, 30°24′31″ E	Grassland	Summit	300 West	12	1,478	24 (53%)	163	1.0
27	0°45′09″ S, 30°24′31″ E	Grassland	Summit	274 West	10	1,481	23 (51%)	299	1.2
28	0°45′17″ S, 30°24′35″ E	Tree plantation	Foot slope	210 South	16	1,460	25 (56%)	67	0.4
29	0°45′18″ S, 30°24′35″ E	Tree plantation	Foot slope	224 Southwest	15	1,440	34 (76%)	366	2.3
30	0°45′17″ S, 30°24′35″ E	Tree plantation	Foot slope	226 Southwest	16	1,438	34 (76%)	126	0.7
31	0°45′18″ S, 30°24′36″ E	Tree plantation	Midslope	216 South	20	1,478	32 (71%)	110	1.1
32	0°45′17″ S, 30°24′37″ E	Tree plantation	Midslope	204 South	19	1,482	28 (62%)	196	1.7
33	0°45′18″ S, 30°24′37″ E	Tree plantation	Midslope	220 Southwest	19	1,495	15 (33%)	43	0.6
34	0°45′11″ S, 30°24′33″ E	Tree plantation	Summit	214 Southwest	21	1,499	36 (80%)	120	0.7
35	0°45′11″ S, 30°24′33″ E	Tree plantation	Summit	212 Southwest	22	1,501	43 (96%)	232	2.5
36	0°45′11″ S, 30°24′33″ E	Tree plantation	Summit	214 Southwest	20	1,495	38 (84%)	230	3.3
Mean								150.8	1.1
CV								64	73

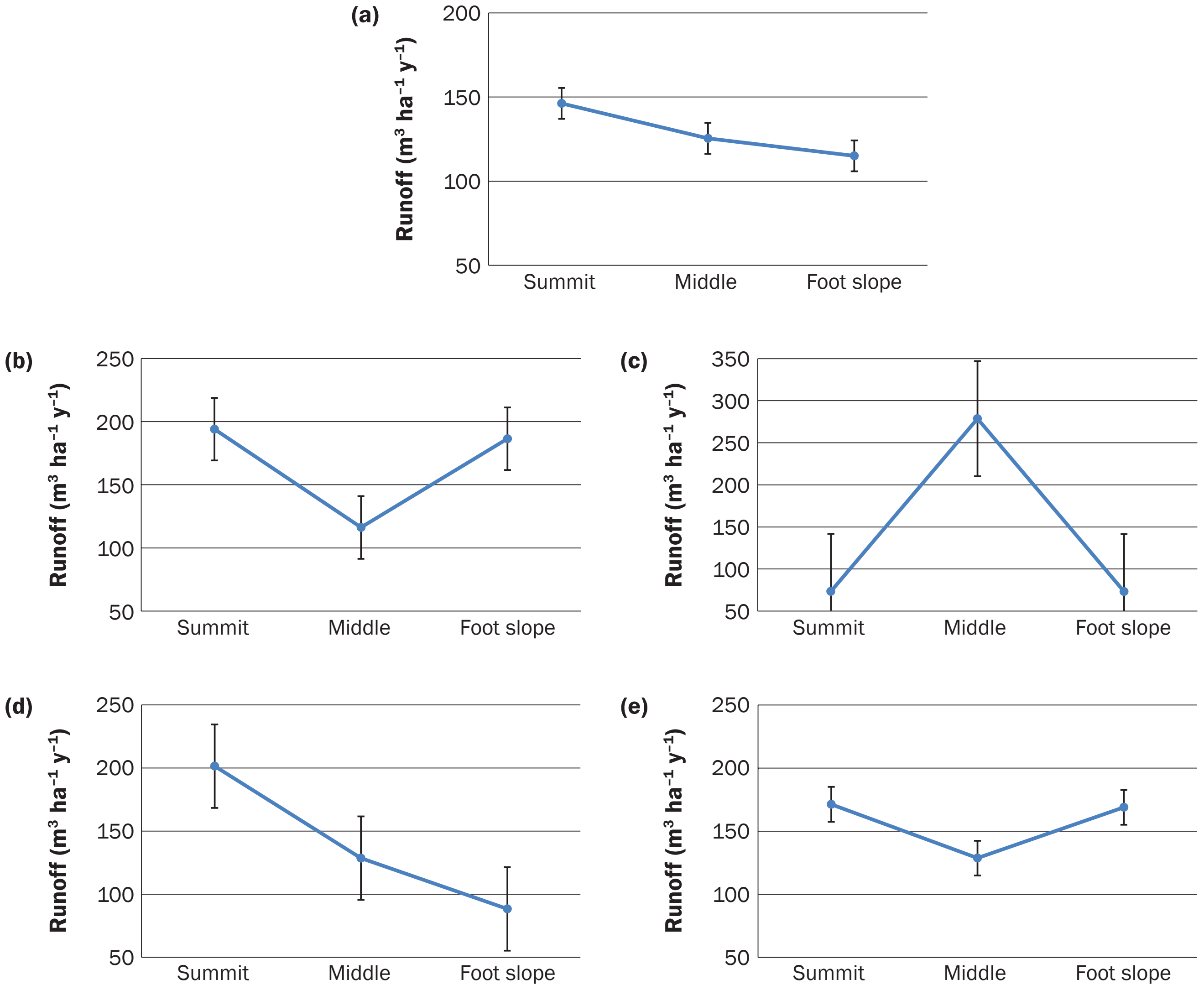
Note: CV = coefficient of variation.

Spatial Variation in Surface Runoff with Respect to Rainfall Events. There were 45 erosive rainfall events received in the year. Suffice to say that not all rainfall events recorded in the study induced surface runoff at all the experimented sites. It is interesting to note that rainfall depth as low as 1.2 mm initiated runoff at some sites. The initiation of runoff by low rain depth events is not unusual in soil erosion studies and is often due to a combination of onsite factors. In studies by Ziadat and Taimeh (2013) and Wei et al. (2007), soil antecedent moisture was detected as the underlying factor, although this is unlikely in our study. Nearly all rainfall events with a depth >10 mm contributed relatively heavy runoff, while rainfall events <10 mm in general caused minor surface runoff. A spatial analysis of proportion of rainfall events initiating runoff at the experimental plots gives an average of 62% ± 14%. For all the observed rainfall events, the highest and lowest number of runoff events initiated at the plots was 43 (96%) and 15 (33%), respectively.

Variation of Surface Runoff Coefficient with Land Use and Slope Segment Configurations. Low runoff coefficients were observed across most sites, indicating the majority of the rainfall received infil-

Figure 6

Slope facet effect on runoff variation across sites and between land use systems ([a] all sites, [b] tree plantation, [c] mulched banana, [d] grassland, and [e] unmulched banana).

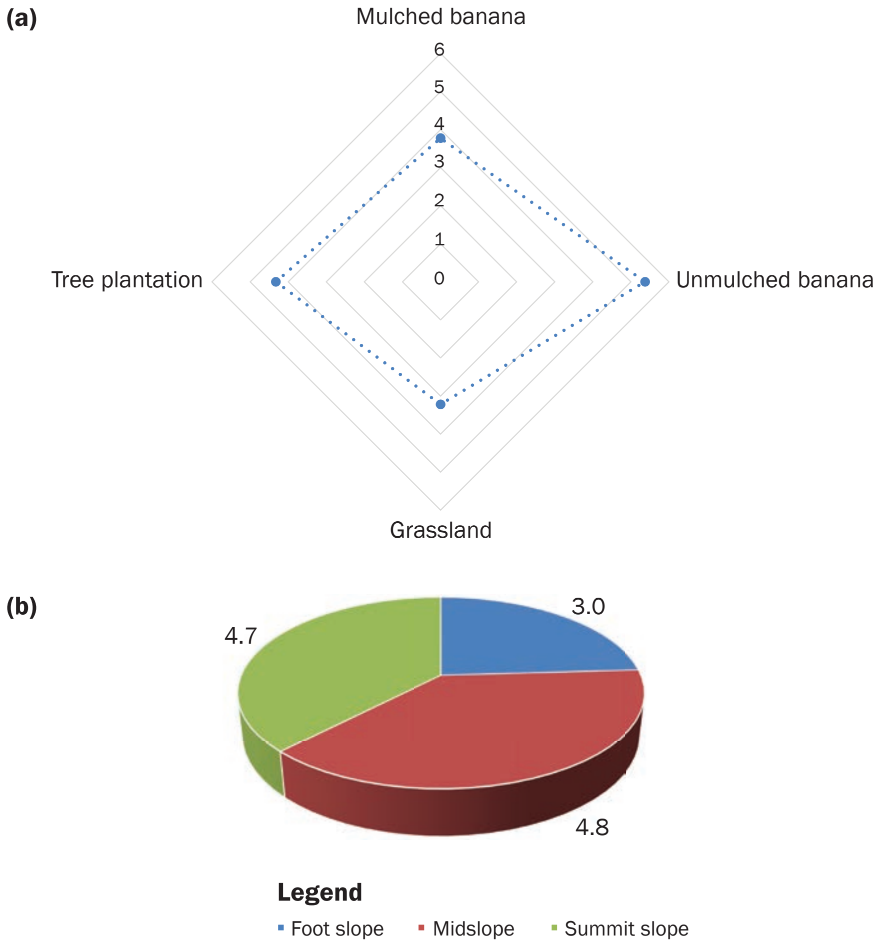


trated the soil. Studies elsewhere by Gardner and Gerrard (2003) also reported unusually low runoff coefficients. Unsurprisingly, the unmulched banana (5.4%) depicts the highest average annual runoff coefficient, while sites with grassland registered the lowest (3.2%), as illustrated in figure 7. It is worth noting that runoff coefficients as high as 96% were recorded from individual rainstorm events at some sites. Across all sites, the average highest runoff coefficient computed was 46%. Sites located at the foot of the hillslope show relatively lower runoff coefficients as opposed to those in the mid and upper hillslope segments. Tree plantation sites characterized by pine and eucalyptus registered relatively higher runoff coefficients. This is similar to the observations of Kothyari (2004), as pine represents maximum biotic pressure and less vegetative cover.

Spatial Variation and Annual Magnitude of Soil Loss. Soil loss from the studied sites (n = 36) on the toposequence varied from 0.2 to 3.3 t ha^{-1} h^{-1}. Annual soil losses registered at the maximum site were 17 times higher than the site bearing the minimum losses. The great difference in the minimum and maximum site observed annual soil loss illustrates the complexity in hillslope erosion studies. The great differences are, however, understandable owing to the differences in terrain and vegetative conditions (table 2). The topographic slope gradient on mulched banana foot slope site (10°) is less than the eucalyptus summit site (20°). Overall, the coefficient of variation in soil loss for all the studied sites was 72%, signifying a high variation. On similar sites, soil loss was found to be more variable than runoff. The observed average annual soil losses for all the monitored sites were 1.1 ± 0.8 t ha^{-1} y^{-1}.

The tolerable soil loss rate for tropical soils is 5 t ha^{-1} y^{-1} according to Lufafa et al. (2003). The magnitude of annual average soil loss rates registered at the studied sites is therefore within the tolerable rates and casts doubt on some of the alarming rates reported for the LVB. Previous studies on soil erosion in the LVB (table 3) have reported substantially higher annual soil loss amounts, even for sites under perennial cropping. This con-

Figure 7
Variation in runoff coefficients (%) with (a) land use system and (b) slope topographic position.



trast is not unusual in soil erosion studies as exemplified by Sougnez et al. (2011), who observed considerably lower rates on steep sparsely vegetated slopes in southeast Spain than reported in previous studies.

Our results also underpin the need to understand soil erosion aspects beyond rill and interill processes. For example, we observed the existence of numerous trails across the toposequence (figure 8). We postulate that the trails hierarchically convey significantly more runoff and soil loss contributing to the reported high stream and lake sedimentation in the LVB. While quantitative data on the contribution of these features are nonexistent, studies by De Meyer et al. (2011) and Bamutaze (2011) lend strong credence to this proposition.

Effect of Land Use and Slope Facet on Annual Soil Loss. Results on variations in observed annual soil loss with land use and slope segment are shown in figure 9. Mean annual soil losses (n = 9: land use system) were in the order of unmulched banana > tree plantation > grassland > mulched banana. Annual soil loss yielded on the unmulched banana was almost two-folds greater than that obtained on sites cropped to mulched banana (1.5 versus 0.8 t ha^{-1} y^{-1}). The mean slope gradient on the sites under mulched banana (12°) was, however, slightly less than those under unmulched banana (14°). The huge contrast (61%) in the annual soil loss between mulched and unmulched banana is sound evidence echoing the premise that fragile sites in the tropics can be sustainably utilized for agricultural purposes with simple and sound soil and water management interventions. The low annual soil losses recorded on toposequence sites under mulched banana land use systems further reiterates the conception that ground cover is more important for mitigating surface flow and neutralizing soil loss than canopy cover. Similar findings on the efficacy of mulch in reducing surface runoff and soil loss have been reported elsewhere (Cook et al. 2006; Lufafa et al. 2003; Smets et al. 2008). Mulch ameliorates the topsoil physical conditions and neutralizes the surface soil detachment capacity of the impacting raindrops. While variations in annual soil loss are observed in the studied land use systems, a statistical test did not find the differences to be significant ($p > 0.05$).

When collapsed to slope facet, annual soil loss showed an expectedly increasing pattern with the upper slopes registering more soil loss and the foot slopes registering the lowest. Average annual soil loss on the upper slope position facets (1.7 t ha^{-1} y^{-1}) were 2.4 times higher than those observed on the foot slope position facets (0.7 t ha^{-1} y^{-1}), giving a percentage difference of 83%. The percentage differences in soil loss for foot slope

Table 3
Comparison of soil losses observed in this study with data from Lake Victoria Basin (LVB).

Location in LVB	Method	Land use	Soil type	Slope (%)	Soil loss (t ha^{-1} y^{-1})	Reference
Masaka	USLE modeling	Banana	Luvisol, Gleysol, Planasol	—	22 to 34	Lufafa et al. (2003)
Rakai	Runoff plots	Banana-coffee, annuals	Luvisol, Regosol, Planasol	—	27 to 86	Majaliwa (2005)
Masaka	Gerlach troughs	Banana sole, banana-coffee	Luvisol	8 to 16	9 to 48	Nadhomi et al. (2006)
Nabajuvi	RUSLE	Grassland, small scale farming	Ferralsol, Planasol, Arenasol	—	25 to 38	Luliro et al. (2013)

Notes: USLE = Universal Soil Loss Equation. RUSLE = Revised Universal Soil Loss Equation.

Figure 8

Connectivity related to footpaths and trails convey more runoff and soil loss than agricultural fields.

sites versus midslope segment and midslope versus upper slope facets were 44% and 42%, respectively. The mean site slope gradient magnitudes were 15°, 14°, and 16°, respectively. Lower toposequence slope facets are generally expected to accumulate more soil organic matter (SOM) (Boling et al. 2008; Tsubo et al. 2006) perennially transported downslope by runoff, which mitigates soil loss. SOM increases the shear strength of the soils and increases the overall soil structural integrity (Nadhomi et al. 2006). The SOM contribution was, however, not empirically tested, and there is need to validate this postulation on the studied sites. Unlike runoff, statistically significant differences in soil loss under land use systems (p = 0.016, LSD = 0.658) and toposequence position (p = 0.035, LSD = 0.57) were detected. Annual soil loss from unmulched banana systems is significantly greater than that from mulched banana and grassland systems. Equally, tree plantation systems generate significantly more annual soil loss than mulched banana systems. Annual soil loss from sites located at the summit is significantly higher than foot slope sites.

Runoff and Soil Loss Relationships Constrained by Land Use System. The relationship between surface runoff and annual soil loss registered in the four land use systems is depicted in figure 10. In general, the results reveal that surface runoff is the main mechanism behind the registered annual soil losses in the study area. Evidently, the strength of surface runoff as an explanatory variable was not homogenous across the land use systems. Interestingly, the greatest contrast occurs in the banana plantation systems with the mulched banana having a higher coefficient of determination (r^2 = 0.78), while the unmulched banana had the lowest (r^2 = 0.36). This implies that runoff accounted for 78% and 36% of the variability in soil loss in the mulched and unmulched banana land use systems, respectively. With the exception of sites cropped to unmulched banana, all other land uses give a relatively strong (>50%) and significant ($p < 0.05$) relationship between surface runoff and soil loss. Mulched banana sites also display a relatively more linear structure in comparison to sites with other land use systems. Some elements of random structure distribution aspects can be observed in the land use systems.

The proportional contribution of the four clustered rainfall regimes to runoff and soil loss is shown in figure 11 and reveal a varied pattern. The lighter rainfall events seemingly induce both runoff and soil loss in equal proportions. Overall it seems the light and moderate rainfall events are more effective in runoff generation, while the heavy and extreme rainfall events entrain and transport more soil particles. The bigger events obviously have more power, but most importantly the duration enables saturation weakening the cohesiveness of the soil particles and their availability for transportation where reasonable slope gradient exists.

Summary and Conclusions

Surface runoff and annual soil losses are low and within the tolerable soil loss rates. This is contrary to previous studies that report extremely higher rates, although some caution should be taken in the comparison. Spatially, a higher diversity is observed in the soil losses, but within the land use systems there are no statistically significant variations. The same pattern is observed with the toposequence position. Annual rainfall depth as the engine for soil erosion was on the lower side, but even a doubling of the rainfall depth is unlikely to trigger soil losses beyond the tolerable levels under the current land use systems. Our results reaffirm the importance of mulch in sustainably utilizing fragile landscapes.

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Figure 9

Variation of soil loss with (a) land use and (b) toposequence position. Vertical lines signify error bars.

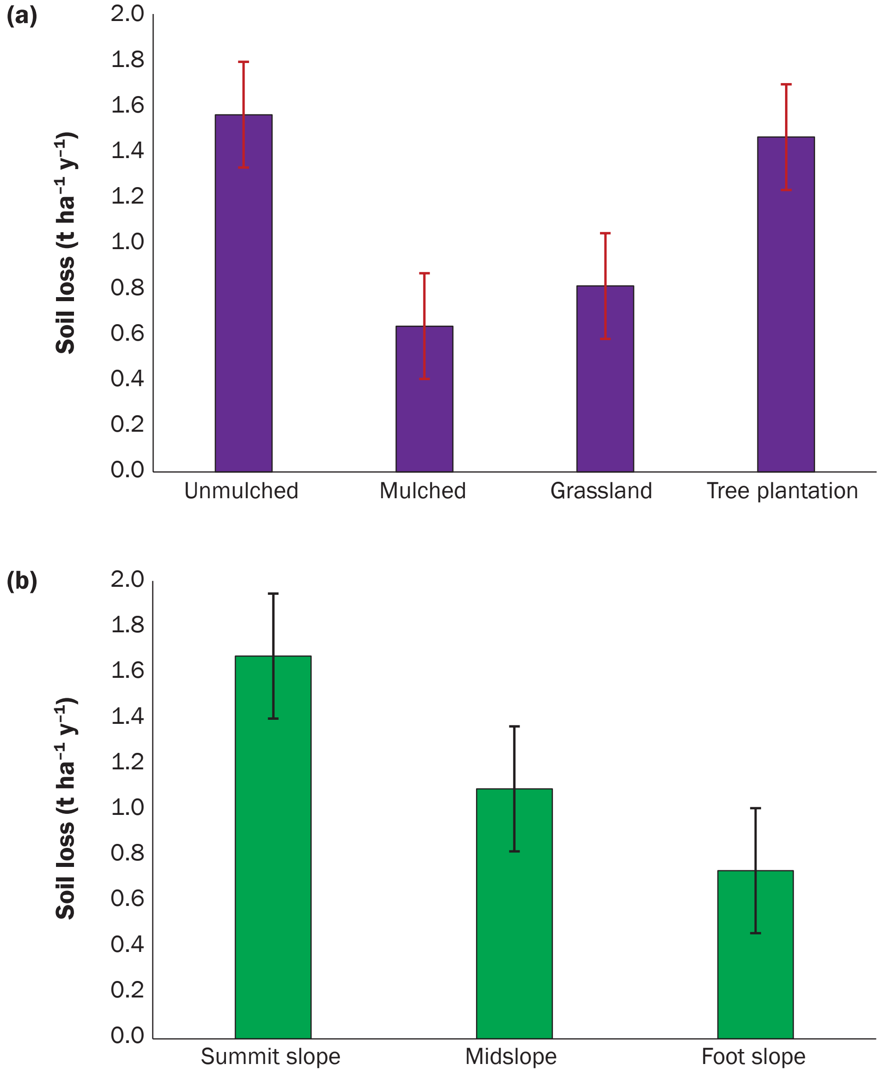

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Figure 10

Regression coefficient of the relationship between runoff and soil loss in the land use systems ([a] unmulched banana, [b] mulched banana, [c] grassland, and [d] tree plantation).

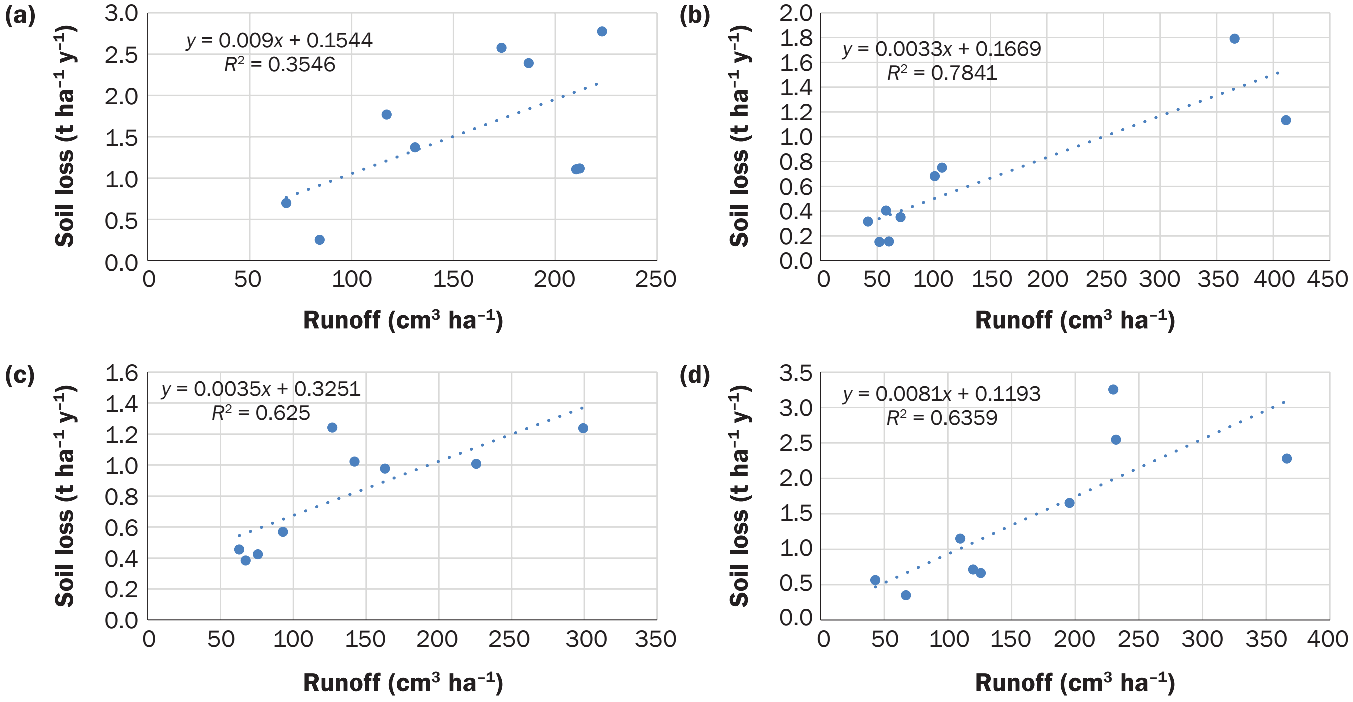
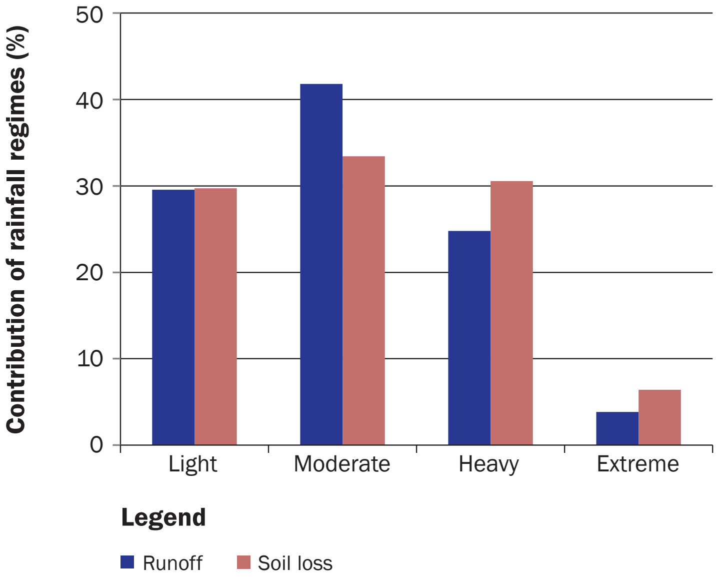


Figure 11

Proportional contribution of rainfall regimes to observed runoff and soil loss.



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