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Assessment and Prevention Strategies of Soil Surface Crusting Caused by Rainfall Events: Case Study of Sebeya Catchment Agricultural Land in Rwanda

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ABSTRACT

The history of soil erosion is an integral part of the agriculture. All over the world, wherever human being started the agricultural operations, there exists the problem of soil erosion in some extent. Soil erosion leads to the reduction of water infiltration rate and enhances runoff and soil degradation. This study focuses on Sebeya catchment located in the Western part of Rwanda. The main objective of this study was to assess various preventive measures against soil surface crusting and development of runoff coefficients in order to minimize the soil loss in Sebeya catchment agricultural fields. The proposed methodology was much concerned with the efficiency analysis of soil conservation practice of mulching in maize cover crops. The names of the three experimental field plots sited are Maize-Fertilizer-Mulching (MFM), Maize-Fertilizer (MF) and Bare Soil (BS) which were set in Rugerero Sector of Rubavu District. Each of these 3 plots was constructed with its runoff collecting tank and they were under similar conditions except land cover. Samples of soil from field plots and water from runoff collecting tanks were tested for soil classification and soil loss estimation from each plot respectively. The analysis of results showed that soil of the experimental plots is a gravelly sand with (sand:56.27%; clay and silt: 3.24% and gravel: 40.49%). Also, the results showed that the plot coded as MFM, has high moisture content with low runoff and soil loss compared to 2 other plots. This research revealed that soil conservation practices such as surface mulching and vegetative cover reduce runoff, soil loss and are well recommended for preventing and controlling soil surface crusting.

Keywords: Soil erosion, mulching, soil crusting, field experiments, Rwanda

1. INTRODUCTION

All over the world, wherever human being started the agricultural operations, there exists the problem of soil erosion. Naturally, rainfall erosion is characterized by a series of many phenomena: compaction, disintegration, detachment, transport and deposition (Tang et al., 2002). These actions result in the formation of seal and subsequently the crust of soils.
(Tang et al., 2002) define a crust as a thin layer at the soil surface characterized by a greater density, higher shear strength and lower hydraulic conductivity than the underlying soil.

The occurrence of soil crusting is extended to over the whole range of climates: drier and humid regions. Soil seals and crusts can significantly reduce infiltration rate and largely blamed for initiating runoff and favoring interrill soil erosion and inhibiting seedling development (Smith et al., 1990). The extreme soil erosion in Rwanda is due to abundant rainfall and agricultural expansion on steep slopes terrain (Karamage et al., 2016).

The main objective of this research was to assess and draw preventive measures against soil surface crusting and development of runoff coefficients in order to propose suitable measures to minimize the soil loss in Sebeya catchment agricultural fields in Rwanda. In a more detailed way, the specific objectives of this study were: (1) to assess the actual status of soil erosion in Sebeya catchment; (2) to simulate rills and interrills by constructing field plots in Sebeya catchment agricultural land; (3) to monitor erosion process and compare soil surface crusting, development of runoff coefficients and soil loss in 3 different scenarios of land cover.

The present study has designed three field experimental plots referred to the standard USLE Plot of 22.1m x 4m which was proposed and tested on a slope of 9% (Lal, 1994). Three field plots were constructed each one with its coupled runoff collection tank. Periodic samplings of soil from field plots and water from runoff collection tanks for soil moisture content and soil loss were done respectively. Sieve analysis was also performed for the classification of the agricultural soil in the experimental field. Many studies revealed that a large number of Best Management Practices (BMPs) such as minimum tillage, surface mulching, contour ploughing, vegetative cover, etc., reduce runoff, soil loss and are best suited to preventing and controlling soil surface crusting (Peigne et al., 2007).

2. METHODOLOGY

2.1 Study Area

2.1.1 Site localization

This study is entirely focused on Sebeya catchment located in the Western Province of Rwanda as presented in figure1. The main river flowing in this catchment is Sebeya, which originates in the mountains of Rutsiro District. The total surface area of Sebeya catchment represents 1.38 % of the total surface area of Rwanda (26,338 km² including water bodies), which totalizes 363.1 km² (IWRM, 2018). The catchment is shared by four administrative units namely Rubavu, Nyabihu, Rutsiro and Ngororero (figure1).

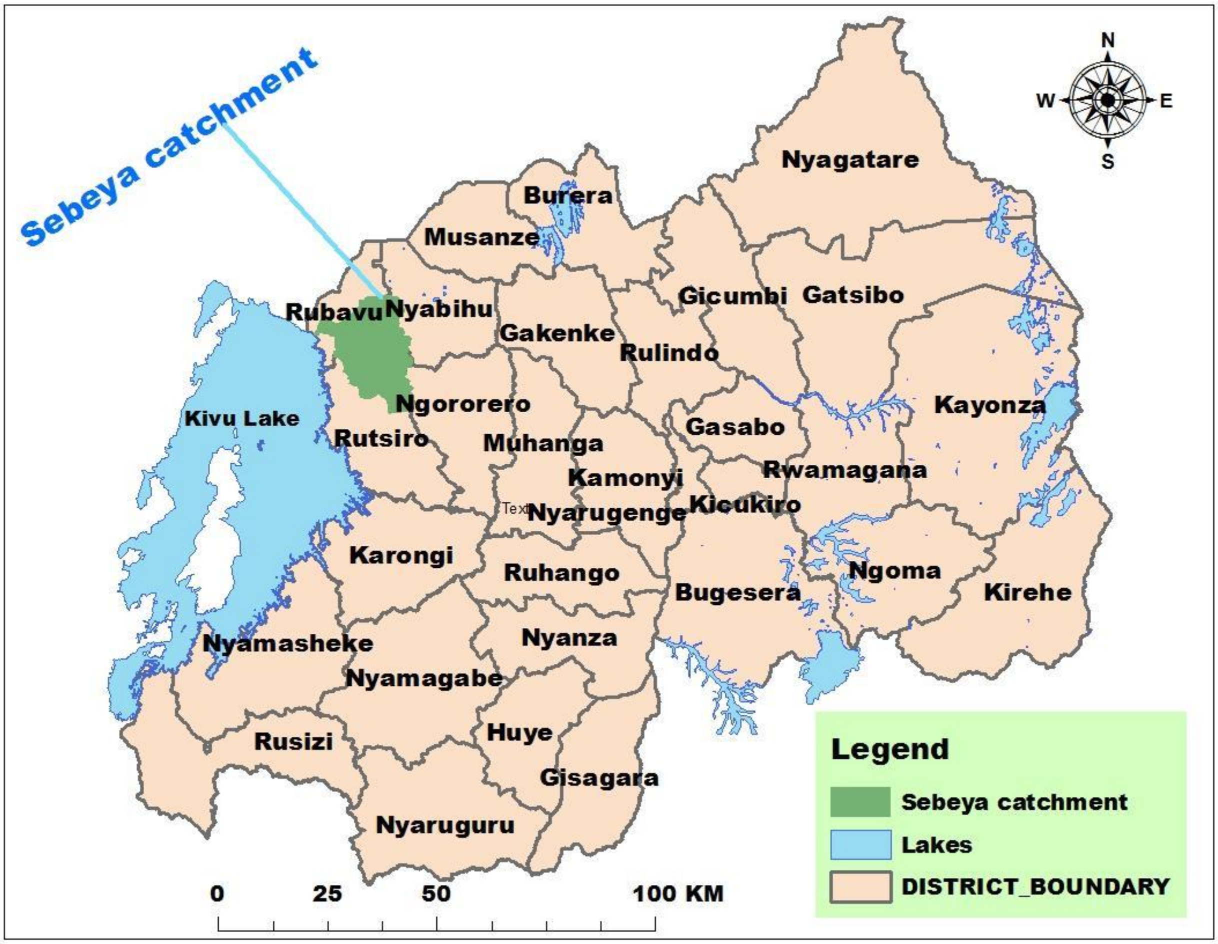

Figure 1. Location of Sebeya catchment

2.1.2 Population density

The average density of Sebeya catchment is estimated to 644 hab/Km^2 while the average population density of Rwanda is about 415 habitants per km^2 (NISR, 2014). The Northern part of Sebeya catchment in Rubavu District (Nyakiriba, Rugerero and Gisenyi sectors) is occupied by a significant urban population. The sectors along the shores of Lake Kivu and along the main road from Rubavu to Musanze are very highly populous with more than 1000 hab/km^2 while the sectors in the highlands of the South-East show the lowest population density fluctuating from 250 to 500 hab/km^2 (IWRM, 2017). High demographic pressure is one the indirect factors accelerating soil erosion in Sebeya catchment.

2.1.3 Soil characteristics

The soil in this catchment favors agriculture due to its high infiltration rates and its high minerals content except for the case of clay soils on flat topography encountered in the catchment. The combination of the geological formation and soil data characterize Sebeya catchment as a fragile ecosystem susceptible to heavy erosion (MoE, 2018).

2.1.4 Site topography and rainfall

Sebeya catchment is located in the high elevation region of the country with altitude varying between 1,462 m to 2,979 m a.b.s.l. (meters above sea level). This catchment is also characterised by steep slopes (varying from 0% to 90%) and abundant rainfall varying between 1,200 mm to 1,700 mm per year revealing that a great part of this catchment falls in medium risk to very high risk of erosion according to the classification of MoE in 2018.

2.2 Data and Methods

2.2.1 Rainfall measurement at the field location

Agro-climatological data are required for planning crops cultivation and forecasting agricultural productivity (Rogers, 2013). In this study, the site rainfall was measured in the field location using a prefabricated rain gauge. The idea of local rainfall measurement was to compare rainfall recorded at Gisenyi meteo station with real rainfall in the experimental field plots. In fact, the variation of a point-rainfall in time and space depends on topographic effects and wind direction (Rodda, 1971).

2.2.2 Field experimental design

The standard USLE Plot of 22.1m x 4m was proposed and tested on a slope of 9% (Lal, 1994). The present study has designed three experimental plots of (21m x 4m) each sloping at about 14%. Plots were sufficiently wide to minimize the border effects and long enough to allow the development of the combined downslope processes of rill and interrill erosion. As shown in figure2, the proposed names for the 3 experimental field plots are: MFM (Maize-Fertilizer-Mulching), MF (Maize-Fertilizer) and Bare Soil (BS). All those plots were constructed in Rugerero sector of Rubavu District and the main characteristics for the 3 constructed plots are as follows:

- The ploughing, levelling and slopping conditions are the same;
- With compost and chemical fertilizer applications, the maize seeding was done in the first 2 plots (MFM and MF) only while the 3rd one (BS) was kept blank without any crop seeding and no fertilizer application;
- Differently to 2 other plots, the 1st plot (MFM) was additionally mulched. All the 3 field plots were under the same conditions except land cover.
- All the borders of each plot were bunded with gabions socked into the ground and wrapped with plastic sheets so that only runoff from direct precipitation on the plot could be collected in the coupled runoff collecting tank;
- Each runoff collecting tank was large enough to store the total runoff after each rainfall event. After each rainfall event and after taking the water sample, each runoff collection tank was emptied through a drainage pipe at its bottom.

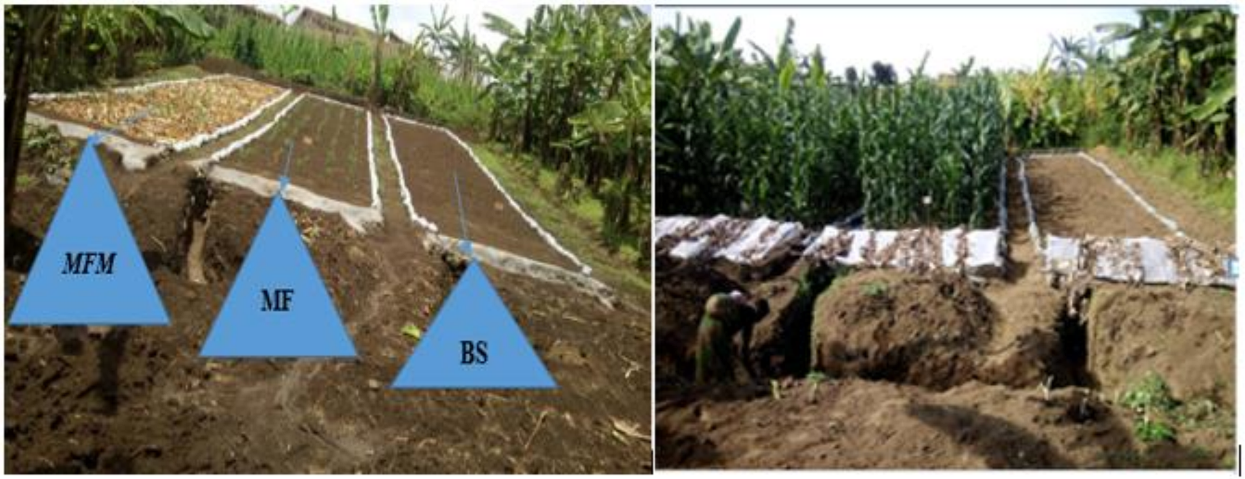

Figure 2. Field plots at initial and middle stages of growing maize

2.2.3 Soil texture determination through sieve analysis

Three soil samples were taken from the experimental field: about 1Kg at the top; 1Kg at the middle and about 1Kg at the bottom and well mixed. About 1Kg of soil sample from a well-mixed soil samples was taken to Soil Mechanics Laboratory of University of Rwanda, College of Science and Technology (UR-CST). The particle size distribution analysis was performed using the method proposed by Bureau of Indian Standards in 1963 known as IS: 2386 (Part I) – 1963. Different sieves with different sizes of 63mm, 50mm, 40mm, 25mm, 20mm, 16mm, 12.5mm, 10mm, 6.3mm, 4.75mm, 2.36mm, 1.18mm, 600µm, 150 µm and 75 µm were used. The Soil Classification was done using MIT (Massachusetts Institute of Technology) Soil Grain Classification Standard.

2.2.4 Sampling and testing of water from runoff collecting tanks

A water sample of 500mL was collected from the runoff collecting tank installed at the bottom of each of the 3 plots. Before taking water samples, the volume of water collected in each tank was recorded and thoroughly mixed. After each rainfall event, the collected three water samples were taken to Soil Mechanics Laboratory of UR-CST to estimate the induced soil loss from each plot. Finally, each runoff collecting tank was emptied through a drain pipe connected at each bottom level in order to be ready for next sampling experiment. About 100mL from the mixed water sample was boiled to vaporize all water on the vaporization dish. The remaining wet soil was then put in an oven-drier during 24 hours at about 105^{o}C. After this time, soil loss per 100mL was estimated.

2.2.5 Determination procedures for soil moisture content

Three samples of soil were taken at 3 different sampling points: at the top, at the center and at the bottom of each plot. A cleaned dried plastic cup of 500 mL was inserted vertically into the soil for taking the soil sample until the bottom of the cup reached the level of the soil surface. Then the cup was returned up without disturbing the state of the soil inside the cup and the weight of the cup with the wet soil was recorded. After drying the sample in an oven at a temperature of 105^0C for 24 hours, the weight of the sample was recorded. The average moisture content for each plot was computed.

2.2.6 Data analysis tools

Using Arc GIS Software, Sebeya catchment was delineated from a Digital Elevation Model (DEM) acquired from University of Rwanda- Center for Geographic Information Systems (UR-CGIS). Microsoft Excel was used to analyze data in terms of figures and tables.

3. RESULTS AND DISCUSSIONS

3.1 Current Situation of Soil Erosion in Sebeya Catchment

Soil erosion within Sebeya catchment was categorized into 6 classes such as 0-5 very low, 5-10 low, 10-25 moderate, 25-50 high, 50-100 very high and greater than100 extremely high in tons/ha/year where around 8000 ha are under high risk, around 6000 ha under very high risk while around 4000 ha are under extremely high risk of soil erosion (MoE, 2018). In Sebeya catchment, the high risk of soil erosion results from improper management of land, heavy rainfall and human activities that disturb the soil.

3.2 Soil Tests and Soil Classification

3.2.1 Sieve analysis

The figure3 represents the grading curve of soil from the experimental field where the sand portion is predominant (sand:56.27%; clay and silt: 3.24% and gravel: 40.49%).

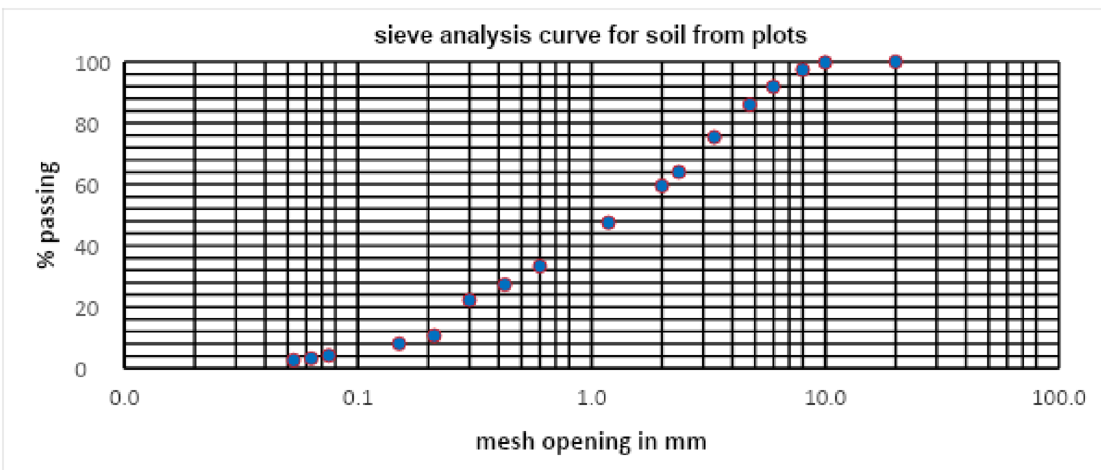

Figure 3. Grading curve for soil sample from the experimental field

Soil particle size distribution, particularly clay, affects soil crusting. A high clay content generally favors aggregation and increases the rate of crust formation. Medium-textured soils (<20% clay) are usually subjected to crusting. Coarse fragments seem to protect the smaller surface aggregates from raindrop impact in the same way as a mulch and increase infiltration with ultimate effect of reducing soil erosion (Collinet & Valentin, 1984).

3.2.2 Moisture content

According to all sampling dates (Figure5), the soil moisture content results revealed that the plot which is fully covered (MFM) had high value of water content compared to the other plots. Generally, aggregates explode more easily when they are initially dry and they are wetted suddenly (Mbwana, 2004). This implies that MFM possesses such high ability to resist to soil detachment. Mulching is one of the most efficient techniques of soil erosion control, where it influences C factor in reducing soil erosion. Covering the ground with mulch saves water by preventing surface evaporation and reduces soil erosion compared to bare agricultural soil. There is a wide variety of permeable mulching materials. Organic mulches conserve water more effectively and do not limit soil water infiltration and retention. Appropriate mulch can reduce the need for irrigation and in some landscapes can eliminate irrigation.

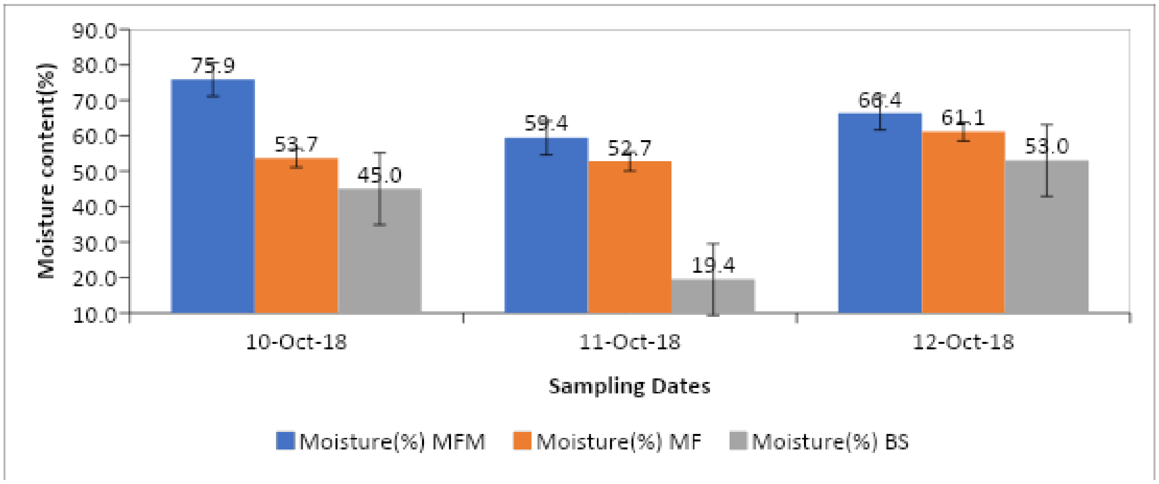

Figure 4. Variation of Soil moisture content

3.2.3 Effects of rainfall on various scenarios of land cover

In order to compare the effects of rainfall on various scenarios of land cover, soil loss and runoff coefficients have been estimated when the 3 plots were exposed to the same rainfall events at different dates (table1). The rainfall intensity was deduced from the field precipitation measurements.

Table1: Effect of rainfall on soil loss and runoff coefficient

Date	i (cm/hr)	MFM		MF		BS	
		R	A(g/m^2/hr)	R	A(g/m^2/hr)	R	A(g/m^2/hr)
08-10-2018	26.23	0.121	8.318	0.144	66.249	0.341	93.068
11-10-2018	14.57	0.131	5.729	0.154	20.261	0.411	68.220
13-10-2018	10.09	0.201	3.519	0.487	40.921	0.631	55.456
14-10-2018	11.21	0.091	3.892	0.120	8.314	0.191	25.888
19-10-2018	6.39	0.191	0.625	0.332	10.609	0.751	33.968
02-11-2018	16.01	0.021	4.500	0.106	25.009	0.121	30.539
11-11-2018	6.34	0.101	3.750	0.202	29.920	0.251	68.714

i = rainfall intensity; R = runoff coefficient; A = soil loss

3.2.4 Effect of land cover on soil loss and runoff coefficient

Among all the three plots (figure5 and figure6), there is variation in soil loss as well as runoff coefficients due to several responsible factors. The results of table1 show that the soil loss and runoff coefficient were very high as observed from BS plot followed by Plot MF and Plot MFM. The reason for a such difference is that all plots are covered differently because the Plot MFM is fully covered, Plot MF medium covered and Plot BS is bare soil which is fully exposed to rainfall. Consequently, the fully exposed Plot BS caused the largest runoff coefficient (0.751) compared to the biggest runoff coefficients of 0.486 and 0.201 in MF and in MFM plots respectively. The largest runoff coefficient observed in BS plot was associated with largest soil loss of 93.067 gr/m^2/hr compared to the observed largest soil loss of 66.249 gr/m^2/hr and 8.318 gr/m^2/hr from MF and MFM plots respectively.

Due to complete surface protection, water samples collected from MFM plot were fairly clean while the collected runoff from BS plot was very high turbid due to the excessive soil loss. Influenced by the rain drop impact, the runoff received in the collection tank was raised for the exposed soil surface in BS plot. The closely spaced maize coverings reduced the flow velocity and consequently the soil detachment and the amount of suspended sediments in the downstream runoff collection tank were also reduced. When exposed on the same rainfall intensity, the responses from the 3 plots showed similar variability in the following order:

$R_{MFM} < R_{MF} < R_{BS}$ and $A_{MFM} < A_{MF} < A_{BS}$.

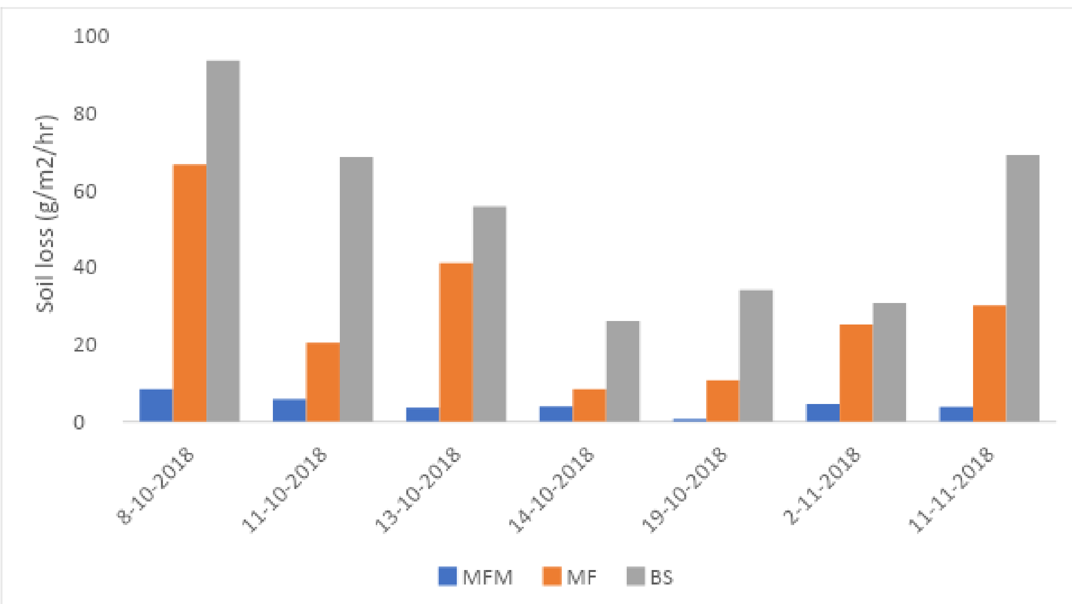

Figure 5. Effect of land cover on soil loss

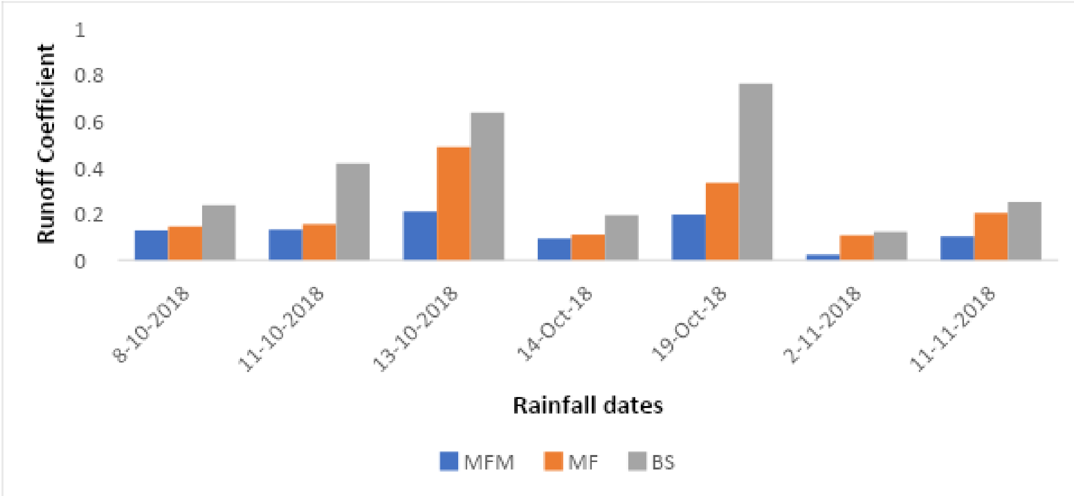

Figure 6. Effect of land cover on runoff coefficient

3.2.5 Development of rills and interrills in the experimental field

After each rainfall event, the routine observations revealed that rills were developed in the experimental plots. Firstly, interrills were formed as shown in figure8. Generally, rills are frequently observed on sloped farmlands where rill erosion significantly contributes to sediment yields. Factors like rainfall, runoff, soil type, land topography, vegetation and tillage systems influence the development of rills. Rill erosion is usually identified as a series of little channels or rills up to 30 cm deep (Cerdan et al., 2002). The loss of the topsoil and nutrients caused by rill erosion will reduce soil productivity while river sedimentation and water-quality deterioration are the main offsite effects of soil erosion. Concentrated flow in rills is one of the main sources of energy for soil detachment (Bradford et al., 1987; Govers et al., 2007).

Figure 7. Development of interrills and rills in BS plot

3.2.6 Effect of rainfall intensity on soil erodibility

Soil erodibility (K) is one of the factors in the Universal Soil Loss Equation (USLE) that refers to the resistance of soil to its detachment by rainfall impact and the force of surface flow. Soil erodibility factor (K) was found to strongly correlate with soil loss (Manyiwa & Dikinya, 2013). In this study, the effect of rainfall intensity on soil erodibility was highlighted by exhibiting the relationship between rainfall intensities and corresponding soil losses from different plots. For all 3 plots, the figures 8, 9 and 10 revealed that the soil loss increase is not in linear relationship with the increase of rainfall intensity because weathering actions have changed the exposed soil type and the antecedent soil moisture conditions prior to the rainfall event. For the same conditions of soil type and rainfall events, high intensity storms increase soil erosion and sediment transport (Mohamadi & Kavian, 2015).

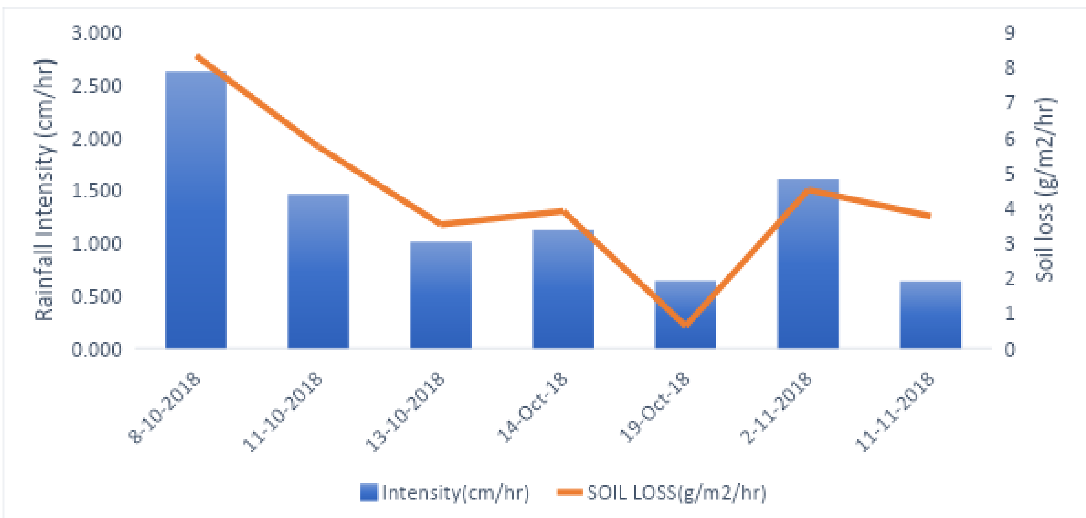

Figure 8. Rainfall fluctuations and variability of soil loss from MFM Plot

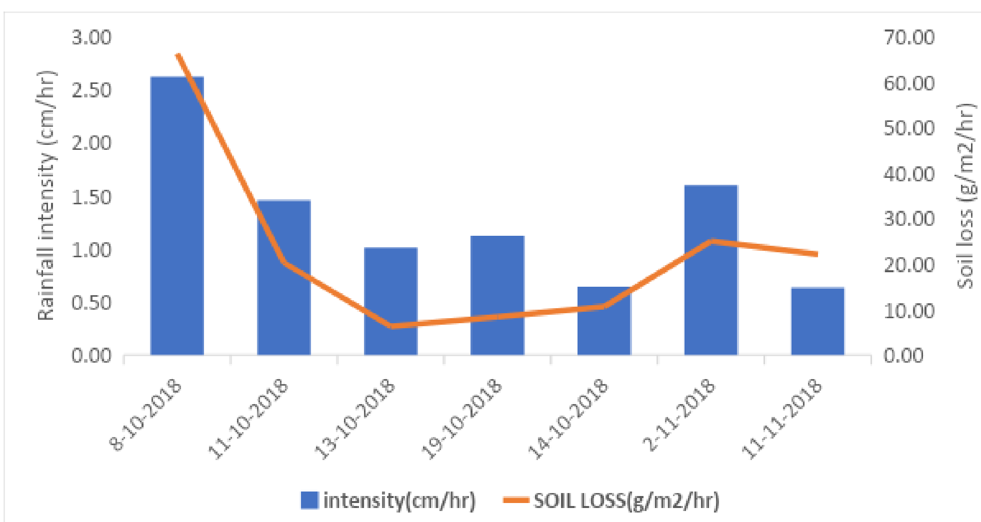

Figure 9. Rainfall fluctuations and variability of soil loss from MF Plot

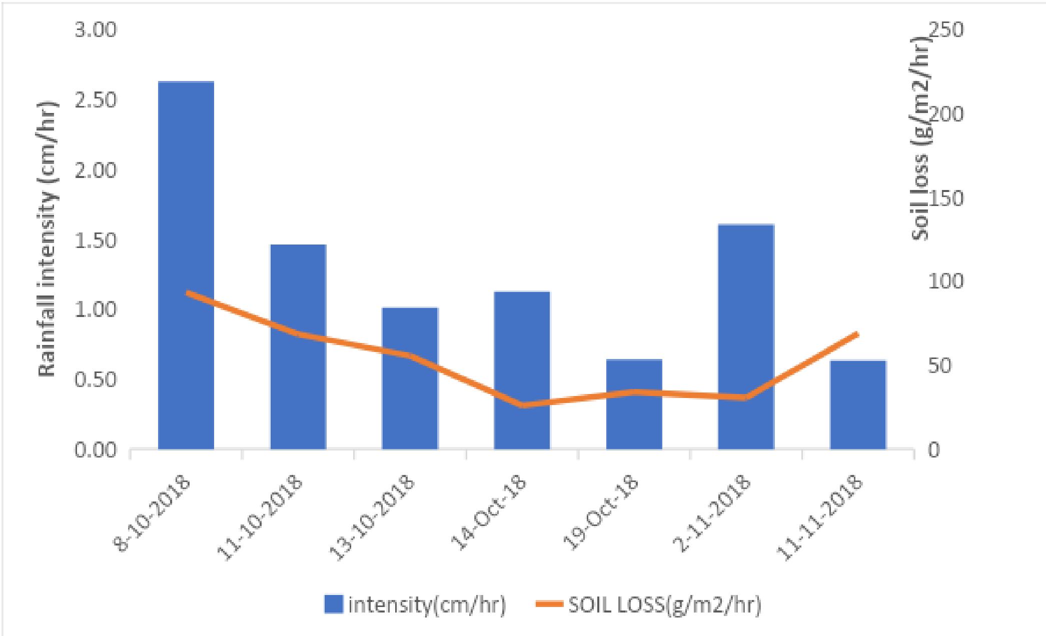

Figure 10. Rainfall fluctuations and variability of soil loss from BS Plot

3.2.7 Effect of rainfall on soil crusting

Land cover and topography, soil type, antecedent soil moisture conditions, rainfall duration and rainfall intensity are major factors affecting runoff coefficient. For all 3 plots, figures 11, 12 and 13 revealed that the runoff coefficient increase is not in linear relationship with the increase of rainfall intensity. For agricultural fields exposed on similar conditions, the runoff coefficient increases with the increase of rainfall intensity (Wenbin et al., 2015). The research carried out by (Bissonnais et al., 2004) stated that runoff coefficients increase with increasing crust development and decrease with vegetation cover development. Under the same rainfall intensities, the present study found that the decrease in runoff coefficient was depending on ground cover from BS plot which was fully exposed to MFM plot which was fully covered. The research conducted by (Mbwana, 2004) states that the repeated soil disturbance arising from tillage and weeding operations triggers runoff coefficients and soil loss. The higher values of runoff coefficients recorded in the bare soil were attributed to lack of protective cover and the degree of crusting.

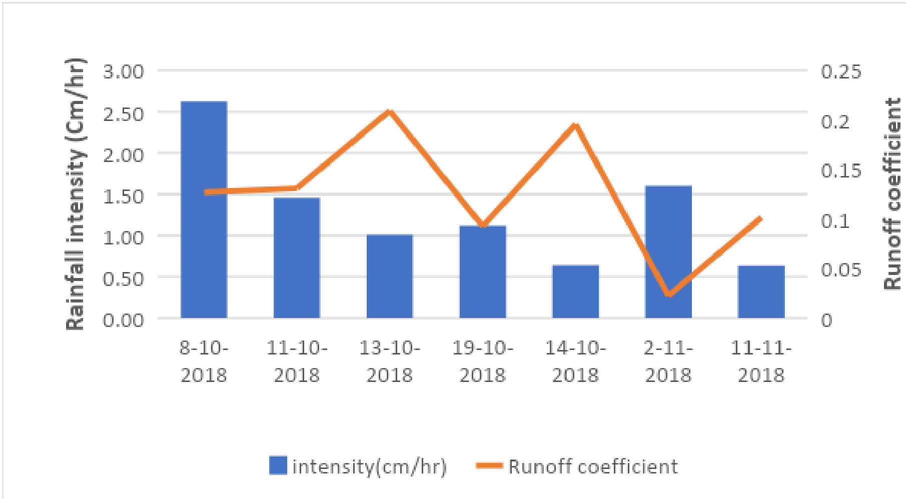

Figure 11. Rainfall fluctuations and variability of runoff coefficients for MFM Plot

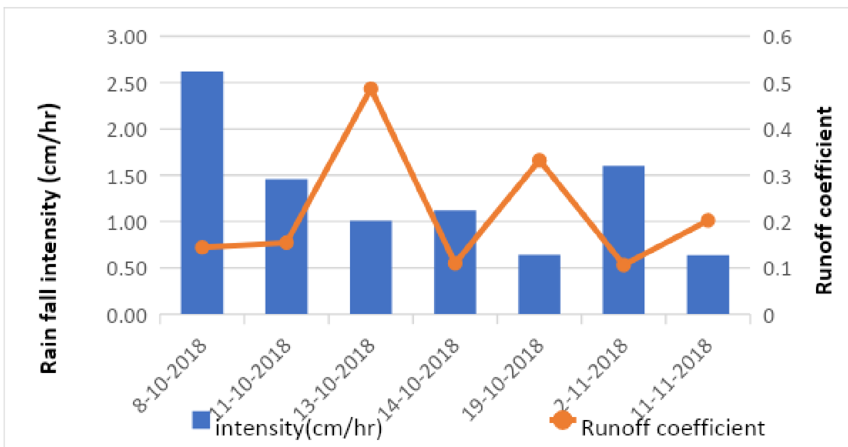

Figure 12. Rainfall fluctuations and variability of runoff coefficients for MF Plot

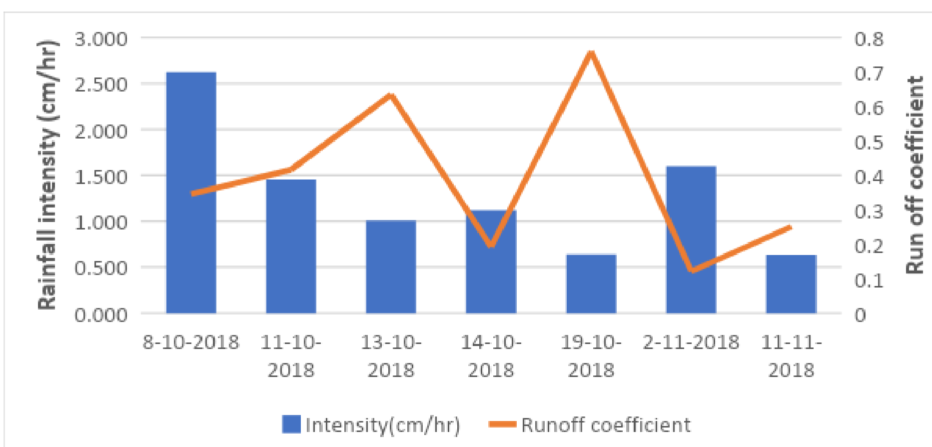

Figure 13. Rainfall fluctuations and variability of runoff coefficients for BS Plot

3.3 Benefits from Investigations in Erosion Plots to The Farmers in Sebeya Catchment

Often, laboratory and field plots are used to obtain experimental data for predicting and evaluating soil erosion and sediment yield.
In this study, field experimentations in erosion plots have been conducted for getting data that can illustrate the knowledge on various techniques used for soil conservation. Field demonstrations have regularly done to local farmers and to other visitors while exhibiting the benefits of soil and water conservation measures in reducing soil loss. Throughout the growing phases of maize crop, various erosion processes (interrills and rills development, soil surface crusting and development of runoff and soil loss) have been observed and evaluated for different scenarios of land cover. As a final result of this paper, farmers should be aware that erosion is much less from a plot which has a good vegetative cover than from a bare plot.

4. CONCLUSION AND RECOMMENDATIONS

The present study aimed to assess various preventive measures against soil surface crusting and development of runoff coefficients in order to minimize the soil loss. Field experimentations in erosion plots have been conducted for getting data that can illustrate the knowledge on various techniques used for soil conservation. When exposed on the same rainfall intensity, the responses from the 3 plots showed similar variability in the following order: $R_{MFM} < R_{MF} < R_{BS}$ and $A_{MFM} < A_{MF} < A_{BS}$. The largest runoff coefficient (0.751) observed in BS plot was associated with largest soil loss of 93.067 gr/m^2/hr compared to the observed largest soil loss of 66.249 gr/m^2/hr and 8.318 gr/m^2/hr from MF and MFM plots respectively. Soil erosion was much less from a plot which has a good vegetative cover than from a bare plot. This means that vegetative cover and mulching have high performance in soil loss reduction. This research highly recommends to combine the cropping techniques with mulching and application of fertilizers in order to improve the soil stability while preventing runoff and soil loss.

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