EFFECT OF POTATO (*Solanum tuberosum* L.) CROPPING SYSTEMS ON SOIL AND NUTRIENT LOSSES THROUGH RUNOFF IN A HUMIC NITISOL

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DECLARATION

This thesis is my original work and has not been presented for award of a degree in any other university.

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DEDICATION

To the humble, courageous soil and water conservationists

to which this work is an inspiration

and

To my mother Teresa Akongó and Father Charles Nyawade

for the humble beginnings

and

To the University of Nairobi, Faculty of Agriculture

for the tutelage and mentorship.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA:	Analysis of Variance
CEC:	Cation Exchange Capacity
CIP:	International Potato Center
EARO:	Ethiopian Agricultural Research Organization
ER:	Enrichment Ratio
GLM:	General Linear Model
KMD:	Kenya Meteorological Department
LR:	Long Rains
MOC:	Mineral Organic Carbon
OC:	Organic Carbon
PN:	Particulate Nitrogen
POC:	Particulate Organic Carbon
PVC:	Polyvynyl Chloride
SOC:	Soil Organic Carbon
SOM:	Soil Organic Matter
SPSS:	Statistical Packages for Social Sciences
SR:	Short Rains
SSR:	Soil Surface Roughness
STATA:	Statistics and Data Software
TN:	Total Nitrogen
UNDP:	United Nations Development Program
WAP:	Weeks After Planting

ABSTRACT

A field study was carried out using runoff plots during the short and long rainy seasons of 2014 and 2015 respectively at the Field Station of Upper Kabete Campus, University of Nairobi. The objectives of the study were to assess the effect of soil surface roughness and potato cropping systems on soil loss and runoff, to determine the effect of erosion on nutrient enrichment ratio and to evaluate the SOM fraction most susceptible to soil erosion. The treatments comprised of Bare Soil (T1); Potato + Garden Pea (*Pisum sativa*) (T2); Potato + Climbing Bean (*Phaseolus vulgaris*) (T3); Potato + Dolichos (*Lablab purpureus*) (T4) and Sole Potato (*Solanum tuberosum L.*) (T5). Soil loss and runoff recorded in each event differed significantly between treatments ($p<0.05$) and were consistently highest in T1 and lowest in T4. Mean cumulative soil loss from T5, T2, T3 and T4 was 39.2, 31.8, 23.5 and 11.0% respectively compared to bare plots, suggesting that T4 plots provided the most effective cover in reducing soil loss. Intercropping potatoes with cover crops reduced runoff by 22-72% when compared with the sole potato, and by 55 to 84% when compared with the bare plots. Regression analyses revealed that both runoff and soil loss related significantly with surface roughness and percent cover (R^2=0.83 and 0.73 respectively, $p<0.05$). Statistically significant linear dependence of runoff and soil loss on surface roughness and crop cover was found in T4 ($p<0.05$) indicating that this system was highly effective in minimizing soil loss and runoff. Enrichment ratio was on average greater than unity for all soil elements analyzed indicating that the erosion process was selective. The correlation coefficients between enrichment ratio of clay and soil nutrients showed strong associations, the highest being with P (r=0.88) and the lowest with K (r=0.75), suggesting that clay particles better account for nutrient losses. Concentrations of SOM in the eroded sediment were higher in the stable fraction, MOC (18.43-19.30 g kg^{-1}), MN (1.67-1.93 g kg^{-1}) than in the labile fraction, POC (7.72-9.39 g kg^{-1}), PN (0.62-0.84 g kg^{-1}) indicating that much of the eroded SOM was in stable form. The highest decline in SOM contents occurred in stable fractions in which MOC reduced by 6.2 to 22% while MN reduced by 6.1 to 21%.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background Information

Soil erosion is the greatest deteriorating factor of soil productivity because of its influence on soil nutrients and properties. The process causes soil loss at a rate of 75 billion tons per year from the world agricultural systems (Quinton *et al*., 2001; Pimentel and Burgess, 2013). These losses mainly occur within the tropics where terrain is sloppy and effective erosion control measures have not been adopted (Nelson *et al.*, 2015). Rwanda alone loses 1.4 million tons of soil per year to erosion (Global soil forum, 2013) while Ethiopian Highlands lose over 1.5 billion tons of topsoil per year (Safene *et al.*, 2006). In South Africa, over 70% of the nation's land surface has been impacted by varying levels and types of soil erosion **(**Ikponmwosa, 2013), while loses in Kenya occur at an average rate of 1.5 billion tons per year (UNDP, 2001).

Soil erosion process is selective, resulting into the finer lighter and more fertile materials being carried away (Lal, 2006). For most of the soils, the enrichment ratio (ER) of the eroded nutrients is greater than unity (Polvykov and Lal, 2004). The ER is particularly high for P, SOC and N due to their strong association with clay which is preferentially mobilized in the eroded sediment (Six *et al.*, 2002; Quinton *et al.*, 2003). Potassium is also highly enriched in the eroded sediment, but losses are more pronounced in the runoff due to its high solubility and mobility (Lal, 2003). The enrichment ratio for SOM however depends on the fraction which is highly mobilized during erosion process. If erosion affects mainly the stable fraction, the enrichment ratio is expected to be high because this fraction has large reservoir in the soil (Wang *et al.*, 2013). Limited research has however been conducted to determine these relationships (Martinez-Mena *et al*., 2008; Cheng *et al*., 2013).

Report by Krishna *et al*., (2009) indicated that approximately 5.5 million tons per year of SOM, N, P and K are lost in the Northern Mountain area of India, while about 40 million tons per year of the same nutrients are lost in China. Similar results have been reported in Nepal where an estimated 1.3 million tons of plant nutrients are displaced annually (MOPE, 2004). The losses of these nutrients are estimated to be at rates of 270 million tons per year in Africa and 1.1milion tons per year in Kenya (UNDP, 2001).

Soil erosion also affects other soil properties which in turn may influence crop production. The process lowers the soil hydraulic conductivity and available soil moisture thus affecting crop growth and development (Duiker, 2014). Clay content of the topsoil normally tends to increase with increasing erosion and this lowers the available water for the crop since clay has high water retention capacity (Mokma and Sietz, 1992). Deterioration of soil structure by soil erosion also leaves a dense crust on the soil surface which in turn greatly reduces water infiltration and increases runoff (Kuhn, 2010). Soil pH of the eroded soil also decreases after successive soil erosion due to high losses of exchangeable bases and this may affect nutrient availability to plants (Gachene *et al.,* 1997). These impacts have in general caused an average annual crop yield decline of 15.2% globally, 8.2% in Africa and 6.2% in Sub-Saharan Africa. These losses are projected to increase to 16.5% and 14.5% for Africa and Sub-Saharan Africa respectively if soil erosion rates continue unabated (Faeth *et al.*, 1994; Pimentel and Burgess, 2013).

In Kenya, soil erosion is a major problem in the highland regions and this has been mainly attributed to intensive cultivation on the rolling topography without adequate soil conservation measures (Tongi and Mochoge, 1993; Gachene *et al.*, 1997). In addition, most farmers tend to raise row crops such as maize, potatoes and beans which provide inadequate vegetation cover, thus leaves most of the tilled soil surface bare and highly susceptible to soil erosion (Stone and Moore, 1997). Some of these crops also retain very little residues and leave the soil exposed to erosion after harvest. Ochuodho *et al.,* (2009) recorded cumulative soil loss of 98 t ha^{-1}under pure cassava cropping systems in Kisii highlands. These losses were attributed mainly to the low surface mulch retained after cassava was harvested and to the up and down slope cultivations. Studies conducted elsewhere in Kenya have shown consistent results (Tongi and Mochoge, 1993; Gachene and Haru, 1997; Khisa *et al.,* 2002), and have pointed out the need to include legume cover crops into various cropping systems to reduce erosion.

Another potential cause of soil erosion that has received little attention in Kenya is the influence of surface roughness under potato cropping systems. This is in accordance with the previous studies that have shown that potato hilling may concentrate surface runoff flow and accelerate soil loss (Chow and Rees, 1994; Xing *et al.*, 2011). Hilling also makes the soil loose and more prone to detachment by soil erosion (Bohl *et al.,* 2005). Surface roughness resulting from potato hilling may also enhance seal formation and enhance runoff generation (Folley *et al.*, 2007).

1.2 Problem Statement

Potato is a major staple and cash crop grown in Kenyan Highlands and covers 60% of the total agricultural lands in these areas (Ng'anga' *et al.,* 2014). Cultivation of this crop is extensively done in pure stands with only about 5.5% of the farmers intercropping it with maize or beans (Muthoni *et al.*, 2003). This is despite the fact that potato cultivation involves disturbance of soil during the growth cycle which makes the soil loose and more prone to erosion (Bryan *et al*., 2004). Potato also delays to establish protective cover after planting and does not yield sufficient surface mulch upon harvest which leaves the soil bare at the critical times when rainfall intensities are usually high and exposes soil to erosion (Chow and Rees, 1994). Soil loss in the potato growing regions of Kenya is therefore high, averaging about 60 t $ha^{-1}yr^{-1}$ (Murugi, 2012).

Some researchers have attributed the high soil loss to potato hilling which changes the soil surface roughness thereby concentrating the runoff flow (Römkens *et al.*, 2002; Longshan *et al*., 2014). Others have argued that soil surface roughness may have little impact on runoff and soil loss (Helming *et al.,* 1998; Darboux and Huang, 2005). These studies did not take into considerations crop cover that may interact with soil surface roughness to influence runoff and soil loss.

These losses are often accompanied by removal of soil nutrients which are highly concentrated on the soil surface (Bryan *et al.,* 2004). In particular, very high values of the enrichment ratio (ER) for P, ranging between 1.1 and 10 have been recorded in Kenyan Highlands (Gachene *et al.,* 1998; Khisa *et al*., 2002). Other nutrients such as OC, K, Ca, CEC, Mg and N have in general recorded ER greater than unity (Tongi, 1990; Zobisch *et al.*, 1994).

The enrichments of these elements have nevertheless received little attention under potato cropping systems in Kenya.

There has also been an attempt to partition the eroded SOM into stable and labile fractions so as to better understand the role of soil erosion in carbon cycling. Some studies have demonstrated that in comparison to the source soil, the eroded sediments are in general much more strongly enriched in labile SOM (Jacinthe *et al*., 2004; Wang *et al*., 2014). On the contrary, others have shown that the high SOM enrichment is not primarily due to the mobilization of labile SOM, but rather to the stable SOM (Martinez-Mena *et al.*, 2008; Berhe, 2012; Cheng' *et al*., 2013). More studies are therefore needed to better understand these relationships.

1.3 Justification

Quantification of runoff and soil loss under potato cropping systems would generate data required for identification of ecologically sustainable potato production. Determination of potato cropping system that minimizes nutrient losses due to erosion would increase nutrient use efficiency and reduce the fertilizer expenses. Understanding the composition of eroded SOM is essential for development of stable soil resource due to proper organic matter management.

1.4 Objectives

1.4.1 Overall objective

To identify a potato (*Solanum tuberosum* L.) cropping system that will minimize soil erosion and ensure sustainable soil productivity.

1.4.2 Specific Objectives

i. To assess the effect of soil surface roughness and crop cover on soil loss and runoff under different potato cropping systems.
ii. To evaluate the effect of potato cropping systems on nutrient enrichment ratio due to erosion in a humic nitisol.
iii. To determine soil organic matter fraction most susceptible to soil erosion under different potato cropping systems.

1.5 Hypotheses

i. Soil surface roughness and crop cover have no influence on soil loss and runoff under potato cropping systems.
ii. Potato cropping systems have no influence on nutrient enrichments.
iii. The labile soil organic matter fraction is not prone to soil erosion.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Soil Erosion and Runoff Processes

Soil erosion by water is a three stage process involving detachment, transport and deposition (Muller-Nedelock and Chaplot, 2012). Detachment involves the displacement of either entire soil aggregates or only parts thereof, mainly by the rainfall splash (Jacinthe and Lal, 2001). Transport involves the translocation of the detached particles as a result of the increased energy of the runoff water. Deposition occurs when the runoff water loses its kinetic energy as a result of an impediment or due to increased infiltration (Lal, 2001). These processes have the potential to export soil nutrients either through the detachment and transport of entire aggregates or by preferential nutrient removal subsequent to aggregate breakdown (Muller-Nedelock and Chaplot, 2012).

Runoff is generated due to infiltration excess or saturation excess (Jayawardena and Rezaur, 2000). Infiltration excess occurs when rainfall intensities exceed the rate at which water can infiltrate into the soil, while saturation excess occurs when rainfall encounters soils that are nearly saturated or fully saturated (Singh, 2009). Saturation excess is considered main mechanism for runoff in areas having humid climate coupled with thick vegetation and permeable soils (Steenhuis *et al.*, 1995).

A certain amount of rainfall is always required before any runoff occurs. This amount is referred to as threshold rainfall and represents the initial losses due to interception and depression storage (Jayawardena and Rezaur, 2000). In areas with only sparse vegetation and where the soil surface is smooth, the threshold raindrop may be only in the range of 3 mm, while in other areas this value can easily exceed 12 mm, particularly where the prevailing soils have a high infiltration capacity (Singh, 2009). The fact that the threshold rainfall has to be surpassed explains why not every rainstorm produces runoff.

Runoff can transport nutrients from the field both in solution and sediment forms, reducing the amounts of nutrients available to support crop production (Djik *et al*., 2002). Nutrient-enriched runoff also contributes to accelerated eutrophication of surface water bodies which can decrease water quality (Dexter and Niedźwiecki, 2004).

2.2 Role of Cover Crops on Runoff and Soil Loss

The effectiveness of a cover crop in reducing soil erosion depends upon the height, continuity and the density of the canopy formed (Morgan, 1995). Shorter plants generally provide better protection than the taller and erect plants due to their higher rainfall interception (Neil, 2012). The provided cover protects the soil from erosion by intercepting raindrop and absorbing their kinetic energy (Karuma *et al*., 2011). Cover crops left as surface mulch and those left growing during offseason confer protection to the soil at the onset of the following seasons when soil is bare (Gachene *et al*., 1997b; Gachene and Haru, 1997; Khisa *et al.,* 2002). The effectiveness of cover crops in controlling soil erosion is attained when a critical threshold of 40% is reached (Mati, 1992; Kironchi, 1998; Khisa *et al.,* 2002).

Indirectly, the SOM and enhanced microbial activity associated with cover crops may over time, increase soil aggregation and water infiltration rates (Dapaah and Vyn, 1998), thus allowing water to move into, rather than on the soil surface. The roots also store and recycle water and mineral elements within a plant hence reducing nutrient loss and further soil degradation (Kironchi and Mbuvi, 1996). Cover crops such as lupins may also be of great importance in soils prone to P fixation as these crops have high P absorption rates and avail it to the subsequent crops upon decomposition (Allison *et al.*, 1997). This in turn may help improve P fertilizer acquisition efficiency and reduce the P loading of any eroded soil. Subsequent crops may in addition benefit from some of the nitrogen fixed by the cover crop.

Murugi, (2012) recorded soil loss amounting to 80 t ha^{-1} under bare plots and 15 t ha^{-1} in plots with beans in a study conducted in Central Kenya Highlands. They attributed the reduction in soil loss to the cover provided by the beans which intercepted the rainfall, spreading it over larger area. Similar results were recorded by Muli and Mwala, (2013) in an experiment conducted under maize-legume intercropping system. Plots with maize and climbing beans reduced soil loss by 10 to 22 times when compared with the bare plots. They attributed this to surface mulch retained by the cover crops and to the roots that directly held the soil firm and reduced their susceptibility to erosion.

Concentration of water at leaf drip points can however result in very high localized rainfall intensities that can exceed infiltration capacities and play a role in runoff generation (Neil, 2012). Stem flows may also concentrate rainfall at ground surface and generate runoff (Mwangi *et al.*, 2015). Some of these crops may also compete with food crops for nutrients, space and light. The most economical cover crops should thus be introduced into the cropping systems in ways that reduce these competitions (Thurtson, 1997).

2.3 Soil Surface Roughness and its influence on Soil Loss and Runoff

Evolution of soil surface roughness (SSR) in time is influenced by the volume and intensity of rainfall, by runoff and soil type (Panachuki *et al.*, 2010; Rosa *et al.*, 2012). Soil surface roughness generally decreases with the increase in volume and intensity of rainfall (Bertol *et al.*, 2006). Due to its unique position, SSR potentially affects surface processes such as infiltration, flow routing, erosion and sedimentation (Darboux *et al.*, 2001). A typical rationale for the SSR effect is from the trapping of water and sediment because rougher surfaces contain many depressions and barriers (Vermang *et al.,* 2010). These features decrease the flow velocity, hence decreasing the flow detachment power and transport capacity. Rougher surfaces also seal less rapidly and tend to have a higher infiltration rate (Longshan *et al*., 2014).

Some researchers have however demonstrated that SSR may trigger soil loss and runoff. Gómez and Nearing, (2005) reported that there were only slight differences in the total runoff and sediment yields between a smooth slope and a rougher slope. Darboux and Huang, (2005) similarly showed that after runoff initiation, a rougher surface might not have the distinctly higher infiltration and may intensify soil erosion. Helming *et al*., (1998) also reported that soil roughness can either converge or diverge flow on the surface and may cause a localized increase in erosion. Surface depressions that trap sediment and surface mounds that increase flow meandering may also lead to a reduced sediment delivery (Góvers *et al.*, 2000; Römkens *et al.*, 2002). Some authors have also demonstrated that SSR may concentrate the surface runoff flow and generate rill network which may accelerate soil erosion (Darboux *et al.,* 2005; Longshan *et al.,* 2014).

Roughness induced by potato hilling has also been found to induce soil loss and runoff because the side slopes of potato hills could change the rate of soil infiltration and the time to initiate runoff (Chow and Rees, 1994; Bohl *et al.*, 2005). The concentrated runoff in the furrow between adjacent row ridges increases transport capacity and carries part or all of the sediment delivered from the row-side slopes. For a long continuous furrow under sloping conditions, the concentrated flow may scour additional sediment from the furrow by rill erosion (Xing *et al.*, 2011). Some researchers have therefore reached a conclusion that the only benefit derived from

SSR is the delay in runoff rather than the decrease of soil erosion amount (Huang and Darboux, 2006; Longshan *et al*., 2014).

2.4 Nutrient Enrichment Ratio due to Erosion

An enrichment ratio (ER) refers to the ratio between concentrations of nutrients in sediment to those in source soil (Tesfahunegn and Vlek, 2014), and is often used as an index of soil productivity (Haregeweyn *et al.,* 2008). Enrichment ratio greater than 1 indicates that soil erosion process is selective and removes mainly the fine particles highly enriched in soil nutrients (Lal and Polyakov, 2004). Higher ER in agricultural systems is mainly attributed to the erosion of inorganic fertilizers, especially if erosion occurs before the nutrients are utilized by crops. Of most importance are the phosphorus, nitrogen and SOM enrichments as these nutrients are highly concentrated on the soil surface, leading to their high susceptibility to soil erosion (Cai *et al.*, 2002). Enrichment ratios ranging between 1 and 6.2 have been recorded for SOM (Lal and Polykov, 2004) while ER higher than 10 has been observed in P (Gachene *et al.*, 1998). Other nutrients such as CEC, N, K, Na, and Mg have recorded ER ranging between 1 and 3 (Gachene *et al.*, 1998; Khisa *et al.*, 2002; Våje *et al.*, 2008).

The mechanism of enrichment is explained by the fact that rainfall slakes and peels the soil aggregates exposing their outer layers which have higher concentration of nutrients compared with the inner core (Ghadiri and Rose, 1991). When water erosion removes entire soil aggregates, the content of nutrients in the eroded sediment is equal to the content of the bulk soil of the topsoil layer, resulting in an ER of 1. Conversely, the breakdown of soil aggregates induces selective erosion with either enrichment or a depletion of sediments in nutrients as compared to the bulk soil resulting in ER above or below 1, respectively (Polyakov and Lal, 2004).

2.5 Soil Organic Matter Fractions

Partitioning SOM into functional fractions is important to better understand its dynamics and roles in ecosystems (Camberdella and Elliot, 1992). Once the fractions are accurately quantified, they are more likely to show differences in susceptibility to land management strategies aimed at conserving plant nutrients and desirable physical properties (Woomer *et al.*, 1994). Such differences cannot be detected in whole SOM. Physical fractionation procedures based on differential densities and sizes have been used to separate coarse fractions from fine fractions (Kader, 2010). The fractions ranging between 53-250µ may provide an accurate estimate of the labile SOM while those finer than 53µ may provide an accurate estimate of the stable pool (Camberdella and Elliot, 1992). Particle size fractionation is based on the concept that SOM fractions associated with particles of different sizes differ in structure and functions and therefore play different roles in SOM turnover (Christensen, 1992).

Each SOM fraction plays a particular role in nutrient release, CEC and soil aggregation (Cheng *et al.*, 2013). Fractions with a rapid turnover rate are assumed to have an important role in nitrogen availability because SOM dynamics and N cycling are closely linked through the processes of N mineralization and immobilization (Berhe, 2012). Fractions with a slow rate of turnover play an important role in cation exchange reactions in sandy soils and are important in soil aggregation (Kader, 2010).

The various SOM fractions are given in Table 1.0.

Table 1.0: Estimated ranges in the amount and turnover times of SOM fractions

Organic Matter Fractions	Proportion of whole SOM (%)	Turn over time (yr)
Litter	-	1-3
Unprotected SOM		
Microbial biomass	2-5	0.1-0.4
Free Particulate POM	18-40	5-20
Light fraction	10-30	1-15
Inter-microaggregate POM	20-35	5-50
Intra-microaggregate POM	5-40	20-50
Silt and clay sized SOM-Stable fraction	50-90	1000-3000

Source: Sleutel, (2005)

2.5.1 Litter

Though many studies exclude litter in SOM definitions, fresh plant residues are considered as the litter fraction and can be an important component of the labile SOM (Paustian *et al*., 1997). Litter quality is equated with the rate at which organic substrates are decomposed and protected against soil erosion (Kader, 2010).

2.5.2 The Microbial Biomass

This fraction comprises of the soil biota and is actively involved in the transformation of organic residues in the soil, and in the dynamics of N, P and S (Dalal *et al.*, 1991). It gives a quick indication of soil biological status in terms of soil fertility (Elliot *et al*., 1996). It also plays a vital role in soil aggregation and therefore important in soil protection against erosion (Six *et al.*, 2002). The fraction is estimated by fumigation extraction and can give a good general measure of active SOM if the C recovered from control soils is not subtracted from treatment soils (Franzluebbers *et al*., 1992).

2.5.3 The Labile Soil Organic Matter

This fraction has particle sizes ranging between 53-250µ and includes the SOM components within the soil inter and intra microaggregates (Six *et al.,* 2002). It can account for 15-40% of the SOM in surface horizons in soils with permanent vegetation, and can be very low (<10%) in long cultivated arable soils (Six *et al.,* 1998). It is recovered by density and size fractionation procedures or combinations thereof (Gregorich and Janzen, 1996).

The fraction consists of the mineral-free SOM composed of partly decomposed plant and animal residues which turn over rapidly and have a specific density that is comparatively lower than that of soil minerals (Alvarez and Alvarez, 2000). It is highly decomposable and is greatly depleted by cultivation (Solomon *et al*., 2000). Often, the decrease accounts for a major part of the initial loss of SOM in the soil when it is first cultivated. In experiments carried out in a Kenyan humic nitisols after a period of 18 years, Murage *et al.*, (2001) and Kapkiyai *et al.*, (1999) demonstrated that this fraction is most closely associated with crop productivity and is more responsive to differences in soil fertility management options.

2.5.4 Stable Soil Organic Matter Fraction (Silt and Clay sized SOM)

Clay and silt (<53 µm) together may account for over 90% of the total SOM, with clay alone generally making up over 50% of it (Christensen, 1996). This fraction is protected physically, chemically and biochemically from the microbial attack and is thus considered stable (Six *et al.,* 2002). The large surface area and charged surfaces of clay particles are responsible for different types of SOM being adsorbed to clay particles (Rabbi *et al.,* 2010). The adsorbed small molecules are unavailable to microorganisms unless they are desorbed and transported into the cell (von Lützow *et al.*, 2007). The biochemical protection occurs through humification process during which plant residues are transformed chemically, biologically and physically into more stable forms (humus) (Virto *et al*., 2010). The resultant humus is structurally different from the original materials and is not available for the microbes (Chefetz *et al*., 2002).

2.6 Effect of Soil Erosion on Soil Organic Matter

In order to understand the role of soil erosion in nutrient cycling, the eroded SOM requires to be partitioned in stable and labile fractions, not only because they are chemically different, but also because of their different behaviors with respect to geomorphic processes (Wang *et al.,* 2014). Some authors have suggested that erosion mainly affects the labile fractions due to the fact that this fraction is located mainly in the light soil aggregates which are easier to be translocated by water (Jacinthe *et al.,* 2004; Schiettecatte *et al.,* 2008; Van Hemelryck *et al.*, 2011; Wang *et al*., 2014). Other researchers have conversely demonstrated that the stable fraction is the most vulnerable to soil erosion due to its strong association with the finest soil particles which are easily mobilized in the eroded sediment (Martinez-Mena *et al.,*2008; Berhe *et al*., 2012; Cheng *et al.,*2013; Wang *et al.*, 2013).

Others have shown that the vulnerability of these fractions depends entirely on the rainfall intensity and runoff discharge rate (Cheng *et al.*, 2010; Martínez-Mena *et al.*, 2012; Chaplot and Poesen, 2012). High rainfall intensities and discharge rates are associated with transport of both the macro and micro aggregates and the release of organic matter in both forms, while low rainfall intensities and runoff discharge rates associates mainly with the transport of light labile fractions.

Soil erosion creates a new component of mineralizable organic matter that is different from the remaining more stable pool (Jankauskas *et al.*, 2007). This is because the transported SOM is no longer under the same physical and environmental conditions that allowed the organic matter to initially stabilize (Rabbi *et al*., 2010). The alteration is initiated by the peeling and slaking effect of rainfall which disrupts the aggregates and release the encapsulated SOM (Polyakov and Lal, 2004). This will enhance SOM decomposition because aggregate breakdown occurs along intra-aggregate pores which are the preferable sites of sorption for SOM as well as other chemicals (Wan and El-Swaify, 1998). Further transformations occur during transportation and deposition phases and can affect the solubility of organic matter and lower the activation energy needed for its decomposition (Berhe and Kleber, 2013). These fluctuating conditions allow the eroded SOM to be decomposed much more rapidly by the soil microbes, in anaerobic conditions to CH_4, CO_2 and N_2O and in aerobic environments to CO_2 and H_2O (Boyle, 2002). The fate of the redistributed SOM thus depends ultimately on the mechanisms of its physical and chemical protection against decomposition, its turnover rates and the conditions under which the SOM is stored in sedimentary settings (Van Hemelryck *et al.*, 2011; Berhe and Kleber, 2013).

The eroded SOM is normally deposited on the down slope resulting into higher SOM enrichment in these zones (Berhe *et al.*, 2012; Wang *et al.*, 2013). In their study, Jankauskas *et al.*, (2007) showed that SOM content decreased by 11.7, 25.3 and 49.0%, on the slightly, moderately and severely eroded slopes, respectively, compared with SOM content on adjacent flat land. Wang *et al.*, (2014) similarly reported a decrease in the SOM content of a soil by 6.0% at the eroding zone and increase by 3.9% at the depositional zone. Increase in soil erosion will therefore generally decrease the SOM content and can therefore be considered as a process that plays a major role in SOM dynamics (Fullen, 2004).

2.7 Effect of Soil Erosion on Crop Production

Soil erosion lowers crop production due mainly to its adverse effects on soil properties and nutrient losses (Mwangi *et al.*, 2015). Erosion reduces plant rooting depth, enhances soil compaction, lowers soil water storage capacity and generally reduces soil workability (Gachene *et al*., 2001). All these hinder crop function and result in yield reduction. Texeira *et al.,* (2005) demonstrated an exponential relationship between crop yield and nutrient losses from runoff and sediment. The relationship indicates that soil erosion has a larger impact in terms of yield reduction in more fertile soils than in the less fertile soils.

Erosion washes away SOC, nitrogen and phosphorus in large amounts due to their strong association with the finest soil particles (Lal, 2003; Subagyono *et al*., 2007). These elements are required in large quantities for crop growth. Soil organic matter in particular is one of the first nutrients to be removed since it has a relatively low density and is highly concentrated on the soil surface (Wang *et al.,* 2014). Loss of these nutrients results in decline in soil fertility. Erosion also reduces the CEC of a soil and affects nutrient availability to crops. Of the most importance is the effect on Ca to Mg ratio (Belay, 1992). A decrease of this ratio to a level less than 3 results in unavailability of Ca and P and this effect is especially serious in acidic soils such as nitisols which are deficient in these elements (Våje *et al.,* 2008). The removal of exchangeable bases also leaves behind the sub soil which in most cases is acidic, thereby affecting nutrient availability (Hu *et al.,* 2013). Soil movement during erosion can also spread crop diseases from soil to plant foliage and from a higher to a lower lying field (Louis *et al.,* 2011). The associated sedimentation damages the young plants and reduces the abundance and diversity of soil microorganisms due to reduction in the substrates (Semalulu *et al.,* 2014).

2.7 Effect of Cropping Systems on Soil Erosion

Soil and water conservation measures are required to reduce rates of soil losses to tolerable values as well as to conserve soil fertility and improve crop production. One of the most affordable means to meet this demand is to identify effective and sustainable cropping systems that can reduce soil erosion (Safene *et al.*, 2006). In general, intercropping systems have been demonstrated to reduce soil loss and runoff when compared to sole cropping systems as this system provides adequate cover density (Zobisch *et al.,* 1994). Chamberlain, (1990) indicated that dense vegetation under strip intercropping slowed runoff and trapped moving soil particles. Wall *et al*., (2013) also showed that soil loss was significantly lower under corn intercropped with clover compared to corn as sole crop. Hays, (2015) also recorded soil loss reduction by 50% when cassava was intercropped with alfalfa compared to cassava as a single crop, while Zougmore *et al.,* (2000) observed that intercropping sorghum with cowpeas effectively reduced water runoff and soil erosion.

Other studies have correlated crop yields with soil loss under different cropping systems and have revealed an inverse relationship. Adekalu *et al.,* (2006) showed that vetch and barley yields increased by more than 50%, especially at plant density of 350 plants m^2 as compared to their sole crops planted under similar plant density. This increase in yield was generally associated with a reduction in water and soil losses. Rotational cropping systems have also been shown to reduce runoff and soil loss due to their role in SOM build-up. Mesto, (2011) demonstrated that soil loss under potato cropping systems decreased by 35% after a 6 year rotational cycle, an observation attributed mainly to increase in SOM.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Description of the Experimental Site

The study was conducted at Upper Kabete Campus Field Station of the University of Nairobi during the short and long rains season of 2014 and 2015 respectively. Kabete lies along latitude 1° 15’ S and longitude 36° 44’ E and at an altitude of 1940 m above sea level (Sombroek *et al*., 1982). The site area falls in agro-climatic zone III and is described as Semi-humid (Sombroek *et al*., 1982). The area has a bimodal distribution of rainfall, with the long rains occurring from early March to late May and the short rains from mid-October to late December. The mean annual rainfall is 1006 mm (Gachene, 1989), with 50.7% and 27.5% of the rain occurring during the long and short rainy seasons respectively (Moges, 1989). Kabete has an estimated mean annual temperature of 17.6 ^{o}C and an estimated evapotranspiration of 1152 mm (Gachene, 1989).

The soils in Kabete are classified as humic nitisols (locally known as Kikuyu red loams) and are derived from the Nairobi trachytic lava (Gachene, 1989). These soils are very deep, well drained, dark red friable clay soils showing an ABC sequence of horizon differentiation with clear and smooth boundaries. The top soil is relatively high in organic matter content and overlies an argillic B horizon. These soils have an erodibility factor (K) of 0.04 (Barber and Thomas, 1979; Gachene, 1982).

3.2 Experimental Layout and Design

Twenty runoff plots each measuring 2.4 m wide and 5.8 m long were laid out in a randomized complete block design on a natural slope averaging 12% (Plate 1.0). The distance between one block to the other was 1.0 m, while that from one plot to the next was 0.5 m. The plots were located in between a fanya-juu terrace on the upper side of the slope and a cutoff drain on the lower end of the slope, and at right angle to the contours. The fanya-juu terrace served to intercept the runoff produced on the area above the plots and prevented it from entering the runoff plots site, while the cutoff drain disposed the runoff produced in the runoff plots site and the sediment discarded after sampling.

Plate 1.0: Plots installed at right angle to the contours and in between a terrace and a cutoff drain

The following five treatments were each replicated 4 times.

Treatment 1 (T1): Bare Soil

Treatment 2 (T2): Potato + Garden Pea (*Pisum sativa*).

Treatment 3 (T3): Potato + Climbing Bean (*Phaseolus vulgaris*)

Treatment 4 (T4): Potato + *Dolichos lablab* (*Lablab purpureus*)

Treatment 5 (T5): Sole Potato (*Solanum tuberosum L.*)

3.3 Installation of Runoff Plots

Metal borders made from strips of 18 gauge iron sheet were buried 15 cm below the ground surface and projected 20 cm above the surface (Fig. 1.0). The soil was then packed around the boundary joints to prevent leakages of runoff water. The strips were fastened together using iron rods bent to form hooks. An end plate made of 18 gauge iron sheet was used to provide a firm seal and smooth connection between the ground surface and the collecting trough.

A collecting trough made of 18 gauge iron sheet was overlapped on the end plate so as to concentrate the runoff and sediment. A conveyance 4 inches diameter PVC pipe was used to connect the collecting trough with the storage tanks, each 1.25 m^3 by volume. Each tank was covered with a metal lid to prevent direct entry of rainfall.

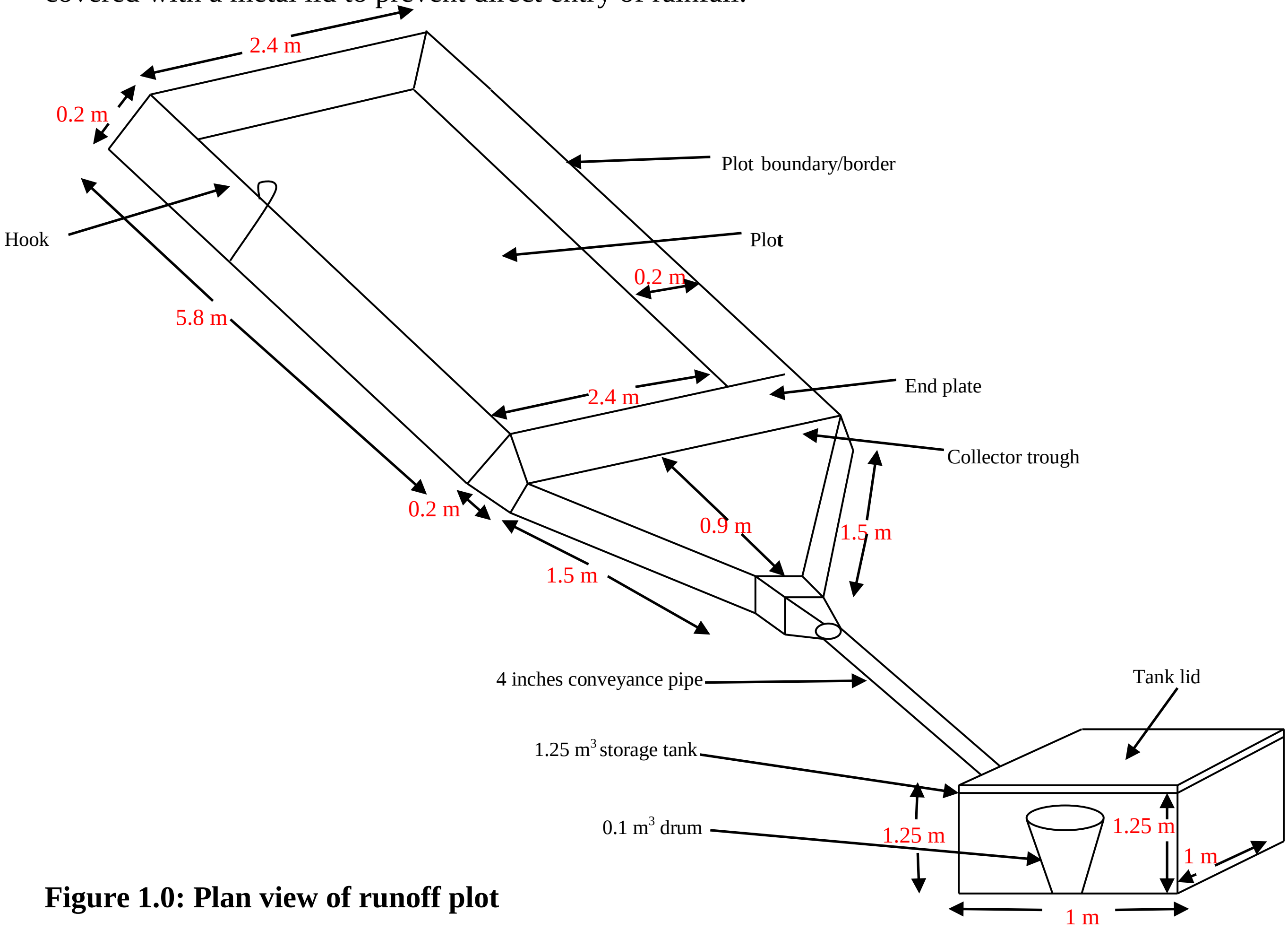

Figure 1.0: Plan view of runoff plot

3.4 Land Preparation and Planting

Potato variety Shangi was used for the experiment since it is one of the potential potato cultivars commonly grown in the highlands of Kenya. Well sprouted uniform tubers were planted at a depth of 12 cm and at a spacing of 30 cm within the rows and 90 cm between the rows. Legumes were intercropped at a spacing of 30 cm between the potato rows. In both cases, one seed was planted per hole. Phosphorus (TSP) was applied at rates of 100 kg-P/ha, Nitrogen (CAN) at 120 kg-N/ha and K (K_2O) at 150 kg-K/ha during planting.

Hilling was carried out by piling the soil around the roots of potato plants to approximately 20 cm height and 15 cm top width. This activity was done at weeding to prevent tuber greening and control potato blight disease (Chow and Rees, 1994). Other management activities such as weeding, crop diseases and pest management were done throughout the season as recommended (EARO, 2004).

3.5 Soil Sampling, Data Collection and Laboratory Analyses

3.5.1 Soil Sampling

Composite soil samples were collected from each plot using soil auger at 0–10 cm and 10-20 cm depths. The soil samples were air-dried, passed through 2mm sieve and analyzed for the soil physical and chemical properties.

3.5.2 Effect of soil surface roughness and crop cover on soil loss and runoff.

3.5.2.1 Soil Surface Roughness Measurements

A relief meter devised by Kuipers, (1957) was used. Soil surface roughness was measured after cultivation and at 2 weeks interval, except during the runoff generating events when measurements were taken to be related with soil loss and runoff.

The relief meter was placed horizontally on the soil surface and the needles were allowed to slide down until their feet freely touched the ground and then locked up in position. The height of each of the needles above the top of the frame was recorded after taking the readings on the graduated board. The needles were then pulled up, locked and the instrument moved to the next position. Measurements were replicated in 3 positions per plot and the following formula was used to calculate surface roughness:

$\text{Surface Roughness } (\%) = \text{LOG } (STDEV) \text{ X } 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$..Equation 1

Where LOG is the logarithm, STDEV is the standard deviation of the pin height measurements.

3.5.2.2 Estimating Crop Cover

Point frame method outlined by Coxson and Looney, (1986) was used. The device was placed in a specific position on the ground and the pins lowered until it first touched a plant leaf. The number of pins that touched the leaves was then recorded. Measurements were replicated 4 times per plot and the percent cover calculated by the equation given below;

$\% \text{ Cover} = \frac{\text{Number of Pins that hit a plant leaf}}{\text{Total Number of Pins}} \text{ x } 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots$..Equation 2

3.5.2.3 Recording Rainfall Data

Total rainfall amount (mm) was recorded after every rainstorm event at an agro-meteorological station located at about 200 m from the experimental site. The data was recorded against the rainfall days.

3.5.2.4 Sampling Runoff and Sediment

Runoff and sediment sampling were collected following procedures outlined by Wendelaar and Purkis, (1979). All measurements were taken in the morning following the runoff events. The end plates and collecting troughs were inspected for soil deposition prior to measurements and the deposited materials were scooped and placed in their respective tanks.

3.5.2.5 Measuring Surface Runoff

The runoff-sludge mixture was stirred thoroughly in the drum until all the sediment came into suspension. The suspension was allowed to settle for 30 minutes before the runoff water overlying the settled sludge was carefully measured using a graduated bucket. Runoff from each plot was converted into mm depth using the following equation;

$Runoff\ (mm) = \frac{\text{Total Runoff Volume } (\text{m}^3)}{\text{Plot Area } (2.40\text{m x } 5.80\text{m})} \text{ x } 1000$……………………………………Equation 3

3.5.2.6 Sediment Measurements

The settled sediment was scooped in a bucket and weighed using a spring balance suspended on a tripod to the nearest 0.05 kg. A 150 g sample of the sludge was oven-dried at 105^{o}C until a constant dry mass was attained. The total runoff weight was also carefully recorded and 100 ml sample oven-dried at 105^{o}C to a constant dry mass. Soil loss was then computed using the following equations:

Soil in the runoff (S1)

To determine the soil in the runoff, the following equation was used.

$\text{S1(g)} = \frac{\text{W1}}{\text{W2}} \text{ X Wa}$…………………………………………………………………Equation 4

Where,

S1= the total dry soil weight contained in runoff measured in the laboratory in g.

W1=the dry soil weight contained in the runoff measured in the laboratory in g.

W2=the wet weight of the runoff sample measured in the laboratory in g.

Wa= the total wet weight of the runoff measured in the field in g.

Soil in the sludge (S2)

To determine the soil in sludge (S2), the following equation was used.

$\mathrm{S2(g)} = \frac{\mathrm{W3}}{\mathrm{W4}} \mathrm{X\,Wb}$……………………………………………………………………Equation 5

Where,

S2=the total soil weight in the sediment from the drum in g.

W3=dry weight of the soil in the sediment sample in g.

W4=the wet weight of the sediment sample in g.

Wb=the total wet weight of sediment from the drum in g.

The total soil loss (S) per plot was calculated as:

$\mathrm{S(g)} = \mathrm{S1} + \mathrm{S2}$………………………………………………………………………Equation 6

3.5.3 Effect of potato cropping systems on nutrient enrichment due to erosion.

Texture was analyzed by hydrometer method as outlined by Anderson and Ingram, (1998). Soil pH was analyzed using 1:2.5 ratio of soil to water (Mehlich *et al.*, 1953), total N by the Kjeldahl, (1883) digestion method, available phosphorus and potassium by (Mehlich *et al.*, 1953), and soil organic carbon by wet oxidation method (Walkley and Black, 1934). Enrichment Ration was calculated as the ratio of nutrient element in the eroded sediment to that in the top source soil (Lal and Polyakov, 2004).

3.5.4 Evaluating the SOM fraction most susceptible to soil erosion.

3.5.4.1 Fractionation Procedure

The SOM was fractionated following procedures described by Cambardella and Elliott, (1992). Air-dried sub samples were sieved and 20 g placed in 250 ml plastic bottle. 70 ml of sodium hexametaphosphate solution was added and the mixture shaken for 15 hrs on an end to end shaker. The content was passed through a series of sieves (2 mm, 250µ and 53 µ) and the fractions collected dried at 50^{o}C for 48 hours in a forced air oven. The 53µ-2mm fraction was referred to as labile SOM. All the material that passed through the 53µ sieve was collected in a flask, swirled to mix thoroughly and a sample of 100 ml taken and oven dried. This sample was referred to as the stable SOM. The oven-dried fractions were ground using mortar and pestle to a very fine material, sieved through 0.149 mm and analyzed for SOC (Walkley and Black, 1934) and N (Kjeldahl, 1883).

3.5.5 Baseline Soil Properties of the Experimental Site

Soil characteristics of the surface horizon (0-20 cm) before the start of the experiment are given in Table 2.0. According to land evaluation specifications by Landon, (1991), the exchangeable potassium (K), clay and silt contents are high while sand content, total N, SOC and SOM fractions (MOC, POC, MN and PN) are moderate. Soil pH and available P are low.

Table 2.0: Baseline soil properties of the experimental site

Soil Property	Soil depth	
	0-10 cm	10-20 cm
pH-H_2O (1:2.5)	5.20	5.20
SOM-C (g kg^{-1})	26.20	26.12
OC %	2.62	2.57
Mineral OC (g kg^{-1})	18.10	18.10
Particulate OC (g kg^{-1})	6.71	6.67
SOM-N (g kg^{-1})	2.60	2.58
Mineral N (g kg^{-1})	1.87	1.84
Particulate N (g kg^{-1})	0.66	0.63
Total N (%)	0.26	0.24
Available P (ppm)	16.90	16.40
K (cmol kg^{-1})	1.80	1.80
Clay (%)	51.00	55.00
Silt (%)	29.20	27.40
Sand (%)	19.80	17.60

3.6 Data Management and Statistical Analyses

The data was entered into excel spreadsheet and summary statistics calculated. Data on the effect of cropping systems on soil loss, runoff and SOM was subjected to ANOVA using Genstat 15th version. The statistical significance was determined at $P \leq 0.05$, while means were separated using the Fischer's least significant difference (LSD) test. Regression and correlation analyses were conducted to establish the relationship between nutrient enrichments and soil loss and between soil texture and selected soil parameters using SPSS 20th volume. Paired t-test and General Linear Model (GLM) analyses were performed using STATA version 20 to determine the interactive impacts of soil surface roughness and crop cover on soil loss and runoff.

CHAPTER FOUR

4.0 RESULTS AND DISCUSSIONS

4.1 Rainfall Distribution

The 2014 short rains were unevenly distributed and were on average lower than the 20 years long term average (Fig. 2.0).

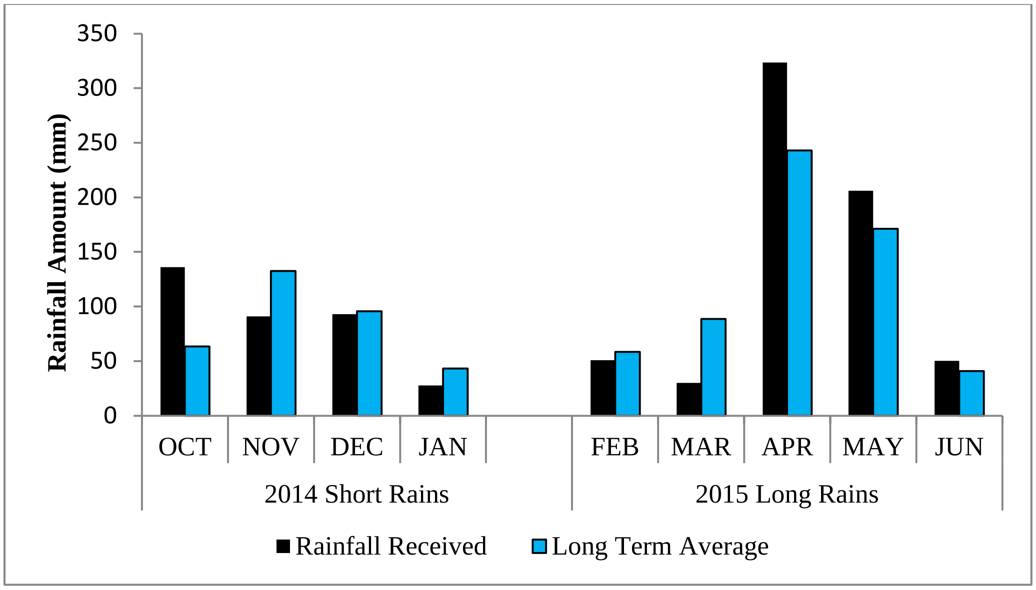

Figure 2.0: Mean monthly rainfall in comparison with the 20 years average

The rains extended until February 2015 and totaled to 348 mm. The total days that received at least 1 mm rainfall, a limit set by the Kenya Meteorological Department as a rainy event (KMD, 2015), were 37. Of this, 13 events (34%) were recorded in the month of October when runoff plots were being constructed.

This observed timing of rainfall agrees with the report by Gachene and Haru, (1997) which stated that most of the erosive rains fall in the first few weeks after the onset of rain when the soil is still bare and thus causes a lot of erosion. According to report by KMD, (2015), rainfall pattern in Kenyan Highlands is erratic, very intense and may record up to 75 mm rainfall in a period less than 2 hours. Three (3) soil loss and runoff generating events occurred on the 21st and 24th of December 2014 and on the 16th of February 2015 with 22 mm,47.7 mm and 58.8 mm of rainfall respectively.

The rains received during March-May 2015 were above the 20 years average and were very intense. There were 31 rainy days with 7 runoff and soil loss events. The month of April alone recorded a rainfall amount of 323.4 mm. Of this, 41% fell within two consecutive days and recorded 58.3 and 75.6 mm on the 25th and 26th days respectively.

The rainfall amount received in the month of May was 206 mm. 78.6% of this amount occurred within three consecutive days and recorded 60.0, 68.4 and 33.6 mm on the 11th, 12th and 13th days respectively. The three-day rainfall accounted for 16 percent of the mean annual rainfall (1006 mm) normally recorded within the area. This was also the time when the highest runoff and soil loss was recorded.

4.2 Establishment of Crop Cover

Crop cover development was generally poor during the 2014 short rains season due to the low and unevenly distributed rainfall (Fig. 3.0).

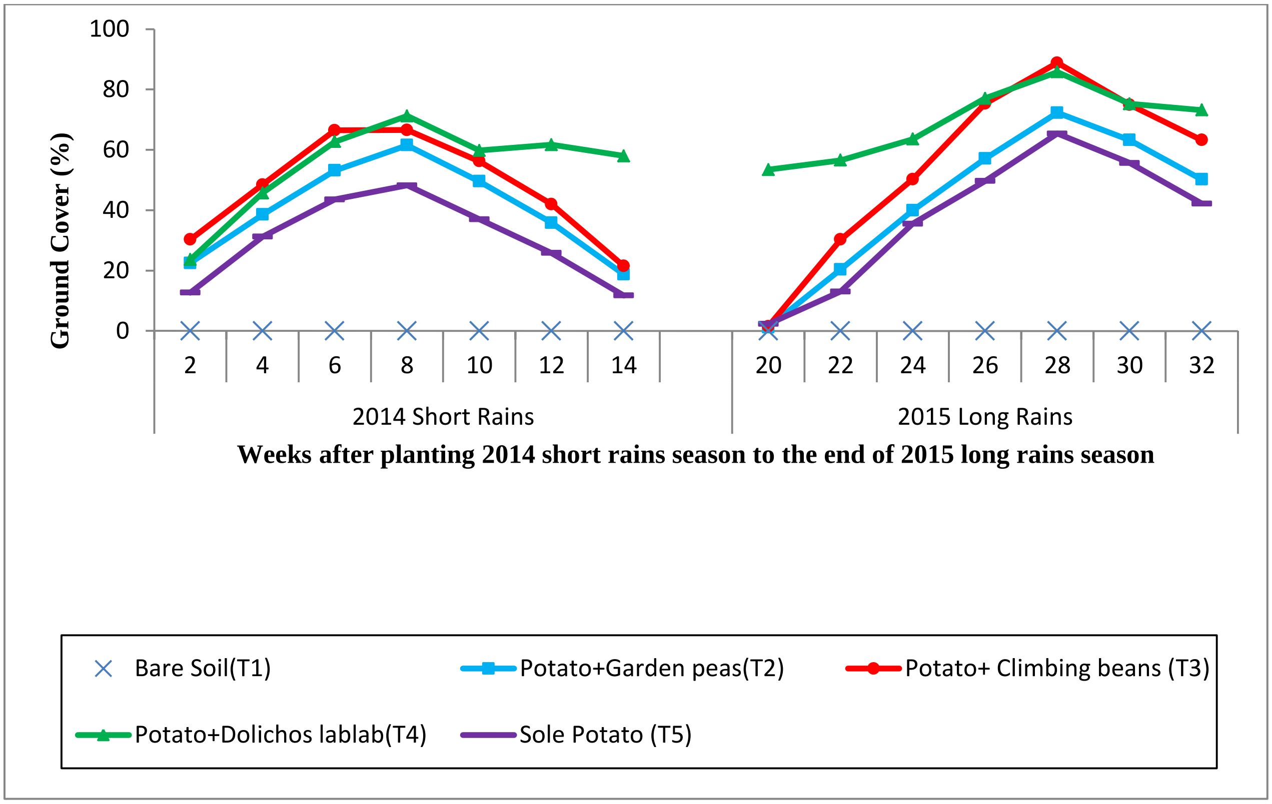

Figure 3.0: Percent crop cover during the experiment period (November, 2014 to June, 2015)

On average, percent cover for potatoes and dolichos (T4) was significantly higher (P<0.05) than all the treatments. This observation was attributed to the dolichos which tolerated the drought conditions which were prevalent in this season. Garden peas delayed to establish and were chocked by potatoes, while climbing bean was adversely affected by the drought conditions. The maximum percent cover was attained on the 8th WAP which significantly differed (P<0.05) between treatments with T4>T3>T2 >T5>T1.

Harvesting was done at 14 WAP by digging up whole plants then separating tubers from roots while legumes were left to continue providing soil cover. Potato residues were retained in their respective plots to provide surface mulch to the soil.

Establishment of the long rains season crop commenced on the 20th WAP (Fig. 3.0). Crop cover recorded at this time was on average less than 5% except in T4 where it was 53.4%. Treatment 4 plots thus maintained post-harvest crop cover above 40% throughout the offseason. This was attributed to the dolichos extended growth pattern and its ability to tolerate drought conditions (Cooks *et al.*, 2002). Climbing beans and garden peas senesced after attaining maturity.

Dolichos seeds were sown in between the previous dolichos plants while residues from the rest of plots were incorporated into the soil at planting. This resulted into a significantly higher ($p<0.05$) crop cover (>40%) for T4 plots than all the other treatments for the first 6 WAP. The maximum soil cover during this season was attained at the 28th WAP which coincided with 8 WAP for 2015 long rains. This cover varied significantly between treatments ($p<0.05$) and was 88.8, 85.8, 72.3 and 65.4% for T3, T4, T2 and T5, respectively. A decline of crop cover was observed from 9th WAP in both seasons because potatoes and legumes lost leaves upon maturity.

4.3 Changes in Soil Surface Roughness

Soil surface roughness (SSR) varied significantly ($p<0.05$) between treatments and ranged from 8.4 to 64.4% during the 2014 SR and 11.4 to 70.1% in 2015 LR (Fig. 4.0).

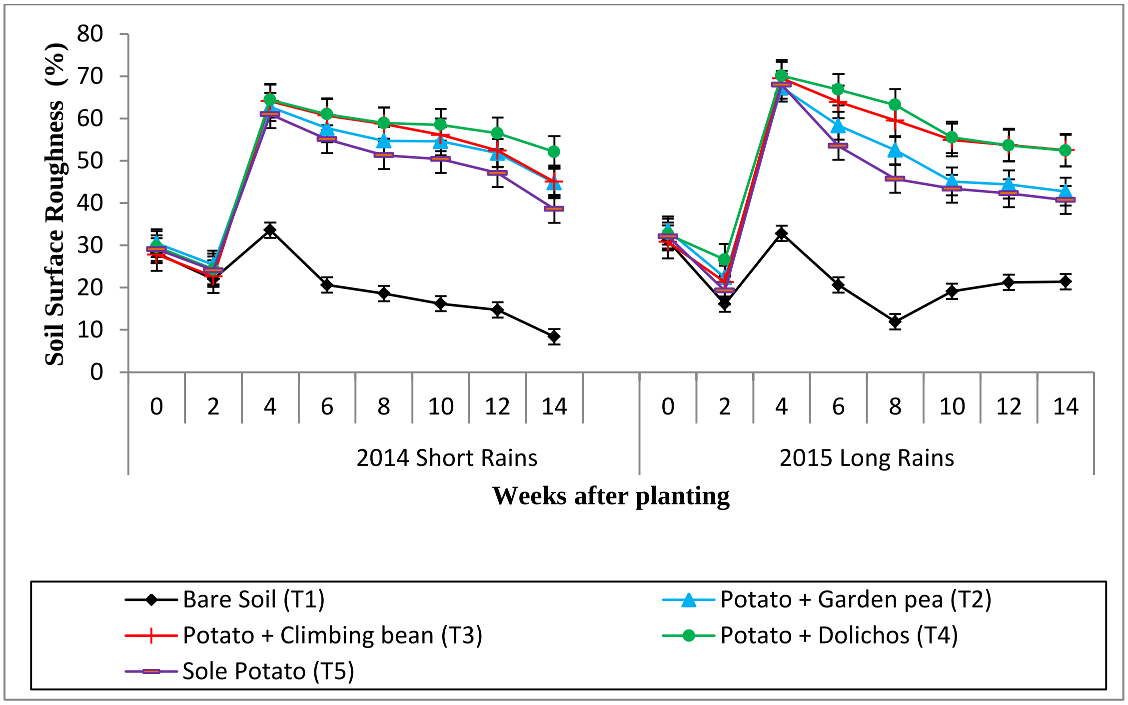

Figure 4.0: Soil surface roughness trend during the study period

The two season average showed a trend of T4>T3>T2>5>T1, suggesting that the SSR decreased with decrease in percent cover. Crop cover may have spread the runoff over a larger area thus enhancing water infiltration rate and decreasing the ability of runoff to reduce the micro relief height. Cover could have in addition dissipated the kinetic energy of rainfall thereby decreasing its ability to detach and smooth the soil.

Soil surface roughness taken soon after planting (2 WAP) indicated a sharp decline. The decline suggests that earlier rain had a greater effect on the soil surface roughness which could be attributed to the consolidation of the loosely tilled soil upon drying, in which case surfacetension forces operate to achieve a suction effect and the shear strength of the soil is increased. Longshan *et al.,* (2014) made a similar observation and attributed it to the sloughing of soil clod upon wetting during the early rainstorms.

Soil surface roughness taken after potato hilling (4 WAP) ranged from 33.6 to 64.4% during the 2014 SR and 32.8 to 70.1% during the 2015 LR. Only T1 plots showed significant difference ($p<0.05$). Hilling created furrows and ridges which altered the local slope of the soil, thus increased the SSR. Such a change in soil characteristic has been demonstrated to increase surface ponding and allow rainwater to infiltrate into the soil, thus preventing runoff and increasing soil moisture storage within the plant root zone (Xing *et al.,* 2011; Karuma *et al.,* 2014; Miriti *et al.,* 2013). Some studies have conversely shown that the change may concentrate the surface runoff flow and initiate soil erosion (Chow and Rees, 1994; Chow *et al.,* 2000; Tiessen *et al.,* 2007).

Soil surface roughness taken immediately after every runoff generating event showed a significant decline. This observation could be attributed to the scouring and smoothening of the ridges by the surface runoff flow. The decline was highest in bare plots and lowest in plots with dolichos suggesting that crop cover had influence on soil surface roughness. The cover provided larger surface area that dissipated the kinetic energy of rainfall and also spread the runoff over a larger area. This reduced the ability of the surface runoff to scour and deposit the soil. The ability of dolichos to provide the highest protective cover against runoff may have been due to its shorter height, higher canopy density and continuity. These features enabled dolichos to achieve maximum rainfall interception and thus explain why soil surface roughness change was consistently lowest in the dolichos plots.

Soil surface roughness of the bare plots increased from 11.9% (8 WAP) to 19.1% (10 WAP) following a three consecutive runoff events that occurred on the 8th week of the 2015 long rains. The high intensity rainfall exceeded the soil's infiltration capacity and thus diminished the influence of SSR on runoff. Surface runoff flow was therefore concentrated leading to rill network formation. This feature created depressions that varied spatially and thus changed the soil surface configuration.

4.4 Effect of Potato Cropping Systems on Soil Loss and Runoff

The mean maximum cover differed significantly ($p<0.05$) between the cropping systems and ranged from 48.3 to 71.2% during the 2014 SR and 65.4 to 88.8% during the 2015 LR (Table 3.0).

Table 3.0: Soil loss and runoff in comparison with maximum crop cover attained during the experimental period

	Short Rains, 2014			Long Rains, 2015			Cumulative Loss		Comparative Loss	
	Cover (%)	Soil loss (t ha^{-1})	Runoff (mm)	Cover (%)	Soil loss (t ha^{-1})	Runoff (mm)	Soil Loss (t ha^{-1})	Runoff (mm)	Soil Loss (%)	Runoff (%)
Treatment										
T1	0.0e	20.4a	15.7a	0.0d	66.0a	53.2a	86.4a	68.9a	100.0	100.0
T2	61.5c	7.2c	10.6c	72.3b	20.3c	20.1c	27.5c	30.7c	31.8	44.6
T3	66.5b	4.9d	4.2d	88.8a	15.4d	17.9d	20.3d	22.1d	23.5	32.1
T4	71.2a	2.5e	3.7d	85.8a	7.0e	7.2e	9.5e	10.9e	11.0	15.8
T5	48.3d	9.1b	13.0b	65.4c	24.8b	26.2b	33.9b	39.2b	39.2	56.9

Means followed by different letters within a column denote significant differences at 0.05 probability level. T1=Bare Soil; T2=Potato + Garden Pea; T3=Potato + Climbing Bean; T4=Potato + Dolichos lablab; T5=Sole Potato.

The differences were attributed to the variations in growth patterns of legumes and their varied abilities to tolerate drought stress conditions (Cooks *et al.*, 2002).

The mean seasonal soil loss ranged from 20.4 to 66.0 t ha^{-1} in bare plots, and 2.5 to 24.8 t ha^{-1} in plots with cover crops. Mean runoff showed a similar trend and ranged from 15.7 to 53.2 mm in bare plots and 3.7 to 26.2 mm in plots with cover crops. These differences were probably due to the variations in crop cover percent among the cropping systems.

Mean cumulative soil loss from sole potato, potato + garden pea, potato + climbing bean and potato + dolichos averaged 39.2, 31.8, 23.5 and 11.0% of the cumulative soil loss from the bare plots respectively, while mean cumulative runoff averaged 56.9, 44.6, 32.1 and 15.8 mm respectively. This indicates that intercrop of potatoes and dolichos provided the most effective cover in reducing soil loss and runoff. This observation was attributed to the dolichos which contributed critical cover above 40% during the off-seasons and effectively minimized soil loss during the subsequent season. The rest of legumes senesced after they attained full maturity and their influence on soil erosion was not any different from those of bare soils during the following season. These treatments thus recorded 60 to 70% of soil loss after potatoes were harvested and at the onset of the seasons when the soil was bare.

Intercropping potatoes with any of the cover crops reduced soil loss and runoff by 19 to 72% and 22 to 72% respectively when compared with sole potatoes. This is because the legumes developed rapidly and protected the soil against erosion. The residue retained from intercropping plots was also relatively higher and functioned to provide surface mulch that protected the soil against erosion.

The results are in agreement with those reported by Khisa *et al.*, (2002) in Gatanga region of Kenya. In their study, *Mucuna pruriens* maintained a cover greater than 40%, 22 weeks after harvest and the control plots comprising of pure maize stand lost up to 9 times more soil than the plots with maize and Mucuna. Gachene and Haru, (1997) similarly recorded 46 times higher soil loss in bare plots than in plots with purple vetch (*Vicia benghalensis*), the latter crop providing effective post-harvest cover after maize was harvested.

4.5 Effect of Soil Surface Roughness and Crop Cover on Runoff and Soil Loss

The effect of crop cover on runoff was significant (*p* = 0.001) and had a negative coefficient (β = -0.13). This indicates that a unit increase in crop cover functioned to reduce runoff when other factors are held constant (Table 4.0).

Table 4.0: Multiple linear regression analyses of runoff under different treatments

Multiple Linear Regression					n=50.00 F(7, 42)=30.30 p>F=0.000 R^2=0.8251
Dependent Variable= Runoff					Root RMSE=2.052
Independent Variables		Coefficients	Standard Error	T	p>[t]
Cover		-0.130	0.035	-3.477	0.001
Surface Roughness		-0.002	0.001	-2.887	0.006
Surface Roughness x Cover		-0.156	0.042	-3.700	0.001
Treatment					
	1	0.000	(base)		
	2	-1.070	1.312	-0.816	0.419
	3	-2.382	1.236	-1.926	0.061
	4	-3.003	1.242	-2.417	0.020
	5	-0.077	1.265	-0.061	0.952
Constant		10.049	0.732	13.731	0.000

T1=Bare Soil; T2=Potato + Garden Pea; T3=Potato + Climbing Bean; T4=Potato + Dolichos lablab; T5=Sole Potato. R^2 shows the proportion of variation in runoff explained by the variation in the independent variables.

The model also indicates that every unit increase in SSR would significantly (p = 0.006; β = -0.002) reduce runoff when other factors are fixed. The coefficient of crop cover (β = -0.130) was however larger than that of the SSR (β = -0.002) indicating that crop cover had a greater effect on runoff. Interaction between crop cover and SSR showed the greatest effect on runoff as was indicated by the largest coefficient (p = 0.001; β = -0.156).

Statistically significant linear dependence of runoff on independent variables was detected in treatment 4 (p = 0.020). Therefore, this is the only treatment that would effectively minimize runoff when compared to the control treatment (base).

The relationships could be modeled by the equation given below:

$$Runoff\ (mm) = \beta_0 + \beta_i X_i + E$$

Where, β_0= Constant, β_i= coefficients of independent variables, X_i= independent variables with significant values, E= Root Mean Squared Error.

The equation would therefore be written as;

$Runoff\ (mm) = 10.0 - 0.13C - 0.002SR - 0.156SRC - 3.003T4$ + E

Where; C=Percent Crop Cover; SR=Surface Roughness; SRC=Interaction between Surface Roughness and Cover; T=Treatments, 10=Constant.

Similar results were recorded with soil loss (Table 5.0). The model reflects that every unit increase in percent cover would significantly reduce soil loss (p = 0.001; β = -0.252) when other factors are fixed as was indicated by the negative coefficient. Soil surface roughness also had a significant effect on soil loss (p = 0.000; β= -0.005), reducing it for every unit increase in SSR when other factors are held constant. The coefficient of crop cover was however larger than that of the SSR indicating that crop cover had a greater effect on soil loss. The interaction between crop cover and SSR showed the greatest effect on runoff (p = 0.001; β = -0.268) as was indicated by the largest coefficient.

Statistically significant linear dependence of soil loss on independent variables was detected in treatment 4 (p = 0.01). Therefore, this is the only treatment that would effectively reduce soil loss when compared to the control treatment (base).

Table 5.0: Multiple linear regression analyses of soil loss under different treatments

Multiple Linear Regression					n=50.00 F(7, 42)=10.10 p>F=0.000 R^2=0.7280
Dependent Variable= Soil Loss					Root RMSE=2.052
Independent Variables		Coefficients	Standard Error	T	p>[t]
Cover		-0.252	0.067	-3.731	0.001
Surface Roughness		-0.005	0.066	-4.074	0.000
Surface Roughness x Cover		-0.268	0.001	-3.977	0.000
Treatment					
	1	0.000	(base)		
	2	-0.861	1.752	-0.491	0.626
	3	-1.586	1.886	-0.841	0.505
	4	-1.724	1.677	-1.028	0.010
	5	-0.801	1.606	-0.499	0.310
Constant		13.890	2.075	6.693	0.000

T1=Bare Soil; T2=Potato + Garden Pea; T3=Potato + Climbing Bean; T4=Potato + Dolichos lablab; T5=Sole Potato. R^2 shows the proportion of variation in soil loss explained by the variation in the independent variables.

The relationship could be modeled by the following equation:

$$Soil\ Loss\ (t\ ha^{-1}) = \beta_0 + \beta_i X_i + E$$

Where,β_0= Constant, β_i= coefficients of independent variables, X_i= independent variables, E= Root Mean Squared Error.

The equation would therefore be written as;

$$Soil\ Loss\ (t\ ha^{-1}) = 13.89 - 0.252C - 0.005SR - 0.268SRC - 1.724T4 + E$$

Where; C=Percent Crop Cover; SR=Surface Roughness; SRC=Interaction between Surface Roughness and Cover; T=Treatments, 10=Constant and E=Root MSE.

These results represent cumulative impacts of crop cover, soil surface roughness and their interactive effects on soil loss and runoff. Crop cover had a greater influence on soil loss and runoff than soil surface roughness. The canopy cover may have provided a larger surface area that greatly reduced the impact of raindrops that otherwise would detach soil particles and make them prone to erosion. The cover may have in addition spread runoff over a larger area thus reducing its velocity and increasing water infiltration capacity. Plant roots may have also stabilized the soil making it less prone to erosion.

Soil surface roughness also showed a significant effect on runoff and soil loss. This is probably due to its ability to increase the soil's water retention and infiltration capacity thereby reducing the speed and volume of runoff. Gomez and Nearing, (2005) observed that bigger and more stable clods can dissipate the kinetic energy of rainfall and decrease the runoff flow velocity, thus reducing its ability to detach, transport and deliver the sediment. Rosa *et al.*, (2012) similarly demonstrated that SSR created by hilling may increase the local slope of the surface thereby spreading the runoff and splash droplets over a larger area.

Soil surface roughness however, showed lesser influence on soil loss and runoff compared to crop cover. This suggests that the effect of SSR on runoff and soil loss declines as rainfall increases. This observation is attributed to the high intensity rainfall that exceeded the soil infiltration capacity. The excess water filled up all the furrows and depressions and consequently transported the detached sediment. The deposition of this sediment covered the furrows and reduced their effective storage capacity.

An interaction between crop cover and SSR showed a greater influence on soil loss and runoff. Although hilling could change the micro-relief of the field and locally increase water runoff and soil loss as reported in previous research (Chow and Rees 1994; Tiessen *et al.,* 2007), the gradual development of crop canopy may form a protective layer over the soil to reduce soil loss. The disturbed soil from potato hilling activity could also be stabilized over time by the natural processes and the resultant ridges may control runoff thereby enhancing water infiltration potential. Hilling could also increase soil moisture in the profile which would stimulate germination of potato and shortens the period of bare soil thus relatively reducing water runoff and soil loss. Xing *et al*., (2011) argued that hilling makes a ridge of soil, which partially disconnects the lateral flow of surface soil water, while increasing aeration of the soil on the hill and supports observations of this study.

Incorporating appropriate indeterminate legume crop such as *Dolichos lablab* maintained critical soil cover of 40% during the off-seasons which protected soil during the transition period between the two seasons. This points out the need to incorporate such legume cover crops into potato cropping systems.

4.6 Enrichment Ratio of Eroded Sediment

The highest value of enrichment ratio (ER) for P (2.98), TN (1.34) and K (1.25) were recorded in sole potato treatments (Table 6.0).

Table 6.0: Chemical and physical enrichment ratios of the eroded sediment

	pH	SOC	MOC	POC	PN	MN	TN	P	K	Sand	Clay	Silt
Treatment	Enrichment Ratio											
T1	1.03	1.16	1.27	1.21	1.13	1.23	1.25	2.01	1.15	0.89	1.18	1.15
T2	1.02	1.09	1.22	1.11	1.08	1.19	1.18	2.44	1.23	0.80	1.13	1.11
T3	1.01	1.06	1.19	1.09	1.06	1.10	1.14	2.34	1.09	0.79	1.11	1.10
T4	1.01	1.01	1.09	1.05	1.03	1.05	1.09	1.87	1.04	0.68	1.09	1.08
T5	1.02	1.13	1.24	1.13	1.11	1.19	1.34	2.98	1.25	0.87	1.15	1.12

T1=Bare Soil; T2=Potato + Garden Pea; T3=Potato + Climbing Bean; T4=Potato + Dolichos lablab; T5=Sole Potato

Potatoes delayed to establish protective cover and left the soil highly exposed to erosion. A substantial amount of the applied fertilizer (N-120 kg/ha, P-100 kg/ha and K-150 kg/ha) may have been washed from these plots following the runoff events that occurred in the first two weeks after planting. Growth of legumes was however rapid and provided protective soil cover which significantly minimized the nutrient losses. Treatment 4 recorded the lowest enrichment ratio of nutrients because dolichos maintained effective crop cover during the transitional period between the two seasons and significantly reduced nutrient losses.

The ER was particularly high for P (1.87 to 2.98) because this element is usually adsorbed and fixed as iron phosphates in acidic soils such as nitisols and is therefore wholly mobilized with the eroded sediment. Brian and Lars, (2013) recorded P enrichment ratio of 7.1 in a Rwandan haplic Nitisols and attributed it to the characteristic low pH and high iron oxides of these soils which favors P sorption. The result thus implies that a slight soil loss through erosion within a short time may lead to greater loss of phosphorus.

Though not fertilized, the enrichment ratio for N, P and K were relatively high in bare plots. This is probably due to the high mobilization of these nutrients in their native organic and inorganic forms. The enrichment ratio for K was however lower than that of N and P because this element is uniformly distributed within the soil profile (Khisa *et al.*, 2002).

The ER for SOC was also high (1.01 to 1.16), indicating selective removal of this nutrient. Soil organic carbon is strongly adsorbed on the fine clay surfaces leading to its high mobilization with the eroded sediment. The SOC ER was highest in the bare plots probably because these plots had no vegetation cover and were kept without fertilizer additions. This may have lowered the aggregate stability of these plots and enhanced their susceptibility to erosion. This is in accordance with the findings by Martínez-Mena *et al*., (2008) which showed that soils with low aggregate stability usually have their macro-aggregates easily disrupted and particles detached by even low intensity storms. The disruption releases SOC in higher concentrations than is in the original soil (Polyakov and Lal, 2004).

The enrichment ratio was greater than 1.0 in all the SOM fractions and was highest in bare treatments (T1) and lowest in treatments comprising of potatoes and dolichos (T4). The stable SOM enrichment ratio varied slightly between treatments, the MOC range being 1.09 to 1.27, while the mineral N ranged from 1.05 to 1.23. The labile SOM enrichment ratio showed larger variations between treatments, but recorded the least values, POC (1.05 to 1.21), PN (1.03 to 1.13).

The enrichment ratio (ER) of SOM fractions higher than unity indicates that the eroded sediment contained higher SOM content relative to the source soil. This is due to the slaking and peeling caused by raindrops as they pound on soil aggregates thereby releasing microaggregates which are more enriched with the SOM. The ER was highest in T1 with no vegetation cover and lowest in T4 with the highest percent cover. Morsli *et al.,* (2005) demonstrated that SOM enrichments are mainly influenced by the soil cover type and that a lower cover would result into a higher ER. Crop cover dissipates the kinetic energy of rainfall, reducing its ability to peel and slake the soil aggregates that would release the sorbed SOM.

The ER of the stable fraction was slightly higher than that of the labile fraction due to the strong association of MOC and MN with the finer clay and silt particles which were preferentially mobilized with the eroded sediment. The ER of labile fractions greater than unity is attributed mainly to the selective transportation of low density POC and PN, and to the disruption of the aggregates which releases the encapsulated POC and PN which are then selectively mobilized with the eroded sediment.

Similar observations have been found by other authors (Jacinthe *et al.,* 2004; Brunet *et al*., 2005; Martinez Mena *et al.,* 2008) and explained it by the fact that soil erosion affects the most superficial soil layers which are highly enriched with SOM. Cai *et al*., (2002) attributed the higher ER of the labile SOM to the erosion of the POC and PN contributed by fertilizer additions and residue returns.

The enrichment ratio for the soil pH (1.01-1.03) was slightly above unity, suggesting that eroded soil material was enriched with bases relative to original soil and may lead to Ca, Mg, K and Na deficiency. The resultant low pH may also favor P fixation in nitisols thus resulting in accumulation of toxic element.

The ER of clay (1.09-1.18) and silt (1.08-1.15) were greater than 1, but that of sand (0.68-0.89) was less than unity, indicating that the erosion process was selective, carrying with it the lighter material (clay and silt) and leaving the heavier material in the plots. This is due to the fact that the energy required to transport silt and clay particles is comparatively lower than that of the coarser sand-sized aggregates (Boix-Fayos *et al.*, 2009).

Higher enrichment ratios have been reported in Kenyan humic nitisols, ranging from 1.10-1.20 for SOC, 1.10-1.30 for TN, 1.12-10.3 for P, and 1.12-1.31 for K (Tongi, 1990; Zobisch *et al.*, 1994; Gachene *et al.*, 2002; Khisa *et al.*, 2002;). This indicates that the Kenyan humic nitisols that have for a long time been regarded as productive may drastically lose its native fertility if no proper soil conservation measures are undertaken.

The soils are deficient of P (Table 2.0), yet this study points out that it is the most vulnerable to losses through erosion. This may warrant heavier application of phosphatic fertilizer given that this element is required in large amounts especially by potatoes. Continued loss of SOM may be more important because this will affect other soil physical and chemical properties such as water holding capacity and soil aggregate stability (Gachene *et al.*, 1997).

Loss of N implies that this element should be applied to these soils in larger quantities given that N sources are mainly external of the soil (Woomer *et al.*, 1994). The eroded N may also end up in water bodies causing eutrophication and may therefore pose hazardous environmental impact.

4.7 Relationships between Enrichment Ratios of Soil Texture and Soil Nutrients

Correlation coefficients between ER of clay and soil nutrients showed strong positive associations, the highest being with P (*r*=0.88) and the lowest with K (*r*=0.75) (Table 7.0).

Table 7.0: Pearson's correlation coefficients between the enrichments of soil textures and selected soil parameters

Parameter	SOC	TN	P	K	Sand	Silt	Clay
Sand	-0.53	-0.49	-0.44	-0.11	1.00	-0.51^{*}	-0.32
Silt	0.84^{**}	0.79^{**}	0.86^{**}	0.73^{**}	-0.51^{*}	1.00	0.86^{**}
Clay	0.83^{**}	0.82^{**}	0.88^{**}	0.75^{**}	-0.32	0.86^{**}	1.00

* Correlation is significant at the 0.05 probability level; ** Correlation is significant at the 0.01 probability level.

The correlation coefficients between the ER of silt and soil nutrients also showed strong positive relationships and the highest value was recorded with P (*r* = 0.86) and the lowest with K (*r* = 0.73). Non-significant (P > 0.05) and weakly negative correlations between the ER of sand and soil nutrients were also observed, suggesting that nutrients are not well associated with sand.

The result implies that silt and clay particles better account for the variability of nutrient enrichments. Tesfahunegn and Vlek, (2014) demonstrated that these particles may account for over 90% of the soil nutrients as their surface areas are high and adsorb high quantities of mineral elements. The silt and clay sized particles are besides easily mobilized by the surface runoff flow compared to the coarser aggregated sand sized aggregates that require higher kinetic energy for transportation. Soils with high clay and silt contents such as nitisols may therefore be highly vulnerable to nutrient losses.

4.8 Soil Organic Matter Components in Eroded Sediment

Soil organic matter concentrations differed significantly ($p<0.05$) between treatments and was highest in T1 and lowest in T4 (Table 8.0). Total SOM varied only slightly, but significantly between the treatments ($p<0.05$), the C range being 27.59 to 28.38 g kg^{-1} and N range being 2.63 to 2.73 g kg^{-1} during the 2014 SR. A similar result was recorded during the 2015 LR with slightly higher values.

Table 8.0: Concentrations of SOM components in the eroded sediment

	Short Rains, 2014						Long Rains, 2015					
	Concentrations (g kg^{-1})											
Treatment	TOC	POC	MOC	TN	PN	MN	TOC	POC	MOC	TN	PN	MN
T1	28.38	9.26	19.25	2.73	0.79	1.90	28.53	9.39	19.30	2.77	0.84	1.93
T2	27.84	8.48	18.64	2.69	0.74	1.86	28.05	8.87	18.65	2.71	0.77	1.81
T3	27.71	7.94	18.43	2.66	0.67	1.84	27.88	8.54	18.44	2.67	0.72	1.78
T4	27.59	7.72	18.20	2.63	0.62	1.76	27.72	8.28	18.23	2.64	0.67	1.67
T5	28.09	8.78	18.75	2.70	0.76	1.88	28.12	9.03	18.77	2.73	0.80	1.89
LSD$_{0.05}$	0.117*	0.207*	0.191*	0.020*	0.019*	0.016*	0.144*	0.209*	0.195*	0.022*	0.020*	0.029*

T1=Bare Soil; T2=Potato + Garden Pea; T3=Potato + Climbing Bean; T4=Potato + Dolichos lablab; T5=Sole Potato; TOC=Total Organic Carbon; POC=Particulate Organic Carbon; MOC=Mineral Organic Carbon; TN=Total Nitrogen; PN=Particulate Nitrogen; MN=Mineral-associated Nitrogen; *significant at $p<0.05$.

The stable SOM fraction showed slight variation between treatments, but recorded higher concentrations than the labile fraction. The differences among treatments were significant ($P<0.05$) and were highest in the bare treatments (T1) and lowest in the treatments comprising of potatoes and dolichos (T4). The MOC ranged from 18.20 to 19.25 g kg^{-1}during the 2014 SR and 18.23 to 19.30 g kg^{-1} during the 2015 LR. The mineral N indicated the same trend and ranged from 1.76 to 1.90 g kg^{-1} during the 2014 SR and 1.67 to 1.93 g kg^{-1}during the 2015 LR.

The labile SOM showed larger variations between treatments than the stable fraction, but recorded the least concentrations. The differences between treatments were significant ($p<0.05$) and were highest in the bare treatments and lowest in treatments comprising of potatoes and dolichos (T4). The POC ranged from 7.72 to 9.26 g kg^{-1}during the 2014 SR and 8.28 to 9.39 g kg^{-1} during the 2015 LR. The particulate N showed a similar trend and ranged from 0.62 to 0.79 g kg^{-1}in 2014 SR and 0.67 to 0.84 g kg^{-1}during the 2015 LR.

The stable SOM fractions (MOC and MN) had higher concentrations of C and N than the labile fraction (POC and PN) indicating that much of the SOM mobilized in the eroded sediment was in stable form. This observation could be due to the fact that soil erosion process sorted out the soil particles mainly according to their sizes. The validity of this separation was verified by the C: N ratio of the eroded sediment which showed similarity and consistency with that of the source topsoil (Fig. 5.0). The finer silt and clay particles which are highly enriched with MOC and MN were therefore mobilized in larger quantities. Boix-Fayos *et al.*, (2009) showed that the energy required to transport these particles is comparatively lower than that of the coarser sand-sized aggregates.

Hu *et al*., (2013) demonstrated that higher losses of stable SOM due to soil erosion are attributed mainly to the differences that exist in particle settling velocities. They showed that suspended coarser aggregated particles associated mainly with the labile SOM settle on the surface quickly due to their higher settling velocities while the finer clay and silt particles associated with the stable fraction are easily carried in the direction of the surface water flow due to their lower settling velocities.

These results contrast the findings by Jacinthe *et al.,* (2004) and Wang *et al.,*(2014) which showed that most of the SOM in the eroded sediments is contributed by the labile SOM due to the fact that this fraction exhibits very low density in comparison to stable fraction. Though the raindrop impact may have disrupted the microaggregates >53 µ and released the encapsulated light labile fraction as suggested by these authors, this particle constituted only 25.9% of the total SOM in the soils (Appendix 1.0) and slightly above 26% in the eroded sediment. Its presence was therefore negligible in the eroded sediment. These previous studies were also conducted at the water catchment scale where non selective erosion processes may have mobilized the coarser particles richer in labile SOM.

The results are however consistent with the findings of Martinez-Mena *et al.,* (2008), Cheng *et al.,*(2010) and Wang *et al.,*(2013) which associated the higher susceptibility of stable SOM fraction to erosion with its much larger reservoir in the soil.

4.9 Relationships between Eroded Sediment and SOM Concentrations

The sediment was highly and positively correlated with the total SOM (*r*=0.75 for TOC and 0.71 for TN), with the stable SOM fractions (*r*=0.70 for MOC and 0.66 for MN) and with the labile SOM fractions (*r*=0.62 for POC and 0.59 for PN). The correlations were highly significant (p<0.05) (Table 9.0).

Table 9.0: Correlation of soil organic matter components with soil loss

SOM Component	Concentrations (g kg^{-1})	Correlation Coefficient (r)
Total OC	28.04	0.75**
Mineral OC	18.75	0.70**
Particulate OC	8.63	0.62*
Total N	2.70	0.71**
Mineral N	1.82	0.66**
Particulate N	0.74	0.59*

* Significant at p=0.01, ** significant at p<0.001

A strong correlation between soil loss and stable organic carbon and nitrogen fractions could be due to mobilization of silt and clay particles which are more enriched with stable SOM. Brunet *et al.,* (2005) argued that rainfall disrupts the soil microaggregates releasing the sorbed MOC and MN in higher concentrations. Oorts , (2007) attributed the stronger association of MOC and MN with the sediment to their dominance in the total SOM pool.

The correlation coefficient of soil loss and labile carbon fraction was also strong due to preferential transport of the light POC and PN, while that between soil loss and total SOM may have been as a result of C and N mobilized from the stable and labile fractions. Other authors have reported similar results (Polyakov and Lal, 2004; Morsli *et al.*, 2005) and explained it by the fact that soil erosion affects mainly the superficial soil layers which are the richest in SOM. Jacinthe *et al.*, (2004) argued that SOM has comparatively lower density making it more prone to detachment by even low-intensity storms.

4.10 C: N ratio of SOM Fractions

The average C: N ratio of the labile SOM in the sediments (11.5) and that of the original soil material before erosion during the 2014 SR (11.2) indicated similarity (Fig. 5.0). The 2015 LR recorded a similar result where the average ratio was 10.4 in the eroded sediment and 10.2 in the original soil material.

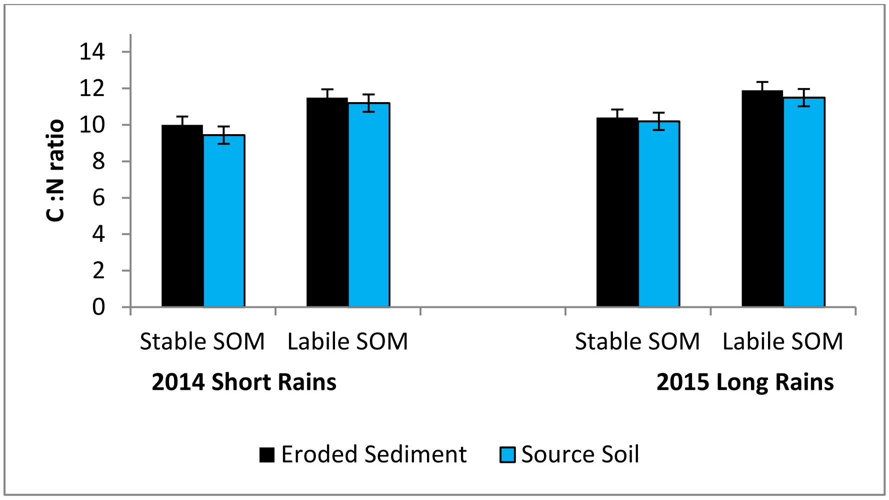

Figure 5.0 C: N ratio of SOM fractions

For the stable SOM, the ratio averaged 10.0 in the eroded sediment and 9.8 in the original soil material during the 2014 SR and 10.4 in the eroded sediment and 10.2 in the original soil material during the 2015 LR.

The similarity of the C: N ratio of SOM fractions of the eroded sediment to that of the original soil material suggests that erosion process separated soil particles based on their size. Natelhoffer and Fry, (2011) argued that erosion process mobilizes C and N wholly with the eroded sediment, thus having no effect on the C: N ratio.

4.11 Effect of Soil Erosion on Soil Organic Matter Fractions

The SOM fractions showed a net decline of organic C and N after two seasons which was equivalent to one year (Fig. 6.0).

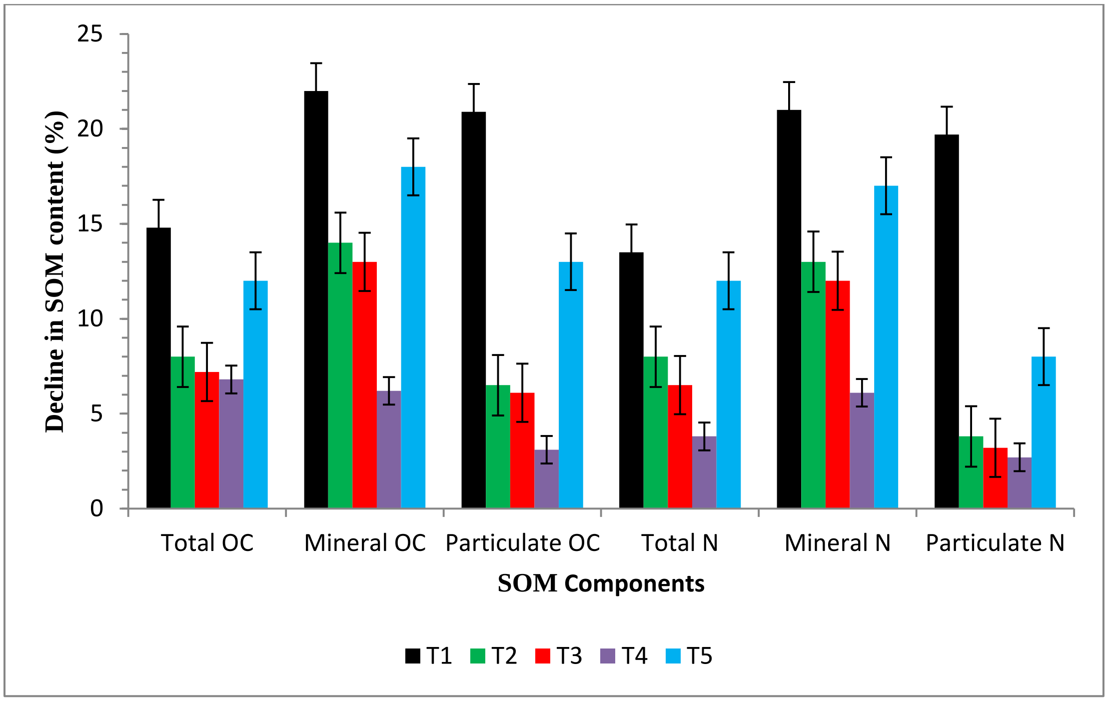

Figure 6.0: Treatment effect on soil organic matter fractions

The decline was highest in bare plots (T1) and lowest in plots with potatoes and dolichos (T4). The stable SOM fractions (MOC and MN) showed the highest percentage decline in C and N contents. The difference between MOC content in the baseline soil (Table 2.0) and that of the soil at the end of the study (Appendix 2.0) indicated a MOC decline at a rate ranging between 6.2 to 22% per year (Fig. 6.0). Similar results were recorded by the MN which declined at a rate ranging between 6.1 and 21% per year. The labile SOM fractions (POC and PN) had the least change in organic C and N. The POC declined at a rate ranging between 3.1 and 20.9% per year while the Particulate N declined by 2.7 to 19.7% per year. The POC and PN contents of the bare plots showed proportionally larger changes than those of the plots with cover crops.

The changes in total SOM contents were contributed mainly by the stable fractions (MOC and MN) and declined at a rate ranging between 6.8 and 14.8% per year for TOC and between 3.8 and 13.5% per year for TN.

The higher reduction in stable SOM fraction contents is probably due to the higher quantities of MOC and MN mobilized in the eroded sediment (Table 8.0). The losses were however more pronounced in the bare soil treatments suggesting that crop cover protected the soil against erosion and minimized SOM losses. The labile fraction recorded the least reduction in C and N which could be explained by the smaller quantities of C and N mobilized in the eroded sediment (Table 8.0).

The greater decline in POC and PN contents in bare plots than in plots with cover crops could be due to the fact that the bare plots had no crop residues and were not fertilized thus lacked the C and N contributed by decomposing litter and fertilizer additions. This implies that the decline in the contents of POC and PN (labile fraction) was mainly contributed by management rather than soil erosion. This was expected because this fraction has been shown to respond rapidly to managerial changes and the content may increase rapidly with residue and manure/fertilizer application (Kapkiyai *et al.,* 1999; Murage *et al.,* 2001). Similar observations have been made by other studies (Jacinthe *et al.,* 2001; McCarty and Ritchie, 2002; Martinez-Mena *et al.,* 2008; Cheng *et al.,* 2010) which have suggested that the POC and PN lost in the cultivated areas is mainly due to the effect of cultivation (low overall biomass production and residue return together with high C mineralization) rather than to water erosion, given that the major part of the SOM lost in sediments is in stable form.

CHAPTER FIVE

5.0 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Soil surface roughness induced by potato hilling interacted with percent crop cover and significantly reduced runoff and soil loss. The losses were higher in bare soils than in the other plots with cover crops suggesting the importance of crop cover in reducing soil loss and runoff.

Dolichos lablab maintained critical soil cover of 40% during the off-seasons which protected soil during the transition period between the two seasons. This demonstrates the need to incorporate appropriate indeterminate legume cover crops in potato cropping systems so as to minimize soil and nutrient losses due to erosion. The hypothesis put forward that soil surface roughness and crop cover have no influence on soil loss and runoff was therefore invalidated.

The enrichment ratios of the analyzed soil properties were on average greater than unity in all the treatments indicating that the eroded sediment were highly enriched with nutrients relative to the source soil material. The enrichments decreased with the increase in percent crop cover indicating that the cropping systems had influence on nutrient losses.

The study also showed that the high SOM enrichment is not primarily due to the mobilization of the labile SOM fraction, but rather to the stable fraction. This is explained by the fact that the stable SOM fraction is strongly associated with the finer clay and silt particles which are preferentially mobilized with the eroded sediment. The study thus accepted the hypothesis put forward that the labile SOM fraction is not prone to soil erosion.

5.2 Recommendations

i. Intercropping potato with Dolichos lablab effectively minimized runoff, soil and nutrient losses. Dolichos lablab should therefore be incorporated into potato cropping systems.
ii. Future research should be directed towards assessing the interactive effects of soil texture, slope and crop cover on soil loss and runoff. The effect of soil surface roughness due to different tillage methods on runoff and soil loss should also be evaluated.
iii. Studies should be conducted to assess moisture and nutrient competition between potatoes and legume cover crops. Such studies should focus on relaying legumes after planting potatoes.
iv. Given that a substantial amount of plant nutrients are carried in solution form, it is important that the nutrient losses in the runoff are also determined.
v. Studies should also be carried out to determine whether slashing and leaving legume cover crops as surface mulch would provide a better management practice than when left to continue growing between the transitional periods.
vi. This study was limited to two rainy seasons and could not assess the effect of soil erosion on soil properties and crop yield and therefore calls for more studies.

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APPENDICES

Appendix 1.0: Relative proportions of SOM fractions

	Relative SOM (%)	
	Source soil material (0-10 cm)	Eroded sediment
MOC	70.6	74.3
POC	25.9	26.2
MN	70.2	73.8
PN	25.4	26.1

Appendix 2.0: SOM Content (0-10 cm) at the end of the study

	SOM Content (g kg^{-1})					
Treatment	TOC	POC	MOC	TN	PN	MN
T1	22.32	5.31	14.12	2.25	0.53	1.43
T2	24.00	6.31	15.66	2.39	0.63	1.61
T3	24.28	6.33	15.90	2.43	0.64	1.62
T4	24.41	6.50	16.98	2.50	0.64	1.70
T5	23.32	5.90	15.19	2.32	0.61	1.54

Appendix 3.0: Composition of the eroded sediment

	OC	N	P	K	pH	Sand	Silt	Clay
	%		ppm	cmol kg^{-1}			%	
Treatment								
T1	3.05	0.32	33.97	2.07	5.30	17.62	34.16	60.18
T2	2.87	0.31	41.24	2.21	5.30	15.84	34.42	56.61
T3	2.78	0.30	39.55	1.96	5.25	15.64	32.12	56.10
T4	2.66	0.28	31.60	1.87	5.25	13.46	31.82	55.59
T5	2.98	0.29	50.36	2.25	5.36	17.23	32.70	58.14