ASSESSMENT OF SOIL EROSION AND LOSS IN SOIL PRODUCTIVITY IN MBINGA DISTRICT: A CASE STUDY OF MAHENGE VILLAGE

BY

COSMAS BENEDICT MABALIKA HAULE

A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT FOR THE
DEGREE OF MASTER OF SCIENCE IN AGRICULTURAL ENGINEERING
OF SOKOINE UNIVERSITY OF AGRICULTURE

2000

ABSTRACT

The study was conducted at Mahenge village, Mbinga District, Tanzania. The objective of this study was to investigate the magnitude of soil erosion and its impact on soil productivity. Data on soil loss, evaporation, pan coefficient (kpan), rainfall, soil physical and chemical properties, crop growth and yield, crop coefficient (kc) soil and topographical maps from field investigation and various documents were collected. Erosion hazard assessment was done using the USLE and mapped by ARC INFO and ARC VIEW GIS packages, whilst the erosion induced loss in soil productivity was evaluated using SEPIM.

Soil loss for different periods of crop growth showed significant difference between bare plots and *ngolo* plots. The same relation was shown between bare plots and bench terraces. ANOVA for crop development showed statistical difference between *ngolo* and bench terrace, with DMRT indicating *ngolo* to be superior in performance compared to the later. In addition *ngolo* had lower reduction in yield with cumulative soil loss than bench terraces.

The results from the soil erosion hazard mapping indicated that accelerated soil erosion by water was a serious problem in agricultural land in Mahenge village. In the absence of support practice Dystric Cambisols had higher erosion rates (258.69 t/ha/year) while Ferrallic Cambisols had lowest average erosion rates (63.28 t/ha/year) in the village. However, in general soil loss tended to vary with varying soil erodibility, support practice, crop cover and topographic factors.

Evaluation of PI and SEPIM models at the experimental site showed that SEPIM had more explanation power than PI although the explanation was highly variable. Analysis of available data using the SEPIM indicated that Haplic Phaeoezem soils had higher production potential (0.80) than other soils. In contrast Haplic Acrisols had the lowest production potential (0.44) mainly due to low soil pH. The simulation results showed that Haplic Phaeozem could lose 24 percent of its production potential after 25 years of continued erosion. On the other hand, Haplic Acrisols improved its production potential by more than 100 percent after 25 years of soil loss. The results showed that reduction in soil productivity due to erosion depended on the properties of the exposed subsoil.

DECLARATION

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

Signature..............................

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

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ACKNOWLEDGEMENT

This dissertation is the result of the fieldwork carried out at Mahenge village in Mbinga District. However, numerous people and organisations have contributed towards its success. This research was made possible by financial support of GTZ made through SACCAR and DAELP. I greatly acknowledge and appreciate the guidance and valuable criticism accorded by my supervisors Drs. Mulengera, M. and S. Thadei during every phase of the study.

I am grateful to staff members of the SUA-Centre for Sustainable Rural Development formerly known as Miombo Woodland Agroecological Research Project at Morogoro, especially Drs. Manabu Tsunoda and A. Tarimo, for their willingness to allow me to use their experimental site and facilities at Mahenge village in Mbinga District. Besides, the equipment and transport to the field during my extension, the soil survey data, evaporation data, and rainfall data provided by the centre were of great importance in this research.

My sincere thanks go to Prof. Michael Stocking of the University of East Anglia for his useful, stimulating and informative articles on soil productivity research he sent me on request. I appreciate his promptness and concern.

I appreciate the advice and courage provided to me by Prof. M. Mbonile, the Head of Geography Department, University of Dar es salaam.

I would like also to take this opportunity to express my sincere gratitude to my colleagues at the DAELP: Stevie Justice Nindi; Chikondi Phiri; Mackinon Tembo; Mulako Sitali; Christian Mgina; Francis Wickedzi, Amini Bakari, John Matiku and Adam Njovu for their encouragement and support they used to offer during our study.

I appreciate the technical assistance provided by Ludovick and Yusuf Matembo of DAELP, Godfrey Mhando of the DALDO office at Mbinga. Together with them I thank my hosts and assistants in the field Daniel Lumbe and Sabas Mbunda of Mahenge village for their tireless support during data collection. Besides, the moral and material support given by the family of Mwangamila, Ngoseki, Bilauri, George, Kagoro, Mhaiki, Chimgege, Munisi, Kajugusi, Salum, Mtolera, Mercy and Rushomesa, deserve special thanks.

Lastly, though not least, I am greatly indebted to my family especially my wife Esther Masele, my daughter Mbuya Veronica for their spirit of courage and tolerance in my absence.

DEDICATION

This work is dedicated to the family of Mabalika for their tireless effort to make my ambition successful.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

ASA – American Society of Agronomy

ASAE – American Society of Agricultural Engineers

CARITAS – International Confederation of Catholic Organizations for Charitable and Social Action

CGIAR – Consultative Group on International Agricultural Research

CSSA – Crop Science Society of America

CTA - The Technical Centre for Agriculture and Rural Co-operation

DALDO – District Agricultural and Livestock Development Officer

DAS – Days after sowing

DMRT – Duncan's Multiple Range Test

EPIC – Erosion Productivity Impact Calculator

ESRI – Environmental Systems Research Institute

FAO – Food and Agriculture Organisation of the United Nations

GTZ – Deutsche Gesellschaft für Technische Zusammenarbeit(GTZ) GmbH

GIS - Geographical Information Systems

IFAD – International Fund for Agricultural Development

ISNAR – International Service for National Agricultural Research

JICA – Japan International Co-operation Agency

MWARP – Miombo Woodland Agro-ecological Research Project

NEST – Nigeria Environmental Study/Action Team

PI – Productivity Index

RUSLE – Revised Universal Soil Loss Equation

SACCAR – Southern African Centre for Co-operation in Agricultural Research and Training

SADC – Southern African Development Community

SADCC – Southern African Development Co-ordination Conference

SCS – Soil Conservation Service

SCSRD – SUA-Centre for Sustainable Rural Development

SEPIM – Soil Erosion Productivity Index Model

SIDA – Swedish International Development Agency

SLEMSA - Soil Loss Estimation Model for Southern Africa

SSSA - Soil Science Society of America

SUA – Sokoine University of Agriculture

UNCTAD – United Nations Conference on Trade and Development

UNEP – United Nations Environment Programme

URT – United Republic of Tanzania

USDA – United States Department of Agriculture

USLE – Universal Soil Loss Equation

1. INTRODUCTION

1.1 Soil Erosion and Agricultural Sustainability

Accelerated soil erosion is the major form of land degradation that has rendered or is rendering vast areas of land useless with respect to crop production (Unger, 1984). On that aspect it has been recognised as a serious global problem that threatens the sustainability of agricultural production (Lal, 1994). Also, this is because most of the potential available land for agriculture is either marginal or is in sensitive ecological regions such as steep slopes. Hebblethwaite (1993) reported that soil erosion degrade 30 percent of rainfed cropland in Central America; 17 percent in Africa; 20 percent in South West Asia; 36 percent in South East Asia. The phenomenon is supported by World Resources Institute (1988) that estimated that six to seven million hectares of agricultural land are rendered unproductive each year due to soil erosion. Also Lal (1984) reported that the problem of accelerated soil erosion is more acute in the semi-arid areas where vegetation is scanty and in the highlands because of steep slopes.

The problem of soil erosion in Tanzania has been identified by a number of researchers (Rapp *et al.*, 1972; Ngatunga, 1981; and Yanda, 1995). Blackwell *et al.* (1991) estimate that about fifty percent of the land in Tanzania is subject to erosion. Matengo highlands where Mahenge village is located is experiencing serious soil erosion by water (Stenhouse, 1944; Allan, 1989; Schmied, 1989; Ellis-Jones *et al.*, 1994; JICA, 1995 and Maggogo *et al.*, 1996). However, the form and causal factors of the problem vary with the soil physical conditions, rainfall pattern, and land use practices. Factors contributing to severe soil erosion by water in Mbinga district have been identified to be the presence of steep slopes with shallow soil depth, high rainfall intensities, deforestation, extensive slash and burn cultivation practices, and uncontrolled fires (Schmied, 1989; Maggogo *et al.*, 1996).

The problem of soil erosion caused by deforestation and extensive slash and burn cultivation in Mbinga District is compounded by rapid population growth (Schmied, 1989). The Matengo highlands in particular have been reported as an area with high population density in the district with some areas having about 120 persons per square kilometres (Schmied, 1989). Due to this rapid increase in population more land has been brought under cultivation and tree cutting for charcoal and fuelwood to meet daily energy requirements have increased considerably. This phenomenon in Matengo highlands has resulted in depletion of Miombo woodland and the Montane forest at an alarming rate (JICA, *1995*). Therefore, it is not by accident that exotic tree species like Grevillea, Eucalyptus and Cypress have currently totally replaced the indigenous tree species in Matengo highlands (Mattee *et al.*, 1996; Tanaka *et al.*, 1996; URT, 1997).

People in Mbinga district especially in Matengo highlands have been aware of the erosion problem that they have developed various forms of traditional soil conservation measures including the famous Matengo pit system (*ngolo* cultivation). The *ngolo* or originally known as '*ingolo kwa mikingana*' which literally means pits in between jointed ridges (Otmar, 1971) were developed as the response to Ngoni invasion and ultimate alienation of their land (Allan, 1989). This confined the

Matengo people in the fragile hill slopes necessitating them to develop means to maintain crop production and overcome erosion.

In most cases *ngolo* are constructed in March or April to avoid the heaviest rainstorms of December and January that would have caused severe erosion on freshly disturbed soils. The effectiveness of *ngolo* depends on both the depth of the pit and strength of the ridge. The depth of pit allows maximum amount of water in excess of infiltration rate to pond and eroded soil to be deposited. Besides, the buried plant residues and grasses in the ridge increase the proportion of organic matter in the soil, thus improving the soil structure and infiltration. Those attributes have made *ngolo* to be a multifunctional system in sustaining productivity as it maintains fertility, conserves the soil, reserves water, improves underground drainage, control weeds, and recovers the soil (Tanaka *et al.,* 1996). In the Matengo highlands *ngolo* have sustained land productivity for over 100 years (Mattee *et al.,* 1996; Tanaka *et al.,* 1996). Experimental findings at Tukuzi and Mahenge village in Mbinga District have confirmed the role of *ngolo* in controlling soil erosion by water (JICA, 1995; JICA, 1996). The effectiveness of the system has also been tried in the Northern parts of Tanzania (Allan, 1989), in Kenya (Gichangi *et al.,* 1989), and in Uluguru mountains (JICA, 1995). Even though the areas have different agro-ecological conditions, *ngolo* cultivation system has proved successful in protecting the soil against erosion and improving soil productivity.

But, now the Matengo pit system faces problems related to soil erosion by water as increased population and consequently land shortage have reduced the fallow period and increased intensive annual cropping on steep slopes. This intensified use of Matengo highlands enhances the risk of soil erosion as people are forced to cultivate even the land formerly regarded as marginal. In most cases hill slopes with gradients of more than forty five percent and hilltops are annually cultivated.

Apart from *ngolo* cultivation, people in Mbinga district have substantial experiences in tree planting (URT, 1997). However, it has been observed that trees are only planted in coffee fields or as woodlots, leaving large parts of annual crop fields bare.

On the other hand the switch from shifting cultivation to semi-permanent and/or permanent farming systems can adversely affect soil properties when no appropriate soil management practices are in use. In most cases continuous farming involves thorough clearing, and intense hoeing which lead to death of roots and tree stumps resulting in reduction of organic matter content in the soil. Such change brought about by continuous cultivation in the Matengo highlands has exacerbated the reduction in organic matter content leading to more leaching, deterioration of soil structure, high bulk density, reduced infiltration capacities, increased runoff, and more soil erosion (Ruthenberg, 1980; Stocking, 1998). The end result of all this is soil degradation that reduces the production potential of the soil resource base resulting into loss of soil productivity (Jacks, 1939; Eckholm, 1976 and Wilken, 1995).

Erosion reduces productivity in short run because of reduction in thickness of A horizon and selective removal of plant nutrients. Furthermore, the change in physical properties of A horizon results in reduced infiltration rate, high bulk density, and less aggregation. In the long run erosion reduces the depth of the rooting zone resulting into reduction in plant available water and crop yield (Young, 1980). Thus, loss of soil productivity is among the major effects of soil erosion that demand to be examined.

The soil capacity to produce crops and sustain its productivity is determined by both the chemical properties (that is, the soil's fertility) and the physical properties of the soil (CTA, 1993). Lal (1979) and CTA (1993) report the decline in the productivity of soils under continuous cultivation even with application of fertilizers. They argue that fertilizers, improved crop varieties, pests and diseases control cannot preserve the deterioration done by water erosion on soil's physical properties especially the reduction in rooting depth which is so gradual and recognised when it is already a critical problem.

Tanzania is among the countries in Africa reported to have permanently reduced soil productivity by more than 20 percent during the past 100 years due to human-induced water erosion (Dregne, 1990). But, in Mbinga District and particularly in Mahenge village as it has been widely reported (Mattee *et al.*, 1996;Hawassi, 1997; URT, 1997) there is significant loss in productivity of food crops especially maize; forcing people to abandon their fields and settlements. On that ground it is important that the effects of erosion-induced loss in soil productivity be quantified for soils of Mahenge village. However, little is known about the erosion-induced loss in soil productivity in Tanzania (Kilasara *et al.*, 1995) and particularly in Mahenge village.

No studies have so far been made to assess the magnitude of soil erosion and the consequent loss in soil productivity in Mahenge village, Mbinga District. Therefore, this research is an attempt to identify, select and/or modify suitable soil erosion-productivity model(s) for use in Mahenge village, Mbinga district.

1.2 Objectives

The overall objective of this study was to assess the magnitude of soil erosion and loss in soil productivity in Mbinga District with particular reference to Mahenge village. The specific objectives of this study were: -

1. predicting annual soil loss for all soil mapping units of Mahenge village using the adapted USLE/RUSLE model,
2. mapping soil erosion variations in Mahenge village using GIS,
3. identifying suitable soil erosion-productivity model to be used in assessing the impact of soil erosion on productivity in Mahenge village, and
4. assessing long-term effects of erosion on soil productivity in Mahenge village.

2. LITERATURE REVIEW

2.1 Soil Erosion Processes

Soil erosion is a three phase process consisting of the detachment of soil particles from the soil mass, transportation of detached materials by agents such as running water and wind, and deposition of the particles when there is no enough energy to transport the detached particles (Assmo and Eriksson, 1994). Zonn (1986) identifies two major kinds of erosion, namely geological and accelerated erosion. Whilst the former is slow, natural, and inevitable process the later is rapid and associated with the activity of man. The unplanned development of natural resources like deforestation, overgrazing, erroneous methods of farming and industrial disturbances of soil are the human activities most blamed for the damage. Lowdermilk (1935) argued that in most cases the rate of accelerated erosion is faster than that of soil formation resulting in limited access to and use of eroded and erosion prone areas as discussed in section 1.1. However, Wilken (1995) reports that the cumulative effect of soil erosion tends to vary widely over even a small piece of land. Thus, necessitating the study of soils which are either current in use or potential for future development. Even though, soil erosion research in the country has long history (Rapp *et al.*, 1972), Msanya (1995) observed that nearly 60 percent of the country's soil conditions are still unknown. In addition, no attempts have been made to develop models for determining appropriate soil and water management required for the control of soil degradation.

2.2 Soil Erosion Modelling

Modelling means estimating an event in advance using predictive equation (Hudson, 1980). On that ground Zöbisch (1989) takes models, as the methods of defining priority areas in order to implement measures according to the urgent need so that resources are properly utilised. In erosion studies, models are basis for understanding erosion processes and their interactions, and for setting research priorities (Nearing *et al.,* 1994). Furthermore, models are used as predictive tools for assessing soil loss for conservation planning, project planning, soil erosion inventories, and for regulation. Thus, making soil loss estimation a necessary prerequisite in agricultural planning (Stocking, 1987).

Soil loss prediction techniques have been developed over many years as understanding of erosion expanded and increasingly more erosion researches were conducted. There are basically three broad categories of erosion models (Morgan, 1986), namely analogue, digital, and physically based models. For fast approximation and least cost, digital models especially of empirical types are widely used. Empirical models are based primarily on observation and are usually statistical in nature. Empirical models are further sub-divided into black box, grey box, and white box. In black box category, only main inputs and outputs are studied, whereas in grey box some details of how the system works are considered and for white box all details of how the system operates are studied.

Out of the three sub-divisions of the digital models, the use of grey box model enables one to make observations, measurement of critical factors and the understanding of the system being studied. For those reasons, this research was based on grey box model that is widely used in erosion studies in most countries: the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978; Renard *et al.*, 1991). The structure of the equation is as follows:

$$A=RKLSCP \tag{2.1}$$

Where

A = soil loss (t / ha – year)
R = rainfall erosivity (MJ-mm/ha-h-year)
K = soil erodibility factor (t. ha. h./ha. MJ. Mm)
L = the slope length factor, dimensionless
S = the slope steepness factor, dimensionless
C = the crop management factor, dimensionless
P = the erosion control factor, dimensionless

As a result of additional research and technology developed after the 1978 USLE handbook (Renard *et al.*, 1994), the USLE has been revised into Revised Universal Soil Loss Equation (RUSLE). The RUSLE still maintains the basic structure of the USLE, outlined above, but the algorithms used to calculate the individual factors have been changed. This empirically-based equation is used to predict long term average annual soil loss from sheet and rill erosion using values representing the four major factors affecting soil erosion by water (Renard *et al.*, 1994). These factors are climate erosivity represented by R, soil erodibility represented by K, topography represented by LS, and land use and management represented by CP. Many researches on soil erosion by water (Tamhane, 1959; Sheng, 1989; and El-Swaify, 1991) support the role of the above factors in erosion process.

2.2.1 Rainfall erosivity

The importances of rainfall in soil erosion processes have been identified by a number of researchers (Ellison, 1947; Lal *et al.,* 1980; Ngana, 1993). These researchers identified five major factors influencing the erosive potential of rains, namely rainfall amount, rainfall intensity, drop size distribution, kinetic energy, and wind velocity.

There is a clear relationship between the amount of rainfall and the amount of soil erosion depending on its annual distribution. However, erosion is worse in regions with alternating wet and dry seasons as soil moisture and cover of vegetation is not continuously maintained (Webster and Wilson, 1980). The first rains after dry season are liable to cause much erosion, as much of the soil surface is bare following the drying of vegetation and bush fires. On the other hand, the heavy rain in the wet season with high soil moisture retards the level of infiltration, make it difficult for soil air to escape and leave no room for additional water, ending in increased runoff and soil erosion (Lee, 1980). However, in statistical terms the correlation between rainfall amount and soil erosion is poor.

It has been reported in a number of publications (Lal *et al.*, 1980; Hudson, 1981; Sheng, 1989; El-Swaify, 1991; Madramootoo and Norville, 1993) that areas in the tropics experience short and high intensity storms associated with big drop size and high number of raindrops per time per area which results in big proportions of the rains that cannot easily infiltrate in the soil (Lal, 1984). As a result runoff and erosion are increased and the proportion of rainfall that percolates into the soil and becoming effective for crop production is reduced (Webster and Wilson, 1980).

Rainfall erosivity can directly be measured by monitoring energy load and splash simultaneously using the Ellison splash cup method (Hudson, 1981; Kinnel, 1974). Other techniques of assessing drop size distribution (Hudson, 1981) include the use of stain method (Neuberger, 1942 and Hall, 1970), and photographic methods (Laws, 1941; Atlas and Plank, 1953). In addition immersion method (Fuchs and Petajanoff, 1937); the flour pellet technique (Bentley, 1904; Laws and Parsons, 1943; and Hudson, 1964); and the use of a tension balance (Neal and Bayer, 1937); on an acoustic device (Kinnel, 1972) or on a pressure transducer (Joss and Waldvogel, 1967).

The data of drop size distribution are expressed as a single index called D_{50} or the median volume drop diameter, which refers to the drop diameter at which 50 percent of the rainfall volume is of drop size diameters less in size and 50 percent bigger in diameter. The D_{50} is affected by several factors including type, amount, duration, and intensity of rain, the velocity and direction of wind, and air temperature (Lal and Elliot, 1994). Laws and Parsons (1943) noted that median drop size tends to increase with increase in rainfall intensity. However, studies of tropical rainfall (Hudson, 1981) indicate that this relationship holds only for rainfall intensity up to 100 mm/hr. At greater intensities, median drop size decreases with increasing intensity, presumably because greater turbulence makes larger drop size unstable.

Rainfall parameters directly related to splash and erosion are difficult to monitor routinely. Attempts have therefore been made to relate rainfall erosivity to practical parameters such as intensity, amount, and duration. So erosivity have been determined by relating the detaching capacity and kinetic energy of rain to commonly measured rainfall parameters. Wischmeier and Smith (1958) analysing drop size distribution data published by Laws and Parsons (1943) found that soil loss by splash, overland flow, and rill erosion are closely related to R-factor (EI_{30}) of the USLE, which is the product of the kinetic energy, E, and the maximum 30-minute rainfall intensity, I_{30}. In practice E is calculated for time interval of equal intensity and summed over all time intervals of an erosive rain storm event:

$$E = 0.119 + 0.0873\log_{10} I \qquad (2.2)$$

Where,

E = kinetic energy (MJ/ha-mm)

I = rainfall intensity (mm/h)

To avoid overestimation of rainfall erosivity by including non-erosive storms, rainstorms with an intensity less than 13 mm/h and separated from other rain periods by more than 6 hours are not included, unless more than 6 mm of rain falls within a 15 min-period (Foster *et al.,* 1981). This is the most widely used method especially for areas with recording raingauge.

Apart from R factor of Wischmeier and Smith (1958) in equation 2.2, kinetic energy is taken to be an appropriate measure of erosivity (Pauwelyn *et al.,* 1988). Based on measurement of rainfall properties in Zimbabwe, Hudson (1963) developed the following equation for tropical rainfall:

$$E = 29.8 - 127.5/I \qquad (2.3)$$

However, Hudson (1981) restricts this index to rainfall intensity equal to or greater than 25 mm/h. Intensity below that threshold are ignored. Kinnel (1981) reworked Hudson's (1963) data and developed a more accurate equation:

$$E = \sum_{p=1}^{p=n} 292.3 * \left(1 - e^{-(0.447 \bullet Ip + 0.112)}\right) * Np \qquad (2.4)$$

Where

Ip = rainfall intensity (cmh^{-1})

Np = amount of rainfall (cm)

E = kinetic energy (Jm^{-2}per storm)

This equation has been used to calculate seasonal rainfall erosivity at the Mahenge village.

In Nigeria, Lal (1976) tested EI_{30}, E>25, and other possible parameters and found that the best correlation of soil loss from small plots was with a new index. The index has the unit mm^2/h:

$$\text{Lal index} = AI_m \tag{2.5}$$

Where

A = amount of rainfall per storm (mm)

I_m = maximum 7.5 minute intensity (mm/h)

Calculating the above indices requires a continuous record of rainfall intensity. Moldenhauer (1980) argues that rainfall erosivity data are most reliable when 20 or more years of recording rain gauge charts are available from which intensity values can be estimated. But, such records are not found in many parts of the world, including Tanzania, particularly in Mahenge village. At these locations the best temporal resolution of rainfall intensity available is the daily/monthly rainfall amount (Morgan, 1986; Elsenbeer *et al.,* 1993). As a result a number of regression equations relating rainfall amount to erosivity index (R) have been developed and are in use (Fournier, 1960; Roose, 1977; Arnoldus, 1980; Pauwelyn *et al.,* 1988). However, Stocking (1987) observed that a variable for erosivity cannot be independent of geographical area, scale, local conditions and types of measurements. In that case, some of these indices are chiefly of regional interest, but have not been verified or tested in other areas.

In this research equation 2.6 described in detail by Moore (1979) for use in East Africa has been used to estimate annual erosivity at Mahenge village using rainfall volume data (1960-1980) from Litembo Mission. The value obtained has been used to calculate long term erosion hazard of the village. The equation is selected from a set of equations for different altitude is as follow:

$$E = 3.96.P + 3122 \text{ (inland} > 1250 \text{ m above sea level)} \qquad (2.6)$$

Where

E = annual kinetic energy at intensity greater than 25mm/h based on 15 minutes periods (J/M^2),

P = mean annual rainfall (mm).

To convert the obtained kinetic energy to Wischmeier's index R to be used in USLE, another equation is used:

$$R_{us} = 0.029.\ E - 26 \qquad (2.7)$$

Where

R_{us} = annual rainfall erosivity (ft.t.in/acre/hour/year)

E = annual kinetic energy (J/M^2).

To obtain SI units, R_{us} is by multiplied by 17.02 (Foster *et al.,* 1981).

2.2.2 Soil erodibility

In addition to rainfall erosivity, soil erodibility (K) too has been identified as an important factor influencing water erosion (Lal, 1977a; Kilewe and Mbuvi, 1987). According to Hudson (1981) soil erodibility refers to the vulnerability of soil to suffer erosion due to the forces causing detachment and transport of particles. The inherent susceptibility of soil to erosion by water is related to the physical and chemical properties of the soil such as structural, and hydrological properties, organic matter content, infiltration capacity, texture, clay content and mineralogy (Lal, 1977a; Kilewe and Mbuvi, 1987). Soil structure is an important parameter to soil erosion as it determines the rate at which water can enter the soil as well as the resistance of soil particles to detachment by rainfall impact and subsequent removal in the surface runoff (Greenland, 1977). The breakdown of aggregates and subsequent detachment of soil particle from bare soil by raindrop impact or overland flow depends on aggregate stability and soil particle size distribution. Lal (1977b) noted that in Brazil under similar rainfall, sandy clay (Bauru) soils at 6 percent slope had higher runoff and soil loss than loamy (Terra Roxa) soils at 10 percent slope due to the difference in soil erodibility. This explains how different soil types respond to incoming raindrops.

The ability of a soil to withstand the forces leading to deterioration of structure depends on the content of organic matter supplied by crop cover (Kandiah, 1979). Organic matter has stabilising effects on the physical properties of the soil as it acts as a binding material of soil particles. In addition, organic matter enhances the microbiological activity of earthworms, nitrogen fixing bacteria and rhizobium. The micro-organisms and soil fauna activities improve the infiltration capacity and nutrition value that enhance crop growth and reduce the impact of erosion. Other important binding materials that enhance structural stability include clay mineral and sesquioxides.

Besides, mineral content of the soils is a major determinant of soil erodibility. Dudal (1980) noted that soils developed from Precambrian Basement Complex (gneiss, granite, and schist) are prone to crusting when exposed to raindrops resulting into reduced infiltration and increased runoff and erosion. Whereas, soils developed from basic rocks have a very stable micro-aggregation (Ahn, 1968). In the RUSLE model the soil erodibility is changing with time due to change in erosion governing forces. However, the rate of change depends on intensity and type of land use and interaction between management and ecological factors (Nearing *et al.,* 1988).

There are several different methods currently used to measure soil erodibility. Under field conditions natural run off plots are used whereas in the laboratory conditions use of rainfall simulation is not uncommon as described by Morgan (1986) and Hudson (1993). Laboratory analysis of soil properties is among the technique of estimating soil erodibility. Laboratory analysis involves the measure of soil's detachability or its resistance to detachment. They are based on properties that govern aggregation and aggregate stability (dispersion ratio, instability index, percent water stable aggregate), transmission and water retention properties (erosion ratio, dispersion-permeability index), raindrop impact (erodibility index, resistance index, KE index, rainulators), and thermodynamic processes that govern slaking or disruption of aggregates (temperature profile during infiltration) as identified by Lal and Elliot (1994). However, the choice of index to use depends on the relevance to processes that govern erosion under field conditions (Bryan, 1968).

It should be noted that the measurements described above are relatively expensive and time consuming. To overcome the limitation, erodibility has been estimated by relating few soil properties affecting it to the measured erodibility values of some soils. Wischmeier and Smith (1978) used nomograph that is based on percentage silt + fine sand, percentage coarse sand, percentage organic matter, soil structure and soil permeability to predict K-values for different soils in United States. Even though the nomograph has been widely used where USLE is used, Ngatunga *et al.*, (1984) found that the soil conditions in the tropics are quite different to those in the temperate countries where it was developed. Holzhey and Mausbach (1977) cautioned that the textural-based indices are not good predictors of erodibility as they are too broad.

Then, Mulengera (1996) relating measured soil erodibility values from different parts in Africa, Asia and Australia to soil properties that govern soil erodibility developed an equation to estimate erodibility. The equation has been used in determining the erodibility values of soil mapping units in Mahenge village. The equation appears as:

$$K = 2.0114 * 10^{-5} M - 0.00155 \qquad (2.8)$$

Where

K = estimated erodibility value (t-ha-h/ha-MJ-mm)

$M = a\,(a + b)$

a = silt + very fine sand (%)

b = coarse sand (%).

2.2.3 Topographic factor

Topographic factor (LS) has been found to be a critical factor in many studies because soil erosion and soil degradation are real threat to agriculture in hilly regions and limit use of agricultural machinery and draft animals in soil tillage (Amien, 1997). In addition, slope characteristics also determine the amount and rate of runoff and erosion by rainwater. The degree and length of slope are the two essential features of topography that affect rainfall-runoff proportion, rainfall impact angle, and erosion. Baver *et al.,* (1972) noted that the degree of slope is more important than length. Not only that runoff and erosion increase with increasing slope steepness and length but also the type of land use practised on particular slope. Djorovic (1980) observed that there is significant difference in soil loss from corn plot to that of wheat and meadow. For example, the maximum soil loss from the plot with corn was 64.0 t/ha per year on slope of 30° whilst the soil loss from wheat and meadow plots were 9.9 and 1.2 t/ha per year, respectively.

The effects of slope length on soil erosion are complex as they are compounded by site conditions such as soil characteristics, hydrological processes and interaction between them (Lal, 1997). It has been found that slope length is more important in generating erosion for steep than for gentle slope gradients (Mutcheler and Greer, 1980). On the other hand, the effects of slope length on runoff depend on several interacting factors namely slope gradient, slope aspect, soil characteristics and soil management (Laflen and Saveson, 1970; Wischmeier and Smith, 1978; Kirkby, 1980; Govers, 1992). For instance longer slopes on structurally unstable soils are prone to crusting and generate more runoff which increase with increase in slope length. In contrast concave slopes and high surface roughness decrease runoff and vice versa for convex slopes and smooth soil surface.

The slope length factor, L (McCool *et al.,* 1989) and slope steepness factor, S (McCool *et al.,* 1987) tend to adjust the predicted erosion rates. Greater erosion rates are produced on longer and/or steeper slopes when compared with those in the USLE (Schwab *et al.,* 1993). The differences are attributed to increasing rill erosion rates, as more runoff accumulates on longer slopes, and greater erosive forces occurring on steeper gradients. These factors can be calculated from the equations:

$$L = \left(\frac{l}{22.13}\right)^{m} \qquad (2.9)$$

Where

L = slope length factor,

l = horizontal projection of slope length in metre,

m = dimensionless exponent (0 to 1).

For conditions where rill erosion and interrill erosion are about equal, McCool *et al.*, (1989) recommended equation 2.10 to be used in estimating m:

$$m = \frac{Sin\theta}{Sin\theta + 0.269(Sin\theta)^{0.8} + 0.05} \qquad (2.10)$$

where

θ = field slope steepness in degrees

But, slope length exponent (m) for conditions where rill is great with respect to interill erosion is given as (McCool *et al.*, 1989):

$$m = \frac{(Sin\theta \ / \ 0.0896)}{(3.0Sin\theta^{0.8} + 0.56)} \times 2 \qquad (2.11)$$

When there is lower ratio of rill to interill erosion the slope length exponent (m) is found as follows (McCool *et al.*, 1989):

$$m = \frac{(Sin\theta \ / \ 0.0896)}{(3.0Sin\theta^{0.8} + 0.56)} \times 0.5 \qquad (2.12)$$

The slope length is measured from where surface flow originates (usually the top of the ridge) to the outlet of the channel or a point downslope where deposition begins (Wischmeier and Smith, 1978).

McCool *et al.* (1987) presented a set of S factors based on the slope length and steepness:

$$S = 3.0 \ (\sin\theta)^{0.8} + 0.56 \ \text{(for } l<4\text{m)} \qquad (2.13)$$

$$S = 10.8 \sin\theta + 0.03 \ \text{(for } l>4,\ s<9\%\text{)} \qquad (2.14)$$

$$S = 16.8 \sin \theta - 0.50 \text{ (for l>4, s>9\%)} \qquad (2.15)$$

Slope length and steepness factors can be calculated together as topographic factor (LS):

$$LS = \left(\frac{l}{22.13}\right)^{m} * (10.8 Sin\theta + 0.03) \text{ (for slope gradient < 9 \%)} \qquad (2.16)$$

$$LS = \left(\frac{l}{22.13}\right)^{m} * (16.8 Sin\theta - 0.5) \text{ (for slope gradient > 9 \%)} \qquad (2.17)$$

$$LS = \left(\frac{l}{22.13}\right)^{m} (3.0(Sin\theta))^{0.8} \text{ (for slope length < 4 m)} \qquad (2.18)$$

2.2.4 Cover and management factor

Plant cover play an important role in protecting soil from erosion by intercepting raindrops and absorbing their kinetic energies, and by impeding of runoff flow (Stocking, 1994). In addition, Penman (1963) and Lee (1980) noted that vegetation increases soil porosity by supporting faunal and other biological activity. Furthermore, vegetation increases the organic matter content that improves soil structural stability and soil infiltration capacity and increases the water storage capacity of the soil resulting into reduced amount of runoff and soil loss (Baver *et al.,* 1972). Therefore management practices that incorporate organic matter like *ngolo* cultivation should be encouraged in erosion prone areas.

However, the effectiveness of plant cover in reducing erosion depends on the height and continuity of canopy, the density of the ground cover and the root density (Elwell, 1980; Elwell and Stocking, 1974). Rose (1994) and Sreenivas *et al.*, (1947) observed that trees intercepting rainfall can shed water as large drops which when falling from a height of several meters can be just as erosive as rain drops due to reduced ground cover.

The impact of crop management is vital in the studies of soil erosion as emphasised by Hudson (1981) who argues that the difference in erosion caused by different management of the same soil is very much greater than the difference in erosion from different soils given the same management. Lal's (1976) studies in Southern Nigeria found that maize-maize without mulch had 23.6 tonnes/ha of soil loss. While maize-maize with mulch and maize-cowpeas (no till) had none, cowpeas-maize had 7.6 tonnes /ha of soil loss, and bare fallow produced 105.3 tonnes /ha of soil loss for the same slope (i.e. 15 percent) and rainfall amount (i.e. 781mm) in the first season. Similarly erosion studies at Tengeru in Tanzania showed that clean weeded coffee lost far more soil than plots under maize (Anderson, 1962), implying that erosion depends not only on what crop is grown, but also how that crop is grown. Thus, perennials would not always conserve the soil better than annuals.

Unfortunately, what has happened in many parts of the world including Tanzania, is that man has removed or altered the vegetation cover so much. Blackwell *et al.*, (1991) reported that the global loss of vegetation cover due to deforestation is 0.2 to 0.4 million hectares per year. They ascertain that the reported deforestation rate is the main cause of accelerated erosion. On the other hand, removal of vegetation cover as a result of uncontrolled burning and continuous cultivation as is happening in Mbinga district and Mahenge village in particular leaves the soil exposed to direct impact from raindrops. This can lead to severe erosion (Penman, 1963; Assmo and Eriksson, 1994) as discussed in section 2.2.2.

Vegetal cover and management factor (C) of the USLE is an important factor because it is related to productivity of soil or its fertility, climatic and management conditions that can be managed to reduce erosion (Renard *et al.* 1991). The C factor is the ratio of soil loss from an area with specified cover and management to that from an identical area in tilled continuous fallow conditions (Wischmeier and Smith, 1978). The soil loss ratios vary with change in soil and cover conditions, which vary with time, thus, C factor is calculated at different crop stages. However, the procedures used in USLE to calculate the C factor have been blamed for over-predicting erosion for variety of conditions (Dissmeyer, 1982). In the RUSLE, a sub-factor method is used to calculate C as a function of four sub-factors given as:

$$C = PLU.\ CC.\ SC.\ SR \tag{2.19}$$

Where

PLU = prior land use subfactor,

CC = plant cover subfactor,

SC = surface or ground cover subfactor,

SR = the surface roughness subfactor.

It has been noted in many researches (Hudson, 1981; Dissmeyer, 1982; and Renard *et al.* 1991) that erosion is the function of the amount of exposed soil. Exposed soils are subject to soil detachment by raindrop impact and surface runoff as rainfall intensity exceeds infiltration rates. Surface or ground cover sub-factor is obtained by either using Wischmeier's (1975) curve for the effect of surface cover (see Fig. 1A in Appendix 1) or the following equation:

$$SC = \exp(-bM) \tag{2.20}$$

Where

SC = the mulch or ground cover sub-factor value

M = the percentage of ground cover.

b = the coefficient assigned a value of 0.025 in USLE, 0.035 in the RUSLE, or 0.05 for certain conditions.

On the other hand, the canopy sub-factor (CC) applies only to the canopy above the bare soil. Canopy over litter is not included because the surface cover is the controlling factor (Dissmeyer, 1982). Fig. 1B in Appendix 1 from Wischmeier (1975) is suggested to be used to calculate the value of canopy sub-factor based on the percentage of bare soil having canopy over it and the average drop height of the canopy.

The prior land use sub-factor, on the other hand, includes the effects from the plant residues, roots and soil reconsolidation (Dissmeyer (1982). Dissmeyer (1982) argues that soil becomes less erodible over time as land is retired from tillage. Wischmeier (1975) based on soil loss data at Zanesville concluded that undisturbed soil was 0.45 as erodible as continually tilled soil. But when cultivation was resumed soil loss increased to a level about 4 times the rate before cultivation. This means that undisturbed soils are less erodible. However, the change in erodibility is soil dependent. Fig. 1C in Appendix 1 can be used to estimate the sub-factor for soil reconsolidation.

The residue effect when land use change is brought about by the fine roots and organic matter which tend to bind the soil into more stable aggregates. The curve in Fig. 1D (Wischmeier and Smith, 1978) describe this effect. However, with time, this effect disappears, making the soil more vulnerable to erosion. Wischmeier and Smith (1978) emphasised that the magnitude of the effect and its duration is a function of the amount and rate of roots and organic matter in the soil at the time of decay plus structure and permeability of the subsoil.

The mat of roots enhances the soil particles ability to aggregate. However, in absence of enough research data on this effect, Dissmeyer (1982) recommended the use of Wischmeier's (1975) curve (see Fig. 1E in Appendix 1) for the effect of grass root network to describe it.

On the other hand, the soil surface roughness has a significant effect on water erosion as it affects infiltration rate, runoff, solar radiation and evaporation rate (Saleh, 1993). On slopes under arable farming the roughness has to include soil and vegetation elements such as soil particle size and clod size distributions, crop stem dimensions, orientation and density. This is because these variables control the soil erosion processes. Soil roughness changes with rain and cultivation. The change in surface roughness (SR) caused by rainfall is one of the important variables to estimate roughness as follows:

$$RR = ae^{-bdp} \qquad (2.21)$$

Where

RR = ratio of measured random roughness (cm) to initial random roughness (cm) measured before rainfall event(s)
ab = constants
dp = cumulative rainfall(cm)or kinetic energy(J/m2)

The relationship above can be used in estimating roughness sub-factor in crop and management factor. Methods used to measure soil roughness include the use of relief meter (Kuiper, 1957), photographic methods (Foster and Meyer, 1972), microprocessor automated rillmeter (Radke et al. 1981), automated profile meter (Podmore and Huggins, 1981), non- contact optical probes (Römkens *et al.,* 1985) and chain method (Saleh, 1993). However, the methods discussed above are labour intensive, expensive, and demand more time to get reliable results, so in this study it was not measured.

To get the seasonal cover-management factor C, summation of specific periods' cover factor multiplied by the ratio of specific periods' erosivities divided by seasonal erosivity value is made.

$$C = \sum Cir_e \tag{2.22}$$

Where

Ci = over factor for period i in a season

r_c = ratio of erosivity of period i in a season over seasonal erosivity R, $= \frac{r_i}{R}$

r_i = rainfall erosivity of a specific period in a rainfall season.

The long term crop management factors used in this study for different land uses in the village were obtained from experimental findings in other parts of the Tropics (Roose, 1977; Singh *et al.,* 1981; Srikhajon *et al.,* 1984).

2.2.5 Support practice factor

Hudson (1981) argues that both the soil characteristics and the management it receives influence the amount of soil erosion at a particular piece of land. But as reported by Troeh *et al.* (1988) growing vegetation, residue cover, and crop and soil management practices are not always enough to prevent excessive soil erosion. Thus, demand for support measures to prevent soil erosion. The most common support practices now in use include contouring, terracing, ridging, and strip cropping.

The support practice factor is the ratio of soil lost from an area with support practice measures to that lost from an area ploughed up and down slope.

Renard *et al.* (1991) argued that support practice factor (P) mainly represents how surface conditions affect flow paths and flow hydraulics. Contouring has been found to be effective on middle range slope of 2 to 8 percent and less effective on flatter and on steeper slopes or under conditions of high rainfall intensity (Wischmeier and Smith, 1978; Schwab *et al.,* 1993). Unlike contouring, ridging facilitates surface drainage and improve rainfall storage capacity (Morgan, 1986) and are widely used in lowlands of Mbinga District.

In steeper slopes up to 50 percent Fanya Juu terraces are recommended for shallow soils (Wenner, 1981) as they involve small amount of excavated subsoil to be exposed. In contrast bench terracing that re-shape the sloping land to more or less levelled plateau, has a risk of medium term reductions in productivity due to soil disturbance and exposed high aluminium and infertile subsoil that reduce the cropping options (Hudson, 1987; JICA, 1996; Amien, 1997). In Mbinga District Matengo pits ('*ngolo*') which are closely similar to tied ridges have been found to be effective in controlling soil erosion in steep Matengo highlands (Stenhouse, 1944; Allan, 1989; JICA, 1995) as discussed in section 1.1.

In spite of the role that the support practices play in erosion control, it has been very difficult to evaluate its effectiveness (Mutchler *et al.,* 1994). This is because tillage treatments introduce various surface configurations on a field. The combinations of these configurations with slope length and steepness complicate the evaluation of support practices in small runoff plots. In that aspect evaluation of support practice demand large space such as watersheds. However, results in the watersheds are difficult to replicate and their results cannot be transferred to other situations (Mutchler *et al.,* 1994).

2.3 Erosion Hazard Assessment

According to Morgan (1986) the assessment of erosion hazard is a form of land resources evaluation, the objective of which is to identify areas of land where sustainable productivity from a given land use is threatened by excessive soil loss. In that sense erosion hazard assessment is not a survey of actual erosion but it describes chance of an environment to allow soil erosion to occur (Stocking, 1987). The assessment results in defining areas similar in their degree and kind of erosion hazard, which is valuable for land use and soil conservation planning. Ideally erosion hazard assessment should involve all the five factors affecting erosion, namely rainfall erosivity, soil erodibility, slope steepness and length, plant cover and soil management practices, and support practices. However, due to practical limitations most studies involve only few of them.

There are different approaches that have been used for erosion hazard assessment. At global level, the task of erosion hazard assessment can be accomplished by using questionnaires sent to governments or desk interpretation of the thematic maps. At national level, various techniques have been employed including erosion intensity indices (such as drainage density and drainage texture) as applied by Morgan (1974) in Malaysia; rainfall aggressiveness (Fournier, 1960); factorial scoring (Stocking and Elwell, 1973) in Zimbabwe; and rainfall erosivity indices (Stocking and Elwell, 1976; Roose, 1977) to show spatial and temporal variations in erosion risk. At local level, land capability classification as developed in United States (Klingebiel and Montgomery, 1966) and soil erosion surveys are the common semi-detailed assessment. In addition, evaluation of erosion can be done in more detail by assessing the intensity of sheet and rill erosion using soil erosion prediction models such as the USLE/RUSLE (Renard *et al.,* 1991) as has been used in this research work.

The end result of erosion hazard assessment is mapping. Mapping of erosion enables location of places where the problem is acute within the area and where it is not, and why it is serious on that particular place (Dregne, 1987). However, as reported by Dregne (1990) erosion maps in Africa are scarce and for Mahenge village in Mbinga district they are non-existent. In Tanzania this situation is attributed by lack of detailed soil surveys and topographic maps, limited necessary data for assessing erosion, and changing land use due to absence of functional land use planning (Mulengera, 1996).

The most common method used in mapping erosion hazard has been overlying erosivity and erodibility factor using transparent paper (Morgan, 1986). However, the method is tedious and time consuming as it involves making different maps for erosivity, erodibility, and other factors where possible. In this research, the ARC/INFO-GIS package was used to digitise the soil mapping unit boundaries from soil survey map (1:25,000) and topographic factors calculated from topographic map (1: 50,000) to produce an erosion hazard map of Mahenge village. The rainfall erosivity was assumed to be constant for all mapping units while soil erodibility values, crop management factors and support practices were different for each soil mapping units. The ARC/INFO-GIS computer software is preferred over others because of its ability to accept, store, manage, retrieve and display both raster and vector data types, as well as ability to convert from one type to the other (Lo, 1994).

2.4 Impact of Soil Erosion on Soil Productivity

IFAD (1992) noted that even though soil erosion is a global phenomenon, the damage it causes to the soil is more severe in the developing countries like Tanzania. Kilasara *et al.* (1995) reported that accelerated soil erosion is a widely spread phenomenon in Tanzania having different forms and intensity affecting all major land use and soil types. In Mbinga district and Matengo highlands in particular approximately more than 70 percent of the agricultural land is on hillsides which are susceptible to accelerated erosion. Unfortunately, production methods do not often consider the sensitivity of the soils in Matengo highlands.

The population pressure in the areas has increased the demand for land and food production. As a result people have been forced to clear forests and to cultivate steeply sloping lands and hilltops, which make up a large part of the land in the village (Magoggo *et al.,* 1996). Population increase has not only led to deforestation of the catchment areas in search of arable land and fuelwood but also has reduced the fallow periods making shifting cultivation no longer sustainable (Rutatora *et al.,* 1995; JICA, 1996). On the other hand, the increase in cultivated area as reported by Rutatora *et al.* (1995) in terms of increase in number of plots and area cultivated have failed to provide source of growth in food production. As over cultivation and expansion of agriculture into more fragile land continues, increased use of inputs such as chemical fertilizers, improved crop varieties, pesticides and insecticides have failed to sustain soil productivity. The introduced permanent cultivation to replace the bush fallow system has led to serious decline in soil productivity (Mattee *et al.,* 1996) in Mahenge village and Matengo highlands in general.

The effects of erosion on soil productivity depend on soil profile characteristics and the landscapes in which they occur (Larson *et al.,* 1983). Soils with favourable characteristics throughout a deep profile exhibit little change in long-term productive potential due to erosion and vice versa for poorly developed soil profile. In addition, soil erosion increases the variability of soils within a field that makes management more difficult. Besides, it has been found that degradation of irreplaceable soil attributes such as water storage capacity, depth, and acidity is not evenly distributed. Murdoch and Smyth (1990) reported that degradation of soil resources is most serious on the steeper slopes and sometimes with unfavourable subsoil because of higher erosion rates. However, it is the best soils that are favoured in terms of resources allocation and maintenance (Murdoch and Smyth, 1990). Therefore, sustainable, effective, and affordable ways of using the poor soils like those of Mahenge village must be found.

As reported elsewhere (Lal, 1979; Stocking, 1985; Dregne, 1990; CTA, 1993; UNCTAD, 1997) deterioration of soil physical properties such as deterioration of soil structures lead to loss of porosity or pore continuity. The formation of crust at the surface due to damage done to the soil structure result into limited water entry, increased runoff, and poor seedling emergence and increased erosion. On the other hand, deterioration of soil structure in the subsoil result in decreased water storage, a lower availability of the water stored, and decreased ability of soil water movement. As erosion adversely change the physical properties of root zone as discussed above, the decrease in crop yield may be permanent (Benson *et al.*, 1989; Dregne, 1990; Favis-Mortlock *et al.*, 1991).

Stocking and Pain (1983) observed that the decline in yield with erosion is caused by the decrease in rooting depth. This reduction in soil depth changes the characteristics of the soil and alters its capacity to support plant growth (Christensen and McElyea, 1988). The most important changes are the reduction of available soil water to plants. The effects of water stress on plant growth include decreased rate of photosynthesis and respiration, loss of cell turgidity, retarded translocation and reduction in cell formation and its ultimate development. But the direct effect of soil moisture deficit on crop yield comes about due to decline in actual crop evapotranspiration (ETa) from maximum crop evapotranspiration (ETm) that end up in yield decrease (Stewart and Musicky, 1982).

Apart from degradation of soil physical properties, soil erosion removes fine and more fertile soil particles. Unfortunately, as reported by Lal (1984), in the tropical soils nutrient reserves are concentrated in the thin top surface horizon. Thus, its depletion makes soil erosion a major agricultural problem as loss of fertility increase production costs. The subsurface horizons exposed in eroded land have low exchange capacity, low inherent fertility, high plant available iron content which inhibit uptake of phosphorus, high aluminium toxicity and have trace element deficiency and high soil acidity. In addition, eroded land results in reduced organic matter content that not only reduces moisture retention, infiltration, and aeration but also limits activity of micro-fauna that contribute to aggregate stability and plant available phosphorus (Lal, 1987). From the discussion above you find that maintenance of inherent soil fertility is the most critical factor related to soil productivity (Hall *et al.*, 1985). Therefore, practices that contribute to its depletion such as deforestation and poorly repeated annual cultivation that cannot compensate it by artificial fertilizer supply due to worsened physical properties and chemical toxicity should ideally be stopped (El-Swaify *et al.*, 1982).

Even though, research in soil erosion has a long history in the country (Rapp *et al.*, 1972) there is little information on the erosion-induced loss in soil productivity in Tanzania (Kilasara *et al.*, 1995). This is because soil erosion-productivity relationships are complex (Doorenbos and Pruitt, 1977; Cassel and Fryrear, 1990; El-Swaify, 1991) and, soil properties are not the sole factors controlling crop yields, others being technological advances in new crop varieties, fertilizer technology, efficient agronomic practices, and climatic factors such as growing season precipitation, evapotranspiration, and temperature. Not only that soil erosion losses by volume or weight are poor surrogates for decline in productivity (Stocking and Peake, 1986) but also existing soil erosion experiments (Lundgren, 1980; Ngatunga, 1981) often do not report yields. In addition Dregne (1990) observed that loss of productivity does not necessarily lead to decline in yield as technology may mask the effects of erosion on decline in productivity, through increased production as discussed above.

However, Crosson and Anderson (1993) observed that research in erosion-induced loss in soil productivity is of great concern to developing countries like Tanzania. This is because its findings can be used in agricultural development planning, assessment of food adequacy to the expanding population, evaluation of agricultural policies (Wolman, 1985), and in development of practices and policies for the restoration of the eroded soils (Pierce and Lal, 1994). Therefore, it is important that the effect of erosion on productivity be quantified on all-important soils over broad geographical areas (Weesies *et al.*, 1994).

2.5 Approaches to Soil Erosion Productivity Studies

There are several methods used to determine erosion productivity relationships (Olson *et al.*, 1994; Kilasara *et al.*, 1995). The most common include desurfacing experiments, whereby topsoil are artificially removed and added to create various topsoil thicknesses. On the other hand laboratory and green house studies involve relating erosion-induced alteration in soil properties to crop yield while reconnaissance surveys involve relating crop performance and yield to qualitative assessment of past soil erosion. Besides, the long-term variable management involves long-term field trials that compare different soil surface management.

Even though the last approach is ideal in erosion productivity studies its database not only takes a long time to establish but also is lacking in Tanzania. Moreover, it is difficult to separate management effects from erosion effects. Therefore, this research is using modelling approach, which involves assessing long-term erosion magnitudes and their impact on soil properties and productivity.

2.5.1 Soil erosion productivity modelling

As discussed in section 2.5, studies on the soil erosion productivity relationships are very recent compared to those for quantifying forms, rates, and extent of erosion. However, quantification of the erosion-induced loss in soil productivity is of great importance for developing countries like Tanzania whose resources are under great pressure as a result of both increasing population and increasing utilisation of marginal lands.

Biot (1988) identified four major types of soil erosion-productivity models, namely process-based models, empirical models, stochastic models, and hybrid models. The process-based models like Erosion Productivity Impact Calculator (EPIC) is composed of physically-based components for simulating erosion, plant growth, and related process and economic components for assessing the cost of erosion and determining optional management strategies (Williams *et al.,* 1984). Since, erosion can relatively be a slow process, EPIC is capable of simulating hundreds of years. However, the model is very sophisticated and its data base is not easily found in developing countries like Tanzania where even soil survey is incomplete (Mulengera, 1996).

On the other hand, empirical models such as Productivity Index (PI) relate inputs and outputs through statistical regression analysis. The PI is a model which relate root growth to soil properties within a profile (Neil, 1979; Kiniry *et al.*, 1983; Pierce *et al.*, 1983). The model assumes that root growth is proportional to productivity. Hence, the properties of soil layers within the rooting zone are major factors constraining crop growth and yield where each property has been related to sufficiency for growth ranging from 0.0 representing conditions which will allow no growth to 1.0 representing growth in an ideal medium. Another assumption is that nutrients are not limiting to plant growth, whilst climate, management, and plant differences are assumed to be constant. The equation to estimate PI as modified by Pierce *et al.* (1983) is:

$$PI = \sum_{i=1}^{r} \left(A_i * C_i * D_i * E_i * R_i \right) \tag{2.23}$$

Where

A_i = sufficiency of available water capacity (SUFFPAW)

C_i = sufficiency of bulk density (SUFFDB)

D_i = sufficiency of pH (SUFFpH)

E_i = sufficiency of electrical conductivity (SUFFEC)

R_i = predicted root fraction in ideal soils as weighting factor

r = number of horizons in the depth of rooting.

Kiniry *et al.* (1983) provides a methodology of estimating the above sufficiencies. The sufficiency of bulk density (SUFFDB) is related to mechanical impedance of root growth. In this case bulk density is taken to be the indicator of soil's sufficiency for root development. Using the sufficiency curve (Fig.1) as suggested by Pierce *et al.* (1983) the value of sufficiency of bulk density used in productivity for soil mapping units were obtained. However, the non-limiting, critical, and limiting tend to vary with family texture class (Table 1A in Appendix 1) (Pierce *et al.* (1983).

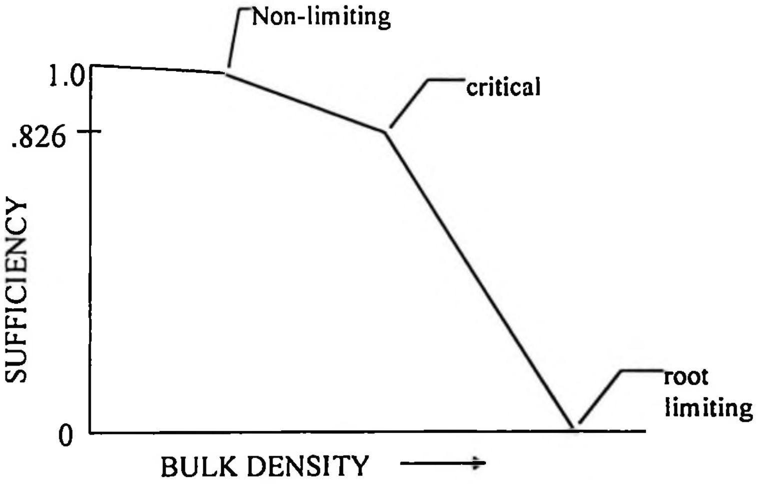

Fig.1: Sufficiency of bulk density used in productivity model

On the other hand the sufficiency of pH is

$$\text{SUFFPHS} = \begin{cases} 1.00 & \text{if } 5.5 < \text{pH} \leq 7.5 \\ 0.16\text{pH} - 0.12 & \text{if } 5.0 \leq \text{pH} \leq 5.5 \\ 0.446\text{pH} - 1.31 & \text{if } 2.9 \leq \text{pH} \leq 5.0 \end{cases} \qquad (2.24)$$

The equation for sufficiency of Electrical Conductivity (SUFFEC) is

$$SUFFEC = \begin{cases} 1.00 & \text{if } EC \leq 2.0 \\ 1.14 - 0.07EC & \text{if } 2.0 \leq EC \leq 16 \\ 0.00 & \text{if } EC \geq 16.0 \end{cases} \qquad (2.25)$$

To quantify soil productivity, each parameter above was evaluated in terms of root response, and each soil layer was weighted according to an ideal root distribution. The predicted fraction of roots which are influenced by the rooting depth were used as weighting factors and were obtained by the following equation (Gantzer and McCarty, 1987):

$$L_D = 0.152 \log[R + (R + 6.45)^{0.5}] - 0.152 \log[D + (D^2 + 6.45)^{05}] \qquad (2.26)$$

Where

L_D = fraction of available water depleted at depth D,

D = depth within the profile, cm,

R = the maximum plant rooting depth, cm.

The effective rooting depth is the soil depth in which the bulk of the roots are concentrated. The effective root depth changes with crop growth. At sowing it is about twice the seeding depth. Whilst the maximum rooting depth is reached at the end of the development stage.

The PI equation is less complex, and requires less input of soil property values than EPIC (Gantzer and McCarty, 1987). The simplicity of the model has been blamed to lead into loss in the description of soil erosion-productivity relationships, and subsequently reducing its accuracy. But, by inclusion of fewer inputs the model is a less costly tool for analysis (Pierce *et al.,* 1983) for developing countries like Tanzania which has limited financial resources and trained manpower to handle the demand of the EPIC discussed above.

Another model in use is the soil life model (Elwell and Stocking, 1984) which considers the minimum productive soil depth required for a particular crop to achieve specified minimum yield. Soil life is taken to be the remaining useful productive life of a soil at existing rates of erosion or at rates that have been calculated from proposed activities (Stocking and Pain, 1983), Elwell and Stocking, (1984) provided the following equation for predicting the life-span of a soil:

$$L_f = \frac{(D_e - D_o)M}{Z - Z_f} \tag{2.27}$$

Where

L_f = soil life-span in years

D_e = depth of available productive soil (m)

D_o = minimum soil depth (or effective minimum rooting depth) for a particular crop (m)

M = bulk mass of soil (t $ha^{-1}m^{-1}$depth of soil) (i.e. bulk density in gm cm^{-3} x 1000)

Z_f= estimated rate of soil formation (t ha^{-1} $year^{-1}$)

Z = predicted rate of soil loss (t ha^{-1} $year^{-1}$)

However, identification of the point at which the soil become unproductive relied on empirical assumptions and the field experience (Stocking and Pain, 1983). Stocking and Pain (1983) based on the concept of minimum soil depth suggest that loss in water holding capacity is the major determinant of crop failure in eroded soils as quantified by Doorenbos and Kassam (1979):

$$1-\frac{Y_a}{Y_m}=ky\left(1-\frac{ETa}{ETm}\right) \tag{2.28}$$

Where

Y_a = actual crop yield (t/ha)

Y_m = potential crop yield under water constraint –free conditions (t/ha)

ky = empirical yield response factor for a given crop type and stage of development

ET_a = actual crop evapotranspiration for the crop development stage under consideration

ET_m = maximum crop evapotranspiration of a disease free crop under water constraint free conditions.

The yield response factor for maize used in this research was 1.25, which account for total growing period (Doorenbos and Kassam, 1979; Stocking and Pain, 1983). The effect of soil moisture stress on plant growth and ultimately yield is a two-stage process (see Fig.2).

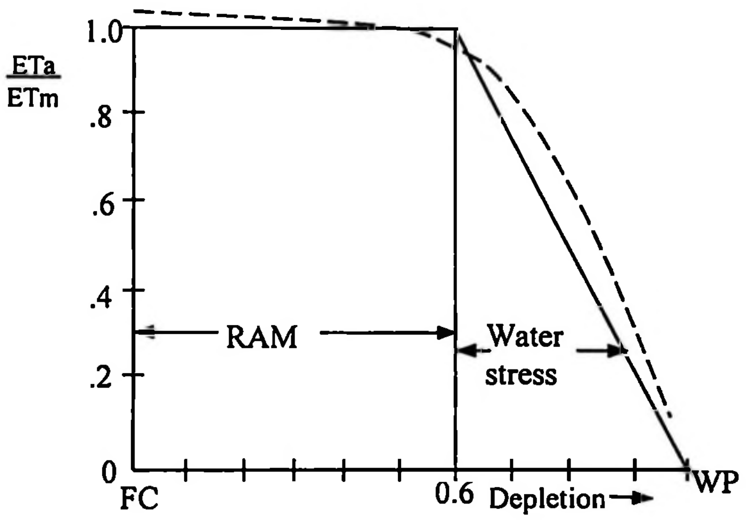

Fig.2: Decrease in ETa due to decreasing soil moisture

The first stage is when crop tolerates soil moisture deficit before actual evapotranspiration (ET_a) falls below potential evapotranspiration (ET_m). The amount of soil moisture at this stage is regarded as Readily Available Soil Moisture (RAM). This is the difference in soil moisture content between field capacity and critical soil moisture. Critical soil moisture content is the soil moisture content at which ET_a starts to drop below ET_m and is calculated as follows (Raes, 1996, Doorenbos and Kassam, 1979):

$$\theta_{critical} = \theta_{FC} - p(\theta_{FC} - \theta_{WP}) \text{ [vol \%]} = \theta_{FC} - RAM \qquad (2.29)$$

where

$\theta_{critical}$ = critical moisture content (vol %)

θ_{FC} = soil moisture at field capacity (vol %)

θ_{WP} = soil moisture at permanent wilting point (vol %)

p = Fraction of soil moisture available

Average depletion factor over root zone

When soil moisture in the root zone is smaller than critical soil moisture content ET_a goes below ET_m. Then, the second stage is entered whereby further reduction in ET_a from ET_m leads to reduction on crop yield. The magnitude of ET_a depends on the remaining soil water [(1- p) Sa D] and ET_m.

To address the features in Productivity Index and yield response to water models, Mulengera (1996) developed a hybrid Soil Erosion – Productivity Index Model (SEPIM) by integrating Productivity Index and Soil Life components as quantified in equation 2.23 and 2.28, respectively. The relationships between the components provide the basis for soil productivity assessment in this research. The new model appears as:

$$Y_{err} = \left[1 - ky\left(1 - \frac{ETa}{ETm}\right)\right]\sum_{i=1}^{r}\left(C_i * D_i * E_i * R_i\right) \qquad (2.30)$$

Where

Y_{err} = production potential of soil (0<=Yerr<=1.0)

For other terms refer to equations 2.23 and 2.28.

In equation 2.30 A_i from Kiniry *et al.* (1983) model has been removed and replaced by a component of reduction in yield as determined in equation 2.28. The model simulates soil productivity by considering its water-holding capacity, crop evapotranspiration, physical and chemical properties of the soil that are important for crop growth. When tested SEPIM was able to explain about 81 percent of the yield variations when soil properties affecting crop development and yield, and actual evapotranspiration were considered. As observed by Mulengera (1996) that when the soil properties of eroded topsoil do not change significantly to those of subsoil, the availability of water to plants is a sufficient measure of the effects of erosion on crop productivity. However, when they change much, then both soil moisture deficit and soil properties are to be used in simulation of the impact of erosion on soil productivity.

Based on available data base and resources both the PI (without A_i) and SEPIM models will be tested and one selected to be used in Mahenge village in Mbinga district as an effort to assess the magnitude and change in soil productivity as affected by erosion. Besides, as noted by Cassel and Fryrear (1990), a model needs to be validated in other Agro-ecological zones apart from where it was developed in order to ascertain its accuracy and efficiency.

3. MATERIALS AND METHODS

3.1 Study Area

3.1.1 Location

Mahenge village is in Mbinga district, Ruvuma region, as shown in Fig. 3. The village is approximately 20 kilometres west of Mbinga town. The village is bordered by Kindimba and Kilanga Juu villages in the East, Litembo in the West, Mbuji in the South, and Wukiro village in the North (Fig. 3).

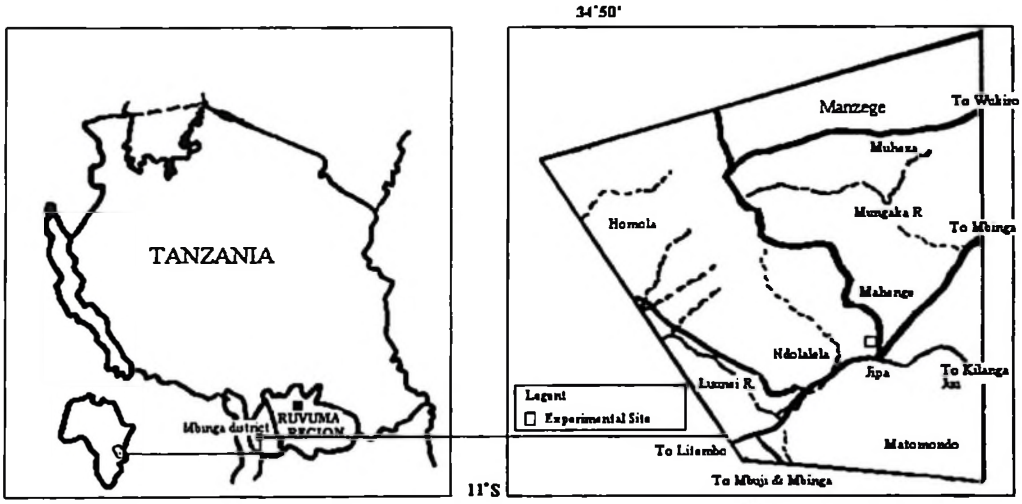

Fig.3: The map of Tanzania showing location of Mahenge village

3.1.2 Climate

There are no specific climatic records for the village, with exception of rainfall data recorded by recording rain gauge installed in 1994 by the Miombo Woodlands Agro-ecological Research Project (MWARP). According to the data collected so far the village receives about 914.2 mm of rainfall per year. The rainfall pattern is unimodal, starting in November and ending in May with much rainfall falling in January, February and March. The mean monthly maximum temperature for the village based on reading from Kindimba village varies from 19.5 °C in June to 26.4 °C in November. In contrast the mean monthly minimum temperature vary from 7.03 °C in July to 15.2 °C in February.

3.1.3 Geology and landforms

The geology of Mahenge village comprises mainly gneissic metamorphic rocks rich in ferromagnesian minerals (Magoggo *et al.,* 1996). The present landscapes in Mahenge village have been shaped by faulting in the West marked by Luunei river and in the East by Mungaka river resulting into highly dissected mountainous landscape with many hills, piedmonts and narrow drainage ways (Magoggo *et al.*, 1996). The hilltops are characterised by rock outcrops at altitude of about 1800 m above sea level whereas the hill slopes lie at altitude between 1550 and 1800 m above sea level with steep slopes ranging between 15 and 45 percent. The Western part of the village is characterised by piedmonts with slope less than 16 percent (Magoggo *et al.*, 1996).

3.1.4 Drainage

Two major rivers drain the village, the Luunei in the West and the Mungaka in the East with many streams and springs that form tributaries to the two rivers. The streams are perennial and offer water for irrigation in the dry season for both coffee in the hill slopes and, maize and vegetables in the valley bottoms.

3.1.5 Soils

The soils of the village (see Fig. 4) have been classified as Leptosols (H1), Cambisols (P1 and P2), Phaeozem (H32), Acrisols (H2 and H33), and Regosols (H31) according to FAO (1988) legend, or Entisol, Inceptsol, Mollisol, and Ultisol according to USDA Soil Taxonomy (1990) (Magoggo *et al.*, 1996). The soil textures of the village are dominantly sandy clay loams with medium available water capacity, low available phosphorus and soil reactions ranging between medium acid to extremely acid in the Nalioba hill.

3.1.6 Vegetation

The natural vegetation of the village was Montane forests, Miombo woodlands and related wooded grasslands (Millington and Townsend, 1989). However, currently they have almost been cleared and totally replaced by exotic tree species mainly Eucalyptus species, Grevillea robusta and Black wattle (Magoggo *et al.*, 1996; Mattee *et al.*, 1996). So the village is faced with extreme loss of biodiversity as wetlands are also cleared for agricultural use.

3.1.7 Land use

The major land uses of Mahenge village (see Fig. 4) (Magoggo *et al.,* 1996) include permanent cultivation of Arabica coffee grown under Grevillea robusta which provide shade. The crop receive much more attention than any other crops in terms of inputs (chemical fertiliser, pesticides, herbicides), and soil and water management (trees on bench terraces and manure application), a situation that has contributed to its increased productivity (Mattee *et al.,* 1996; URT, 1997). It is under coffee plants where Irish potatoes are also grown.

Apart from coffee, maize, wheat, and beans are also grown using *ngolo* cultivation. Maize is planted in December and harvested in July to August and wheat is planted in March to April and harvested in September to October while beans are planted in March to April and harvested in June to July.

Maize is the most important cereal crop grown in Mahenge village, as it is the staple food crop in the area. It ranks first in number of producers, area grown, and total cereal production (Hawassi, 1997). However, the crop faces a number of problems including low soil fertility, poor husbandry, low productivity, insects (especially maize stalk borers -*Busseola fusca*), and diseases (especially maize leaf blight pathogen -*Helminthosporium spp*) (Mattee *et al.,* 1996).

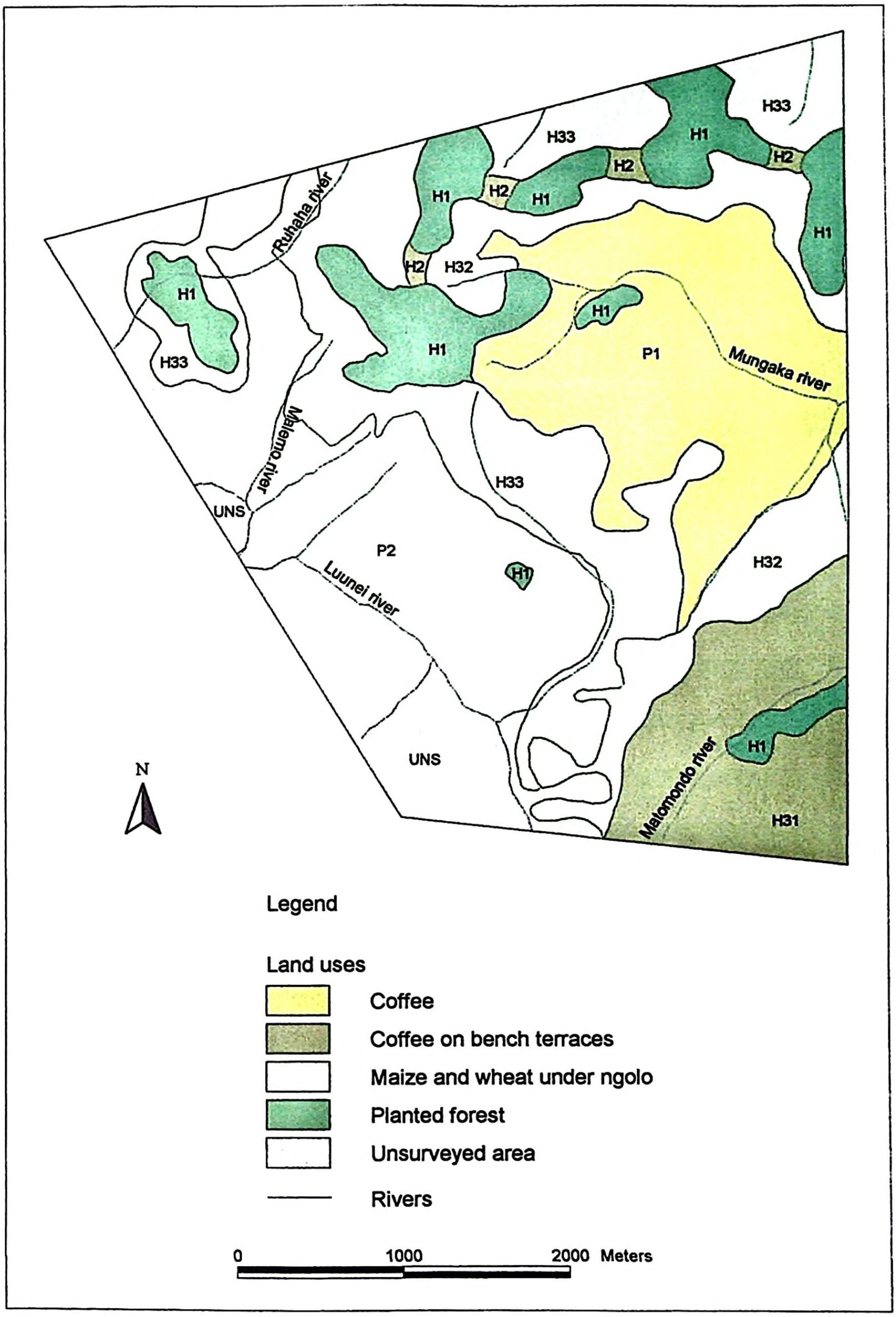

Fig. 4: Land uses map of Mahenge village

Another important land use is bottomland farming, where river valleys are cultivated and planted with maize, beans and vegetables such as pumpkins, spinach, cabbages and tomatoes during the dry season. On the other hand, there is unusual farming practice in the village where sweet potatoes and sometimes cassava are grown on down-slope ridges.

In addition, pigs, goats, cattle, and chicken are important livestock found in the village. Pigs are under zero grazing, cow and goats are under semi-zero grazing, and chicken are under free range. Pigs and chicken are important source of protein in the village and are kept by most households. The increase in the number of cattle in the village has been blamed for deterioration of soil as they are grazed in the fields soon after harvest leading to destruction of soil structure. However, there is new development in the village as CARITAS (International Confederation of Catholic Organizations for Charitable and Social Action) has introduced dairy cattle which are kept under zero grazing and whose dung is used as farmyard manure on both cash and food crops.

3.2 Experimental Procedures

3.2.1 Experimental design and runoff plot management

A Complete Randomised Design (CRD) experiment was employed with three treatments and two replicates set up at the village. The treatments included the Matengo pits (*ngolo*) planted with maize, bench terraces planted with maize and bare fallow plots. The plots measured 30 m long downslope by 6.5 m wide (area 195

m^2).The individual plots were bounded by wooden planks on the upslope ends and longitudinal sides and tanks with length of 6.5 m, width of 0.65 m, and depth of 0.6 m constructed at their lower slope ends to collect eroded soil and runoff.

All the plots were cultivated using hand hoes prior to planting. For *ngolo* plots plant residues were arranged in square grids measuring 2 m X 2 m. The soil from the centre of the squares was dug to cover the plant remains, forming a pit at the centre surrounded by horizontal and vertical ridges. Maize seeds were planted on the ridges. Maize seeds used were of cultivar H 614 bred by East African Maize Improvement Program. Two seeds of maize were planted per hole on 18th January 1999 at spacing of 90 cm between rows and 25 cm between plants with plant population of 780 and 708 per plot for terrace and *ngolo*, respectively. Thinning was done four weeks after planting to leave one seedling per space. A compound fertiliser, that is, Di-Ammonium Phosphate (DAP 18-46-0) at the rate of 50 kg per hectare was applied as basal dressing at planting. Four weeks after planting the emerging seedlings were side dressed with DAP at the rate of 150 kg per hactare and again after five weeks with Urea at the rate of 200 kg per hectare after first and second weeding. However, weeding that was done at flowering time was not followed by application of fertiliser. Weeding for cropped plots was carried out using a hand hoe.

But, for bare plots that were established in the last rain season, all plant remains were removed and cultivated up and down the slope. The bare plots were weeded by hand pulling of emerging weeds several times.

3.2.2 Soil loss

Soil losses were, for logistic reasons, determined only on a monthly basis and not for individual storms in the growing season. To aid fast settling of sediment in the collected runoff a flocculating agent (Calcium chloride) was added to the runoff suspension for about an hour prior to emptying. The clear water was emptied using small plastic containers to avoid disturbance of the settled sediment. Then, the remaining sediment were thoroughly mixed to form a sludge that were put into the plastic buckets and measured using a spring balance (Salter type) and its wet weight recorded. A sample of 1 kg was taken from thoroughly mixed sludge from each tank, air dried at the site and later oven dried for 24 hours at 105°C for a constant weight determination at the Department of Agricultural Engineering and Land Planning, Sokoine University of Agriculture.

3.2.3 Crop development and yield measurements

During crop development, data collected included plant height, and crop cover at different growth stages, plant population, cob numbers, cob mass, grain mass, and stover mass at harvest. Six randomly selected sub-areas were marked for each plot. The random selection of sub-areas was done using a table of random numbers. The plant heights were measured from a sample of 3 plants from each sub-area at interval of two weeks from the soil surface to the top of leaf using a steel tape. Crop cover at interval of 2 weeks was measured using sighting frames as per procedures explained in detail by Elwell and Gardner (1975) and Elwell and Wendelaar (1977). Samples of maize stovers from six square metres of sub-areas earmarked above were taken. The stovers were cut at the soil surface. The number of maize plants, and cobs per sub-area were counted. Then, the maize cobs were separated from the stovers and shelled manually. The maize grain, cobs, and a sample of 3 stovers were weighed and dried at 70°C to a constant weight for about 48 hours.

3.2.4 Bulk density and soil moisture data collection

Core samples of soil were taken using a core cylinder. In this research the core had diameter of 5 cm and height of 5 cm. Samples for bulk densities were taken at the interval of two weeks throughout the growing season at soil depths of 0-25, 25-50, 50-80, and 80-150 cm.

Soil moisture in runoff plots was measured at the interval of two weeks at the depth of 0-30cm, 30-45cm, 45-60cm, and 60-120cm. Soil samples from six locations in each plot were taken at those depths using an auger to make a composite sample for each depth range. The composite samples were put in plastic bags, and sealed immediately to prevent the loss of moisture en route to the laboratory at DAELP. While at the profile soil moisture were determined from core samples collected for determination of bulk density.

3.3 Soil Analysis

3.3.1 Bulk density

The bulk density of the soil was obtained by weighing an oven dry undisturbed soil sample of known volume (Blake and Hartge, 1986).Values of bulk density for mapping units (see Table 1C in Appendix 1) were obtained from soil survey report for the Mahenge village (Magoggo *et al.*, 1996).

3.3.2 Gravimetric soil moisture

At the laboratory soil moisture was determined by gravimetric method as outlined by Gardner (1986). The moist samples were weighed, dried to constant weight in an oven at 105°C for 24 hour and reweighed. The difference in weight due to loss of water was divided by the dry weight of the soil to give the percent of moisture on a dry weight basis:

$$\theta_m = 100\frac{(m_2 - m_3)}{(m_3 - m_1)} \quad \text{[mass \%]} \qquad (3.1)$$

Where

θ_m = dry mass water percentage

m_1 = mass of container

m_2 = mass of container and wet soil sample

m_3 = mass of container and dry soil sample.

3.3.3 Volumetric soil water contents

Volumetric moisture content (v/v %) at field capacity (FC) and permanent wilting point (PWP) was determined using pressure plate apparatus (Klute, 1986). Whilst those of mapping units were based on profile available water capacities determined during soil survey (Magoggo *et al.*, 1996). The volumetric water content was determined as:

$$\theta_v = 100\frac{(m_2 - m_3)}{(\rho_w . V_b)} \text{ [vol \%]} \tag{3.2}$$

or

$$\theta v = \rho_b \, \theta_m \tag{3.3}$$

Where

θv = volumetric water content (vol %)

ρ_w = the density of water (g/cm^3)

V_b = the bulk volume of the soil sample

ρ_b = the bulk density of the soil sample

θ_m = dry mass water percentage

3.3.4 Soil reaction

Soil reaction (pH) measurement at the experimental site (see Table 1B in Appendix 1) was made on extracts of soil suspensions at a ratio of 0.01 M: Calcium Chloride ($CaCl_2$). This method is favoured over others in the tropical soils because the values obtained are less dependent on the dilution ratio (Landon, 1991). The values of pH in water are higher than those in Calcium Chloride suspensions by the range of 0.5 to

0.9 units (Landon, 1991). Soil survey pH values (see Table 1C in Appendix 1) for the mapping units in the village (Magoggo *et al.*, 1996) were reduced by 0.84 based on soil analysis at the experimental site.

3.3.5 Electrical conductivity

The measurements of electrical conductivity (see Table 1B in Appendix 1) were made at the depth of 0-30 cm, 30-60 cm, and 60-120 cm on extract from soil: water mixtures using salinity sensor and pressure vacuum cup (Rhoades, 1982) because they are easier to handle.

3.3.6 Particle size distribution

Particle size distribution value for representative soil profiles for soil mapping units were obtained from soil survey data by Magoggo *et al.* (1996).

3.3.7 Organic carbon

Organic carbon which is taken to be a measure of the quantity of organic matter content in a soil was found following the Walkley and Black dichromate (rapid titration) method (Nelson and Sommers, 1982). The results were expressed as percentage by weight of organic carbon in the soil. To obtain the percentage of organic matter in the soil, values of organic carbon were multiplied by conversion factor of 1.72 (Landon, 1991).

3.4 Erosion Hazard Assessment

The USLE was employed to assess the potential erosion risk for Mahenge village. To estimate sheet and rill erosion using the USLE it is necessary to measure and/or estimate all parameters in the equation 2.1 as discussed in section 2.2 and 2.3.

Using a topographic map sheet no. 297/4 at a scale of 1: 50,000 obtained from Mapping Unit, Ministry of Land, Dar Es Salaam topographic factor values were obtained. In absence of Digital Elevation Model in the ARC/INFO-GIS package used, the topographic factors (LS) were derived manually. First the topographical map grids of one square kilometre were divided into four equal square grids. These grids were enlarged to help separation and counting of contours. Then a number of transects were placed over a grid. This allowed the average number of times transects crossed contours per kilometre to be obtained. The average slope, then, was calculated as (Wentworth, 1930):

$$Averageslope = \left(\frac{no.contour.per.km * contour.\mathrm{int}\,erval}{636.6}\right)100 \qquad (3.4)$$

Wentworth (1930) derived this equation based on the assumption that the greater the total number of the contours there are in any given area the greater the average slope will be. The size of grid has a considerable influence on the identification of small areas of steep slopes. However, a larger number of small grid squares creates a tedious burden in counting contour crossings and calculating average slope. Stocking and Elwell (1973) used the methodology to map erosion hazard in Zimbabwe. A fixed slope length of 100 metres was taken as suggested by Stocking (1987) assuming final erosion hazard assessment will be of bounded plot of 100 metres length. The slope length and slope steepness factor (LS) for each grid square found by equations 2.10, 2.16 and 2.17.

The rainfall erosivity (R) factor was obtained using equation 2.6 based on mean annual rainfall volume for 1960 - 1981 seasons from Litembo Mission, soil erodibility factors (K) were calculated using soil survey data (Magoggo *et al.*, 1996) and equation 2.8. The soil map 1:25,000 of the village obtained from SUA Centre for Sustainable Rural Development (SCSRD) office at SUA, Morogoro provided the boundaries for variation in soil erodibility.

The combined crop and management factor (C) and support practice factor (P) for the experimental site was calculated based on soil loss data from bare plots to that under *ngolo* and bench terraces. However, as long term assessment is concerned suggested experimental C values for tropical crops, coffee (Roose, 1977), Maize (Singh *et al.*, 1981) and disturbed hill forest (Srikhajon *et al.*, 1984) were obtained from literature as my research could not generate all the needed data. In order to account for long term change in support practices, P values for *ngolo* were calculated based on contour cultivation from slope gradient and oriented ridge height, and adjusted for expected storm erosivity and row-grade variable as discussed in detail by Troeh *et al.*, 1991. On the other hand, P values for bench terraces were calculated as per procedures outlined by Foster and Highfill (1983).

The soil erosion hazard map was generated from interaction of themes in digitezed soil map which included values of soil erodibility, rainfall erosivity, crop cover management factor and support practice values for each soil unit and slope steepness map which contained topographical factors for different grid squares outlined in section 3.4. As hinted in section 2.3, the ARC/INFO-GIS computer package was employed to digitize the maps and calculations of variation in erosion rates over the Mahenge village and map layout were performed using ARC/VIEW-GIS package. Finally, the values of predicted soil losses were used to classify the village into potential soil erosion risk categories as given in Fig. 16.

3.5 Determination of Crop Water Requirement

3.5.1 Determination of reference crop evapotranspiration (ETo)

In this research four years evaporation data (see Table 1D in Appendix 1) measured using (Class A) evaporation pan placed at Kindimba village about six kilometres east of the experimental site were obtained from SUA Centre for Sustainable Rural Development's (SCSRD) office at SUA. These were used to calculate ETo as expressed in equation 3.5:

$$ETo = k_{pan} * E_{pan} \tag{3.5}$$

where

E_{pan} = mean daily evaporation for the period (mm/day)

k_{pan} = pan coefficient (Doorenbos and Pruitt, 1977)

For the calculations of crop water requirements shorter periods of at most 10 days (decades) are required. To convert the monthly data to 10-day values a graphical interpolation method is used as explained in detail by Doorenbos and Pruitt (1977).

3.5.2 Determination of maximum crop evapotranspiration (ETm)

Maximum crop water evapotranspiration, ET_m, was determined as:

$$ET_m = k_c * ET_o \qquad (3.6)$$

where

k_c = crop coefficient (Doorenbos and Pruitt, 1977)

3.5.3 Determination of crop coefficient (kc)

In this research crop coefficient values for different crop growth stages were obtained from a k_c curve as follows:

(i) By determining the average planting date from local information;

(ii) By determining the average duration of the 4 growth stages; and

(iii) By using the suggested kc values for various stages from a special table and then developing a kc curve(see Fig. 5) (Doorenbos and Kassam, 1979).

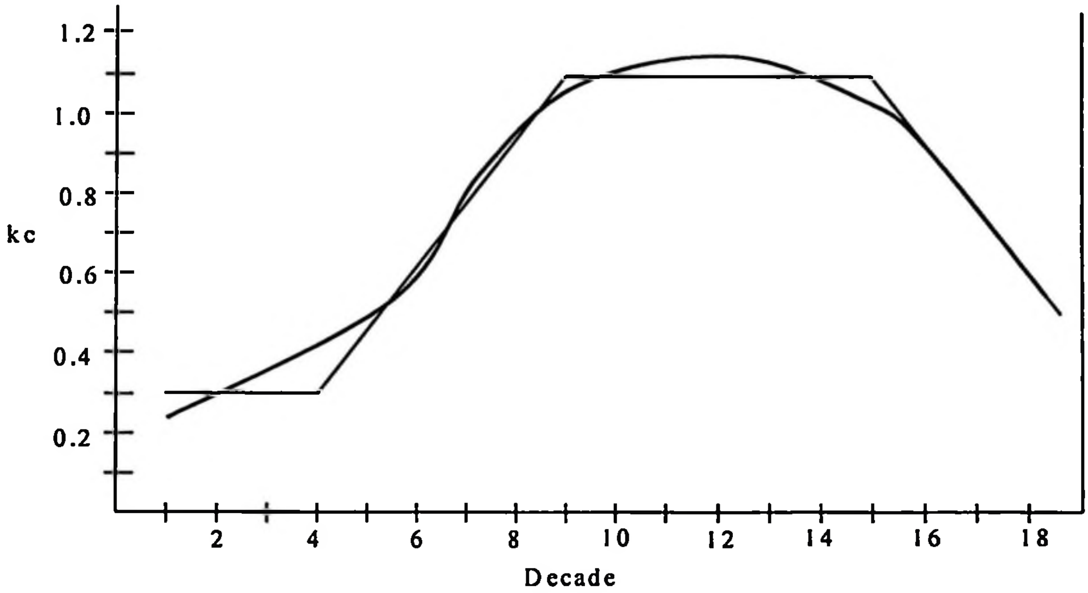

Fig.5: Crop coefficient (kc) curve for maize

The planting dates for determination of ET_m were 1st December and 18th January for long-term and 1998/99 growing seasons, respectively.

3.5.4 Determination of actual crop evapotranspiration (ETa)

As discussed in section 2.5.1 the effect of water stress on crop yield, first demand determination of total amount of water that a crop can extract from its root zone, TAM, which is given as follows:

$$TAM = DSa \text{ [mm (water)]} \qquad (3.7)$$

Where

TAM = total available soil moisture

D = effective root depth

Sa = available soil moisture = $\theta_{FC} - \theta_{WP}$

The root depth of 30 cm for establishment, 100 cm for vegetative and flowering, and 150 cm for yield formation and ripening growth stages were used in the calculation of TAM and actual evapotranspiration for maize.

Secondly, the fraction (p) of total available soil moisture that a crop can extract from the soil without suffering water stress is the Readily Available Soil Moisture (RAM):

$$RAM = p\ TAM = p\ D\ Sa \quad (\text{when } ET_a = ET_m) \tag{3.8}$$

Where

RAM = readily available soil moisture

p = the depletion factor

When the soil moisture content is within the RAM, that is, maximum allowable depletion, actual evapotranspiration (ET_a) is equal to potential crop evapotranspiration (ET_m). RAM in that sense is an indicator of crop tolerance to water stress. Doorenbos and Pruitt (1977) suggest that maize can tolerate depletion of 60 percent of its available soil moisture before ET_a is reduced below ET_m. Beyond this depletion level ET_a becomes smaller than ET_m until the next heavy rainfall for rainfed agriculture (See equation 2.29).

For rainfed agriculture rainfall is the only source of water and is regarded as a crucial resource for crop production. This is because rainfall recharges the soil moisture. However, its amount, distribution pattern and its intensity of occurrence tend to vary across the locations and over time (Singh, 1996). In this study rainfall data for the village from 1995–1999 were obtained from MWARP's office at SUA. These data were taken from recording rain gauge of tipping bucket type installed with a data logger at the experimental site. But, the data were of limited time and for certain rainfall periods data were missing due to instrument failure. To overcome those weaknesses a long-term trend of rainfall was necessary. Historical data of Litembo mission, which is 3 km west of Mahenge village for the period of 1960 to 1981 (see Table 1E in Appendix 1), was obtained from Directorate of Meteorology at Dar Es Salaam. The rainfall decade values were obtained by graphical interpolation methods from mean monthly rainfall data for twenty growing seasons.

The rainfall decade values from Litembo Mission, ET_m data from Kindimba village and root zone water storage capacities of the soils at Mahenge village (Maggogo *et al.* (1996) were used to calculate long term actual evapotranspiration values. Water available in root zone for each 10 days interval was obtained by the differences between water added and lost from the soil. When available soil water exceeded field capacity, additional water was not added to the supply because it becomes unavailable to plants by storage beyond the root zone or by drainage to the water table (Tanner, 1967; Doorenbos and Kassam, 1979).

As shown in Fig. 2, actual evapotranspiration rate depends on ET_m and available water in the root zone. Water available in root zone for each 10 days interval of calculation was obtained using water balance (see equation 3.8). AW_i at the beginning of each rain season was assumed to be negligible. However, for 1998/99 growing season the AW_{i-1} was measured as planting was done two weeks after the start of heavy rainfall.

$$AW_i = AW_{i-1} + PR_i - RO_i - PEL_i - ET_{ai-1} \qquad 3.8$$

Where

AW_i = Water available in root zone at time interval i,

AW_{i-1} = Water available in the root zone at time i-1,

PRi = precipitation volume at time interval i,

RO_i = runoff volume that occurred during time interval i,

PE = percolation volume during the computation interval i,

ET_{ai-1} = actual evapotranspiration volume at time interval i-1.

In calculation of ET_a values it was assumed that evapotranspiration dropped linearly from maximum evapotranspiration levels in proportion to soil water availability after water depletion has reached 60 % of the soil water storage capacity as shown in Fig. 2. Based on level of moisture depletion beyond this critical point, ET_a values were obtained from values of ratio of ET_a/ET_m (see Fig. 2) as a function of soil moisture as shown in Fig.2. The root depth used to calculate ET_a were 30 centimetres for establishment stage, then, increasing linearly to 100 centimetres for vegetative and flowering stages, and 150 centimetres for yield formation and ripening stages.

3.6 Statistical Analysis

Crop yield data for 1995/96, 1996/97, 1997/98 and 1998/99 seasons were regressed with cumulative soil loss for those periods. In addition, analysis of variance (ANOVA) using EXCEL and MSTAT-C packages were performed to evaluate how plant height, and crop cover values from different treatments and times were varying. Mean separation was achieved by Duncan's Multiple Range Test (DMRT).

3.7 Assessment of Relative Productive Potential of Soils of Mahenge Village

SEPIM model as given by equation 2.30 was selected and used to quantify the relative productivity of soils in Mahenge village in the study period and for long-term based on soil properties observed during the study and on soil survey reported by Maggogo *et al.* (1996), respectively. Three soil units (Haplic Acrisols, Haplic Phaeozem and Ferrallic Cambisols) were selected and assessed. These soils cover 46 percent of the total area in the village. The major land uses for soils selected are wheat and maize under ngolo. Maize is the major food crop grown in the village. However, the productivity of maize in the village is low (Hawassi, 1997; URT, 1997), so justifying their selection under the current study.

4. RESULTS AND DISCUSSION

4.1 Effects of Soil and Water Conservation Measures on Soil Erosion

Erosion rates for different soil and water conservation (SWC) measures were observed and recorded at the MWARP's experimental site at Mahenge village. The total soil losses from *ngolo*, bench terrace, and bare plots for four growing seasons (1995/96 to 1998/99) are presented in Table 1.

Table 1: Seasonal erosion rates (t/ha) at Mahenge village

SWC	1995/96*	1996/97*	1997/98**	1998/99**
Bare	***	***	91.09	157.59
Bench terraces	2.35	1.76	8.53	3.19
Ngolo	2.32	1.23	13.34	7.11

*JICA (1998) **Own ***No data

Use of soil and water conservation measures, that are, bench terraces and *ngolo* resulted in significant reduction (p=0.05) in soil erosion by water compared to bare plots. The use of bench terraces reduced soil loss by about 90.6 and 98 percent for 1997/98 and 1998/99 growing seasons, respectively. On the other hand *ngolo* reduced soil loss by 85.4 and 95.5 percent in 1997/98 and 1998/99, respectively.

The results for seasonal distribution in soil loss for 1998/99 season are given in Table 2. The analysis of variance (see Table 2A in Appendix 2) for the soil loss indicated that there was statistical significant difference (p=0.05) in soil loss between soil

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Use of soil and water conservation measures, that are, bench terraces and *ngolo* resulted in significant reduction (p=0.05) in soil erosion by water compared to bare plots. The use of bench terraces reduced soil loss by about 90.6 and 98 percent for 1997/98 and 1998/99 growing seasons, respectively. On the other hand *ngolo* reduced soil loss by 85.4 and 95.5 percent in 1997/98 and 1998/99, respectively.

The results for seasonal distribution in soil loss for 1998/99 season are given in Table 2. The analysis of variance (see Table 2A in Appendix 2) for the soil loss indicated that there was statistical significant difference (p=0.05) in soil loss between soil conservation measures throughout the growing period with exception of 103 Days After Sowing (DAS).

Table 2: Soil loss (kg/plot) at experimental plot for 1998/99 season

DAS	2	14	42	72	103
BBT1	4.67	6.84	6.37	12.66	2.38
BBT2	16.35	14.43	4.85	52.69	3.35
N1	9.05	28.17	21.78	123.75	2.47
N2	6.04	13.47	10.67	54.84	6.93
B1	694.88	475.98	276.03	1148.97	59.59
B2	816.24	462.19	236.16	1951.63	24.27

BT (1, 2) = Bench terraces N (1, 2) = *Ngolo* B (1, 2) = Bare plots

The soil loss from bare plots was significantly higher than those from both *ngolo* and bench terrace plots. However, soil losses from *ngolo* were not significantly different (p=0.05) from those in bench terrace plots. Soil loss for the two treatments tended to decrease with increase in crop cover. But, 42 DAS up to 72 DAS soil loss tended to increase with increase in cover. This could be due to high rainfall erosivity (see Table 2B in Appendix 2) and/or reduced storage capacity and infiltration rate of the *ngolo* pit. The importance of crop cover in reduction of soil erosion has been well researched (Stocking, 1994).

4.2 Effects of Soil and Water Conservation Measures on Soil Moisture

Gravimetric soil moisture measurements for *ngolo*, bare, and bench terrace plots at the experimental site over the depth rooting zone during the 1998/99 growing season were made and (see Table 3A in Appendix 3) are presented in Figs. 6 to 8.

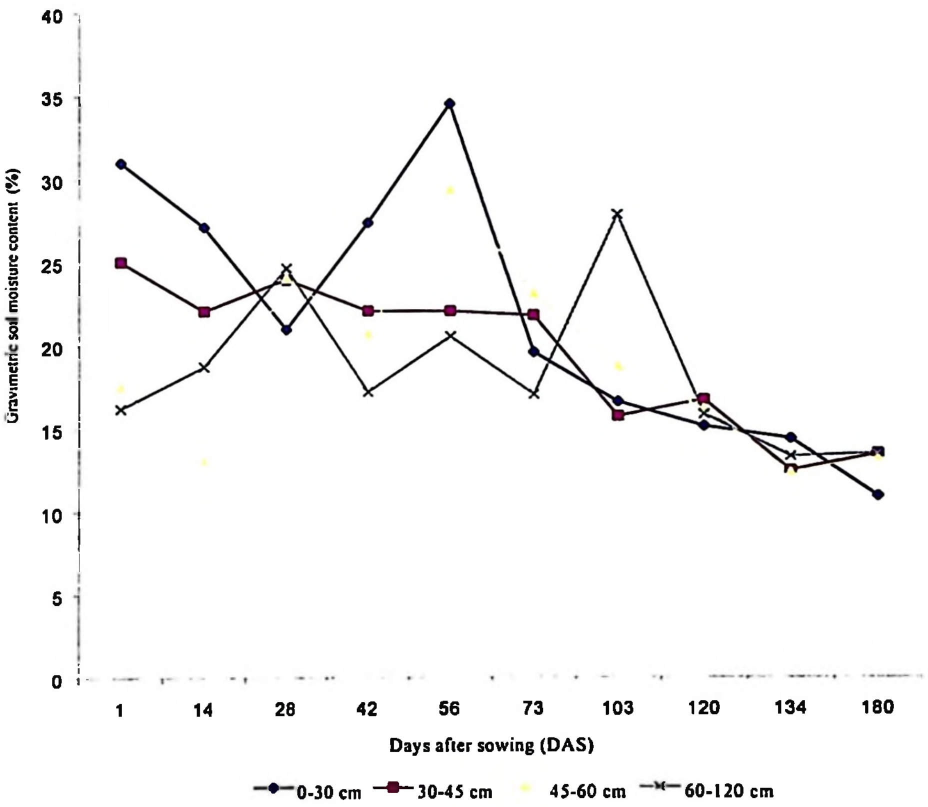

Fig.6: Gravimetric soil moisture for bare plot

The analysis of variance (see Table 3B in Appendix 3) for soil moisture data (see Table 3A in Appendix 3) showed that there was no significant statistical difference (p=0.05) in gravimetric soil moisture storage between the soil and water conservation measures throughout the growing season.

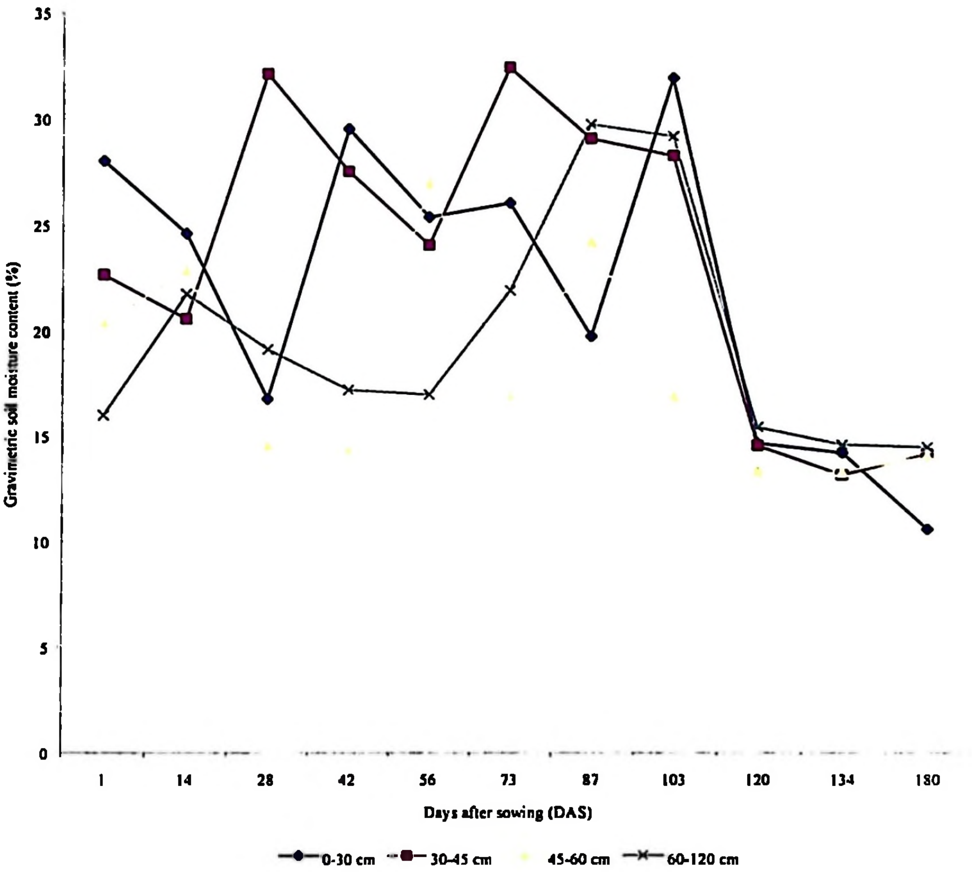

Fig.7: Gravimetric soil moisture for bench terraces

However, significant difference (p=0.05) in soil moisture with depth was observed at planting, 14 Days After Sowing (DAS), and 180 DAS. At planting all treatments showed high soil moisture content in the upper 0-30 cm (see Fig. 6-8). But from 14 days after sowing (DAS) much of soil moisture were observed at the depth of 0-30 and 30-45 cm for bench terraces and bare plots. On the other hand *ngolo* plots had much soil moisture at depth of 60-120 cm.

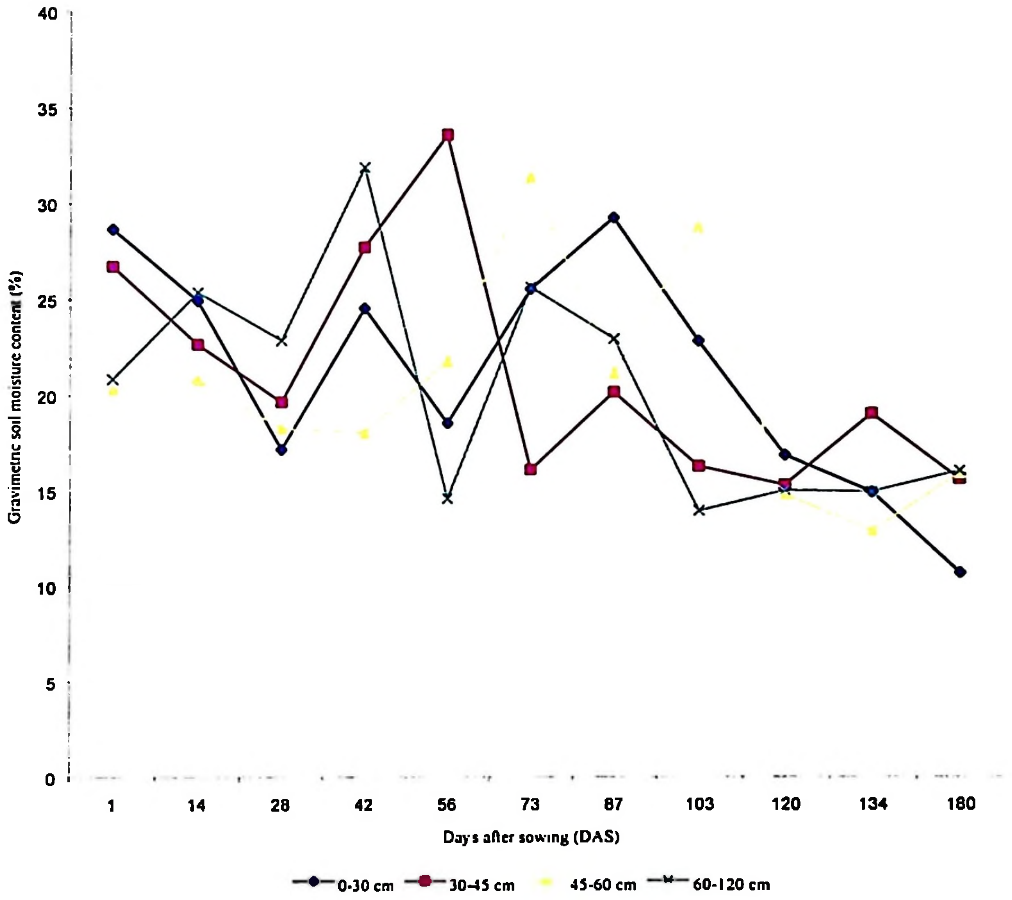

Fig.8: Gravimetric soil moisture for *ngolo* plot

Even though the analysis of variance showed that there was no significant statistical difference (p=0.05) in moisture content between treatments, the Duncan's Multiple Range Test confirmed that *ngolo* had more soil moisture stored within depth considered than other practices. Lyimo and Kangalawe (1996), and Martin *et al.* (1998) have also observed such findings.

The higher soil moisture in the upper soil layer for bench terrace and bare plots could be contributed to poor infiltration rate. Pearson *et al.* (1995) observed that under bare soil, downward movement of silt and clay particles might fill subsoil pores, thus reducing infiltration and increasing the tendency to crust. This wetting to the shallow depth in bench terraces increased the chance of ponding and waterlogging as a result of reduced runoff.

In contrast the increase in moisture content with depth in *ngolo* plots was contributed by improved structure. The incorporation of plant residues during *ngolo* construction increased the amount of organic matter in the soil which contributed to the formation of aggregates and promotion of permeability and ultimately increased the water holding capacity (Young, 1976). In addition, the pit between the ridges in *ngolo* allow water in excess of infiltration rate to be retained during the intense rainfall (Lyimo and Kangalawe, 1996; Tanaka *et al.,* 1996) so increase soil moisture storage capacity of the system.

4.3 Effects of Soil and Water Conservation Measures on Crop Development

Crop development parameters particularly plant heights and crop covers at different times in the growing period were measured as per procedures outlined in section 3.2.3 and are given in Table 4A in Appendix 4. The results are illustrated by Figs. 9 and 10.

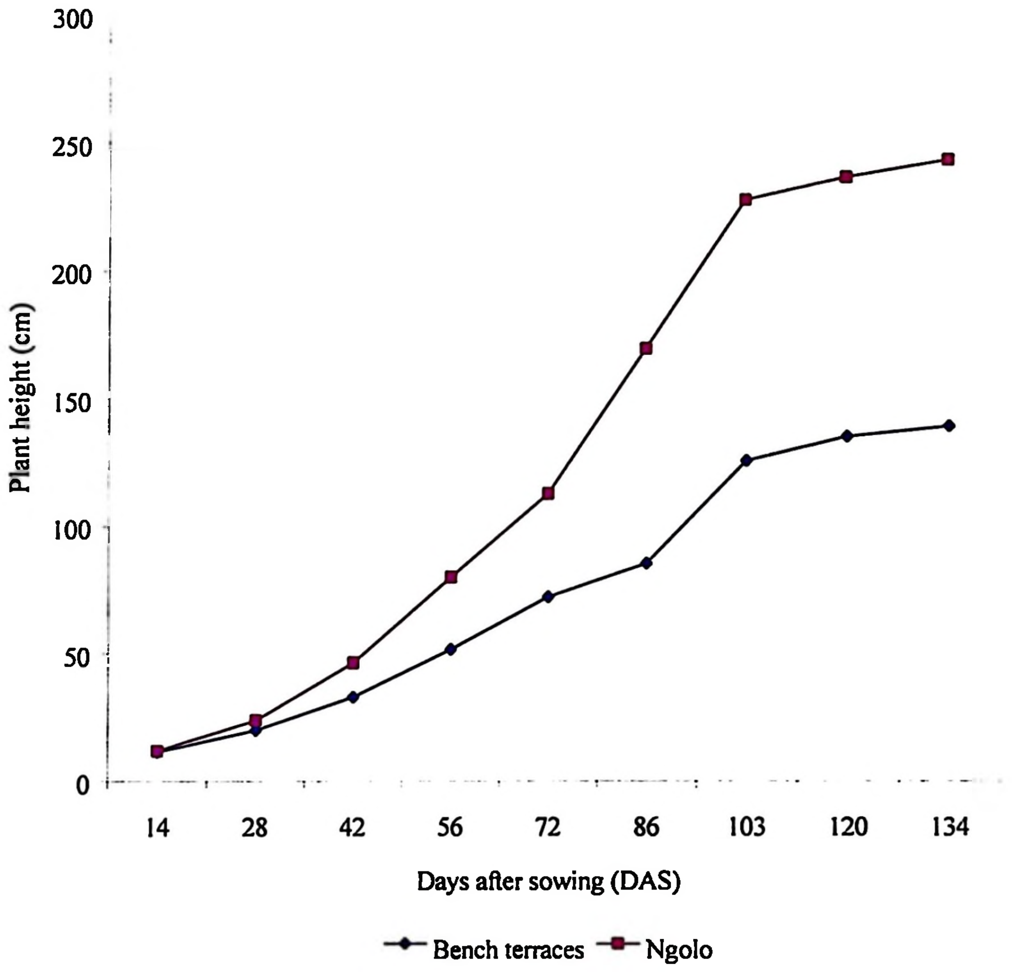

Fig.9: Effects of soil conservation measures on plant height

Maize growth on *ngolo* plots registered high plant height (Fig. 9) and crop cover (Fig. 10) values compared to those on bench terraces. The crop cover tended to increase with plant height until 86 DAS and 120 DAS for bench terraces and *ngolo*, respectively. Then crop cover decreased with increase in plant height.

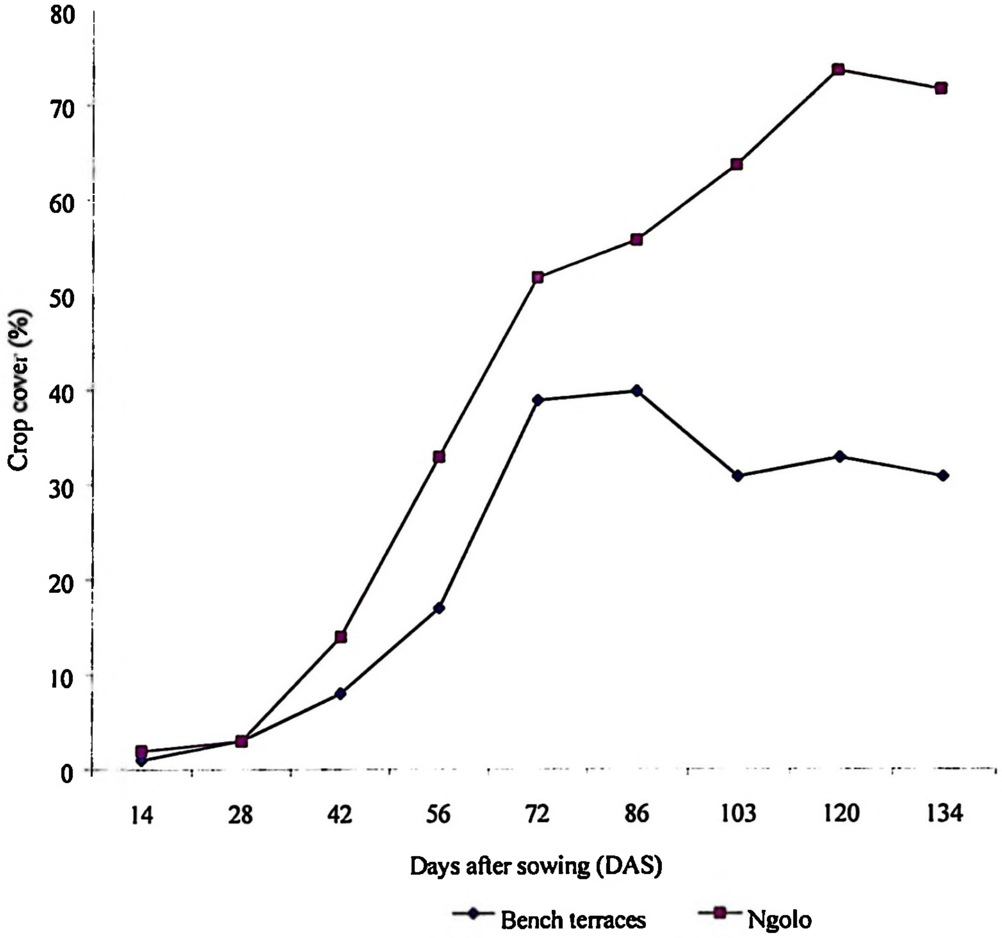

Fig.10: Effects of soil and water conservation measures on crop cover

Results from ANOVA showed that there was significant statistical difference in crop cover (see Table 4B in Appendix 4), and plant height (see Table 4C in Appendix 4) with time for different treatments. The difference in crop development was more marked beginning 28 DAS and 42 DAS for plant height and crop cover, respectively.

The difference in crop development between *ngolo* and bench terrace plots could be explained by the variation in important soil properties that determined crop growth such as soil pH. This is because low pH values reduce bacterial activity and nitrification of organic matter. At experimental site there was little variation in organic matter content between treatments due to long term use of *ngolo* system. But, in both treatments organic matter contents tended to decrease with depth. Müller-sāmann and Kotschi (1994) observed that the subsoil of Acrisols like those of experimental site are chemically impoverished as aluminium, iron, and manganese toxicity are more likely to occur due to low soil pH. These conditions could be the reason behind stunted maize growth at the experimental site, a situation also observed by Hudson (1987), JICA (1996) and Amien (1997).

This variation in crop development was also supported by the days to 50 percent flowering and silking. For *ngolo* plots the days to 50 percent were 87 and 102 days, respectively, while those of bench terraces were delayed by two weeks relative to the former. The number of days to 50 percent flowering is an important parameter in rainfed agriculture. Not only because the rainfall is low and erratic in distribution, but also because moisture stress at this period can lead to total crop failure (Doorenbos and Kassam, 1979; Unganai and Kabanda, 1994).

4.4 Effects of Cumulative Soil Loss on Maize Yield

The relationships between cumulative soil loss and maize grain yield for *ngolo* and bench terraces at the experimental site for four growing seasons (1995/96-1998/99) are illustrated in Figs.11 and 12 respectively. In both treatments maize grain yield tended to decrease with increase in cumulative soil loss over time. This could be due to decline in level of soil fertility with duration of continuous cultivation. The results showed that the decline in yield with cumulative soil loss over time was much higher in bench terraces than *ngolo* plots despite the former having lower cumulative soil loss and higher population density as discussed in 3.2.1.

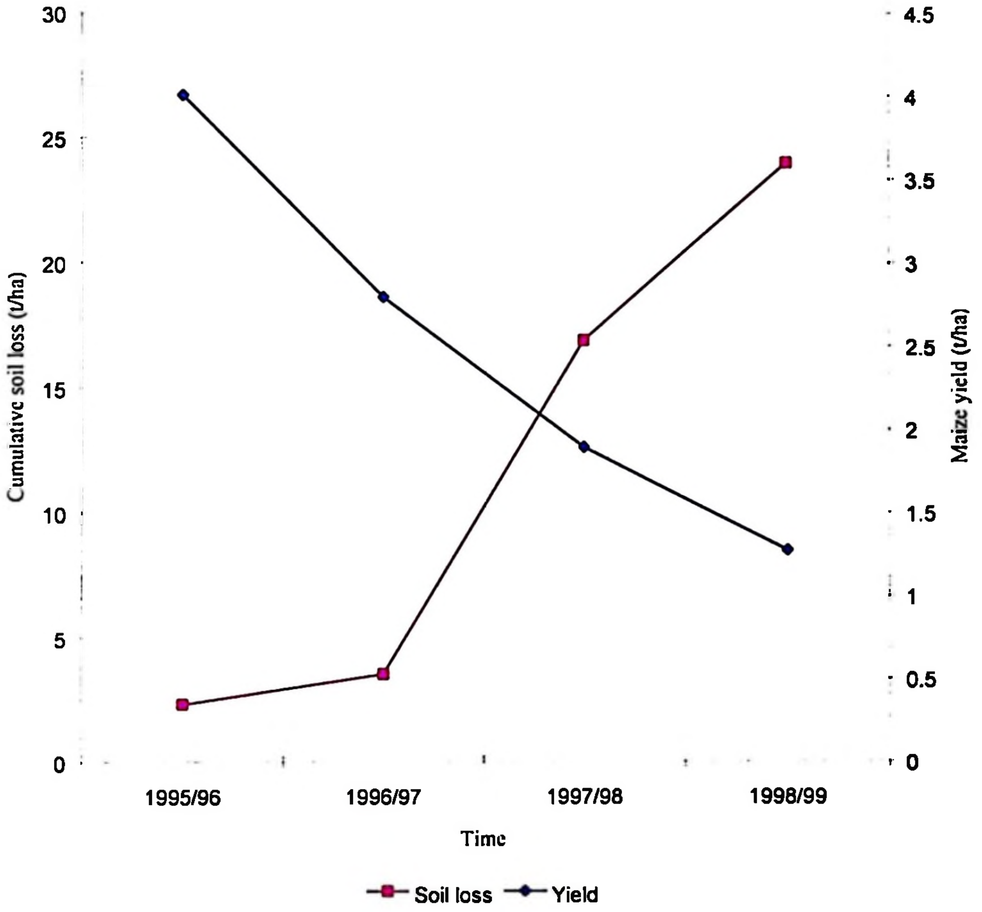

Fig.11: Cumulative soil loss-yield relationships for *ngolo* cultivation

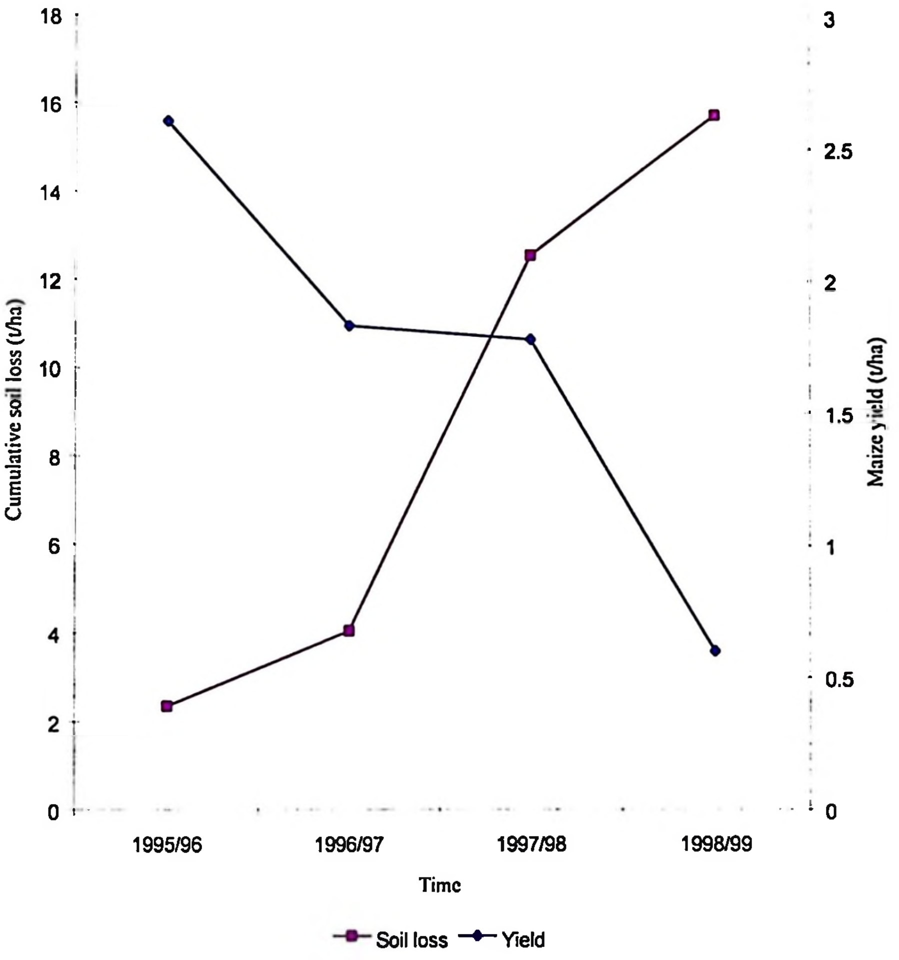

Fig.12: Cumulative soil loss yield-relationships for bench terraces

As shown in Table 3 only 60 percent of plants in bench terraces set cobs, which were small and poorly filled with grain. During the flowering periods some plants (though could not be quantified) showed signs of curling and later withered before setting cobs. Apart from grain yield *ngolo* and bench terraces differed in other yield aspects as shown in Table 3.

Table 3: Cob with grain, cob, and stover yields for SWC at experimental site for 1998/99 season

SWC	% of Cob with grain	Cob (kg/ha)	Stover (kg/ha)
Bench terraces	60	223.5	2544.16
Ngolo	91.3	884.7	4473.00

The outbreak of maize leaf blight disease could be the reason behind that drastic fall in crop yield for 1995/96-1998/99 growing seasons. There is a need to find maize varieties, which is more resistant to the disease and suited to the ecological conditions of the area. Currently the introduced maize variety H-625 from Kenya has shown good promise in terms of yield and its resistant to the fungus disease in the village.

Both linear and nonlinear regression analyses were performed to evaluate the effects of cumulative soil loss on maize yield. The results are given in Table 4. As shown in Table 4 cumulative soil loss was able to explain about 86 and 82 percent of variations in maize yield for four growing seasons in *ngolo* plots for linear and nonlinear relationships, respectively; although soil losses in terms of depth were a millimetre when the soil losses in weight were converted using measured bulk densities. While for bench terraces linear relationship had more explanatory power than nonlinear relationship (see Table 4).

Table 4: Effects of cumulative soil loss on maize yield

SWC	Regression equation	r^2
BT	$Y = -0.111X + 2.68$	0.756
	$Y = 3.0231e^{-0.0805X}$	0.68
N	$Y = -0.1044X + 3.7074$	0.86
	$Y = 3.7491e^{-0.04276X}$	0.82

Y = Yield X = Cumulative soil loss

On the other hand soil moisture has been identified as the most important requirement for maize production (Unganai and Kabanda, 1994) as the crop is highly intolerable to drought. The data for 1995/96, 1996/97, 1997/98 and 1998/99 (see Table 5A, 5B, 5C, 5D in Appendix 5) growing seasons at the experimental site showed fluctuation in available moisture to plants over the growing periods. For 1995/96 and 1997/98 growing seasons the crop received adequate water supply to meet crop requirements from planting up to decade 15 (see Table 5A and 5C in Appendix 5). But, from then up to 18th decade the crop experienced slight water deficit as indicated by ET_m being larger than ET_a. In contrast the 1998/99 growing season experienced soil moisture deficit in decade 4, 9 up to 18 (see Table 5D in Appendix 5). The water deficit for both seasons occurred from the stage when the crop was flowering up to yield formation stage.

Moisture stress for 1998/99 growing season was more serious because of both late planting (3rd decade of January instead of 1st decade of December) and termination of rainfall when crops were at yield formation. Thus for most part of the growing season, the crop depended on soil stored moisture to meet its requirements. Therefore, management practices that maintain wet soil surface for quite long as *ngolo* are desirable and showed success under experimental conditions as discussed in section 4.2 and 4.3.

However, the degree of yield losses likely to occur for various soils will depend on the interaction of soil physical, chemical, and biological properties, the crop being grown, and weather conditions before and during the growing season.

Siebert and Belsky (1990) have discussed the effect of bench terraces on soil productivity and crop yield in detail. Temple (1972) based on studies in the Uluguru mountains in Tanzania has noted that bench terraces are unsuitable to farming in mountainous areas like those of the Matengo highlands in Mahenge village. Bench terraces expose infertile subsoils. These poor soil conditions in the bench terraces as discussed in 4.2 and 4.3 greatly affected yield. However, the extent of subsoil exposure and its effect on crop yield tend to vary from one site to another depending on topsoil depth, slope steepness, method of construction, and susceptibility of the crop to adverse effect of the chemical and physical characteristics of the soil (Siebert and Belsky, 1990).

4.5 Assessment of PI and SEPIM at Experimental Site

Table 5 gives the PI (without A_i) and SEPIM values of soils at the experimental site as a function of soil properties. At the experimental site soil physical and chemical properties (see Table 1B in Appendix 1) and water supply patterns (see Table 5E and Table 5F in Appendix 5) were used in the calculation of both PI and SEPIM. The soil at the experimental site had low pH (see Table 1B in Appendix 1), which limited the PI and better growth of maize plants. But, there was no evidence for salt problem at the site as indicated by low value of electrical conductivity and so its sufficiency was assumed to be 1.0.

Table 5: Productivity Index (PI) and SEPIM values at the experimental site

Soil depth (cm)	BT	N	SEPIM			
			1995/96	1996/97	1997/98	1998/99
0-10	0.191	0.205				
10-20	0.119	0.128				
20-30	0.087	0.093				
30-40	0.066	0.075				
40-50	0.049	0.057				
50-60	0.037	0.042				
60-70	0.035	0.036				
70-80	0.024	0.025				
80-90	0.013	0.014				
90-100	0.004	0.004				
PI	0.62	0.68	0.59 (BT) 0.65 (N)	0.61 (BT) 0.67 (N)	0.61 (BT) 0.67 (N)	0.46 (BT) 0.51 (N)

The regression analysis was performed to evaluate the performance of PI (without A_i) and SEPIM models at experimental site as given in Table 6.

Table 6: Influence of PI and SEPIM on maize yield at experimental site (1995/96-1998/99)

Model	Regression equation	r^2
PI	$Y = 13.08X - 6.407$ (for BT and N)	0.16
	$Y = 0.02162e^{6.8437X}$	0.15
SEPIM	$Y = 9.4051X - 3.6349$ (for BT)	0. 51
	$Y = 9.1927X - 3.2579$ (for N)	0.36
	$Y = 0.0153e^{8.0789X}$ (for BT)	0.95
	$Y = 0.1299e^{4.5804X}$ (for N)	0.51

The lower explanatory power of PI could be due to limited data used for testing. Therefore, attempts should be made to incorporate the data from other area for further analysis in the future.

On the other hand, SEPIM values at experimental sites tended to vary from one season to another depending on the amount of available water. The values for ngolo ranged from 0.51 to 0.67 whereas those of bench terraces were from 0.49 to 0.61. SEPIM had the higher explanatory power for both linear and nonlinear relationships for variations in maize yields in bench terraces (see Table 6). But, in *ngolo* plots the variation in maize yields with SEPIM was explained better by nonlinear relationships implying that the rate of change with time was not uniform. However, the results show the accurracy of the SEPIM to explain yield variation to be highly variable.

SEPIM explains about 50 % of the yield variations for the ngolo cultivation while it explains about 95 % of the variations for the bench terrace treatments. This shows that both PI (without A_i) and SEPIM models need further evaluation. But based on those results, SEPIM looks a better choice for investigating long term effects of soil erosion on productivity in the village.

4.6 Erosion Hazard Assessment for Mahenge Village

Studies of erosion hazard demand identification and description of factors influencing the distribution of erosion. In this study the measured rainfall erosivity, soil erodibility, and topographic factors and the estimated crop cover and support practices components of USLE were made based on data from soil survey, topographic maps, literature and field observations as discussed in 2.2 and 3.4. The obtained values of the components (see Table 7) were used in the prediction of annual soil loss for the village.

Table 7: USLE components used in erosion hazard assessment and predicted annual soil loss

Code	Land use	R (MJ.mm/ ha.h.y)	K (t.ha.h/ MJ.mm)	LS	C	P	Erosion rate (t/ha)	
							Mean	Range
H1	Planted forest	3554.4	0.0125	3.747-17.321	0.4*	1.0	156.79	66.75-243.19
H2	Coffee on bench terraces	3554.4	0.0304	3.747-9.880	0.3**	0.48	127.52	58.40-153.99
H31	Coffee on bench terraces	3554.4	0.0140	7.916-17.322	0.3**	0.63	103.90	62.66-163.35
H32	Maize, wheat under *ngolo*	3554.4	0.0202	3.747-15.013	0.502***	0.47	170.29	63.39-293.04
H33	Maize, wheat under *ngolo*	3554.4	0.0153	3.798-14.183	0.502***	0.47	115.89	48.03-181.81
P1	Coffee	3554.4	0.0237	7.078-14.486	0.3**	1.0	258.69	94.58-365.68
P2	Maize, wheat under *ngolo*	3554.4	0.0288	5.745-14.183	0.502***	0.14	63.28	21.54

* Srikhajon *et al.* (1984) ** Roose (1977) *** Singh *et al.* (1981)

The collected erosion data (see Table 8) at Tukuzi village (Nindi, 1999), which is found in the same ecological zone with Mahenge village show that the effectiveness of *ngolo* tend to decrease with increase in slope as the depth of pits are reduced.

Table 8: Soil loss (t/ha) at Tukuzi village

SWC	Slope	1994/95	1995/96	1996/97	1997/98
Ngolo	16 %	2.4	1.2	1.34	3.49
Bare	16 %	39.0	38.6	42.34	55.75
Ngolo	37%	5.8	1.4	3.6	10.04
Bare	37%	55.7	80.6	67.7	91.59

Source: Nindi (1999)

The combined values for C and P factors for erosion data in Table 1 for Mahenge and Table 8 for Tukuzi village were calculated. The CP values are 0.08 for *ngolo* and 0.05 for bench terraces for Mahenge village. The CP values for *ngolo* at Tukuzi are 0.05 for 16% slope and 0.07 for 37% slope, respectively. The result shows that the combined CP factor values used in simulation were higher than those observed at the experimental sites. These values were used because reliable values could not be obtained.

The value of rainfall erosivity was assumed to be constant throughout the village. Whereas the values of slope steepness (see Fig. 13) and topographic factor (see Fig. 14) were varying even within the same soil unit due to great difference in terrain even for a short distance. Soil erodibility values (see Fig.15) tended to vary from one soil unit to another due to the difference in soil properties. Crop management and support practice factors were varying with land use.

The result of erosion hazard assessment is given in Fig. 16. The soil loss results from erosion hazard mapping in the village were grouped into four classes depending on the severity of the erosion. The map showed correspondence between potential soil erosion hazard and changes in both slope steepness (see Fig. 13) and soil erodibility factor (see Fig. 15). The soil loss prediction showed that Dystric Cambisol soils had higher average erosion rates (258.69 t/ha/y) than others. These soils are found in the steep slope in the village. In addition, the soils lack support practices and is more erodible. The Dystric Cambisols covers about 20 percent of the total area in the village. Haplic Phaeozem were second to Dystric Cambisols in the amount of soil lost (170.29 t/ha/y) due to the presence of steep slopes. Dystric Leptosols were next to Haplic Phaeozem with average soil loss of 156.79 t/ha/y despite having less erodible soils. The rocky hill summits and shoulders in these soils are more likely to experience much runoff due to absence of support practices.

On the other hand, Ferrallic Cambisols had the lowest average annual soil loss (63.28 t/ha/y) in the village despite higher erodibility value. Effectiveness of support practice (*ngolo*) and the gentle slope covering the soil unit in relation to other areas had contributed to lower erosion rates.

The discussion above shows that the determination of factors influencing soil erosion and their distribution in a given area should be the prerequisite in any attempt to prevent soil loss, introduce soil and water conservation measures, improve and/or restore soil productivity.

It should be noted at this point that the prediction of soil loss at the village did not consider the deposition and sorting erosion processes. Changes of soil erodibility with erosion were also not considered and the actual topographic factors were different from the values used where slope length was fixed to 100 m. In addition the influence of crop rotation practised by farmers in the village was not considered in the prediction. As the result the predicted soil losses in the village is probably much higher than actual losses experienced by farmers in the village who have been able to maintain the depth of the soil for over 100 years using *ngolo* system.

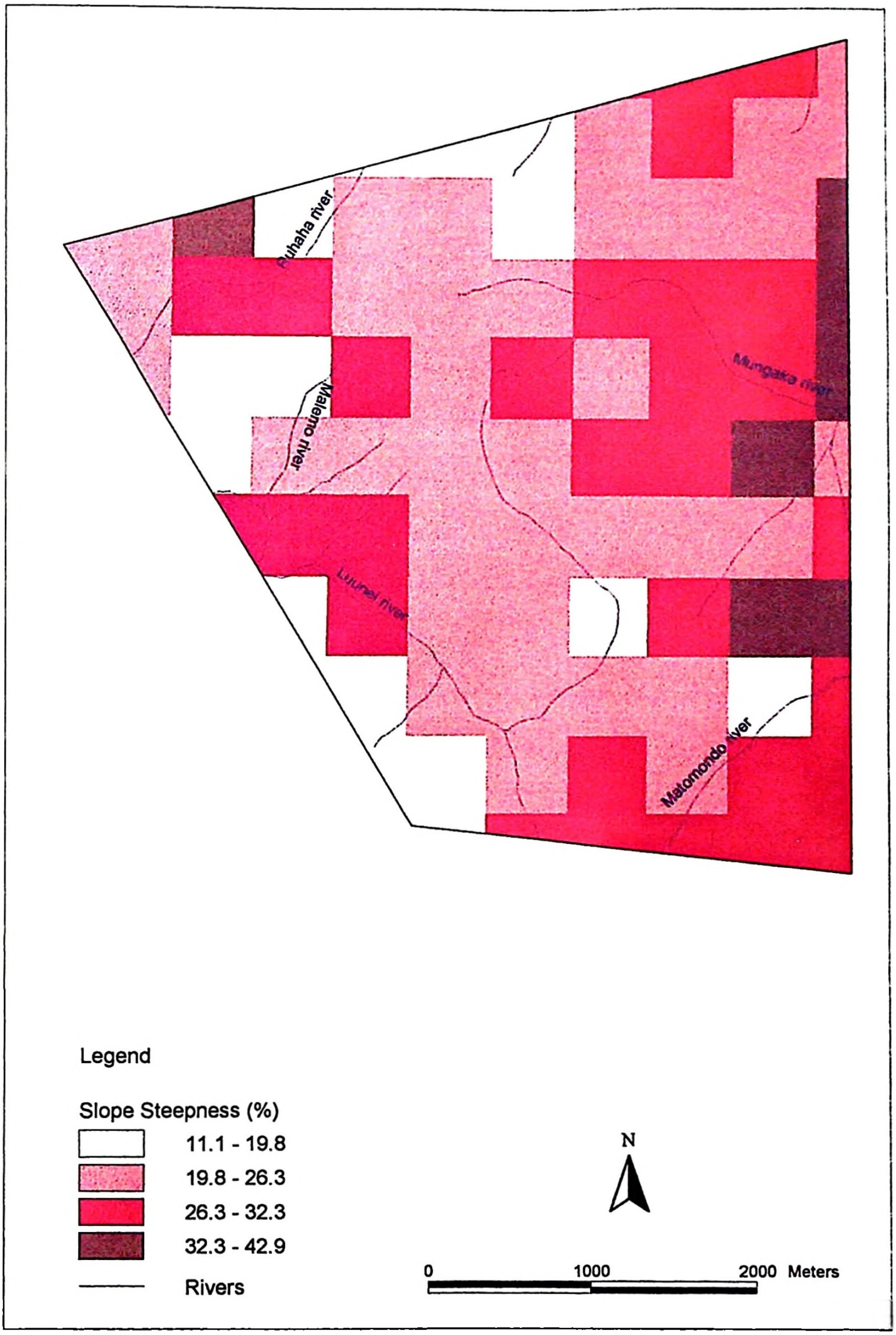

Fig. 13: Slope steepness map of Mahenge village

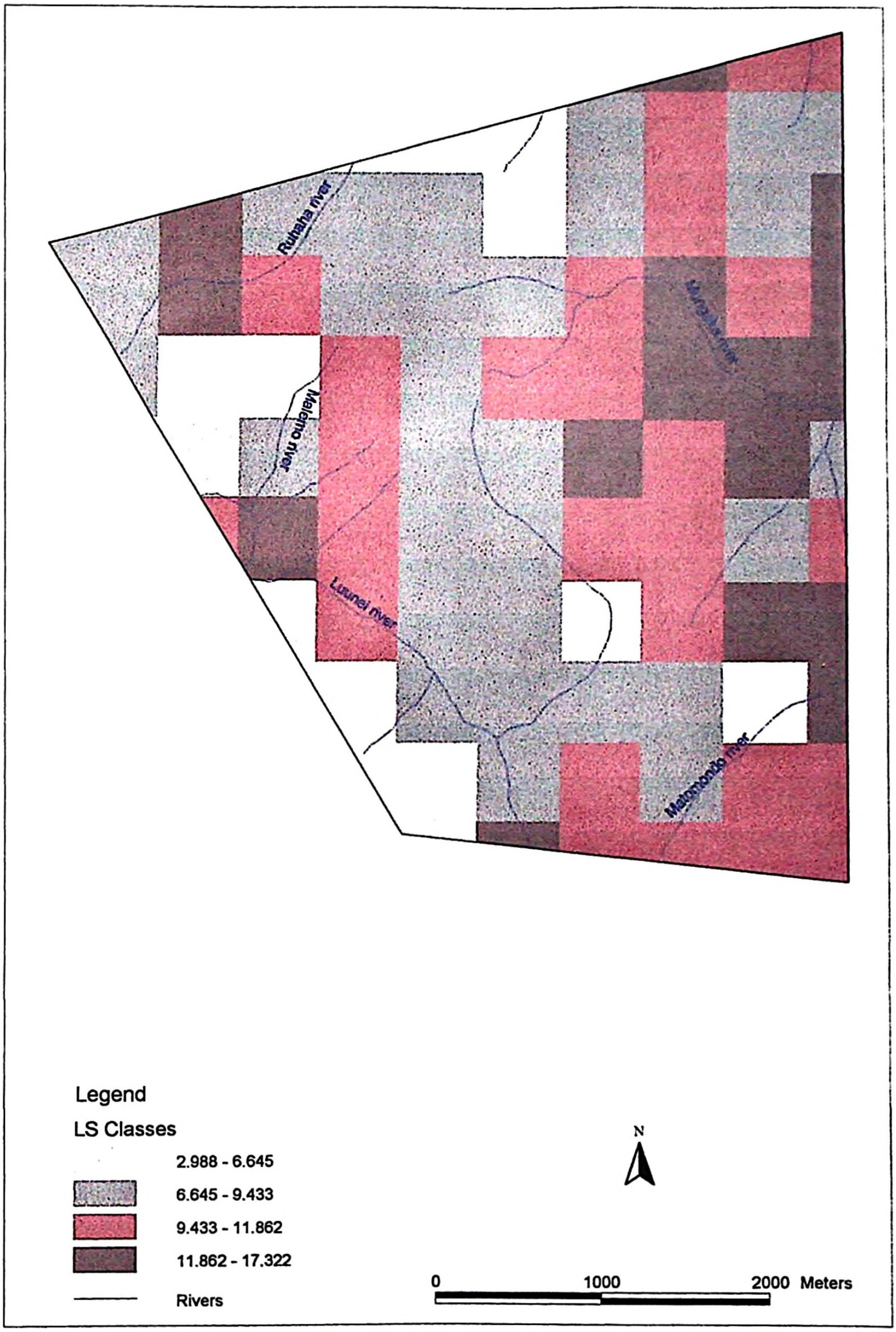

Fig. 14: Topographic map of Mahenge village

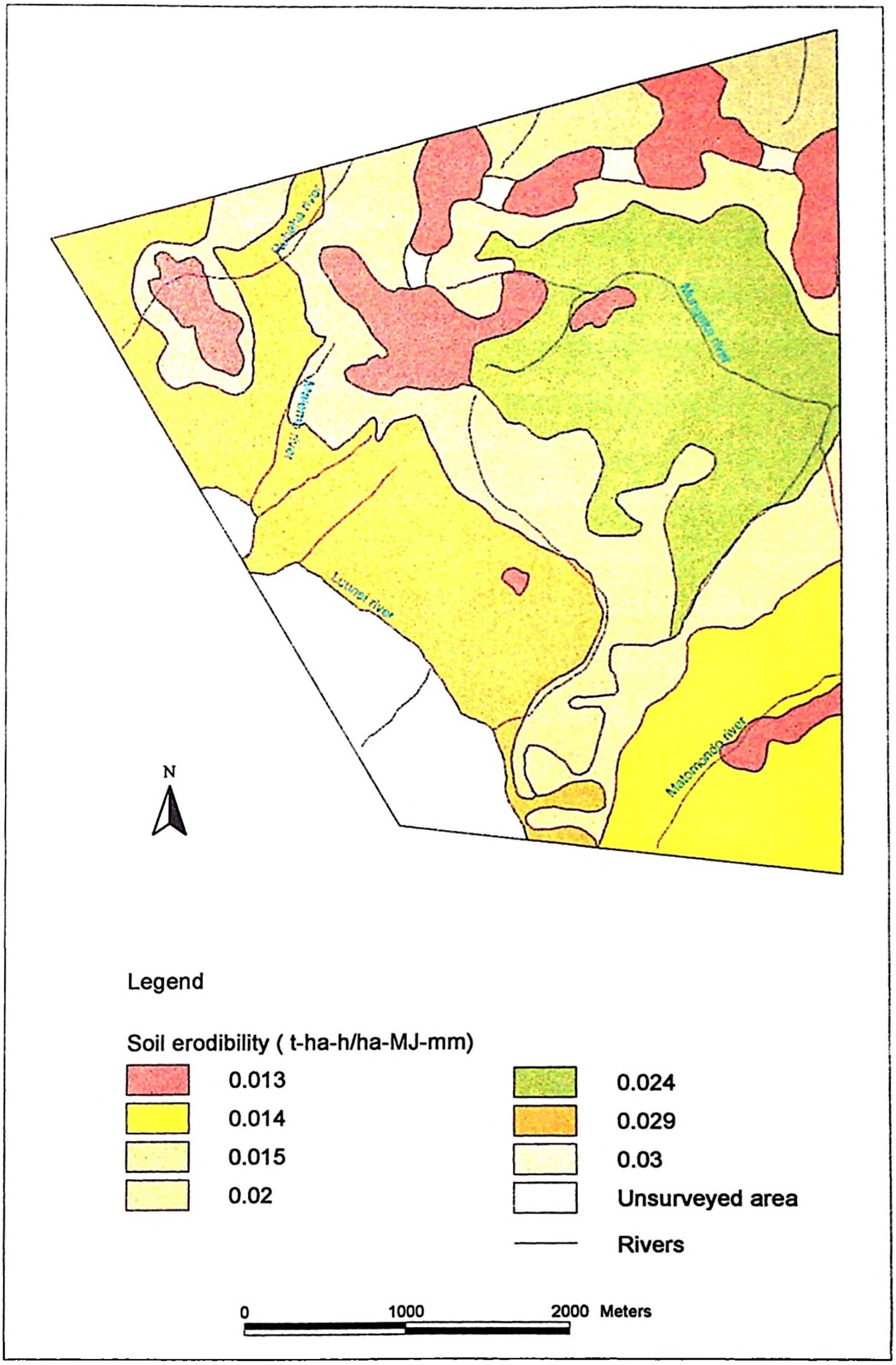

Fig. 15: Soil erodibility map of Mahenge village

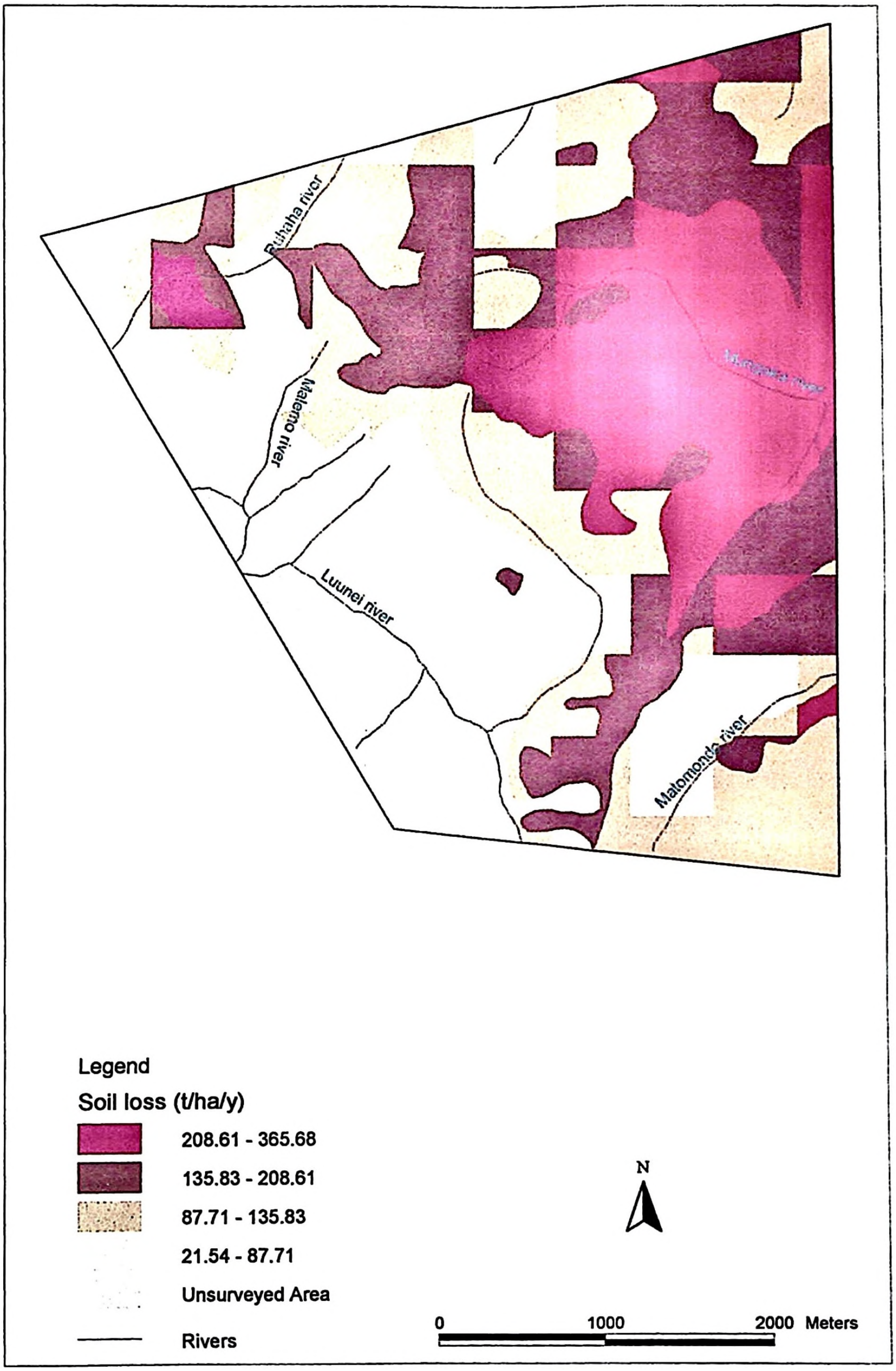

Fig. 16: Soil erosion hazard map of Mahenge village

4.7 Long-term Change in Erosion Induced Loss in Soil Productivity

The long-term change in relative production potential due to erosion was estimated for three soils (Haplic Phaeozem, Haplic Acrisols, and Ferrallic Cambisols) of Mahenge village. The selected soils are the most used in food production. Other soils have rock outcrops, boulders, and stones. These soils include Dystric Leptosols, Eutric Regosols, and Dystric Cambisols, which are placed under planted forest or used for coffee under ngolo as discussed in section 3.1.7 and shown in Fig. 4. As it has been noted by Hawassi (1997) and URT (1997) that in Matengo highlands and Mahenge village in particular food production is faced with serious decline in productivity. The assessment was based on USLE, and SEPIM parameters calculated using equations 2.1, and 2.30.

Change in PI (without A_i), which is a component of SEPIM was calculated for different soil depths (see Table 9) remaining after periods of soil loss. SEPIM calculations were based on assumption that the erosion rates would remain constant and change in SEPIM is due to change in rooting depth after a period of erosion. The soil loss values for three soils in the village were converted to equivalent depths. To change the quantities of soil in tonnes to depths in metres, the bulk mass value of 1200 (t/ha/m) for sandy clay loam soi,l which dominate the village was used. Soil erosion was simulated at the rate indicated in Table 10 for 25, 50 and 100 years.

Table 9: Productivity Index (PI) of soils at Mahenge village

Soil type	H32				H33				P2			
Depth	Pr	25	50	100	Pr	25	50	100	Pr	25	50	100
0-10	0.153	-	-	-	0.093	-	-	-	0.142	0.135	-	-
10-20	0.116	-	-	-	0.070	-	-	-	0.105	0.090	-	-
20-30	0.094	-	-	-	0.068	-	-	-	0.073	0.069	0.118	-
30-40	0.082	-	-	-	0.056	-	-	-	0.071	0.061	0.011	-
40-50	0.069	0.141	-	-	0.035	-	-	-	0.054	0.050	0.067	-
50-60	0.060	0.108	-	-	0.029	0.113	0.087	-	0.045	0.041	0.056	0.112
60-70	0.052	0.082	-	-	0.024	0.085	0.065	-	0.037	0.035	0.045	0.078
70-80	0.043	0.069	-	-	0.022	0.052	0.054	-	0.032	0.028	0.038	0.058
80-90	0.036	0.056	0.130	-	0.018	0.043	0.046	-	0.027	0.024	0.030	0.046
90-100	0.027	0.046	0.091	-	0.014	0.035	0.038	-	0.026	0.018	0.025	0.038
100-110	0.024	0.034	0.060	-	0.011	0.032	0.032	0.080	0.017	0.012	0.018	0.027
110-120	0.018	0.027	0.048	-	0.008	0.026	0.027	0.057	0.013	0.007	0.012	0.018
120-130	0.016	0.021	0.036	-	0.005	0.022	0.022	0.041	0.009	0.002	0.007	0.011
130-140	0.010	0.016	0.026	-	0.002	0.018	0.019	0.033	0.003	0.001	0.002	0.003
140-150	0.008	0.011	0.018	0.053	0.00	0.014	0.015	0.027	0.00	0.00	0.00	0.001
150-160	0.003	0.01	0.012	0.017		0.011	0.012	0.020				
160-170	0.00	0.002	0.005	0.006		0.008	0.009	0.014				
170-180						0.005	0.006	0.009				
180-190						0.002	0.003	0.005				
190-200						0.00	0.000	0.001				
PI	0.81	0.62	0.43	0.07	0.45	0.47	0.44	0.29	0.65	0.57	0.43	0.28

H32 = Haplic Phaeozem, H33 = Haplic Acrisols, P2 = Ferrallic Cambisols, Pr = Present, 25, 50, 100 years

Table 10: Long term change in production potential at Mahenge village

Code	Soil type	Initial soil depth (cm)	Depleted soil (mm /year)	Initial SEPIM	SEPIM values after years of soil loss		
					25	50	100
H32	Haplic Phaeozem	170	14.19	0.80	0.61	0.42	0.069
H33	Haplic Acrisols	200	9.66	0.44	0.46	0.43	0.28
P2	Ferrallic Cambisols	150	5.27	0.64	0.56	0.42	0.27

In this study, Haplic Phaeozem with the depth of 170 cm showed sharp decline in soil productivity with continued erosion with time. The soils lost 24 percent of its productivity potential after only 25 years. After 100 years the Haplic Phaeozem will loose more than 99 percent of its production potential and the remaining root depth (see Table 9) will not be able to support plant growth. Therefore, the Haplic Phaeozem with much higher productivity potential but showing a loss of its productivity potential faster than other soils demand more attention to protect it from further degradation as most of the cultivation in the village is done on it.

On the other hand, Haplic Acrisols with the least production potential (0.44) improves its production potential after 25 years of soil erosion due to the exposure of soil layers with good soil properties. However, after 50 years of soil loss it will start losing its productivity. Haplic Acrisols with soil depth of 200 centimetres is able to sustain its moderate production potential for much longer time despite the relative higher rate of erosion. These illustrate that soil erosion rates alone are not necessarily good indicators of damage to productivity as observed also by Larson *et al.* (1983).

Ferrallic Cambisols is able to maintain its productivity for much longer time than Haplic Phaeozem, mainly due to lower rate of soil erosion during the time of simulation. However, both Haplic Phaeozem and Ferrallic Cambisols initially show large decline in production potential than Haplic Acrisols, with the first 30-centimetre loss of topsoil.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The need for an assessment of erosion hazard in Mahenge village is provided by socio-economic conditions such as rapid population growth and change in land uses, which threaten the sustainability of soil resource base. The assessment of magnitude of erosion-induced loss in soil productivity is necessary for determination of the rate of soil degradation on land resource in use and for management and restoration of eroded lands. Assessment of soil erosion demands study and analysis of all factors affecting erosion by water. The results presented in this research are based on field measurements and estimates of USLE variables from available data. Then, based on estimates and statistics available the following conclusions can be made on this study:

- The threat of soil erosion by water in the village is evident due to the presence of deforestation, cultivation in steep hill slopes with poor crop cover and highly erosive rainfall.
- The accuracy of CP values used in the RUSLE equation showed to be appreciably different from the short-term experiment values in Tukuzi and Mahenge village.
- The extent of soil erosion destruction in the village is not uniformly distributed as shown by erosion hazard map (Fig. 16).

- Under experimental conditions *ngolo* cultivation and bench terraces have proved to be effective in controlling erosion at the village. However, their effectiveness is influenced by slope steepness and slope length.
- There was no serious water stress during the study period.
- Even though there is no statistical difference ($p=0.05$) in control of erosion between *ngolo* and bench terraces, the *ngolo* is more superior in improvement and maintenance of soil productivity as indicated by high plant height, crop cover and grain yield.
- Evaluation of PI and SEPIM at the experimental site showed that SEPIM had more explanation power than PI; although the explanation was highly variable from $r^2 = 0.36$ for linear regression (or $r^2 = 0.51$ for exponential regression) for ngolo to $r^2 = 0.51$ for linear regression (or $r^2 = 0.95$ for exponential regression) for bench terraces.
- The impact of erosion on soil productivity at the village tended to vary from one soil to another with Haplic Phaeozem having rapid initial decline in productivity potential as obtained using SEPIM.
- The rate of loss in productive potential of soil depends on its inherent soil characteristics and management it receives both of which affects the rate of soil erosion.

5.2 Recommendations

Based on the findings of this study it is therefore, recommended that:

- To alleviate excessive soil erosion in sloping areas of Mahenge village and Southern highlands in general, there should be an effort to increase the extent and diversity of vegetation cover of the land by enhancing agroforestry practices.
- The CP values in the RUSLE equations need to be accurate for reliable prediction. This could be addressed through establishing the necessary data base.
- If bench terraces are to be adopted for food crop production, then application of appropriate fertilizers, and liming are necessary to address the poor soil conditions.
- Establish more weather stations so as to increase the database required for monitoring and prediction of crop production trends in the rural area.
- The prediction accuracy of the SEPIM model though better than PI model did not show the desired consistence; thus there is a need for further evaluation of the model in the highland and other areas.

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APPENDICES

APPENDIX 1

Family texture class, Predicted Water Depletion and Root Fractions for ideal soil, Soil physical and chemical properties of the experimental plots and soil units of Mahenge village, and evaporation data.

Table 1A: nonlimiting, critical, and root-limiting bulk densities for each family texture class

Family Texture class	Nonlimiting Bulk Density	Critical Bulk Density	Root-Limiting Bulk Density
	---------------	g/cm^3--------	
Sandy	1.60	1.69	1.85
Coarse loamy	1.50	1.63	1.80
Fine loamy	1.46	1.67	1.78
Coarse silty	1.43	1.67	1.79
Fine silty	1.34	1.54	1.65
Clayey:			
35-45%	1.40	1.49	1.58
45%	1.30	1.39	1.47

Source: Pierce *et al.*, 1983

Table 1B: Soil physical and chemical properties for PI at experimental site

Treatment	Depth (cm)	Texture	Bulk density (g/cm3)	pH (CaCl2)	EC (mS/Cm)	O.M
N1	0-30	SC	0.83	4.4	0.10	3.08
	30-60	C	0.83	4.6	0.04	2.09
	60-120	SC	0.89	5.1	0.02	1.17
N2	0-30	SC	0.79	4.4	0.02	3.27
	30-60	SC	0.92	4.5	0.05	1.86
	60-120	SC	0.92	4.8	0.06	0.91
BT1	0-30	SC	0.86	4.3	0.02	2.80
	30-60	SC	0.86	4.3	0.03	1.41
	60-120	C	0.90	4.7	0.03	0.95
BT2	0-30	SC	0.88	4.3	0.03	3.04
	30-60	SC	0.93	4.3	0.01	1.99
	60-120	C	0.95	5.0	0.06	0.95
Fallow	0-25	SCL	1.1	4.6	0.00	3.15
Profile	25-50	C	1.2	4.4	0.00	1.65
	50-80	C	1.2	5.1	0.00	0.95
	80-150	C	1.2	5.3	0.00	0.50

N1,2=*ngolo* replication one,or two BT1,2=bench terrace replication one or two
O.M = organic matter content

Table 1C: Soil physical and chemical properties for determination of PI for soils of Mahenge village

Soil type	Depth (cm)	Texture (%)	B.D g/cm^3	pH (H_2O)	OM	EC
Dystric Leptosols	0-30	C = 25, S = 13, VFS = 12, CS = 3	1.1	4.4	3.9	0.04
	30-60	C = 24, S = 11, VFS = 13, CS = 3	1.2	4.4	2.2	0.02
Ferrallic Cambisols	0-30	C = 30, S = 25, VFS = 11, CS = 6	1.0	5.6	4.8	0.08
	30-70	C = 30, S = 24, VFS = 11, CS = 6	1.4	5.5	4.47	0.03
	70-150	C = 32, S = 23, VFS = 11, CS = 6	1.3	5.6	1.2	0.02
Haplic Phaeozem	0-30	C = 24, S = 23, VFS = 7, CS = 6	0.9	5.7	5.85	0.04
	30-70	C = 23, S = 25, VFS = 8, CS = 6	1.0	5.8	6.36	0.03
	70-150	C = 24, S = 24, VFS = 8, CS = 9	1.2	5.6	3.78	0.01
Haplic Acrisols	0-30	C = 22, S = 27, VFS = 10, CS = 6	0.9	5.4	7.2	0.09
	30-70	C = 37, S = 15, VFS = 8, CS = 4	1.5	4.9	2.9	0.02
	70-150	C = 49, S = 8, VFS = 9, CS = 4	1.5	5.1	0.52	0.01
Dystric Cambisols	0-30	C = 24, S = 23, VFS = 10, CS = 5	1.2	4.5	4.1	0.03
	30-70	C = 25, S = 28, VFS = 9, CS = 5	1.7	4.6	1.03	0.02
	70-150	C = 17, S = 9, VFS = 9, CS = 8	1.8	4.7	0.17	0.01
Haplic Acrisols	0-30	C = 25, S = 17, VFS = 10, CS = 4	1.0	4.9	4.8	0.01
	30-70	C = 28, S = 12, VFS = 10, CS = 4	1.3	4.8	2.4	0.02
	70-150	C = 43, S = 11, VFS = 9, CS = 3	1.4	4.9	0.69	0.01
Eutric Regosols	0-30	C = 23, S = 15, VFS = 10, CS = 6	1.1	5.6	3.95	0.03
	30-40	C = 23, S = 14, VFS = 11, CS = 7	1.1	5.7	3.09	0.02

B.D = bulk density

S = Silt, VFS = Very fine sand, CS = Coarse sand =Parameters used to calculate M
Source: Magoggo *et al.* (1996)

Table 1D: Evaporation data (average of four years) in mm

Month	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
Epan (mm)	2.5	4.1	0.6	1.8	1.9	1.9	2.1	2.5	3.1	3.5	3.6	2.6

Source: JICA (unpublished)

Table 1E: Rainfall data (mm) of Litembo Mission used (1960/61-1980/81)

	Dec	Jan	Feb	Mar	Apr	May
1960/61	68.834	292.1	324.61	184.91	135.12	28.448
1961/62	396.49	278.13	305.05	257.55	150.87	24.13
1962/63	148.59	242.7	117.4	399.9	87	0
1963/64	359.5	297.2	213.5	175.8	27.9	26.7
1964/65	122.6	416.6	237.6	459.6	257.8	15.2
1965/66	482.5	221	248.9	309.4	76.2	27.2
1966/67	228.5	250.2	306.2	242.5	237.4	38.1
1967/68	387.6	145.1	396.2	266.6	157.4	12.7
1968/69	195.6	182.9	226	248.8	119.3	1.2
1969/70	174.3	386.6	256.5	372.1	72.2	0
1970/71	335.7	71.2	315	328	152.5	5
1971/72	240.5	193.9	144.4	223	74.7	55.5
1972/73	184	209.5	171	193.7	102.4	9
1973/74	242	292.9	111.5	189.7	272.4	91.4
1974/75	190.4	322.7	187.4	263.2	109.1	6.8
1975/76	199.5	288.6	266.6	228.7	162.9	24.5
1976/77	89.5	292.4	111.7	222	199	89.4
1977/78	144.9	441.6	132.6	439.6	68.9	1.4
1978/79	312.3	155.5	357.5	303.5	190.2	3.3
1980/81	269.9	143	274.1	230.7	100.9	62.3

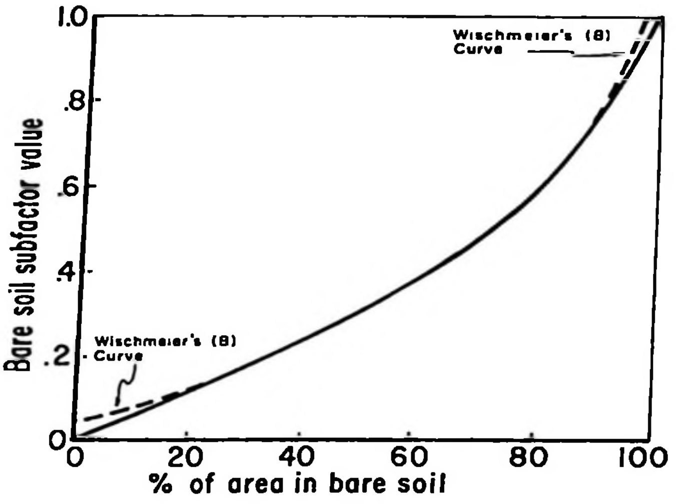

Fig. 1A: The bare soil sub-factor

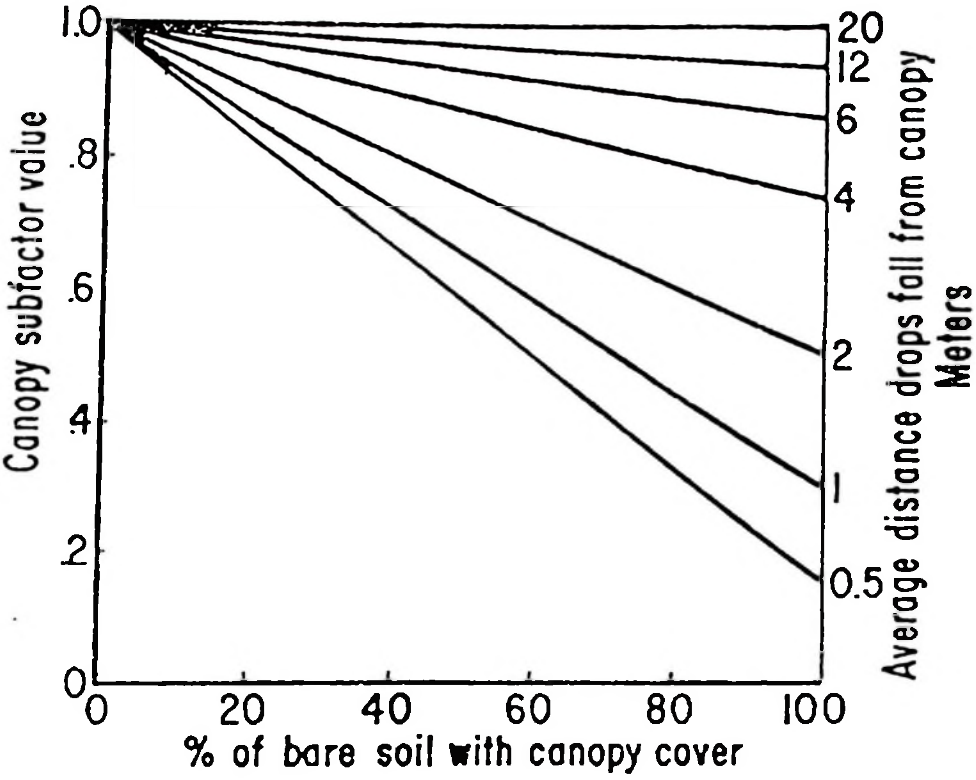

Fig. 1B: The canopy sub-factor

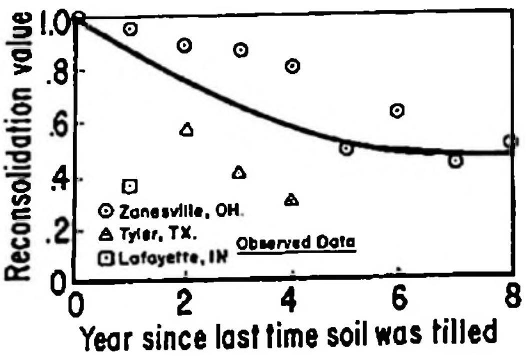

Fig. 1C: The sub-factor for soil reconsolidation

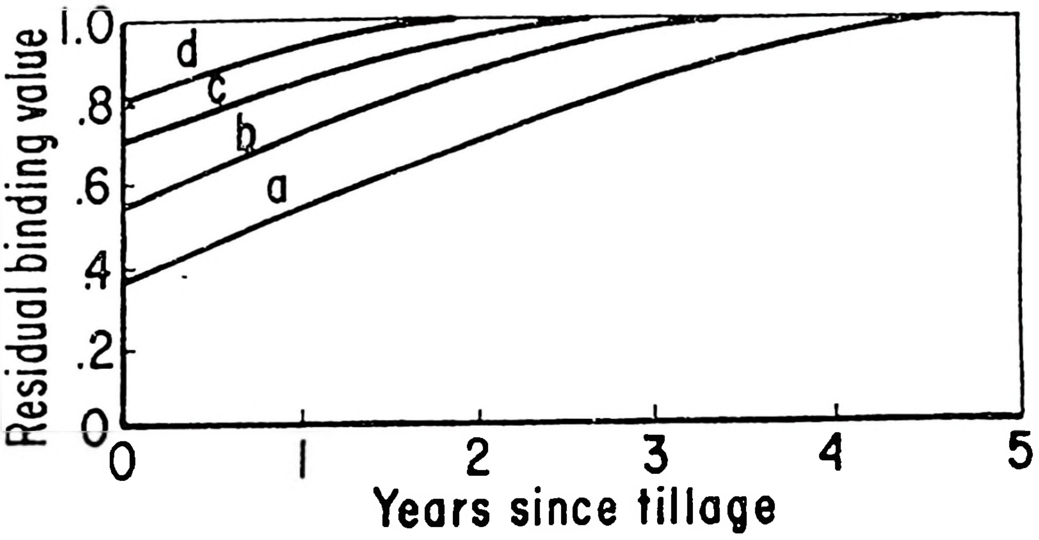

Fig. 1D: Residual binding sub-factor

Legend:

- a. – Topsoil has good initial fine root mat, and subsoil has good structure and permeability.
- b. - Topsoil has poor initial fine root mat, and subsoil has good structure and permeability.
- c. - Topsoil absent with poor initial fine root mat. Subsoil has good structure and permeability.
- d. - Topsoil absent with poor initial fine root mat. Subsoil has poor structure and permeability.

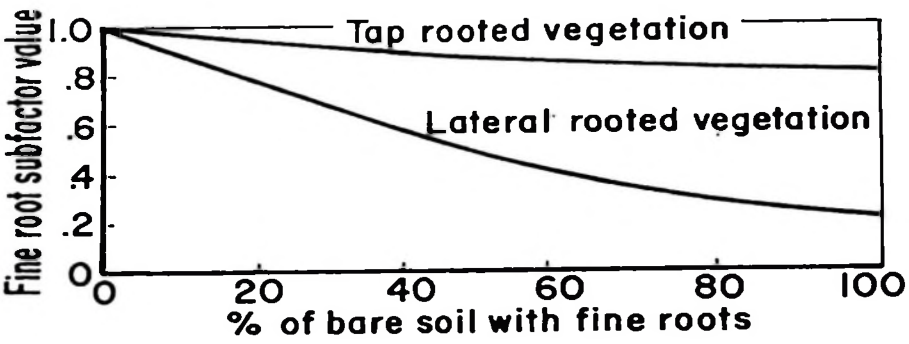

Fig.1E: The sub-factor for fine roots in the top 30 to 50 mm of soil

APPENDIX 2

Analysis of variance tables for soil loss, and 1998/99 Rainfall Erosivity values at experimental site - Mahenge village.

Table 2A: ANOVA for soil loss at experimental plot in 1998/99 growing season

Factor A = Soil and water conservation measures

Table 2A: 2 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	2817.966	2817.966	1.2202	0.3844
Factor A	2	743089.817	371544.909	160.8803	0.0062
Error	2	4618.898	2309.449		
Total	5	750526.682			

Coefficient of Variation: 18.64%

Table 2A: 14 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	72.802	72.802	0.9150	
Factor A	2	274147.773	137073.886	1722.7968	0.0006
Error	2	159.129	79.565		
Total	5	274379.704			

Coefficient of Variation: 5.35%

Table 2A: 42 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	459.375	459.375	2.3067	0.2682
Factor A	2	80262.021	40131.010	201.5092	0.0049
Error	2	398.305	199.152		
Total	5	81119.700			

Coefficient of Variation: 15.23%

Table 2A: 72 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	99799.553	99799.553	0.8850	
Factor A	2	2960419.479	1480209.740	13.1259	0.0708
Error	2	225539.548	112769.774		
Total	5	3285758.580			

Coefficient of Variation: 60.25%

Table 2A: 103 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	148.802	148.802	0.6131	
Factor A	2	1943.912	971.956	4.0047	0.1998
Error	2	485.410	242.705		
Total	5	2578.124			

Coefficient of Variation: 94.44%

Table 2B: Total kinetic energy (KE) and rainfall erosivity index (EI_{30}) for rainstorms of 1998/99 growing season

Rainstorm event	Date	Rainfall amount (mm)	Max. 30-minute intensity I_{30} (mm/h)	Kinetic energy (J/M^2)	EI30 Jmm/m^{2}h	EI_{30} MJmm/ha-h
1	4/12/98	4.5	13.5	70.1	946.35	9.4635
2	6/12/98	7.0	13	105.12	1366.56	13.6656
3	11/12/98	5.5	10	76.68	766.8	7.668
4	29&30/12/98	10.5	13	130.32	1694.16	16.9416
5	31/12/98	6.5	12	94.45	1133.4	11.334
6	5/1/99	40.5	52	933.98	48566.96	485.6696
7	15/1/99	26.5	33	470.64	15531.12	155.3112
8	13/1/99	3.5	7	41.89	293.23	2.9323
9	16/1/99	10.0	13	140.7	1829.1	18.291
10	16/1/99	6.5	9	73.11	657.99	6.5799
11	18/1/99	39.5	37	765.37	28318.69	283.1869
12	21/1/99	17.0	23	301.78	6940.94	69.4094
13	23/1/99	15.0	25	304.42	7610.5	76.105
14	24/1/99	8.5	15	140.53	2107.95	21.0795
15	26/1/99	11.0	12	143.48	1721.76	17.2176
16	28&29/1/99	45.0	20	666.77	13335.4	133.354
17	29/1/99	10.0	16	176	2816	28.16
18	31/1/99	12.5	24	290.05	6961.2	69.612
19	31/1/99	12.5	21	224.28	4709.88	47.0988
20	1/2/99	5.5	5	41.96	209.8	2.098
21	8/2/99	11.5	16	185.96	2975.36	29.7536
22	9/2/99	22.0	32	433.53	13872.96	138.7296
23	11/2/99	7.0	16	176	2816	28.16
24	16/2/99	6.5	8	73.11	584.88	5.8488
25	17/2/99	5.0	4	32.63	130.52	1.3052
26	20/2/99	12.0	17	186.23	3165.91	31.6591
27	21/2/99	7.0	12	104.28	1251.36	12.5136
28	22/2/99	11.0	16	171.34	2741.44	27.4144
29	23/2/99	20.5	40	515.57	20622.8	206.228
30	24/2/99	8.5	9	98.1	882.9	8.829
31	27/2/99	4.5	8	53.91	431.28	4.3128
32	1/3/99	33.5	22	599.62	12311.64	123.1164
33	2/3/99	30.0	54	756.87	40870.98	408.7098
34	4/3/99	7.5	15	140.99	2114.85	21.1485

Table 2B: continued

35	5/3/99	10.5	14	153.56	2149.84	21.4984
36	6/3/99	14.5	17	232.86	3958.62	39.5862
37	7/3/99	12.0	5	84.73	423.65	4.2365
38	8/3/99	6.0	6	48.54	291.24	2.9124
39	9/3/99	30.5	32	491.8	15737.6	157.376
40	10/3/99	12.5	17	188.79	3209.43	32.0943
41	11/3/99	20.0	33	436.29	14397.57	143.9757
42	13&14/3/99	20.0	18	352.48	6344.64	63.4464
43	15/3/99	24.5	15	277.25	4158.75	41.5875
44	18&19/3/99	12.5	15	156.31	2344.65	23.4465
45	20&213/99	17.5	13	198.27	2577.51	25.7751
46	21&22/3/99	19.0	16	240.72	3851.52	38.5152
47	25/3/99	25.0	26	421.26	10952.76	109.5276
48	26/3/99	14.0	11	163.86	1802.46	18.0246
49	27&28/3/99	7.0	10	78.9	789	7.89
50	28&29/3/99	22.5	20	311.59	6231.8	62.318
51	29&30/3/99	25.0	10	259.81	2598.1	25.981
52	2/4/99	5.0	4	35.92	143.68	1.4368
53	3/4/99	7.0	4	42.5	170.0	1.70
54	4/4/99	13.5	7	132.34	926.38	9.26
55	5/4/99	13.5	5	109.97	549.85	5.4985
56	6/4/99	8.0	6	64.72	388.32	3.8832
57	7/4/99	12.0	9	115.69	1041.21	10.4121
58	8/4/99	9.0	7	61.43	430.01	4.3001
59	8&9/4/99	7.0	3	46.06	138.18	1.3818
60	9&10/4/99	31.0	14	389.46	5452.44	54.5244
61	12/4/99	14.0	19	218.25	4146.75	41.4675
62	15/4/99	4.0	5	29.07	145.35	1.4535
63	30/4/99	7.5	8	67.94	543.52	5.4352
64	4/5/99	4.0	7	45.18	316.26	3.1626
					Total	**3467.04**

APPENDIX 3

Gravimetric soil moisture data and its Analysis of Variance Tables

Table 3A: Gravimetric soil moisture content (%) for runoff plots at Mahenge 1999

Date	Treatment	Soil depth (cm)			
		0-30	30-45	45-60	60-120
18/1/99	BT1	27.6	22.8	24.2	17.9
	BT2	28.4	22.5	16.5	14.1
	N1	28.7	29.9	19.2	13.7
	N2	28.6	23.6	21.4	28
	B1	30.8	21.8	17.5	12.6
	B2	31.2	28.3	17.6	19.8
1/2/99	BT1	25.1	24.6	23.6	22.5
	BT2	24.1	16.6	22.1	21
	N1	25.4	22.7	20.8	29.5
	N2	24.5	22.7	20.9	21.3
	B1	30.4	21.5	12.2	21.3
	B2	23.9	22.7	14	16.2
15/2/99	BT1	20.7	25.8	18.28	17.5
	BT2	12.9	38.6	10.9	20.8
	N1	12.1	19.6	18.2	26.8
	N2	22.3	19.8	18.4	19
	B1	21.9	28	18.8	13.1
	B2	20.1	20.1	29.5	36.3
1/3/99	BT1	31.5	24.1	14.2	21
	BT2	27.7	31.1	14.6	13.5
	N1	22.7	24.7	12.7	20.8
	N2	26.5	30.9	23.5	43.1
	B1	27.7	21.2	19.7	18.8
	B2	27.2	23.1	21.7	15.7
15/3/99	BT1	26.6	15.5	22.8	13.1
	BT2	24.3	32.8	31.4	21
	N1	20.7	44.5	21.1	20.4
	N2	16.5	22.9	22.6	8.9
	B1	36.5	13	19.8	19.3
	B2	32.8	31.3	39.2	21.9
1/4/99	BT1	24.3	41.5	11.3	20.5
	BT2	28	23.7	22.7	23.5
	N1	27.3	17.6	31.5	29.7
	N2	24	14.8	31.6	21.8
	B1	24.2	21.4	19.4	19.1
	B2	26.2	23.2	26.8	20.9
15/4/99	BT1	23.8	38.1	28.7	19.8
	BT2	15.9	20.4	20	40
	N1	33.6	18.9	21.5	20.1
	N2	25.2	21.7	21	26
	B1	16.4	21.7	25.9	13.2
	B2	22.9	22.1	20.5	21
1/5/99	BT1	13.9	11.5	8.7	9.9
	BT2	10.1	12.2	15.6	11.9
	N1	14.3	14.5	12.5	14.2
	N2	15.8	10.5	10.2	12
	B1	12.2	14	12.1	14.7
	B2	11.9	9.9	18.5	12

Table 3A: continued

15/5/99	BT1	16.35	15	12.03	14.53
	BT2	13.24	14.38	14.88	16.58
	N1	16.72	16.22	14.62	14.98
	N2	17.23	14.64	15.2	15.29
	B1	15.34	16.33	15.42	15.04
	B2	14.98	17.27	17.09	16.73
1/6/99	BT1	13.74	14.47	13.04	13.55
	BT2	14.92	12.11	13.82	15.88
	N1	13.99	9.67	12.22	14.35
	N2	14.85	15.36	13.77	15.76
	B1	16.0	15.58	10.64	15.86
	B2	14.07	22.77	14.18	10.8
17/7/99	BT1	10.58	13.18	14.05	14.31
	BT2	10.79	15.38	14.35	14.88
	N1	11.25	14.55	14.62	14.82
	N2	10.31	16.91	17.49	17.49
	B1	11.97	13.62	13.40	14.08
	B2	9.92	13.44	13.26	12.98

Table 3B: ANOVA Tables for Gravimetric soil moisture content during 1998/99 season at experimental plot

Factor A = Soil and water conservation measures, Factor B = Soil depth

Table 3B: 1 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	7.370	7.370	0.4023	
Factor A	2	24.101	12.050	0.6578	
Factor B	3	497.875	165.958	9.0595	0.0026
AB	6	43.229	7.205	0.3933	
Error	11	201.505	18.319		
Total	23	774.080			

Coefficient of Variation: 18.79%

Table 3B: 14 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	36.507	36.507	5.8416	0.0342
Factor A	2	42.723	21.362	3.4182	0.0701
Factor B	3	132.893	44.298	7.0883	0.0064
AB		120.047	20.008	3.2016	0.0453
Error	11	68.743	6.249		
Total	23	400.913			

Coefficient of Variation: 11.33%

Table 3B: 28 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	32.480	32.480	0.6447	
Factor A	2	65.953	32.976	0.6545	
Factor B	3	186.273	62.091	1.2324	0.3444
AB	6	241.594	40.266	0.7992	
Error	11	554.207	50.382		
Total	23	1080.507			

Coefficient of Variation: 33.44%

Table 3B: 42 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	65.010	65.010	2.1217	0.1732
Factor A	2	68.110	34.055	1.1114	0.3634
Factor B	3	324.825	108.275	3.5336	0.0519
AB	6	326.377	54.396	1.7753	0.1938
Error	11	337.055	30.641		
Total	23	1 121.376			

Coefficient of Variation: 23.82%

Table 3B: 56 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	73.850	73.850	1.0723	0.3227
Factor A	2	56.551	28.275	0.4106	
Factor B	3	236.781	78.927	1.1460	0.3735
AB	6	426.682	71.114	1.0326	0.4543
Error	11	757.585	68.871		
Total	23	1551.450			

Coefficient of Variation: 33.83%

Table3B: 72 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	0.015	0.015	0.0005	
Factor A	2	21.031	10.515	0.3756	
Factor B	3	29.288	9.763	0.3488	
AB	6	502.339	83.723	2.9908	0.0551
Error	11	307.925	27.993		
Total	23	860.598			

Coefficient of Variation: 22.08%

Table3B: 86 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	1.042	1.042	0.0208	
Factor A	2	116.216	58.108	1.1588	0.3494
Factor B	3	3.063	1.021	0.0204	
AB	6	273.044	45.507	0.9075	
Error	11	551.608	50.146		
Total	23	944.973			

Coefficient of Variation: 30.44%

Table 3B: 120 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	185.927	185.927	2.2176	0.1645
Factor A	2	202.463	101.232	1.2074	0.3357
Factor B	3	98.075	32.692	0.3899	
AB	6	535.030	89.172	1.0636	0.4384
Error	11	922.263	83.842		
Total	23	1943.758			

Coefficient of Variation: 40.17%

Table 3B:134 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	1.013	1.013	0.7377	
Factor A	2	8.297	4.148	3.0217	0.0900
Factor B	3	2.449	0.816	0.5946	
AB	6	10.150	1.692	1.2322	0.3608
Error	11	15.102	1.373		
Total	23	37.010			

Coefficient of Variation: 7.60%

Table 3B:148 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	9.600	9.600	1.6916	0.2200
Factor A	2	7.128	3.564	0.6280	
Factor B	3	14.316	4.772	0.8409	
AB	6	50.903	8.484	1.4949	0.2663
Error	11	62.425	5.675		
Total	23	144.372			

Coefficient of Variation: 16.75%

Table 3B: 180 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	2.048	2.048	0.8488	
Factor A	2	7.703	3.851	1.5966	0.2462
Factor B	3	65.654	21.885	9.0721	0.0026
AB	6	1.158	0.193	0.0800	
Error	11	26.535	2.412		
Total	23	103.097			

Coefficient of Variation: 11.37%

APPENDIX 4

Crop development data, ANOVA Tables for crop cover and plant height during the 1998/99 growing season at experimental plot in Mahenge village

Table 4A: Crop development characteristics at the experimental site 1998/99 season

DAS	Treatment	Cover (%)	Height (cm)	DAS	Treatment	Cover (%)	Height (cm)
14	BT1	2	12.6	86	BT1	78	140.3
		0	11.6			50	102
		2	13			41	94.3
		1	9.3			34	70.6
		1	10.6			30	79.6
		1	11			24	58.6
	BT2	1	12.3		BT2	48	102.3
		1	13			33	56.3
		2	11			18	64.6
		0	13			29	82.6
		2	13			53	95
		0	9.6			44	85.3
	N1	4	13.3		N1	59	208
		13	14			53	199.6
		0	12			55	184.3
		1	11.6			50	141
		1	13.6			67	174.6
		1	11.6			54	142.3
	N2	2	12.3		N2	58	227
		1	10.3			51	139
		1	11.3			61	135.3
		0	11			52	138.3
		1	10.6			50	152.3
		2	15			64	206.3
28	BT1	4	26.6	120	BT1	77	231.3
		2	22.3			49	188
		2	21.6			28	152.3
		2	16			26	89.6
		4	19.3			17	95.6
		2	20			8	70
	BT2	3	20.6		BT2	28	128.6
		2	18.6			35	64
		2	19			11	82.3
		5	18.3			13	121.3
		6	20.6			53	167
		2	20			27	126
	N1	7	26		N1	67	278.3
		3	31.6			85	289.3
		2	27.3			73	228.6
		2	23			58	196.3
		3	31.6			94	222.3
		5	26.6			67	213.6
	N2	3	18.3		N2	72	253.3
		1	20.3			60	233.3
		4	22.3			71	174.6
		3	18.6			61	182

Table 4A continued

		2	17			7	199.3
		4	28.3			73	278.6
42	BT1	14	47.6	134	BT1	83	239.3
		8	36.6			49	207.6
		8	34			35	158
		8	30.6			35	101
		8	27.6			26	105.3
		6	28.3			11	81.3
	BT2	8	34		BT2	37	142.6
		7	28.3			47	69.3
		4	27.3			29	90.3
		8	36.3			15	128
		10	38.3			11	174
		8	30			27	134.3
	N1	27	56		N1	94	287.3
		20	50.3			92	295.6
		16	46.6			54	235
		7	41.3			81	204
		15	54			74	230
		13	46.3			71	218.3
		13	46.3		N2	84	267.3
	N2	7	38			72	245.3
		12	39.6			66	184
		12	43			59	193
		8	42.6			52	207.3
		18	58.6			86	295
56	BT1	29	84.6	144	BT1	69	244
		23	59.3			34	211
		16	57.6			32	163
		16	48.3			33	106.6
		14	50.6			17	110.3
		11	41.6			10	88
	BT2	17	50		BT2	47	147.6
		12	35			13	75
		16	41.6			18	95.3
		17	56			32	133.3
		26	57			48	178.6
		14	42.3			19	138.3
	N1	54	102		N1	93	294
		39	90.6			88	302
		33	86.3			83	243.3
		25	71			51	209.3
		29	86			62	237
		25	76.6			76	224.3
		40	84		N2	66	270
		28	70			69	250.6
		25	67.6			56	195
		20	66.6			68	199
		22	69.6			67	214

Table 4A continued

		54	96	84	299.3
72	BT1	68	112.3		
		44	81.6		
		36	70		
		42	57		
		42	69		
		41	45.3		
	BT2	43	71.3		
		29	49.3		
		34	52		
		30	64.3		
		39	76		
		27	67.6		
		60	144.3		
	N1	59	131		
		51	111.6		
		54	91		
		40	121.6		
		45	110		
		66	122.6		
	N2	43	110.3		
		56	90.6		
		48	94.3		
		35	94.3		
		67	140.3		

Table 4B: ANOVA Tables for crop cover

Factor A = Block and Factor B = Soil and water conservation measures

Table 4B: 14 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	8.167	8.167	1.2864	0.2808
Factor A	5	27.333	5.467	0.8611	
Factor B	1	8.167	8.167	1.2864	0.2808
AB	5	39.833	7.967	1.2549	0.3488
Error	11	69.833	6.348		
Total	23	153.333			

Coefficient of Variation: 151.18%

Table 4B: 28 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	0.042	0.042	0.0224	
Factor A	5	13.375	2.675	1.4383	0.2853
Factor B	1	0.375	0.375	0.2016	
AB	5	16.375	3.275	1.7609	0.2016
Error	11	20.458	1.860		
Total	23	50.625			

Coefficient of Variation: 43.64%

Table 4B: 42 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	51.042	51.042	2.5584	0.1380
Factor A	5	108.708	21.742	1.0898	0.4182
Factor B	1	210.042	210.042	10.5280	0.0078
AB	5	51.708	10.342	0.5184	
Error	11	219.458	19.951		
Total	23	640.958			

Coefficient of Variation: 40.45%

Table 4B: 56 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	22.042	22.042	0.2902	
Factor A	5	570.208	114.042	1.5015	0.2663
Factor B	1	1395.375	1395.375	18.3721	0.0013
AB	5	400.875	80.175	1.0556	0.4342
Error	11	835.458	75.951		
Total	23	3223.958			

Coefficient of Variation: 34.57%

Table 4B: 72 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	130.667	130.667	1.7007	0.2119
Factor A	5	947.833	189.567	2.4672	0.0803
Factor B	1	1040.167	1040.167	13.5380	0.0022
AB	5	308.167	308.167	4.0108	0.0636
Error	11	1152.500	76.833		
Total	23	3579.333			

Coefficient of Variation: 18.99%

Table 4B: 86 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	60.167	60.167	0.4112	
Factor A	5	838.000	167.600	1.1453	0.3798
Factor B	1	1600.667	1600.667	10.9385	0.0048
AB	5	48.167	48.167	0.3292	
Error	11	2195.000	146.333		
Total	23	4742.000			

Coefficient of Variation: 23.26%

Table 4B: 120 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	600.000	600.000	3.5928	0.0846
Factor A	5	3401.000	680.200	4.0731	0.0244
Factor B	1	9600.000	9600.000	57.4850	0.0000
AB	5	726.500	145.300	0.8701	
Error	11	1837.000	167.000		
Total	23	16164.500			

Coefficient of Variation: 24.04%

Table 4B: 134 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	155.042	155.042	0.8420	
Factor A	5	1492.708	298.542	1.6213	0.2340
Factor B	1	10045.042	10045.042	54.5533	0.0000
AB	5	1465.708	293.142	1.5920	0.2415
Error	11	2025.458	184.133		
Total	23	15183.958			

Coefficient of Variation: 26.37%

Table 4C: ANOVA for plant height

Factor A = Block and Factor B = Soil and water conservation measures

Table 4C: 14 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	0.135	0.135	0.0469	
Factor A	5	4.378	0.876	0.3044	
Factor B	1	1.815	1.815	0.6309	
AB	5	7.565	1.513	0.5259	
Error	11	31.645	2.877		
Total	23	45.538			

Coefficient of Variation: 14.20%

Table 4C: 28 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	104.167	104.167	7.5761	0.0188
Factor A	5	57.198	11.440	0.8320	
Factor B	1	96.000	96.000	6.9821	0.0229
AB	5	44.350	8.870	0.6451	
Error	11	151.243	13.749		
Total	23	452.958			

Coefficient of Variation: 16.67%

Table 4C: 42 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	56.734	56.734	1.3661	0.2672
Factor A	5	216.814	43.363	1.0441	0.4397
Factor B	1	1116.570	1116.570	26.8858	0.0003
AB	5	136.647	27.329	0.6581	
Error	11	456.831	41.530		
Total	23	1983.596			

Coefficient of Variation: 16.09%

Table 4C: 56 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	588.060	588.060	4.7372	0.0522
Factor A	5	986.018	197.204	1.5886	0.2424
Factor B	1	4884.907	4884.907	39.3511	0.0001
AB	5	442.673	88.535	0.7132	
Error	11	1365.500	124.136		
Total	23	8267.159			

Coefficient of Variation: 16.82%

Table 4C: 120 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	520.802	520.802	2.0384	0.1811
Factor A	5	3107.929	621.586	2.4329	0.1018
Factor B	1	12430.602	12430.602	48.6528	0.0000
AB	5	959.564	191.913	0.7511	
Error	11	2810.458	255.496		
Total	23	19829.354			

Coefficient of Variation: 17.62%

Table 4C: 96DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	512.450	512.450	0.7265	
Factor A	5	8893.749	1778.750	2.5216	0.0934
Factor B	1	43053.013	43053.013	61.0340	0.0000
AB	5	1034.222	206.844	0.2932	
Error	11	7759.335	705.394		
Total	23	61252.769			

Coefficient of Variation: 20.70%

Table 4C: 120 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	2499.000	2499.000	1.1773	0.3011
Factor A	5	14514.181	2902.836	1.3675	0.3082
Factor B	1	63396.760	63396.760	29.8659	0.0002
AB	5	4645.592	929.118	0.4377	
Error	11	23349.814	2122.710		
Total	23	108405.347			

Coefficient of Variation: 25.92%

Table 4C: 134 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	2248.470	2248.470	1.0122	0.3360
Factor A	5	15786.803	3157.361	1.4213	0.2906
Factor B	1	63150.296	63150.296	28.4274	0.0002
AB	5	4467.968	893.594	0.4023	
Error	11	24436.044	2221.459		
Total	23	110089.581			

Coefficient of Variation: 25.18%

Table 4C: 148 DAS ANALYSIS OF VARIANCE TABLE

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Value	Prob
Replication	1	2336.427	2336.427	1.0840	0.3201
Factor A	5	15168.309	3033.662	1.4075	0.2950
Factor B	1	64771.258	64771.258	30.0511	0.0002
AB	5	4283.635	856.727	0.3975	
Error	11	23709.102	2155.373		
Total	23	110268.730			

Coefficient of Variation: 24.07%

APPENDIX 5

Evapotranspiration, and AWC data

Table 5A: ETo, kc, ET_m, ET_a, and Rainfall data for 1995/96 season

Month	Decade	ETo (mm/day)	kc	ETm (mm/day)	ETm (mm/decade)	ETa (mm/decade)	Rainfall (mm)
Dec	1	2.14	0.28	0.59	5.9	5.9	28
	2	1.95	0.33	0.64	6.4	6.4	41
	3	1.92	0.40	0.77	7.7	7.7	55
Jan	1	2.01	0.48	0.96	9.6	9.6	77
	2	2.0	0.58	1.16	11.6	11.6	86
	3	2.41	0.78	1.88	18.8	18.8	89
Feb	1	2.81	0.93	2.61	26.1	26.1	81
	2	3.28	1.01	3.31	33.1	33.1	78.6
	3	2.31	1.07	2.47	24.7	24.7	76
Mar	1	1.32	1.1	1.45	14.5	14.5	78
	2	0.48	1.11	0.53	5.3	5.3	70
	3	0.79	1.1	0.87	8.7	8.7	59
Apr	1	0.94	1.06	0.99	9.9	9.9	35
	2	1.26	1.0	1.26	12.6	12.6	23
	3	1.27	0.92	1.17	11.7	8.3	14
May	1	1.47	0.8	1.17	11.7	8.8	10
	2	1.52	0.68	1.03	10.3	8.6	6.0
	3	1.52	0.55	0.84	8.4	7.6	4.0
Total		Seasonal ETm			237.0	228.2	

Table 5B: ETo, kc, ETm, ETa, and Rainfall data for 1996/97 season

Month	Decade	ETo (mm/day)	kc	ETm (mm/day)	ETm (mm/decade)	ETa (mm/decade)	Rainfall (mm)
Dec	1	2.14	0.28	0.59	5.9	5.9	52.45
	2	1.95	0.33	0.64	6.4	6.4	76.8
	3	1.92	0.40	0.77	7.7	7.7	75.45
Jan	1	2.01	0.48	0.96	9.6	9.31	69.6
	2	2.0	0.58	1.16	11.6	11.6	82.45
	3	2.41	0.78	1.88	18.8	18.8	80.75
Feb	1	2.81	0.93	2.61	26.1	26.1	81.15
	2	3.28	1.01	3.31	33.1	33.1	83.8
	3	2.31	1.07	2.47	24.7	24.7	83.8
Mar	1	1.32	1.1	1.45	14.5	14.5	85.35
	2	0.48	1.11	0.53	5.3	5.3	86.55
	3	0.79	1.1	0.87	8.7	8.7	72.1
Apr	1	0.94	1.06	0.99	9.9	9.9	57.0
	2	1.26	1.0	1.26	12.6	12.6	45.25
	3	1.27	0.92	1.17	11.7	11.35	32.55
May	1	1.47	0.8	1.17	11.7	11.35	19.25
	2	1.52	0.68	1.03	10.3	9.99	8.29
	3	1.52	0.55	0.84	8.4	8.15	4.25
Total		Seasonal ETm			237.0	235.45	

Table 5C: ETo, kc, ETm, ETa, and Rainfall data for 1997/98 season

Month	Decade	ETo (mm/day)	kc	ETm (mm/day)	ETm (mm/decade)	ETa (mm/decade)	Rainfall (mm)
Dec	1	2.14	0.28	0.59	5.9	5.9	52.45
	2	1.95	0.33	0.64	6.4	6.4	76.8
	3	1.92	0.40	0.77	7.7	7.7	75.45
Jan	1	2.01	0.48	0.96	9.6	9.31	69.6
	2	2.0	0.58	1.16	11.6	11.6	82.45
	3	2.41	0.78	1.88	18.8	18.8	80.75
Feb	1	2.81	0.93	2.61	26.1	26.1	81.15
	2	3.28	1.01	3.31	33.1	33.1	83.8
	3	2.31	1.07	2.47	24.7	24.7	83.8
Mar	1	1.32	1.1	1.45	14.5	14.5	85.35
	2	0.48	1.11	0.53	5.3	5.3	86.55
	3	0.79	1.1	0.87	8.7	8.7	72.1
Apr	1	0.94	1.06	0.99	9.9	9.9	57.0
	2	1.26	1.0	1.26	12.6	12.6	45.25
	3	1.27	0.92	1.17	11.7	11.35	32.55
May	1	1.47	0.8	1.17	11.7	11.35	19.25
	2	1.52	0.68	1.03	10.3	9.99	8.29
	3	1.52	0.55	0.84	8.4	8.15	4.25
Total		Seasonal ETm			237.0	235.45	

Table 5D: ETo, kc, ETm, ETa, and Rainfall data for 1998/99 growing season

Month	Decade	ETo (mm/day)	kc	ETm (mm/day)	ETm (mm/decade)	ETa (mm/decade)	Rainfall (mm)
Jan	3	2.41	0.28	0.67	6.7	6.7	136.0
Feb	1	2.81	0.33	0.93	9.3	9.3	41.0
	2	3.28	0.40	1.31	13.1	13.1	36.0
	3	2.31	0.48	1.11	11.1	8.08	55.0
Mar	1	1.32	0.58	0.76	7.6	7.6	157.5
	2	0.48	0.78	0.37	3.7	3.7	98.5
	3	0.79	0.93	0.73	7.3	7.3	139.0
Apr	1	0.94	1.01	0.95	9.5	6.4	111.0
	2	1.26	1.07	1.35	13.5	10.15	19.5
	3	1.27	1.1	1.39	13.9	11.6	17.5
May	1	1.47	1.11	1.63	16.3	11.72	6.0
	2	1.52	1.1	1.67	16.7	11.2	0.5
	3	1.52	1.06	1.61	16.1	11.88	0.0
June	1	1.52	1.0	1.52	15.2	10.2	0.0
	2	1.52	0.92	1.39	13.9	9.3	0.0
	3	1.55	0.80	1.24	12.4	8.3	0.0
July	1	1.61	0.68	1.09	10.9	9.8	0.0
	2	1.68	0.55	0.92	9.2	8.3	0.0
	Season	ETm			206.4	164.63	

Table 5E: Available soil moisture (mm) at experimental site during the 1998/99 growing season

	Soil Depth (cm)			
Date	0-25	25-50	50-80	80-150
18/1/99	54.25	37.25	47.1	99.4
1/2/99	64.25	36	56.1	141.4
15/2/99	66.75	51.5	53.1	152.6
1/3/99	72.5	53.5	51.9	135.8
15/3/99	69.5	51.25	71.4	137.9
1/4/99	69	17.25	54.9	74.2
15/4/99	41	10.5	54.6	73.5
1/5/99	32	15.25	48.3	24.5
1/6/99	32.75	26	46.2	93.59
17/7/99	63.25	47	35.1	98.7

Table 5F: Available Water holding Capacities (% vol.) for soils of Mahenge village and long term evapotranspiration values

		Soil depth (cm)			ETa
Code	Soil type	0-30	30-70	70-150	(mm)
H1	Dystric Leptosols	4.4	10.6		210.08
H2	Haplic Acrisols	12.8	15.7	13.7	235.6
H31	Eutric Regosols	4.4	10.6		203.44
H32	Haplic Phaeozem	11.4	10.7	16	235.12
H33	Haplic Acrisols	17.4	22.7	10.1	236.11
P1	Dystric Cambisols	13.5	16.4	11.5	235.06
P2	Ferrallic Cambisols	8.5	20	16	236.13

Source: Magoggo *et al.* (1996)