ESTABLISHMENT OF CRITERIA FOR CLASSIFICATION AND MAPPING OF SOIL EROSION AT FARM SCALE LEVEL: A CASE STUDY OF SOKOINE UNIVERSITY OF AGRICULTURE FARM, MOROGORO, TANZANIA

BY

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ABSTRACT

The depth of the topsoil and estimated soil loss were used to assess the extent of past erosion and susceptibility to soil erosion of the Typic Rhodustalf and Typic Ustorthent, in the central part of the Sokoine University of Agriculture farm. The topsoil depth ranges: <15cm, 16 – 20cm and >20cm were used to categorise soils as highly eroded, moderately eroded and least eroded. Parameters of the Universal Soil Loss Equation: rainfall erosivity, soil erodibility, crop cover and management, and topographic factors were used to assess the susceptibility of soils studied to erosion. The following soil erosion susceptibility ranges: < 4Mg/ha/year, 4 – 8Mg/ha/year and >8Mg/ha/year were studied and used to represent highly eroded, moderately eroded and least eroded soils. For both criteria, areas with similar erosion classes were delineated, and both soil erosion susceptibility and soil erosion severity maps were drawn at scale 1: 5 000. The impact of soil erosion on maize yield was assessed using the two criteria. Generally there was a decline in maize yield as a result of increase in erosion.

For the same erosion category, the Typic Rhodustalf had a higher yield than the Typic Ustorthent. The impact of estimated soil erosion susceptibility on maize yield was more consistent than that of topsoil depth.

There existed a high correlation between estimated soil erosion susceptibility and maize grain yield (r^2 = 0.60) and biomass (r^2 = 0.49). In case of the topsoil depth criterion, the relationship was lower with r^2 = 0.20 for grain yield and r^2 = 0.26 for

There existed a high correlation between estimated soil erosion susceptibility and maize grain yield ($r^2 = 0.60$) and biomass ($r^2 = 0.49$). In case of the topsoil depth criterion, the relationship was lower with $r^2 = 0.20$ for grain yield and $r^2 = 0.26$ for biomass. However, in the Typic Rhodustalf the correlation was high, grain yield ($r^2 = 0.70$) and biomass ($r^2 = 0.46$), while in the Typic Ustorthent the relationship was extremely low; grain yield ($r^2 = 0.09$) and biomass ($r^2 = 0.24$).

Soil erosion susceptibility was therefore found to be a better criterion for assessing soil erosion than topsoil depth. However, multiple regression analysis of maize yield and other soil parameters produced high correlation, implying that the use of the topsoil depth can be improved by including some other soil parameters like bulk density and organic carbon for estimating the extent of past erosion.

DECLARATION

I, WILLIAM KAPELE do hereby declare to the Senate of Sokoine University of Agriculture that this dissertation is my original work and that it has not been submitted for a degree in any other university.

Signature..

Date..............26/07/2000..............

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LIST OF ABBREVIATIONS AND SYMBOLS

ι	Shear stress of flow
θ	Slope angle (degrees)
ι_c	Sediment transport capacity of rills
γ_w	Specific gravity of water
a	maximum width of eroded area in a gully
AI_m	Rainfall erosivity index
ANSWER	Area Non-point Source Watershed Environment Response Simulation
B	maximum depth of eroded area in a gully
BD	Bulk density
C	Crop cover and management factor of the (USLE) equation
CEC	Cation exchange capacity
CREAMS	Chemicals Runoff and Erosion rising from Agricultural Management Systems
Dc	Detachment capacity of flowing water
D_I	Estimated soil loss from interrill erosion
DR	Dispersion ratio
EI_{30}	Rainfall erosivity index
FAO	Food and Agriculture Organisation
H	Highly eroded
I	Rainfall intensity
K	Soil erodibility factor

KE>25	Rainfall erosivity index
K_r	Soil rill erodibility
KYERMO	Kentuky Erosion Model
L	Least eroded
LS	Slope length and steepness factor of the (USLE) equation
M	Moderately eroded
Mn	%silt * (%silt + % sand)
P	Support practice factor of the (USLE) equation
PLU	Previous land use factor of the (USLE) equation
Q	Runoff time
R	Rainfall erosivity
RT	Typic Rhodustalf
SDR	Sediment delivery ratio
SLEMSA	Soil Loss Estimation Method for Southern Africa
SUA	Sokoine University of Agriculture
ULSE	Universal Soil loss Equation
UT	TypicUstorthent
V	Rainfall amount
WEPP	Water Erosion Prediction Project
X	Slope length and steepnes factor of the (SLEMSA) equation

CHAPTER ONE

1 INTRODUCTION

1.1 Background Information

Soil erosion is an important process of land degradation in the tropics and subtropics. The process is largely influenced by high intensity storms, and bad agricultural practices, which include burning, bush clearing and overstocking (Rapp *et al.*, 1973a; Watson, 1973; Lal, 1994; Hudson, 1995). The consequences of soil erosion include among other things low soil fertility and agricultural productivity (Kilasara *et al*,. 1995a,b).

Recognition of soil erosion problems in Tanzania dates well back in the 19th century (Christiansson, 1981). In Tanzania, efforts to combat soil erosion have been concentrated in mountainous areas (Rapp *et al.*, 1973a) probably because the consequences of its effects are more severe in such areas (Ngatunga *et al.*, 1984), than in those areas with relatively low slope gradients (Turner *et al.*, 1984).

Accelerated soil erosion is a common phenomenon in agricultural lands where the slope gradient is 8% or less. Such areas are mostly affected by either rill or overland erosion or both. Features due to these types of erosion are not visible but the effects are detrimental over a long period of time.

Accelerated soil erosion varies both in time and space. Variation in time is gradual due to the effect of soil formation. However, soil erosion variation in space is more pronounced due to similar variation of the factors that affect the process. The study of spatial distribution of soil erosion is important in establishing areas of different degrees of erosion in the field, to which different management practices can be applied. Apparently in the inter-tropical zone of Africa and Tanzania in particular, the spatial approaches are very limited. This is partially attributed to lack of appropriate tools and methods for mapping soil erosion. For the few studies that have been conducted in Tanzania, mapping was done at small scales. For instance, Cook (1975) mapped soils of Dodoma at a scale of 1:50 000, while Ndyetabula (1988) mapped the degree of soil erosion in Morogoro at the same scale. Other researchers who mapped soil erosion at the same scale include Mulengera (1996) and Mboya (1998). Mapping soil erosion at large scale, so as to provide useful information for farm management is rare, not only in Tanzania but in the rest of East Africa. Gachene (1995) mapped soil erosion susceptibility of 4 ha in the Faculty of Agriculture farm, University of Nairobi, in Kenya. The work was based on the Universal Soil Loss Equation (Wischmeier and Smith, 1978).

Considering the fact that soil erosion is so widely spread in Tanzania, there is a need to develop a simplified and reliable criterion to map it. Developing of spatial approaches and testing them is crucial for soil resource inventories and planning for the most appropriate use of land. This is very important for both land and soil surveyors use. Mapping of soil erosion would allow for the delineation of areas affected by different rates of soil erosion on which appropriate land use and management can be applied. It is for this reason that this study was initiated with the overall objective of establishing criteria for mapping soil erosion at the farm level.

The specific objectives were as follows:

(i) To develop criteria for classifying soil erosion based on the USLE model and depth of topsoil.

(ii) To assess criteria for classifying soil erosion based on the USLE model and depth of topsoil.

(iii)To map soil erosion classes using the two criteria above.

CHAPTER TWO

2 LITERATURE REVIEW

2.1 Soil erosion

Soil erosion can be defined as the removal of the topsoil (both soluble and insoluble material) by wind, water and gravitational pull (Troeh, 1980; Lal, 1990; Nill *et al.*, 1996). This process involves the detachment and transport of sediments, in particular, silt, sand, clay, organic matter and solutes, from one place to another (Morgan, 1988; Lal, 1990).

Two types of soil erosion are recognised: geological and accelerated soil erosion (Hudson, 1995; Schwab *et al.*, 1996). Geological soil erosion is natural and is brought about by movement of earth bodies, mountains rising and valley cuttings. This type of soil erosion is sometimes called the smoothening process (Hudson, 1995). According to Hudson (1995), geological erosion is less destructive than accelerated erosion.

Accelerated soil erosion on the other hand results from human disturbance of the natural climate-soil-vegetation equilibrium through one or a combination of deforestation, bad agricultural practices, overgrazing and construction (Lal, 1990; El-Swaify and Pla-Sentis, 1998). These activities are known to accelerate the rate of soil detachment and transport by wind and water especially on slopping land (Lal, 1990).

2.2 Soil erosion processes by water

Soil erosion by water occurs in several forms. The more common ones are interrill (rainsplash and overland flow), rill and gully erosion (Nearing *et al.*, 1994). Piping, mass flow and stream bank erosion are more localised to some areas (Hudson, 1995).

2.2.1 Interril erosion

2.2.1.1 Rainsplash

Rainsplash is the detachment of soil material by the impact of falling raindrops (Lal, 1990; Hudson, 1995; Nill *et al.*, 1996; Wan and El-Swaify, 1998). This type of interrill erosion is largely influenced by soil properties, land form, rainfall characteristics and vegetation cover (Schwab *et al.*, 1993; Nearing *et al.*, 1994), and the moisture status of the soil. According to Lal (1990) the latter also accounts for the erodibility of the soil. Recently, several workers demonstrated the contribution of the land slope steepness on the distribution of the soil due to splash erosion (Daniels *et al.*, 1985; Mulengera, 1996; Wan and El-Swaify, 1998; and Zhang *et al.*, 1998).

Several efforts have been made to estimate sediment yield from rainsplash. The commonest one being the Water Erosion Prediction Project model (Nearing *et al.*, 1994). According to these authors, soil loss through interrill erosion can be estimated thus:

$$Di = K_i I^2 \qquad (1)$$

Where Di = estimated soil loss from interrill (rainsplash) erosion

K_i = interrill erodibility

I = rainfall intensity

Within the East African region other efforts to estimate interrill erosion were made in Kenya by Sutherland and Bryan (1991).

2.2.1.2 Overland flow

Overland flow is the uniform removal of a thin sheet of soil from an area, commonly with slopes steeper than 3% (Turner *et al.*, 1984), by detaching action of raindrops and transportation by flowing water (Hudson, 1995). Overland flow is affected by runoff, rainfall intensity, topography, infiltration rate and soil properties (Agarwal and Dickinson, 1991; Nearing *et al.*, 1994; Schwab *et al.*, 1996). According to Rose (1994), overland flow can be estimated when rainfall rate and infiltration rates are known.

Estimation of overland flow is commonly limited to small plots ($1m^2$), and does not take into account the physical conditions of the land surface (Turner *et al.*, 1984; Rose, 1994). According to Rose (1994) overland flow can be estimated using the model below:

$$R = Q + K_p\left(\frac{\partial\theta}{\partial t}\right) \qquad (mm/s) \qquad (2)$$

Where Q = run off time

K_p = constant dependent upon the length and slope roughness of the plane.

$\partial\theta$ = change in slope gradient

∂t = change in time

Other equations have been developed to estimate overland flow (David and Beer, 1975; Ewing and Mitchell, 1986).

2.2.2 Rill erosion

Rill erosion occurs as a result of accumulation water on the surface, which supplies the energy to detach and transport soil particles (Schwab *et al.*, 1996). Rills are created at critical distances down slope where overland flow is concentrated and channelled. The result is creation of shear forces that the soil cannot resist, thus forming channels (Meyer *et al.*, 1975; Morgan, 1988).

Several models have been developed to estimate soil loss due to rill erosion (Meyer *et al.*, 1975; Elliot and Laflen, 1993). These models were worked out from hydraulic processes in the soil (Elliot and Laflen, 1993; Nearing *et al.*, 1994). According to Elliot and Laflen (1993), such models assume that rill erosion is dependent upon rill erodibility of the soil. Hence:

$$D_c = K_r(\iota - \iota_c) \qquad (3)$$

Where D_c = detachment capacity of clear water flow.

K_r = soil rill erodibility

ι = shear stress of flow (Pa)

= $\gamma_w r_n s$

γ_w = specific weight of water (Nm^{-3})

r_n = rill hydraulic radius (m)

s = hydraulic gradient (mm^{-1})

ι_c = critical hydraulic shear strength (Pa)

According to Nearing *et al.* (1994), the critical shear stress need not be emphasised since it is not the threshold level below which there is no soil detachment.

Another method for estimating rill erosion was developed by Lal and Elliot (1994). According to these authors

$$D_c = (\tau - \tau_c)\left(1 - \frac{Q_s}{T_c}\right) \tag{4}$$

Where D_c = rill detachment (kg/m^2s)

Q_s = rate of sediment transport in rills (kg/m s)

T_c = sediment transport capacity of rills (kg/m s)

τ = shear stress of flow (Pa)

τ_c = critical hydraulic shear strength (Pa).

Other estimates of rill erosion have been done by Gerasimenko (1980) and Mtakwa (1986).

2.2.3 Gully erosion

Gully erosion results from deepening and widening of rills, which then become difficult to obliterate by normal cultural practices (Hudson, 1995; Schwab *et al.*, 1996). Gullies are mostly formed as a result of mismanagement of the land (Bocco *et al.*, 1990; Selem and Zinck, 1994). Nonetheless, this process can also result from subsurface hydrological processes like, tunnel erosion, in which the subsurface flow exerts enough power to flush out from the tunnel (Hudson, 1995). Eventually it exposes the subsurface network as a gully (Hudson, 1995). This is common in soils having low permeability in the subsurface, and high exchangeable sodium and magnesium. According to Hudson (1995) gullies are also common in areas affected by landslides.

The amount of soil lost in gullies can be estimated by the volumetric method (Hudson, 1995), which measures the volume of soil lost in each section of the gully.

$$Volume = \sum (A_i + A_{i+1})\frac{L}{2} + (A_{i+1} - A_{i+2})\frac{L}{2} + ... + (a_{n-1} + A_n)\frac{L}{2} \qquad (5)$$

Where A = cross sectional area of a gully section

L = length between two successive cross section.

n = number of sections in a gully

i = section number

In some instances, the severity of gully erosion can be measured by the frequency of occurrence, area and the susceptibility of the area to gully erosion (Selem and Zinck, 1994).

2.2.4 Landslides

Landslides result from mass movement of soil especially in areas whose slopes are steep (Lal, 1990) and more pronounced in slope gradients greater than 32° (Temple and Rapp, 1972). Landslides prone areas are characterised by a surface soil loosely aggregated and an underlying impervious soil (Lopez and Zinck, 1991). When the topsoil is saturated with water, it can move *en masse* down slope, thus creating scars (Hudson, 1995).

Volume of soil loss through landslides can be estimated using the equation below (Temple and Rapp, 1972):

$$\text{Volume} = \pi ab \sin\theta \,(0.21a + 0.146L) \qquad (6)$$

Where a = maximum width of the eroded area

b = maximum depth of the eroded area, measured vertical distance from the surface

θ = slope angle

L = total length of the eroded slope

The extent to which the land has been affected by landslides can be measured by frequency of occurrence, total area affected and susceptibility of the land to landslides (Lopez and Zinck, 1991).

2.2.5 Other forms of erosion

Other forms of erosion are mostly localised to some areas, these include pedestal, pinnacle and piping erosion (Hudson, 1995).

Pedestal erosion occurs when easily eroded soil is protected on the surface by stones or tree roots. While the surrounding soils are eroded, pedestals or wall-like structures are capped by the stone or tree root, and are then left standing from the surrounding soil (Hudson, 1995).

Pinnacle erosion occurs mainly in gully beds, where deep vertical rills widen and join until pinnacles are formed and left standing like islands on the gully bed. Pinnacles form when resistant material cap the pinnacles like pedestal erosion (Hudson, 1995).

Piping erosion is the formation of continuous channels underground as a result of water infiltrating and moving down to a less permeable layer, at which water starts to move laterally, carrying with itself finer particles through the porous layer (Hudson, 1995). If lateral flow increases, more particles will be detached including some of the porous material, thus widening the pipes that end to develop tunnels.

2.3 Factors affecting water induced soil erosion

Water induced soil erosion is affected by climate, soil, vegetation and topography (Hudson, 1995). Soil, vegetation and topography can be altered by human interference, while climate is almost beyond that (Schwab *et al.*, 1996).

2.3.1 Climate

Climatic factors affecting soil erosion are precipitation (rainfall), temperature, wind, humidity and solar energy. Rainfall is the major climatic factor affecting soil erosion (Hudson, 1965). The capacity of the rainstorm to cause erosion is called rainfall erosivity (Lal and Elliot, 1994; Hudson, 1995; Schwab *et al.*, 1996). Rainfall intensity, amount, energy load, seasonality and variability affect soil loss, hence erosivity (Hudson, 1965; Lal, 1976; Wischmeier and Smith, 1978).

The amount of rainfall affects the amount of runoff, while intensity affects overland flow. Seasonality affects the amount of soil loss since a storm that comes after a dry spell will have direct impact on soil that is void of vegetation, thus causing erosion. High intensity storms are characterised by large sized raindrops, and higher number of drops per unit area at a time. This increases the rate of detachment and transport of particles (Hudson, 1995). Amongst all rainfall parameters enumerated above, momentum (Williams, 1969; Kinnell, 1973), drop size (Bisal, 1960; Nearing and Bradford, 1987) and kinetic energy (Wischmeier and Smith, 1978; Kinnell, 1981; Mutchler *et al.*, 1994) have been found to give good estimates of soil loss and erosivity. However, drop size is not commonly used because of the difficulty of its measurement. (Wischmeier and Smith, 1978; Hudson, 1995)

Consequently, many workers (Wischmeier *et al.*, 1958; Hudson, 1965; Carte *et al.*, 1974) have worked out erosivity indices which are based on the kinetic energy and rainfall intensity. Accordingly, a variety of erosivity indices have been developed to estimate the erosive power of rainfall in a variety of climatic conditions (Hudson, 1965; Lal, 1976; Wischeier and Smith, 1978).

There are mostly three rainfall erosivity indices that are commonly used to estimate the power with which a storm can cause erosion. These are: EI_{30}, KE>25 and AI_m Amongst these, EI_{30} is the mostly used one (Hudson, 1995; Mkoga, 1998). This index was developed by Wischmeier and Smith (1978) from soil splash, overland flow and rill erosion experiments. It was estimated from long-term continuous storm data as a product of an individual storm's kinetic energy (E) and the maximum 30 minutes storm intensity (I_{30}). The 30 minutes maximum storm intensity is calculated from recording rain gauge charts. The value of this index is then doubled to obtain the intensity in millimeters per hour basis. According to the authors, annual erosivity is the calculated as the summation of individual erosivities (equation 7 below).

$$R = \sum_{i=1}^{n} \left(EI_{30} \right) \tag{7}$$

Where n = number of storms in a year

The EI_{30} index was found to over estimate erosivity at high intensities (Wischmeier *et al.*, 1958) in the tropics, thus a maximum intensity of 76 mm/h was recommended. However, (Wischmeier and Smith, 1978) proposed a value of 63.5 mm/h for the same region. This index has been found to give good estimates of soil loss in Tanzania (Ngatunga *et al.*, 1984).

KE>25 index is a product of kinetic energy greater or equal to 25mm/h and the corresponding amount of rainfall (Hudson, 1965). This index was developed by

Hudson (1965) after observing that the EI_{30} was overestimating erosivity at intensities lower than 25 mm/h.

The AI_m index on the other hand, is calculated as the product of the amount of rainfall and peak intensity (Lal, 1976).

Both KE>25 and AI_m indices have been observed to provide unsatisfactory results (Stocking and Elwell, 1973; Elwell, 1977) although AI_m was reported by Lal (1976),. to estimate erosivity well in Nigeria.

Although rainfall erosivity indices provide accurate results, their use in the developing world is limited due to unavailability of long term storm data (Lal, 1976; Mulengera, 1996). Annual rainfall has been used to estimate rainfall erosivity in many parts of the tropics, with successful results in Nigeria (Kowal and Kassam, 1976) and Lal (1976), Zimbabwe (Elwell, 1977), Tanzania (Mulengera, 1996), and other parts of East Africa (Moore, 1979).

2.3.2 Soil

The capability of soil to be eroded is called erodibility, commonly denoted as K. Different soils have different degrees of susceptibilities to erosion due to the variation in their inherent (physical, chemical and mineralogical) properties (Schwab *et al.,* 1996). Wischmeier and Mannering (1969) described soil erodibility as a complex property, which depends upon a variety of factors. The authors found soils high in silt, but low in clay and organic matter to be highly erodible, whereby, the reduction in silt content resulted in soils being less erodible regardless of their sand or clay content.

Soil organic matter content is the second important soil characteristic that influences soil erodibility. This parameter contributes significantly to the stability of aggregates (Hillel, 1980), which in turn promotes the soil's resistance to erosion (Falayi and Lal, 1979). Rainfall energy is required to start runoff, and final infiltration rate (beyond which runoff starts) increases directly with organic mater content (Wischmeier and Mannering, 1969). Soils low in organic matter have been observed to be highly susceptible to erosion (Massey *et al.*, 1953; Lowrance and Williams, 1988; Tanaka and Aase, 1989; Kreznor *et al.*, 1989; Landon, 1991; Heil *et al.*, 1997).

Soil erodibility is commonly calculated from measured soil loss and rainfall erosivity index (EI_{30}) as follows:

$$K = \frac{A}{EI_{30}} \qquad (8)$$

Multi-factorial models are commonly used to estimate the erodibility of the soil (Wischmeier and Smith, 1978; Gachene, 1995; Mulengera, 1996).

A wide range of soil parameters have been used to estimate soil erodibility. Wischmeier and Smith (1978) developed the model which took into account soil structure, profile permeability, silt, clay and organic matter content. Gachene (1982) estimated soil erodibility of some Kenyan soils based on their dispersion ratio, clay content, bulk density and organic carbon content. Mulengera (1996) estimated satisfactorily soil erodibility by considering soil structure and profile permeability, on top of the parameters taken into account by Gachene (1982). However, where soil data is limited certain authors have been obliged to use a single parameter (Nyenza, 1995; Mulengera, 1996; Mkoga, 1998).

2.3.3 Topography

Topographic factors influencing detachment and transport of sediments are slope steepness, length and shape (Ngatunga *et al.*, 1984; Moore and Burch, 1986; McCool *et al.*, 1993; Schwab *et al.*, 1996). Steep slopes have high runoff thus allowing more sediments to be eroded (Kinnell and Cumming, 1993; Huang, 1998). Longer slopes allow accumulation of overland flow, which in turn increases rill erosion (Gilley *et al.*, 1987; McCool *et al.*, 1987; McIsaac *et al.*, 1987). Concave slopes are less erodible than convex slopes (Moore and Burch, 1986).

The slope length and steepness (LS) factors were derived from stream power theory (Yang, 1971; Yang, 1972), which describes erosion associated with rill flow (Lal and Elliot, 1994). The LS factor was found by Moore and Burch (1986) to be a measure of sediment transport capacity, based on the assumption that water on the surface has the ability to detach and transport soil by virtue of its position on an arbitrary datum.

The slope length factor is a measure of the ratio of soil loss from an area of a particular slope length, to that of length of some standard conditions (Wischmeier and Smith, 1978; Meyer, 1982; Stocking, 1987). Several equations have been developed based on a wide range of slope lengths in a variety of agro-climatic areas (Wischmeier and Smith, 1978; Meyer, 1982; Stocking, 1987; McCool *et al.*, 1993; Renard *et al.*, 1994). Equation for estimating this factor vary widely with slope steepness gradient (Wischmeier *et al.*, 1958; Ngatunga *et al.*, 1984; McCool *et al.*, 1987; McIsaac *et al.*, 1987; McCool *et al.*, 1993).

2.3.4 Vegetation

Vegetation reduces soil erosion by intercepting the flow, thus reducing the energy of the raindrop, surface sealing, and eventually runoff (Gregory and Ghebreiyessus, 1987; Schwab *et al.*, 1996). This has been observed in a number of recent studies (Nyenza, 1995; Mtakwa and Shayo-Ngowi, 1997; Mkoga, 1998). Vegetation improves aggregation and porosity of the soil by action of roots and decaying plant residues, which increase biological activities in the soil. (Gilley *et al.*, 1987).

2.3.5 Land use

This is another factor that contributes to a great extent, the rate of soil erosion. A land use type that leaves the soil surface void of vegetation increase the rate of soil loss by exposing the land to the agents of soil erosion. Some bad agricultural practices that have been associated with soil erosion include: cultivation or keeping livestock on steep slopes, shifting cultivation and deforestation (Queblating, 1984; Barrows, 1991). This has been reported in Tanzania by Rapp *et al.* (1973a). However, the rate of soil loss can be reduced by adopting some support practices, that is, using mechanical and biological control structures (Hudson, 1995). It is also of great importance that a type of use a piece of land is put to, should ensure sustenance of land resources.

2.4 Methods of assessing soil erosion

Extensive work has been done to understand the way erosion factors affect soil erosion (Wischmeier *et al.*, 1958; Hudson, 1965; Wischmeier and Mannering, 1969; Elwell, 1977; Wischmeier and Smith, 1978; Meyer, 1982). Accordingly, new approaches have been developed to predict soil erosion (Lopez and Zinck, 1991; Lal, 1994; Selem and Zinck, 1994; Mutchler *et al.*, 1994). These methods can be distinguished into three categories: direct, indirect and spatial approaches.

2.4.1 Direct measurements

There exist several methods with which the quantity of soil loss through erosion can be determined (Meyer, 1994). Of these, the use of erosion pins (Mtakwa, 1986) and direct measurement of sediment yield from erosion plots (Mutchler *et al.*, 1994) are the mostly used approaches.

2.4.1.1 Use of pins and rainfall simulators

This approach is mainly used for assessing rill and interrill erosion (Mtakwa, 1986; Meyer, 1994) to determine soil loss. The erosion pin is basically a benchmark, whose head is taken to be a reference height. The extent of soil loss or deposition is measured by the increase or decrease in height of the exposed erosion pin.

2.4.1.2 Measurement of sediment yield from erosion plots

The sizes of these plots vary from about 1 m^2 (Mutchler *et al.*, 1994), to 10 m^2 (Loch and Freebairn, 1984). The plots are normally used for studying interrill erosion (Meyer, 1994). Due to the small size of the plots, simulated rainfall is quickly shed off as overland flow, and there is no accumulation of overland flow that can create rills. Small plots provide accurate information about the factors affecting soil erosion, but the results are not easily transferable to the field (Mutchler *et al.*, 1994).

The standard USLE plots are widely used for studying both rill and interrill erosion. The plot dimensions are 22.1 m long and 4.1 m wide, with a slope gradient of 9%, thus making the LS factor of USLE unity (Wischmeier and Smith, 1978). These plots have been used extensively in estimating soil erosion in the tropics (Temple, 1973; Murray-Rust, 1973; Lundgren, 1980; Ngatunga *et al.*, 1984; Mtakwa, 1986; Mahoo, 1992; Gebremedhin, 1996; Mtakwa and Shayo-Ngowi, 1997, Vaje, 1998).

Apart from the use of small and standard USLE plots, soil erosion can also be measured on larger areas encompassing watersheds or a catchment. Such studies are carried out on large areas which commonly include at least one natural drain way (Mutchler *et al.*, 1994). Large plots are very good for assessing the impact of support practices on soil erosion, which can otherwise not be done on etither small plots or USLE plots (Mutchler *et al.*, 1994). Data on soil loss and runoff is collected using

Parshall flumes, H-flumes, water storage recorders, and pumping samplers. A few such studies have been done in Tanzania (Murray-Rust, 1973; Rapp *et al.*, 1973b; Lundgren, 1978). Some models have been developed to estimate runoff in water sheds (Borah, 1989a,b; Nearing *et al.*, 1989a).

2.4.1.3 Measurement of sediment yield from river basin

Measurement of sediment yield from river basins can provide important information about the rate of soil erosion in the watershed upstream (Walling, 1994). Suspended sediments of a river are measured by using manual samplers or automated continuous samplers. A few studies on river sediment yield have been documented in Tanzania (Temple and Sundborg, 1973) and elsewhere (Demmak, 1978; Oyebande, 1981).

2.4.2 Indirect methods

These methods are used to predict soil erosion and are commonly classified as physically or process-based and empirical models (Nearing *et al.*, 1994).

2.4.2.1 Process based models

Physically based models represent individual components affecting soil erosion and their interactions. These models are mainly used to determine the process that dominates erosion, in order to be given special attention (Ewing and Mitchell, 1986; Nearing *et al.*, 1994). The models use hydraulic equations, which are more precise in estimating the erosion process than regression equations of empirical models. The

The USLE model was developed by Wischmeier and Smith (1978). This model estimates long-term annual soil loss for at least 20 years. The model is in the form:

$$A = R\,K\,L\,S\,C\,P \qquad (9)$$

Where A = predicted annual soil loss (Mg/ha-year)

R = annual rainfall erosivity index (MJ mm/ha year)

K = soil erdibility (Mg-ha-h/ha-MJ-mm)

L = slope length factor (dimensionless)

S = slope steepness factor (dimensionless)

C = crop cover and management factor (dimensionless)

P = support practice factor (dimensionless)

The USLE model has stood the test of time, as a tool for estimating the rate of soil erosion (Wischmeier and Smith, 1978; McCool *et al.*, 1987; McIsaac *et al.*, 1987; McCool *et al.*, 1993). This model can be used to calculate sediment yield using sediment delivery ratio (SDR) to account for deposition. The model is a component of the Chemical, Runoff and Erosion from Agricultural Management Systems (CREAMS) model (USDA, 1980). It has several inconveniences which make it to be less adopted to other parts, particularly in the tropics (Renard *et al*, 1994). A few attempts have been made to modify it and hence use it for estimating and classification of soil erosion under the tropical conditions (Cook, 1975; Gachene, 1982; Dissmeyer, 1982; Mulengera, 1996; Mulengera and Payton, 1998).

FAO (1979) made some modification of the USLE equation by introducing categories of climate, soil, topographic factors as means of improving it.

Soil Loss Estimation Method for Southern Africa (SLEMSA) model was initially designed to replace the ULSE for use in the tropics especially in Southern Africa (Stocking and Elwell, 1973; Stocking, 1987), which was found to be deficient in estimating the erosive power of rainfall and soil erodibility. It takes the form:

$$Z = K \times C \times X \qquad (10)$$

Where Z = estimated annual soil loss (t/ha-year)

K = mean annual soil loss caused by a given rainfall energy (J/m^2) for a standard plot 30 m long by 10 m wide and 4.5% slope, under weed free conventionally tilled bare fallow management.

C = ratio of soil loss from cropped plot to that of a standard SLEMSA plot, using percentage canopy cover

X = ratio of soil loss from a plot length l and slope steepness S, to that of a standard SLEMSA plot

In appreciation of this, the model has been widely used to classify soil erosion in the tropics (Cook, 1975; Gachene, 1995; Mulengera, 1996).

The SLEMSA model has been used to map the risk of soil erosion. The approach is also called factorial scoring, and it involves the use of a base map divided into grid units, rated on a scale of 1 to 5 factors of erosion, namely: erosivity, erodibility, slope, ground cover, and human occupation (Stocking, 1987). The factors are scored and summed up to give a total score, which is then compared to an arbitrarily chosen classification of low, moderate and high risk of erosion. The scores are mapped and areas with similar erosion risk delineated. This model has been used to classify erosion at small scale and medium scale mapping by Stocking and Elwell (1973) and Stocking (1987) in Zimbabwe and Ndyetabula (1988) in Tanzania.

Soil erosion leads to removal of topsoil, and as such reduction in topsoil depth. Topsoil depth has been adopted by some workers to measure the extent of past erosion in East Africa (Kilasara *et al.*, 1995b; Kaihura and Lungu, 1996; Saether *et al.*, 1997; Gachene *et al.*, 1998). This has also been done elsewhere in the world (McDaniel and Hajeck, 1985; Tanaka and Aase, 1985; Lo, 1989; Tegene, 1992; Littleboy *et al.*, 1996).

This approach involves excavation of mini pits from which the depth of the topsoil is measured, and categorised into a maximum number of erosion classes.

2.5 Testing the soil erosion classes

Establishment of soil erosion classes is of no significance unless the established classes are evaluated. Two approaches have been used, either by actual measured sediment losses or crop yield.

2.5.1 Measurement of sediment yield to validate erosion models

Soil erosion models especially the ULSE have been widely used to assess soil erosion. High correlation has been observed between actual measured sediments and predicted rainfall erosivity (Lal, 1976; Mkoga, 1998). Estimated soil erodibility has also been observed to be highly correlated to measured soil loss (Gachene, 1982; Mulengera, 1996). Information on the SLEMSA model is scanty. The use of the soil erosion-crop productivity relationships to evaluate erosion models is highly limited. Nonetheless, a few have been conducted with the USLE model (Mokhtaruddin *et al.*, 1984; Melo-Filo and Silva, 1993; Stocking *et al.*, 1997) with some success.

2.5.2 Use of topsoil depth

This criterion has been widely used to assess the impact of soil erosion classes on crop productivity. Topsoil depth reduction has been found to reduce crop yield in a variety of studies (Kilasara *et al.*, 1995b). In the tropics, this has been documented in India (Littleboy *et al.*, 1996), Australia (Tanaka and Aase, 1985), United States of America (McDaniel and Hajeck, 1985; Andraski and Lowery, 1992), Taiwan (Lo, 1989), Ethiopia (Tegene, 1992) and in Kenya (Gachene *et al.*, 1998). In Tanzania, this relationship was observed by Kilasara *et al.* 1995b, Kaihura and Lungu (1996) and Saether *et al.* (1997).

De-surfacing experiments have been used to emulate natural erosion (Lo *et al.*, 1995). This too has been demonstrated to reduce crop yield in Nigeria (Lal, 1981; Mbagwu *et al.*, 1984), Canada (Izaurralde *et al.*, 1985; Larney *et al.*, 1995) and in Indonesia (Siebert and Scott, 1990). However, these experiments have been criticised for not simulating natural erosion, which is selective in nature (Pierce and Lal, 1994).

2.6 Mapping of soil erosion

Soil erosion mapping delineates areas threatened by erosion at different levels, and depends very much on the criterion used to establish the various classes. The mapping exercise depends on the scale of mapping and the parameters used for assessing erodibility of the soil. General mapping uses small scale, remote sensing techniques and complemented with ground features to represent soil features. Only a few observations are made per unit area. This has been demonstrated by several workers in Tanzania (Cook, 1975; Ndyetabula, 1988; Mulengera, 1996; Mulengera and Payton, 1998; Mboya, 1998).

On the other hand, detailed erosion hazard mapping requires a lot of soil data with more observation per unit area of land than generalised mapping. Though expensive, detailed mapping provide precise estimate of erosion, and has been demonstrated by

Gachene (1995) in Kenya. The depth of the topsoil has not received interest in as far as mapping soil erosion is concerned.

2.7 Synthesis of literature review

The types of soil erosion have been briefly discussed in the preceding sections of this chapter, with emphasis on water induced erosion. The common forms of soil erosion by water are interrill, rill, gully and some specialised forms of erosion. These forms have been discussed in great detail, with some particular reference to estimation of sediment yield. Soil erosion is mainly influenced by climate, vegetation, topography, soil type and land use. These factors do not act in isolation, but act simultaneously, to cause soil loss.

The impact of soil erosion is well documented. Amongst other things, the process results in soil loss, nutrient loss and eventually decline in crop yield. Studies on soil erosion have thus been conducted, mainly on direct measurement of soil loss (using erosion pins, runoff plots and river sediments) and indirectly using process based models (WEPP) and empirical models (USLE, SLEMSA).

Although there is abundance of literature on types, factors and impact of soil erosion, little has been done to assess the spatial distribution of soil erosion in the developing world.

CHAPTER THREE

3 MATERIALS AND METHODS

3.1 Location of the study area

The study was conducted at SUA farm located in Morogoro, Tanzania, at latitude 6° 51' S and longitude 37° 39' E. It is bordered by the Uluguru Mountains on the south west, Mindu hills on the west and Lugala hills on the North West (Fig. 1). The total area of the farm is approximately 2 300 ha (Mpepo, 1986). The study site is located in the South Eastern part of the farm, with an area of 25 ha. The study area borders the Dar es Salaam-Iringa road in the West, and Morogoro-Mzinga road in the East.

3.2 Climate, geology and soils of the study area

3.2.1 Climate

The climate of the study area is transitional between sub-humid and semi-arid (Kilasara *et al.*, 1995b), with a bimodal type of rainfall. Annual rainfall averages about 853.5 mm. The short rains (locally called *vuli*) starts from November and ends in January, with a peak in December. The long rains (locally called *masika*) extents from March to May with a peak in April (Fig. 2). Evapotranspiration rates are highly variable throughout the year. The highest rates are observed between September and March, and the lowest in June, July and August. Between March and May rainfall exceeds evapotranspiration (Figure 2).

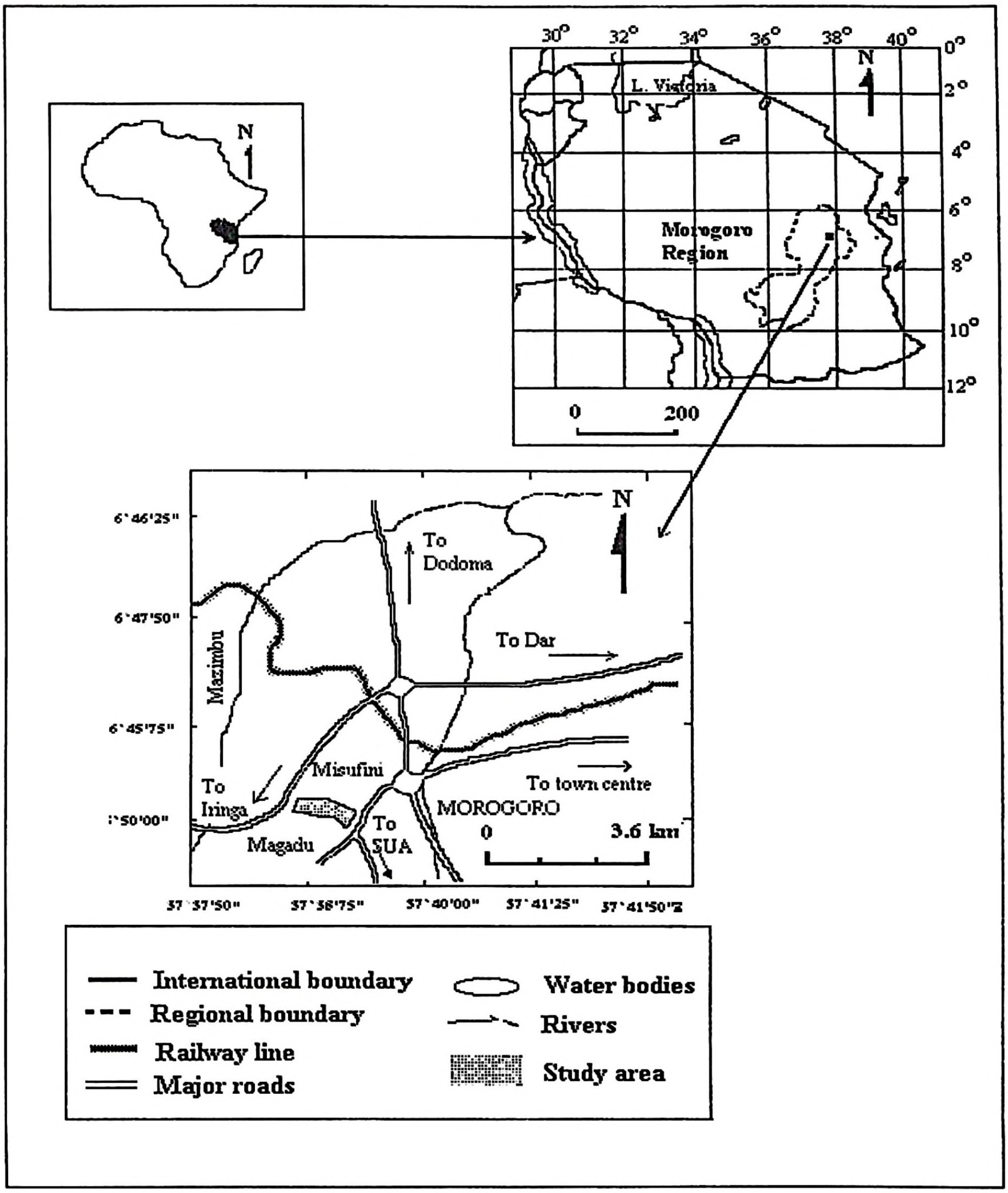

Fig. 1 Location of study area

The study area is normally warm throughout the year. The temperatures average 24 °C, with mean maximum and minimum temperatures of 30 °C and 18 °C, respectively (Fig. 2).

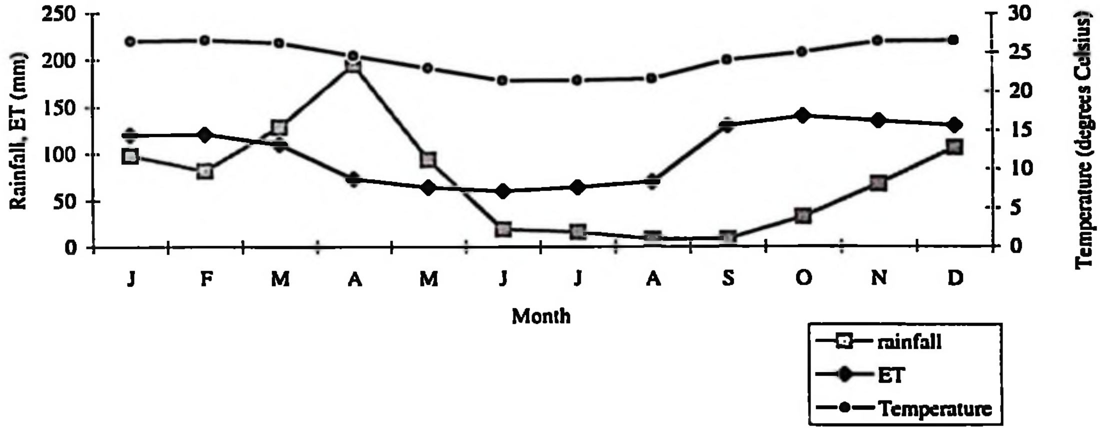

Fig. 2. Monthly rainfall, evapotranspiration and temperature of the study area for the period of 1971-1995 (Source: SUA Meteorological Station)

3.2.2 Geology

The study area on which SUA farm is located belongs to the Usagaran System of the Mozambican belt, with Precambrian gneiss (Saggerson, 1962; URT, 1976). The predominant rocks are metamorphic horneblende-pyroxene granulites.

3.2.3 Soils

The study area contains two soil types, *Typic Rhodustalf* and *Typic Ustorthent* (Soil Survey Staff, 1998), which are located on gentle slopes ranging between 0.5° to 7° in both soil types. The areas with these soil types will be referred to as site 1(*Typic Rhodustalf*) and 2 (*Typic Ustorthent*) respectively.

3.3 Land use

The farm was originally a sisal estate, and was handed over to the University in 1965. Currently, it is entirely under arable agriculture, whereby the majority of the natural vegetation has been removed. However, there is a pre-dominance of grass species especially *Andropogon* spp, *Hyperrhenia* spp and *Themeda* spp (Kaaya, 1989). The main crops grown include maize, sorghum, beans and rice. All crops are rainfed, and primary tillage is mechanised with lighter machinery. Harvesting and weeding are done manually.

3.4 Assessment of soil erosion

Two separate approaches were employed to assess soil erosion in the study area. The criterion developed by Gachene (1995) was employed to assess erosion susceptibility in the study area, while that of Kilasara *et al.* (1995a) was used to distinguish varying degrees of past erosion. The method by Gachene (1995) was improved to include the crop cover and management factor, the use of the EI_{30} index, instead of an equation, for estimating rainfall erosivity, and finally estimation of the LS factors using equation for slopes less than 9° (MacCool *et al.*, 1993).

3.4.1 Determination of soil erosion susceptibility classes

3.4.1.1 Topographic survey

Prior to the determination of the susceptibility of the soil to erosion, a detailed topographic survey was carried out with an intention of determining the slope characteristics of the land. With the aid of an automatic level, survey staff, ranging rods and a survey chain, a network of 20m spaced grid points was established for making observations. For each of the points, slope length, slope aspect and slope gradient were determined using the procedure outlined by FAO (1990). These parameters were recorded for use in estimating the susceptibility of the land to erosion. Slope gradient was calculated from readings of the automatic level using the equation below:

$$\%\ \text{slope} = \Delta\ \text{reduced level/grid spacing} \qquad (11)$$

where: Δ reduced level = difference in reduced levels of adjacent grid points

3.4.1.2 Soil sampling

At each grid point, a mini pit of 30 cm by 30 cm was dug to a depth of 50 cm. The morphological properties of each pit were recorded and compared with those of the next pit. Representative soil samples of areas having pits with similar characteristics were obtained for laboratory analyses.

3.4.1.3 Laboratory analysis

The soil particle size distribution, dispersion ratio, bulk density and organic carbon were determined. Particle size distribution was measured following the procedure by Gee and Bauder (1986). The dispersion ratio was measured by method of Middleton (1930). Bulk density was determined using the method by Blake and Hartge (1986), while organic carbon was measured by the wet combustion method (Nelson and Sommers, 1982).

Evaluation of erosion classes was done on two types of soils, *namely Typic Rhodustalf* and *Typic Ustorthent*, which were classified by Kaaya (1989). The criteria developed by Gachene (1995) and Kilasara *et al.*, (1995a) were adopted for erosion hazard mapping, and mapping of the extent of cumulative erosion, respectively.

3.4.1.4 Determination of soil erosion susceptibility classes

Data acquired in sections 3.4.1.1 and 3.4.1.2 were processed to estimate the L, S and K factors of the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The L and S factors were determined using the procedure by MacCool *et al.* (1993), while the K factor was estimated using the model developed by Gachene (1982). The rainfall erosivity factor was taken to be the average of the EI_{30} values of Morogoro soils (Nyenza, 1995; Mkoga, 1998). The crop cover and management factor was calculated empirically using the previous land use (PLU) sub-factor by using the Dissmeyer (1982) equation:

$$LS = \left(\frac{l}{22.13}\right)^{m} (10.8 \sin\theta + 0.03) \qquad (12)$$

$$\text{Where: } m = \frac{\beta}{\beta + 1} \qquad (13)$$

$$\beta = \frac{\left(\frac{\sin\theta}{0.0896}\right)}{\left(3.0(\sin\theta)^{08} + 0.56\right)} \qquad (14)$$

l = slope length (m)

θ = slope angle (degrees)

$$K = 0.297 + 0.069DR - 0.001Clay - 0.011OC - 0.14BD \qquad (15)$$

Where DR = dispersion ratio (%)

Clay = percent clay

OC = organic carbon (%)

BD = bulk density (g cm^{-3})

$$PLU = \sum_{i=1}^{n} F \times \frac{EI_{30(F)}}{EI_{30(Total)}} \qquad (16)$$

Where F = factor for the crop growth stage

$EI_{30(F)}$ = monthly erosivity corresponding to a crop growth stage (MJ mm ha^{-1} h)

$EI_{30(Total)}$ = total or annual erosivity (MJ mm ha^{-1} h^{-1})

I = number of months in a year

Based on the above information, different erosion susceptibility classes were formulated using a Turbo Pascal Programming Language (Appendix 1).

The erosion susceptibility classes were soil loss <4 000 kg/ha, 4 000 – 8 000 kg/ha, and > 8 000 kg/ha (by frequency distributions), to represent least erodible, moderately erodible and highly erodile soils, respectively. These classes will be referred to as L, M and H for least erodible, moderately erodible and highly erodible, respectively in the rest of the text.

3.4.2 Determination of the extent of past erosion

Soil samples were obtained from the grid points established in section 3.4.1, from which data on the following soil morphological characteristics were obtained: soil texture by the feel method, consistence of wet and dry soil, soil structure and colour. Soil texture, structure and consistence were determined following the procedure outlined by FAO (1990). The soil colour was determined using the Munsell Soil Colour Chart (1994). These parameters were thereafter used to determine the limit between the topsoil and subsoil in respective soil pit. The thickness of the former was therefore recorded in cm. The individual erosion classes were recorded as <15cm, 16-20cm and >20cm, to represent highly eroded, moderately eroded and least eroded erosion classes. In the remaining part of the text these classes will be identified as H, M and L respectively. These classes were obtained from the cluster diagram which was made by plotting topsoil depth versus number of occurrence of a topsoil depth.

3.4.3 Mapping of soil erosion

Both severity and susceptibility erosion classes were mapped at a scale of 1:5 000. Areas with the same erosion class were put under the same mapping unit.

3.5 Assessment of the applicability of the soil erosion classes

Maize (*Zea mays*), cultivar Kito was grown as a test crop on each of the erosion susceptibility and severity classes. For each soil erosion class three plots measuring 5m × 5m were planted with maize at a spacing of 90cm × 30cm. Half the recommended nitrogen fertiliser in the form of urea (40 kg/ha nitrogen), was applied to the crop three weeks after emergence. The crop was grown under rainfed conditions, and other agronomic husbandry practices like weeding and pesticide application were carried out as usual.

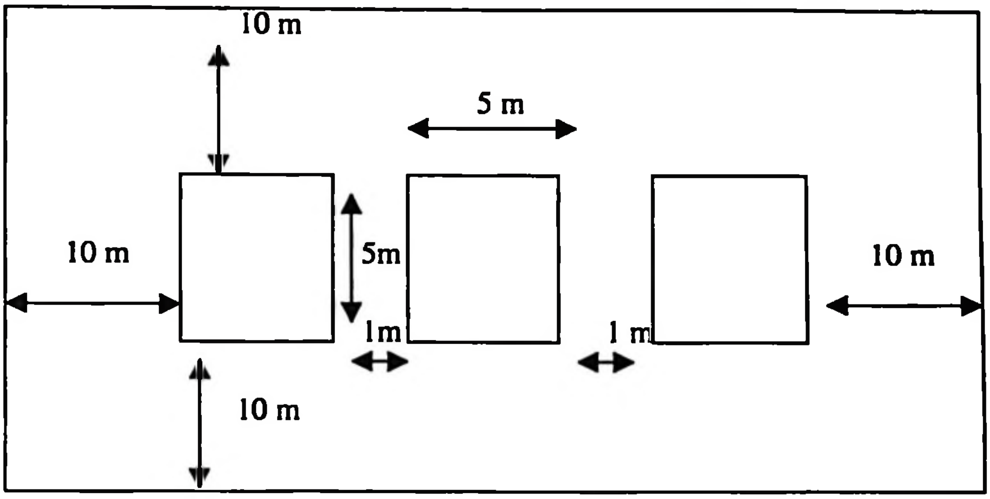

Fig. 3. Plot layout for the maize crop on a respective erosion susceptibility or severity class

At tasseling, 50 days after emergence, ten representative maize stalks from each plot were harvested, chopped to smaller pieces and then dried in the oven at 75 °C for 48 hours to obtain plant dry mass, after which they were weighed. Maturity was observed 90 days after emergence in which maize cobs from each plot were harvested, sun dried and threshed. The grain weight was obtained using a balance. Moisture content of the grain was determined using a moisture meter, and the weight of the grains was converted to dry basis (12% moisture content).

3.5.1 Statistical analysis

Data from grain yield and dry matter were analysed by Microsoft Excel 7.0, by subjecting them to a one way analysis of variance. Least Significance Difference was used to separate the means. Correlation coefficients and regression were run between topsoil depth and dry matter and grain yield, and between estimated soil loss and yield parameters using MSATC.

CHAPTER FOUR

4 RESULTS AND DISCUSSION

4.1 Characteristics of the soils in the study area

The physical properties of the soils of the two study sites are shown in Table 1. The soils of both sites were had relatively high clay content. It ranged from 30 to 49%, and increased with depth from the Ap to the B horizon in both sites. On site 1, the silt content varied between 3.7 and 7.5% while on site 2 it ranged from 3.7 to 6.2%. The textural class for the two sites ranged from sandy clay loam in the topsoil to sandy clay or clay in the subsoil.

The topsoil had relatively high bulk density values. They ranged from 1.39 to 1.54 Mg/m^3. The subsoils were more compacted as exemplified by the relatively high bulk density values. The latter ranged from 1.39 to 1.63 Mg/m^3.

The available water capacity in both soils did not vary appreciably from one soil to another, neither did it change substantially with soil depth (Table 1).

The chemical properties of the soils are shown on Table 2. Both soils were slightly acidic with pH (water) that ranged from 6.1 to 7.0. Both soils had relatively high cation exchange capacity (26.5 - 56.5 cmol(+)/kg) clay. The exchange sites were dominated by exchangeable calcium and magnesium. The content of exchangeable sodium and potassium was extremely low in both soils. The total organic carbon content of both soils was relatively low in the topsoil (1.09 - 1.17%), and decreased with depth. The content of total nitrogen ranged from 0.14 to 0.18% in the topsoil of both soils, and it decreased only slightly with depth.

There was a slight difference between the two soils in terms of their available phosphorous content. The soils in site1 had 1.75mg/kg P in the topsoil while in site 2 the phosphorous content was 3.51 mg/kg. In both soils the level of phosphorous decreased sharply in the B horizon.

Based on the characteristics of the soils, the soils in site 1 and 2 were classified in accordance to the Soil Survey Staff (1998) as *Typic Rhodustalf* and *Typic Ustorthent* respectively. These terms are used in the rest of the text to denote the soil on site1 and site 2 respectively.

Table 1. Physical properties of the soils in the study area

Site	Soil type	Horizon	Depth (cm)	Bulk density	Water holding capacity (%)		Available water capacity	Particle size distribution (%)			Textural Class name
				(Mg/m³)	0.3bar	15 bar	(%)	clay	silt	sand	
1	RT	Ap	0-17	1.39	21.7	9.7	12.0	30.2	6.2	63.6	SCL
		B21t	17-42	1.41	25.9	12.3	13.6	46.1	3.7	50.2	SC
		B22t	42-411	1.39	26.7	13.3	13.4	49.6	4.9	45.5	SC
		B23t	100-121	1.43	27.7	13.2	14.5	44.5	6.2	49.3	SC
		B24t	121-146	1.53	30.4	13.8	16.6	49.1	7.5	43.4	C
		C	>146	n\a	n\a	n\a	n\a	N\a	n\a	n\a	n\a
2	UT	Ap	0-8	1.54	24.4	13.2	11.2	30.1	4.9	65.0	SCL
		B21t	8-20	1.51	26.6	16.6	10.0	30.8	3.7	59.5	SC
		B22t	20-80	1.54	17.4	11.6	5.8	40.5	5.4	54.1	SC
		C	>80	1.63	N\a	n\a	n\a	34.8	6.2	59.0	SCL

Note:

RT: Typic Rhodustalf

UT: Typic Ustorthent

SCL: sandy clay loam

SC: sandy clay

C: clay

Table 2. Chemical properties of the soils in the study area

Site	Soil type	Depth (cm)	pH		Cation exchange capacity(cmol(+)/kg)		BS (%)	Exchangeable bases (cmol(+)/kg)				OC (%)	N (%)	P (mg/kg)
			1:2.5 water	1:2.5 $CaCl_2$	Clay	Soil		Na^+	K^+	Mg^{2+}	Ca^{2+}			
1	RT	Ap	6.4	5.6	32.80	6.74	53.0	0.13	0.18	1.48	4.32	1.09	0.14	1.75
		B21t	6.1	5.1	26.51	5.02	36.6	0.18	0.18	1.98	2.65	0.58	0.11	1.75
		B22t	6.6	5.4	26.62	4.95	34.8	0.16	0.09	2.72	1.98	0.39	0.10	0.88
		B23t	6.8	5.5	54.13	5.25	21.0	0.24	0.13	2.67	2.21	0.35	0.06	0.88
		B24t	6.9	5.6	56.51	6.94	24.4	0.45	0.12	2.98	3.39	0.26	0.08	0.88
2	UT	Ap	6.8	5.8	36.26	12.74	89.0	0.15	0.35	2.06	8.78	1.17	0.18	3.51
		B21t	6.5	5.5	36.98	15.68	57.2	0.30	0.21	1.56	6.90	0.80	0.12	2.75
		B22t	6.9	5.7	30.43	13.72	71.0	0.21	0.06	2.10	7.37	0.54	0.11	0.88
		C	7.0	6.1	35.75	13.23	91.7	0.29	0.08	2.14	9.72	0.31	0.07	0.63

Note:

RT: = Typic Rhodustalf

$$BS = \left[\frac{Ca^{2+} + Mg^{2+} + Na^{+} + K^{+}}{CEC} \right]$$

UT: = Typic Ustorthent

BS = base saturation (%)
K^+ =exchangeable potassium
OC = organic carbon
CEC = cation exchange capacity
Mg^{2+} = exchangeable magnesium
N = total nitrogen
Na^+ = exchangable sodium
Ca^{2+} = exchangeable calcium
P = availabe phosphorous

4.2 Potential soil loss in the study area

4.2.1 Estimation of potential soil loss

Table 3 shows the frequency distribution of estimated soil loss on both sites of the study area. Values ranged from 1.0 to 17 Mg/ha/year.

Table 3. Frequency distribution of estimated soil loss in the study area

Estimated soil loss (Mg/ha/annum)	Frequency of occurence		
	Site 1	Site 2	Sites 1 and 2
1-1.99	28	0	28
2-2.99	53	5	58
3-3.99	30	15	45
4-4.99	9	44	53
5-5.99	5	14	19
6-6.99	6	11	17
7-7.99	9	7	16
8-8.99	8	4	12
9-9.99	8	2	10
10-10.99	5	1	6
11-11.99	3	1	4
12-12.99	1	2	3
13-13.99	0	1	1
14-14.99	0	1	1
15-15.99	0	0	0
16-16.99	0	0	0
>17	0	3	3

At site 1 the estimated soil loss ranged from 1 to 12.99 Mg/ha/year. Further examination of the results shows that in site 1 potential soil loss of 2 –2.99 Mg/ha/year was the most frequently encountered or estimated value, followed by the 3 –3.99 and 1 – 1.99 Mg/ha/year. There were much fewer values that ranged from 4 Mg/ha/year and above.

At site 2, the estimated loss values ranged from 2 to 17 Mg/ha/year. The most frequently encountered soil loss ranged from 4 to 4.99 Mg/ha/year. This was followed by the 3 – 3.99 and 6 – 6.99 Mg/ha/year, respectively. Values of 7 Mg/ha/annum or more were comparatively very few.

Based on the above distribution of potential soil loss estimates, three soil erosion susceptibility classes were established for each site as follows: highly erodible (H), slightly erodible (M) and lastly least erodible (L) representing erosion hazard of more than 8 Mg/ha, 4 - 8 Mg/ha, and less than 4 Mg/ha/year respectively (Figures 4 and 5).

4.2.2 Spatial distribution of soil erosion susceptibility in the studied area

At site 1, the areas under different erosion susceptibility classes differ considerably (Map 1). Soil erosion class L was the largest, occupying 7.4 ha (59.5%), followed by soil erosion class M, which covered an area of 3.4 ha (27.4%). Soil erosion class H was least occupying an area of 1.6 ha (13.1%). At site 2 the distribution of the erosion susceptibility classes followed this trend: class M covered 8.6 ha (61.9%), class L occupied 2.3 ha (18.2%) and class H occupied 1.7 ha (13.6%).

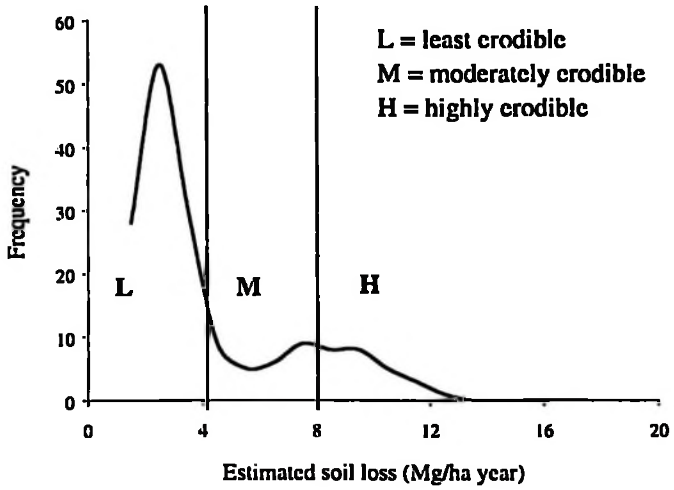

Fig. 4. Soil erosion susceptibility classes at site 1

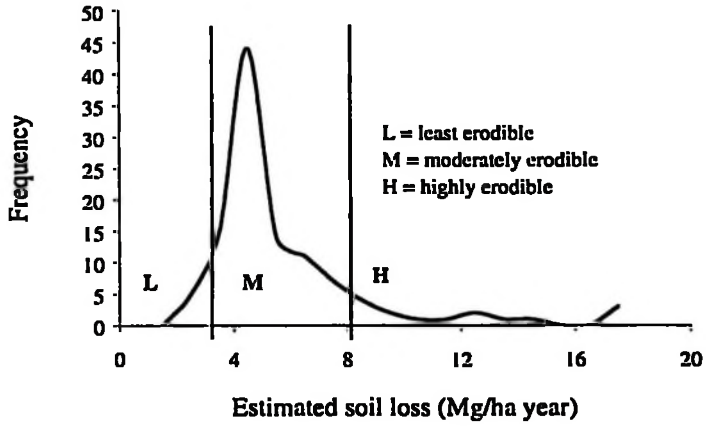

Fig. 5. Soil erosion susceptibility classes at site 2

4.3 Topsoil thickness of the soils in the study area

The distribution of topsoil depth in the study area is shown in Table 4. Values of the topsoil depth varied widely over the two sites.

Table 4. Distribution of topsoil depth in the study area

Topsoil depth (cm)	Frequency of occurrence		
	Site 1	Site 2	Sites 1 and 2
10	1	4	5
11	1	4	5
12	2	7	9
13	14	13	27
14	14	20	34
15	9	16	25
16	11	14	25
17	8	23	31
18	8	20	28
19	6	13	19
20	6	6	12
21	4	6	10
22	4	3	7
23	2	3	5
24	4	2	6
25	2	2	4
26	2	5	7
27	1	1	2
28	4	3	7
29	1	0	1
30	2	0	2
32	1	2	3
40	1	0	1
42	1	0	1
50	1	0	1

At site 1 the topsoil depth varied from 10 to 50 cm, while at site 2 it ranged from 10cm to 32 cm.

The distribution of the topsoil thickness in the study area followed nearly the same trend for both sites (Figures 6 and 7). At site 1, the largest number of observations were found to lie between 13 and 15 cm. The remaining observation clustered in the following order: 16-20 cm > 21-26 cm> 27 cm.

At site 2, majority of the observations made had a topsoil depth that ranged from 13 to 19 cm. Examination of Table 5 reveals that this range tended to split into two subclasses, one in which the topsoil depth varied from 13 – 15 cm with a median of 14 cm and the other one with a topsoil range of 16 – 19 cm with a median of 18 cm. The frequency of topsoil depth above 20 cm seemed to vary irregularly, but in a decreasing manner with increase of topsoil depth.

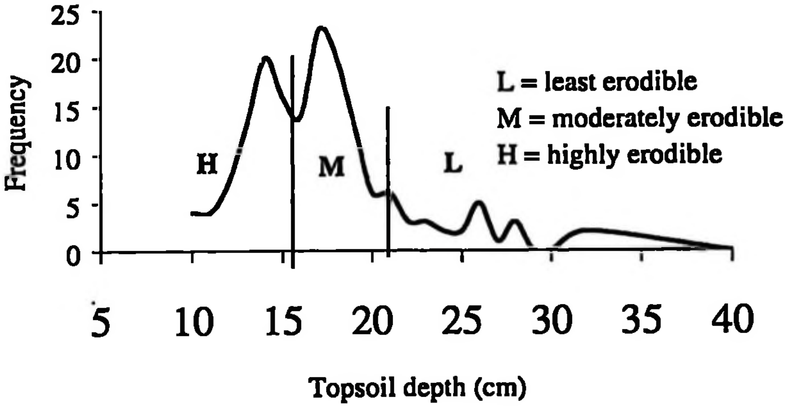

Fig. 6. Frequency distribution of topsoil depth and soil severity classes for site 1

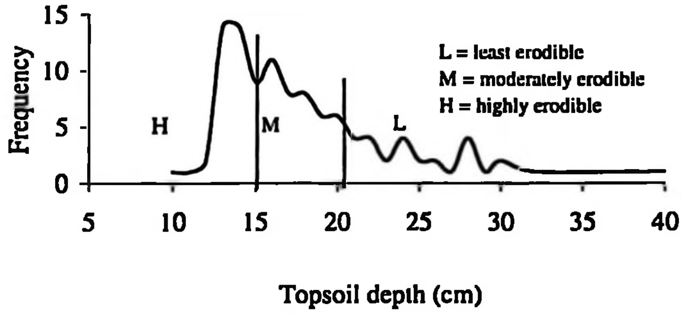

Fig. 7. Frequency distribution of topsoil depth and soil severity classes for site 2

Based on these groupings, the study area was divided into three erosion severity classes: least eroded (L), representing topsoil depth of < 15 cm; moderately eroded (M), representing depth range of 16 - 20 cm; and highly eroded (H), representing topsoil depth of >20 cm.

4.3.1 Mapping of the severity of soil erosion in the studied area

At site 1, there is a great distinction between the soil erosion classes. As indicated in Map 2, the most prevalent erosion severity class was M, occupying an area of 5.7 ha, followed by erosion class H and eventually erosion class L. They occupied in thew same order, 5.7 ha (45.5%), 4.6 ha (38.3%) and 3 ha (16.2%) of the studied area, respectively.

The study area at site 2 was almost equally sub-divided into the three soil erosion severity classes. Soil erosion severity classes H and M, each occupied an area of 4.4ha (35.5%), while soil erosion severity class L occupied 3.6 ha (29%).

4.4 Soil erosion susceptibility and crop production relationships

Table 5 shows the relationship between estimated soil loss and maize grain and biomass yields in the study area.

Table 5. Maize grain and biomass yield of the erosion susceptibility classes of the studied area

Site	Erosion susceptibility class	Maize yield (Mg/ha)	
		Grain	Biomass
Site 1	High (H)	2.176^a	1.746^a
	Moderate (M)	2.880^b	1.742^a
	Least (L)	3.417^c	2.355^b
Site 2	High (H)	1.913^a	1.264^a
	Moderate (M)	3.125^b	1.895^b
	Least (L)	3.004^b	2.337^c
Both sites	High (H)	2.815^a	1.919^a
	Moderate (M)	3.027^a	1.822^a
	Least (L)	2.798^a	2.190^b

Grain yield tended to increase from the highly susceptible class to the least susceptible class at site 1. There was maize grain and biomass yield reductions of 175 and 1kg/Mg of estimated soil erosion, respectively, between soil erosion susceptibility class H and M. Maize grain and biomass yield reductions of 134 kg/Mg (16%) and 155 kg/Mg (26%) were observed between class M and L, respectively.

At site 2 grain yield and biomass decreased from low erosion susceptibility class to high erosion susceptibility class. There was a grain yield and biomass decline of 136 (36%) and 134 kg/Mg (46%) between the highly erodible and least erodible soils, respectively. Maize grain and biomass yield decrease of 152 (39%) and 158 kg/Mg (33%), were observed between erosion susceptibility classes H and M. On the other hand, maize grain and biomass yield loss of 30 (4%) and 111 kg/Mg (19%) of soil loss, were observed between soil erosion susceptibility classes M and L.

Generally, at site 1 grain yield difference was statistically significant ($P<0.05$) amongst the susceptibility classes. There was a grain and biomass yield loss of 2.9 kg/Mg and 152 kg/Mg of soil loss, between the highly susceptible class and in the least susceptible one, respectively.

Values for site 2 followed the same trend and were comparable to those obtained at site 1, though significant difference was only observed between the highly susceptible class and the rest of the classes. Grain yield reduction of 57 kg/Mg of soil loss, and loss, and biomass reduction of 2.7 kg/Mg increase in estimated soil biomass reduction of 92 kg/Mg of soil loss.

4.5 Soil erosion severity and crop productivity relationships

Table 6 shows the effect of cumulative soil loss on maize biomass and grain yield in the studied area.

Table 6. Variation of erosion on maize grain and biomass yield with soil erosion severity in the study area

Site	Erosion class	Maize yield (Mg/ha)	
		Grain	Biomass
Site 1	High (H)	2.646^{a}	1.723^{a}
	Moderate (M)	3.306^{b}	2.255^{b}
	Least (L)	3.473^{b}	2.390^{b}
Site 2	High (H)	2.642^{a}	1.577^{a}
	Moderate (M)	2.697^{a}	1.828^{a}
	Least (L)	3.070^{a}	2.381^{b}
Both sites	High (H)	2.645^{a}	1.665^{a}
	Moderate (M)	2.819^{a}	1.913^{b}
	Least (L)	3.271^{b}	2.385^{c}

At site 1, soil erosion severity class H had significantly lower grain yield than classes M and L ($P<0.05$). Erosion class L had the highest grain yield though it did not differ significantly from that of class M. The same trend was observed with biomass yield. A similar increase occurred with the biomass but in this case there was a significant difference ($P<0.05$) between the moderately (M) and high (H) erosion classes. Grain and biomass yield increased by nearly 132 and 106 kg per cm extra topsoils between the high and moderate erosion classes respectively.

4.6 Causes of Maize yield variation due to changes in soil erosion susceptibility class

Both maize grain and biomass yield were correlated to a number of parameters which were used to estimate the soil loss (Table 7). The maize grain yield was significantly ($P< 0.05$) correlated to the organic carbon content ($r^2 = 0.\ 11$), bulk density ($r^2 = 0.\ 27$) and dispersion ratio ($r^2 = 0.\ 23$), slope ($r^2 = 0.\ 34$)

As far as biomass yield is concerned, it was significantly correlation with a number of the parameters which form the basis for estimating soil loss as follows: slope (r^2 = 0. 35), clay content (r^2 = 0. 16) and bulk density (r^2 = 0. 12) (Table 7).

Table 7. Regression equations relating maize yield and parameters used to estimate soil loss

Dependent variable	Independent variable	Regression equation	r^2	Mse	Std. Error
Biomass	SL	$DM = 0.107SL + 2.487$	0.49***	0.10	0.32
	OC	$DM = 0.9727OC + 0.5818$	0.11*	0.18	0.42
	BD	$DM = 2.4262BD - 1.7366$	0.27***	0.14	0.38
	CLAY	$DM = 0.0113Clay + 2.4829$	0.04NS	0.19	0.43
	DR	$DM = 0.036DR - 1.2541$	0.23**	0.15	0.39
	Slope	$DM = -0.176S + 2.3539$	0.34***	0.13	0.36
Grain	SL	$Y = -0.1656SL + 3.177$	0.60***	0.15	0.39
	OC	$Y = 1.0432OC + 1.4112$	0.06NS	0.36	0.60
	BD	$Y = 2.2114BD - 0.4755$	0.12*	0.34	0.58
	CLAY	$Y = -0.0298Clay + 4.0782$	0.16**	0.32	0.56
	DR	$Y = 0.0819DR + 1.0212$	0.03NS	0.37	0.61
	Slope	$Y = -0.2488S + 3.4551$	0.35***	0.25	0.50

Note:
SL = estimated soil loss (Mg/ha year), OC = organic carbon (%), BD = bulk density (Mg/m^3), DR = dispersion ratio, DM = biomass (t/ha), Y = grain yield (Mg/ha), MSe = Mean square error, Std err = standard error

4.7 Contribution of various soil erosion determinants to maize yield in the studied area

Maize grain and biomass yield were highly correlated ($P<0.05$) to various combinations of the soil parameters (Table 8). However, the most significant combinations were equation 1 comprising of topsoil depth, organic carbon, bulk density, Mn factor and slope gradient (r^2 = 0.65 for grain yield and r^2 = 0.73 for biomass). Equation 2 comprised of topsoil depth, organic carbon, dispersion ratio, Mn factor and slope gradient ($r^2 = 0.62$ for grain yield and $r^2 = 0.72$ for biomass). The other equations which were also significant ($P<0.05$) included

Table 8. Multiple regression equations relating maize yield and selected soil parameters

Dependent	Independents	Regression equations	r^2	Mse	std err
Grain Yield 1	D, OC, BD, CL, Mn, S	$Y = 4.862 + 0.058D - 1.372OC + 3.24BD - 0.0172CL - 0.0517DR - 7.584Mn - 0.252S$	0.65***	0.16	0.4
2	D, OC, BD, DR, Mn, S	$Y = 4.819 + 0.063D - 2.314OC + 3.385BD - 0.5DR + 5.795*10^{-4}Mn - 0.329S$	0.62***	0.17	0.41
3	OC, BD, CL, S	$Y = 2.052 - 0.348OC + 1.703BD - 0.0931CL - 0.215S$	0.47***	0.22	0.47
4	OC, BD, DR, Mn, S	$Y = 1.844 + 0.0126OC + 1.634BD - 0.0214CL - 5.361*10^{-4}Mn - 0.193S$	0.48***	0.22	0.47
Biomass 1	D, OC, BD, CL, Mn, S	$DM = -1.729 + 0.0414D - 1.69OC + 2.772BD + 6.192*10^{-3}CL + 6.586*10^{-3}DR + 1.867*10^{-3}Mn$	0.73***	0.06	0.25
2	D, OC, BD, DR, Mn, S	$DM = -1.723 + 0.0396D - 1.334OC + 2.719BD + 6.002*10^{-3}DR + 1.384*10^{-3}Mn - 0.129S$	0.72***	0.06	0.25
3	OC, BD, CL, S	$DM = -0.772 + 0.0714OC + 2.039BD - 3.822*10^{-3}CL - 0.142S$	0.53***	0.1	0.32
4	OC, BD, DR, Mn, S	$DM = -2.41 - 0.543OC + 1.842BD + 0.0247DR + 1.39*10^{-3}Mn - 0.132S$	0.59***	0.	0.3

Note:
SL = estimated soil loss (Mg/ha year) D = topsoil depth (cm), OC = organic carbon (%), BD = bulk density (Mg/m^3), DR = dispersion ratio, Mn = (%silt*(%silt+%sand), DM = biomass (t/ha), Y = grain yield (Mg/ha), Mse = Mean square error, Std err = standard error

The estimated potential soil loss in the study area is extremely low compared to the figures reported by Gachene (1995), who estimated values as high as 400Mg/ha/year on much steeper slopes and rainfall. Working on a watershed in Illinois, Kreznor *et al.* (1992) estimated using the USLE model, soil erosion level of 3.4 to 65 Mg/ha/year. This difference could be attributed to differences in slope gradient and soil erodibility.

The fact that the Typic Ustorthent showed a higher susceptibility to erosion than the Typic Rhodustalf. This may probably partly be explained by differences in the intrinsic soil properties between them notably in terms of bulk density values, and base saturation The climate, cover and the support practice factors were the same for both sites, and would not account for such a difference. However, in site 1, the slope gradient was generally lower (0.2 to 7%), and the portion of the land with nearly flat topography was much bigger than in site 2, which characteristically had a large portion covered by a higher slope gradient.

The topsoil depth of both soils falls in the range reported by earlier workers (Kilasara *et al.*, 1995a; Massawe, 1996; Saethar *et al.*, 1997). Both sites resemble each other in being dominated by a soil with relatively thin topsoil (13 – 20 cm).

Like in all other cases where topsoil thickness has been determined, the accuracy with which the boundary between the topsoil and subsoil can be determined depends on the distinctiveness between the two layers with respect to the determinant parameter(s). Experience shows that spatial differences are bound to occur and when the frequency of change becomes high the susceptibility of the results becomes more pronounced.

The class limits among the erosion severity classes were determined from the clustering of the field measured topsoil thickness, and not chosen arbitrarily as it has been in previous studies (Cook, 1975; Gachene, 1995; Kilasara *et al.*, 1995a; Mulengera, 1996). The established classes are natural and undoubtedly conform with soil genesis. This may be the reason why the obtained classes were significantly different with regard to their productivity as measured by maize yield.

These results reconfirm the significance of topsoil in determining the productivity of the land as reported earlier (Lo, 1989; Tanaka and Aase, 1989; Tegene, 1992; Saether and Moen, 1994; Kilasara *et al.*, 1995b; Gachene *et al.*, 1998; Kaihura *et al.*, 1998).

There is a need to make comparison between the usefulness of the soil erosion susceptibility and erosion severity criteria developed. The erosion susceptibility criterion estimates potential soil loss based on slope characteristics, the land cover conditions, the rainfall and the erodibility of the soil in question (Gachene, 1995; Mulengera, 1996). The susceptibility criterion employs laboratory analysis, field measurements and collection of reliable rainfall data, which is essential to accurately estimate potential soil loss. However, it is laborious and also difficult for resource poor farmers to be able to meet the associated cost for such studies. Therefore, the use of this criterion can only effectively be limited to few areas where all the required information can be met by the client or farmer.

The erosion severity criterion depends entirely on the topsoil thickness (Kilasara *et al.*, 1995a). Nonetheless, it has been found to yield reliable results in the past (Saether and Moen, 1994; Massawe, 1996; Saether *et al.*, 1997). However, according to Kreznor *et al.* (1992) the criterion is likely to underestimate soil erosion when employed on an entire catchment, where erosion processes such as gullies are active. Also, where tillage erosion is significant and depending on the ploughing pattern being adopted, certain differences in topsoil depth which do not bear any relationship with real erosion are likely to occur. In agricultural lands (with slope gradient of <8%) where development of gullies is rare, the topsoil depth criterion still remains the simplest and probably the cheapest indicator of accumulated effects of accelerated soil erosion. Nonetheless, this criterion requires some experience in soil morphology.

With respect to the sensitivity of both criteria, it is difficult to advance any conclusion. The degree of similarity in distribution of the various classes established following the two criteria appear to be very low. In most cases a given soil erosion susceptibility class corresponds with several soil erosion severity classes. These differences could be attributed to localised differences in soil physical properties, such as soil colour consistency and texture, which are used to determine the limit between the topsoil and the subsoil (Lal and Singh, 1995, 1998).

The relationship between soil erosion susceptibility and soil erosion severity criteria need to be worked. By the fact that the soil erosion susceptibility class deals with soil loss estimation, then the best way to assess it is to determine soil loss from a known susceptibility. Several studies have been conducted with respect to this (Gachene, 1982; Mulengera, 1996).

The soil erosion severity criterion can not be assessed in the same manner as it reflects the cumulative effects of past erosion. Several workers, however, have established relationships between extent of soil erosion and the productivity of the land (Lo, 1989; Tanaka and Aase, 1989; Tegene, 1992; Kilasara *et al.*, 1995b; Kaihura and Lungu, 1996; Gachene *et al.*, 1998)

It is now established that soil erosion causes decrease in crop yield (Rehm, 1978; Lal, 1981; Larney *et al.*, 1995; Izaurralde *et al,*. 1998). This implies that the relationships between crop productivity of different erosion classes can be used to assess the relevance the criteria for mapping soil erosion. Previous studies have shown the said parameters to be related to soil erosion (Ngatunga et al., 1984; McCool et al., 1987; McIsaac et al., 1987; McCool *et al.*, 1993). Clay content of the topsoil was found to increase with soil loss (Schertz *et al.*, 1985; Lowery *et al.*, 1995). Bulk density and dispersion ratio have also been observed to slightly increase with soil erosion (Wischmeier and Mannering, 1969; Kaihura *et al.*, 1998).

Organic carbon has been widely observed to decrease with increase in soil erosion (Massey *et al.*, 1953; Wischmeier and Mannering, 1969; Lowrance and Williams, 1988; Tanaka and Aase, 1989; Kreznor *et al.*, 1989; Arrouys and Pelissier, 1994). This however deviates from the current study whereby crop yield was lowly correlated to soil erosion. The variation therefore is attributed to that previous studies were mainly on humic soils, from which significant organic carbon reduction occurred with soil erosion. Landon (1991) and Baize (1993) observed that organic carbon content of less than 2.87% to be very low, thus making the soil vulnerable to the agents of soil erosion (Heil *et al.*, 1997). At very low organic carbon contents, then soil erosion will have little effect on soil organic carbon decrease.

The Mn factor was found to be lowly correlated to crop yield, which was somehow contradicting Wischmeier and Smith (1978) and Mulengera (1996), who observed the Mn factor to be highly correlated to soil erosion. Nonetheless, these studies were mainly on silty soil, and in case of soils with low silt content, the relationship will not hold, and will underestimate soil erosion (Wischmeier and Smith, 1978).

CHAPTER FIVE

5 CONCLUSIONS AND RECOMMENDATIONS

From this study, the following conclusions and recommendations can be made:

5.1 Conclusions

1. In the study area, three soil erosion susceptibility classes: highly eroded, moderately eroded, and least eroded, were established in the study area, based on the natural clustering of estimated soil loss. Site 1 was basically dominated by estimated soil loss of equal to or greater than 3.99 Mg/ha/year. In site 2 a greater part of the area was characterised by estimated soil loss of between 3.99 and 6.99 Mg/ha/year These differences are attributed to both soil intrinsic characteristics and topographic factors.

2. Three soil erosion severity classes: highly eroded, moderately eroded and least eroded, were established based on clustering of measured topsoil depth. Site 1 was dominated by topsoil depth between 16 and 20 cm, while site 2 was dominated by topsoil depth of less than 20 cm.

3. There existed a considerable difference in the distribution and size of the various erosion classes established by the two criteria in the study area. Soil erosion severity criterion produced more mapping units than the soil erosion susceptibility criterion.

5.2 Recommendations

1. The effects of soil erosion on crop yield are cumulative, thus carefully planned long term experiments have to be designed to establish and validate criteria to be used for erosion mapping purposes across a variety of soil types.
2. The depth of the top soil as a criterion, and being easier and cheaper to use, should be improved and where possible, with inclusion of some soil parameters that can be easily associated with past erosion, like organic carbon and bulk density.
3. It is further recommended that the use of Geographical Information System (GIS) be used in mapping soil erosion at the farm level.

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APPENDICES

APPENDIX 1: Turbo pascal program used for analysing the soil data

```
Program Soil_Erosion_hazard_Mapping
  {This Program calculates soil erodibility and topographic
   (LS) factors for soil erosion hazard mapping};

 USES CRT;
  CONST
   lno = 167;
   l = 20;                  {This is the slope length}
    empty = ' ';
   Erosivity = 2188.4;      {This is the rainfall erosivity factor}
   Cfactor = 0.70796;       {This is the crop cover factor}
{l, erosivity and Cfactor can be changed to suit your set of data}


 TYPE
   names = string[7];
   erosion_rec = RECORD
      class, no: integer;
      location : names;
      X, Y, Z, Beta, M, Lfactor, Sfactor,
      DR, DRfactor, Clay, Clayfactor, OC, OCfactor,
      BD, BDfactor, Kfactor, Hazard:real;
      End;
    mapping = ARRAY[1..lno] of  erosion_rec;
   VAR
     eros_info:mapping;
  Procedure pause;
 VAR proceed:char;
  begin
   writeln('Press any key to continue...');
    readln(proceed)
  end;

  Procedure Init(var eros_info:mapping);
   VAR
    i:integer;
   Begin
    for i:= 1 to lno do
    Begin
     eros_info[i].no:= 0;
     eros_info[i].location:=empty;
```

```
   eros_info[i].X:=0;
   eros_info[i].Y:=0;
   eros_info[i].Z:=0;
   eros_info[i].Beta:=0;
   eros_info[i].M:=0;
   eros_info[i].Lfactor:=0;
   eros_info[i].Sfactor:=0;
   eros_info[i].DR:=0;
   eros_info[i].DRfactor:=0;
   eros_info[i].Clay:=0;
   eros_info[i].Clayfactor:=0;
   eros_info[i].OC:=0;
   eros_info[i].OCfactor:=0;
   eros_info[i].BD:=0;
   eros_info[i].BDfactor:=0;
   eros_info[i].Kfactor:= 0;
   eros_info[i].hazard:= 0;
   eros_info[i].class:= 0;
  End;
 End;

Procedure read_data(var eros_info:mapping);
  var
   i:integer;
  datafile:text;
  Begin
   ASSIGN (datafile, 'a:\pascal\hazdatay.pas');

   RESET (datafile);
   For i:= 1 to lno do
    Begin
    readln(datafile);
    read(datafile,
        eros_info[i].no,
        eros_info[i].location,
        eros_info[i].X,
        eros_info[i].DR,
        eros_info[i].Clay,
        eros_info[i].OC,
        eros_info[i].BD);
    End;
   Close(datafile)
   End;

  Procedure Erosion(var eros_info:mapping);
   var
```

```
 i:integer;
Begin
 for i:= 1 to lno do
  Begin
   eros_info[i].Y:= sin(eros_info[i].X)/0.0896;
   eros_info[i].Z:= 3.0*exp(0.8*ln(sin(eros_info[i].X))) + 0.56;
   eros_info[i].Beta:= eros_info[i].Y/eros_info[i].Z;
   eros_info[i].M:= eros_info[i].Beta/(1 + eros_info[i].Beta);
   eros_info[i].Lfactor:= exp(eros_info[i].M*ln(1/22.13));
   eros_info[i].Sfactor:= 10.8*sin(eros_info[i].X) + 0.03;
   eros_info[i].DRfactor:= 0.069*eros_info[i].DR;
   eros_info[i].Clayfactor:= 0.001*eros_info[i].Clay;
   eros_info[i].OCfactor:= 0.011*eros_info[i].OC;
   eros_info[i].BDfactor:= 0.14*eros_info[i].BD;
   eros_info[i].Kfactor:= 0.297 +  (eros_info[i].DRfactor) -
                  (eros_info[i].Clayfactor) -
                  (eros_info[i].OCfactor) -
                  (eros_info[i].BDfactor);
   eros_info[i].hazard:= (erosivity * Cfactor *  eros_info[i].Lfactor *
                       eros_info[i].Sfactor * eros_info[i].Kfactor)/100;
   IF (eros_info[i].hazard<=40) THEN eros_info[i].class:= 1
    ELSE IF (eros_info[i].hazard>40) AND (eros_info[i].hazard<=80)
     THEN eros_info[i].class:=2
      ELSE IF (eros_info[i].hazard>80) AND (eros_info[i].hazard<=120)
       THEN eros_info[i].class:=3
        ELSE IF (eros_info[i].hazard >120) THEN eros_info[i].class:=4;
    End;
  End;

Procedure write_results(eros_info:mapping);
 var
 i:integer;
 resultfile: text;

  Begin
   ASSIGN (resultfile, 'a:\pascal\hazresy2.pas');
   REWRITE (resultfile);
   writeln(resultfile, 'No.':4, 'Loc.':10, 'Lfactor':10, 'Sfactor':10,
                    'Kfactor':10, 'Risk':13, 'class':10);
   writeln(resultfile);

  For i:= 1 to lno do
    Begin
     writeln(resultfile, eros_info[i].no:4,
            eros_info[i].location:10,
            eros_info[i].Lfactor:10:4,
```

```
          eros_info[i].Sfactor:10:4,
          eros_info[i].Kfactor:10:4,
          eros_info[i].hazard:13:4,
          eros_info[i].class:10);
   End;
   Close(resultfile);
  End;

  Begin
   clrscr;
   Init(eros_info);
   read_data(eros_info);
   Erosion(eros_info);
   write_results(eros_info);
  END._
```

NOTES:
This program allows the user to change the values of the rainfall erosivity factor (R) and the slope length, for as long as the two are constant in a particular data set.

APPENDIX 2: Estimated soil loss and topsoil depth of the study area

site	Station	depth (cm)	risk (t/ha)	slope
1	A-20	21	1.572	2.67
1	A0	20	1.035	4.17
1	A+20	20	2.104	5.87
1	C-20	24	2.175	5.87
1	C0	18	1.901	5.1
1	C+20	17	1.601	4.37
1	C+40	15	0.460	1.08
1	C+60	17	0.680	1.79
1	C+ 80	23	0.505	1.28
1	C+100	15	0.633	1.65
1	C+120	19	0.707	1.89
1	E-20	17	0.718	1.79
1	E0	18	0.472	1.11
1	E+20	14	0.541	1.38
1	E+40	14	0.350	0.83
1	E+60	17	0.481	1.21
1	E+80	17	0.547	1.4
1	E+100	16	0.625	1.63
1	E+120	18	0.580	1.57
1	E+140	20	0.668	1.84
1	E+160	17	1.005	2.67
1	E+180	18	1.176	3.4
1	E+200	18	0.721	2
1	G-20	15	0.941	2.55
1	G0	18	0.657	1.72
1	G+20	15	0.327	0.76
1	G+40	21	0.255	0.57
1	G+60	21	0.319	0.75
1	G+80	17	0.493	1.26
1	G+100	16	0.630	1.66
1	G+120	16	0.717	1.92
1	G+140	16	0.906	2.48
1	G+160	16	1.208	3.38
1	G+180	15	1.430	4.18
1	G+200	15	1.604	4.75
1	I-20	18	0.277	1.03
1	I0	15	0.311	1.18
1	I+20	14	0.277	1.03
1	I+40	17	0.421	1.66
1	I+60	19	0.393	1.54
1	I+80	32	0.554	1.44
1	I+100	17	0.767	2.07
1	I+120	16	0.771	2.08
1	I+140	18	1.262	3.54
1	I+160	15	1.398	3.95

Table continues

1 I+180	19	1.468	4.16
1 I+200	17	1.451	4.11
1 K-20	19	0.515	2.08
1 K0	17	0.497	2
1 K+20	18	0.366	1.42
1 K+40	26	0.269	0.64
1 K+60	27	0.235	0.54
1 K+80	19	0.394	1.02
1 M-20	18	0.928	2.72
1 M0	11	0.515	1.99
1 M+20	23	0.626	1.12
1 M+40	16	0.560	1.77
1 M+60	18	0.574	1.56
1 O-20	10	0.418	1.47
1 O0	11	0.412	1.44
1 O+20	17	0.559	1.57
1 O+40	19	0.630	1.78
1 O+60	9	0.648	1.84
1 Q-20	12	0.382	1.32
1 Q0	13	0.490	1.75
1 Q+20	13	0.551	1.99
1 Q+40	16	0.619	1.76
1 Q+60	14	0.597	1.68
1 S-30	14	0.953	3.6
1 S-20	14	0.534	1.92
1 S0	14	0.401	1.39
1 S+20	16	0.481	1.73
1 S+40	14	0.509	1.82
1 S+60	15	0.428	1.5
1 U-30	12	0.272	1.06
1 U-20	18	0.529	1.9
1 U0	17	0.364	1.25
1 U+20	17	0.357	1.22
1 U+40	16	0.395	1.37
1 U+60	16	0.401	1.39
1 W-35	17	0.416	1.13
1 W-20	14	0.492	1.37
1 W0	13	0.354	1.21
1 W+20	17	0.339	1.15
1 W+40	14	0.285	0.94
1 W+60	13	0.386	1.17
1 Y-40	25	0.458	1.26
1 Y-20	13	0.445	1.22
1 Y0	14	0.399	1.08
1 Y+20	17	0.399	1.08
1 Y+40	23	0.372	0.99
1 Y+60	18	0.288	0.73
1 A1-40	26	0.678	1.96
1 A1-20	22	0.669	1.93
1 A1O	26	0.521	1.72

Table continues

1 A1+20	17	0.237	0.57
1 A1+40	18	0.410	1.11
1 A1+60	19	0.550	1.55
1 C1-40	19	0.487	1.4
1 C1-20	19	0.499	1.44
1 C10	21	0.524	1.52
1 C1+20	12	0.517	1.45
1 C1+40	14	0.555	1.57
1 C1+60	18	0.202	0.5
1 E1-40	15	0.662	1.97
1 E1-20	13	0.536	1.56
1 E10	12	0.726	1.84
1 E1+20	13	0.836	2.15
1 E1+40	19	0.641	1.55
1 E1+60	19	0.655	1.64
1 E1+80	17	0.577	1.42
1 G1-40	18	0.561	1.55
1 G1-20	15	0.561	1.55
1 G10	21	0.561	1.65
1 G1+20	18	0.485	1.58
1 G1+40	15	0.256	0.75
1 G1+60	16	0.212	0.59
1 G1+80	19	0.463	1.5
1 G1+100	13	0.544	1.8
1 G1+120	22	0.675	2.28
1 G1+140	24	0.563	1.87
1 G1+160	14	0.653	2.2
1 G1+180	17	0.617	2.07
1 G1+200	25	0.765	2.04
1 G1+220	28	0.665	1.75
1 G1+240	32	0.419	1.03
1 I1-40	17	1.846	5.07
1 I1-20	12	1.647	4.5
1 I10	15	1.945	5.36
1 I1+20	15	1.962	5.83
1 I1+40	13	1.768	5.23
1 11+60	14	1.910	5.67
1 I1+80	14	1.865	6.09
1 I1+100	21	1.551	4.75
1 I1+120	19	1.225	3.7
1 I1+140	20	1.347	3.76
1 I1+160	22	0.304	0.7
1 I1+180	17	0.549	1.41
1 I1+200	17	0.761	2.03
1 I1+220	15	0.874	2.36
1 I1+240	18	0.958	2.61
1 K1-40	14	1.217	3.2
1 K-20	13	1.197	3.2
1 K1OO	13	0.752	2.05
1 K1+20	13	1.334	3.81

Table continues

1 K1+40	14	1.453	4.17
1 K1+60	16	1.492	4.56
1 K1+80	14	1.629	5
1 K1+100	16	2.432	7.61
1 K1+120	12	1.983	6.51
1 K1+140	12	2.354	6.61
1 K1+160	15	2.250	6.45
1 K1+180	11	1.919	6.22
1 K1+200	28	1.688	4.77
1 K1+220	26	1.526	4.29
1 K1+240	20	1.644	4.64
1 MI-40	10	0.555	1.35
1 MI-20	11	0.681	1.7
1 M100	13	0.806	2.05
1 M1+20	14	0.922	2.38
1 M1+40	10	1.026	2.67
1 M1+60	20	1.013	3.02
1 M1+80	18	1.705	5.25
1 M1+100	18	2.097	6.9
1 M1+120	26	1.923	6.3
1 M1+140	28	2.167	6.06
1 M1+160	14	2.329	6.54
2 AO	40	8.943	3.45
2 A1	18	10.175	3.55
2 A2	17	5.505	2.17
2 A3	20	5.942	2.72
2 A4	15	12.950	5.68
2 A5	15	17.597	7.58
2 BO	17	17.308	6.42
2 B1	30	17.636	6.54
2 B2	13	11.964	4.54
2 B3	24	7.186	3.26
2 B4	13	8.611	3.87
2 B5	16	8.990	4.03
2 C0	16	13.916	5.23
2 C1	19	12.103	5.37
2 C2	14	9.350	4.21
2 C3	16	6.872	2.81
2 C4	14	4.945	1.91
2 C5	13	4.823	1.86
2 D0	18	5.083	1.96
2 D1	18	4.945	1.91
2 D2	15	4.331	1.8
2 D3	18	4.204	1.75
2 D4	20	4.340	1.68
2 D5	16	4.190	2.83
2 E0	13	4.823	1.86
2 E1	21	4.823	1.86
2 E2	11	4.780	1.8
2 E3	14	4.162	1.73

Table continues

2 E4	21	3.817	1.48
2 E5	16	3.201	1.24
2 F0	18	4.415	1.71
2 F1	13	4.732	1.83
2 F2	14	4.812	1.81
2 F3	17	4.317	1.63
2 F4	19	3.332	1.29
2 F5	15	2.625	1.01
2 G0	14	4.505	1.74
2 G1	14	4.734	1.78
2 G2	13	4.749	1.79
2 G3	19	7.322	2.91
2 G4	17	6.974	2.78
2 G5	21	6.687	2.67
2 H0	24	6.952	2.86
2 H1	20	7.702	3.15
2 H2	20	9.461	3.83
2 H3	19	6.263	2.59
2 H4	16	6.342	2.54
2 H5	22	7.080	2.82
2 I0	16	7.042	2.98
2 I1	17	7.100	3
2 I2	18	8.393	3.52
2 I3	15	4.143	1.71
2 I4	13	3.181	1.31
2 I5	28	2.840	1.17
2 J0	19	4.770	2.05
2 J1	19	4.743	2.04
2 J2	14	4.850	1.91
2 J3	17	4.333	1.71
2 J4	27	4.491	1.85
2 J5	28	2.513	1.03
2 K0	13	5.380	2.11
2 K1	13	5.094	2
2 K2	24	4.857	1.96
2 K3	25	2.714	1.12
2 K4	20	4.066	1.68
2 K5	15	7.713	3.11
2 L0	22	4.477	2.16
2 L1	23	4.305	2.08
2 L2	17	4.857	1.96
2 L3	28	4.519	1.86
2 L4	30	3.757	1.55
2 L5	16	3.190	1.32
2 M0	16	2.851	1.12
2 M1	22	3.879	1.88
2 M2	17	5.860	2.35
2 M3	23	4.960	2
2 M4	13	4.178	1.67
2 M5	21	3.486	1.39

Table continues

2 N0	15	4.897	1.92
2 N1	32	3.757	1.48
2 N2	14	5.869	2.32
2 N3	14	5.869	2.32
2 N4	13	4.676	1.86
2 N5	22	4.134	1.65
2 O0	13	6.096	2.37
2 O1	14	6.250	2.38
2 O2	16	3.358	1.34
2 O3	12	5.704	2.26
2 O4	14	3.801	1.52
2 O5	12	4.280	1.71
2 P0	15	5.897	2.3
2 P1	28	4.870	1.87
2 P2	42	5.617	2.38
2 P3	13	6.323	2.49
2 P4	9	4.588	1.83
2 P5	13	4.236	1.69
2 Q0	29	5.062	1.94
2 Q1	24	4.330	1.7
2 Q2	14	3.736	1.6
2 Q3	20	5.314	2.11
2 R0	18	4.687	1.84
2 R1	14	4.792	1.88
2 R2	26	5.126	2.18
2 R3	15	6.009	2.4
2 S0	25	4.138	1.63
2 S1	16	4.345	1.71
2 S2	50	6.564	2.68
2 T0	14	3.757	1.48
2 T1	26	3.808	1.58
2 U0	18	3.786	1.49

APPENDIX 3: Analysis of variance tables for site 1

Appendix 3.1: Soil erosion susceptibility classes analysis

Anova: Single Factor analysis of the effect of erosion susceptibility on maize grain yield

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	3	6.538	2.179	0.001
MOD	6	17.278	2.880	0.005
LOW	9	30.753	3.417	0.257

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between Groups	3.654	2	1.827	13.141	0.001	3.682
Within Groups	2.086	15	0.139			
Total	5.740	17				

Anova: Single Factor analysis of the effect of erosion susceptibility on maize biomass

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	3	5.237	1.746	0.002
MOD	6	10.274	1.712	0.014
LOW	9	21.198	2.355	0.024

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between Groups	1.799	2	0.899	51.107	0.000	3.682
Within Groups	0.264	15	0.018			
Total	2.063	17				

Appendix 3.2: Topsoil depth classes analysis in site 1

Anova: Single Factor analysis of the effect of topsoil depth on maize grain yield

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	9	23.816	2.646	0.13
MOD	3	9.918	3.306	0.0
LOW	6	20.835	3.473	0.40

ANOVA TABLE

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between Groups	2.729	2	1.364	6.797	0.008	3.682
Within Groups	3.011	15	0.201			
Total	5.740	17				

Anova: Single Factor analysis of the effect of topsoil depth on maize biomass

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	9	15.511	1.723	0.009
MOD	3	6.764	2.255	0.003
LOW	6	14.337	2.389	0.031

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between Groups	1.772	2	0.886	53.268	0.000	3.682
Within Groups	0.250	15	0.017			
Total	2.022	17				

Appendix 4: Analysis of variance of site 2

Appendix 4.1: Soil erosion susceptibility classes analysis

Anova: Single Factor analysis of the effect of erosion susceptibility on maize grain yield

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	9	27.034	3.004	0.018
MOD	9	28.128	3.125	0.336
LOW	6	11.475	1.913	0.016

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between Groups	6.0390349	2	3.0195175	21.809541	7.491E-06	3.4667949
Within Groups	2.9074371	21	0.1384494			
Total	8.946472	23				

Anova: Single Factor analysis of the effect of erosion susceptibility on maize biomass

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	9	21.037	2.337	0.145
MOD	9	17.055	1.895	0.008
LOW	6	7.589	1.265	0.004

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between Groups	4.143	2	2.071	34.829	0.000	3.467
Within Groups	1.249	21	0.059			
Total	5.392	23				

Appendix 4.2: Topsoil depth classes analysis of site 2

Anova: Single Factor analysis of the effect of topsoil depth on maize grain yield

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	6	15.853	2.642	0.815
MOD	12	32.362	2.697	0.374
LOW	6	18.422	3.070	0.011

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between Groups	0.702	2	0.351	0.895	0.424	3.467
Within Groups	8.244	21	0.393			
Total	8.947	23				

Anova: Single Factor analysis of the effect of topsoil depth on maize biomass

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	6	9.464	1.577	0.161
MOD	12	21.930	1.828	0.126
LOW	6	14.287	2.381	0.225

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between Groups	2.077	2	1.038	6.577	0.006	3.467
Within Groups	3.315	21	0.158			
Total	5.392	23				

Appendix 5: Analysis of variance of both sites 1 and 2

Appendix 5.1: Soil erosion susceptibility classes analysis

Anova: Single Factor analysis of the effect of erosion susceptibility on maize grain yield

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	12	33.572	2.798	0.151
MOD	15	45.406	3.027	0.210
LOW	15	42.228	2.815	0.735

Anova: Single Factor analysis of the effect of erosion susceptibility on maize biomass

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between	0.467	2	0.234	0.612	0.547	3.238
Within	14.888	39	0.382			
Total	15.356	41				

Anova: Single Factor

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	12	26.274	2.190	0.178
MOD	15	27.329	1.822	0.018
LOW	15	28.787	1.919	0.321

ANOVA

Source of	*Sum of*	*Degrees of*	*Mean*	*Fcalc.*	*P-value*	*F crit*
Between	0.943	2	0.471	2.743	0.077	3.238
Within	6.702	39	0.172			
Total	7.645	41				

Appendix 5.2 Topsoil depth classes analysis in site 2

Anova: Single Factor analysis of the effect of topsoil depth on maize grain yield

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	15	39.669	2.645	0.363
MOD	15	42.280	2.819	0.358
LOW	12	39.257	3.271	0.231

ANOVA

Source of Variation	*Sum of Squares*	*Degrees of freedom*	*Mean Square*	*Fcalc.*	*P-value*	*F crit*
Between Groups	2.725	2	1.362	4.206	0.022	3.238
Within Groups	12.631	39	0.324			
Total	15.356	41				

Anova: Single Factor analysis of the effect of topsoil depth on maize biomass

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
HIGH	15	24.975	1.665	0.068
MOD	15	28.694	1.913	0.131
LOW	12	28.624	2.385	0.118

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.509	2	1.755	16.775	0.000	3.238
Within Groups	4.080	39	0.105			
Total	7.589	41				