THE INFLUENCE OF TILLAGE IMPLEMENTS AND PRACTICES ON SOIL AND MOISTURE CONSERVATION OF A CRUSTING SOIL

by

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DECLARATION

I, Martin Nyambe Sishekanu hereby declare that this thesis is my original work and has not been presented for a degree in any other University. All facts and opinions have been distinguished and attributed to the respective sources.

Signed Date : 25/07/06

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This thesis has been submitted with our approval as University supervisors.

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DEDICATION

I dedicate this thesis foremost to the Lord my God who oversaw me through the period of my study. Secondly, to my beloved wife Lydia Nosiku (Likomba) and family at large whose sacrifice and patience made it possible for me to come to the completion of this study.

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LIST OF ANNOTATIONS AND ABREVIATIONS

% S	Slope percentage
%SA	Percent of stable aggregates
ρ	density (kgm^{-3})
σ	the standard deviation per the treatment plot readings.
θ_0	the fraction volumetric moisture content at the measurement potential (cm^3cm^{-3})
θ_n	the fraction volumetric moisture content at initial potential (cm^3cm^{-3})
ρb	is the soil dry bulk density (gm/cm^3)
ρw	density of water (1 gm/cm^3)
0 FYM	the Zero (0) tonnes farmyard manure treatment
^0c	degrees centigrade
10 FYM	the Ten (10) tonnes farmyard manure treatment
A	Rainfall amount (mm)
A_c	Area of the cone (cm^2)
AEZ	Agro-ecological zone ASALsArid and Semi-arid Lands
b	parameter for capillary scales approximately 0.55
C	Constant; coefficient
CI	Cone resistance ($N\ cm^{-2}$)
cm	centimetre
CS	Compression of spring (cm)
d	depth (mm, cm)
E	Total kinetic energy of all rainfall ($Jm^{-2}mm^{-1}$)
EI	an index, the measure of erosivity which is the product of kinetic energy of storm and the maximum 30-minute intensity ($Jm^{-2}.mmh^{-1}$)
FAO	Food and Agricultural Organization of the United Nations
FC	Field capacity
g	gram
h	hour

ha	hectare
HD	Horizontal distance
I_{30}	Maximum 30-minute intensity (mms^{-1})
ILCA	International Livestock Centre for Africa
J	Joules
K_0	Un-saturated hydraulic conductivity measurements (mms^{-2})
KE>25	Total kinetic energy of all rain falling at more than 25 mm per hour (Jm^{-2}mm^{-1})
kg	kilogram
kN	kilonewton
KNDFRC	Katumani National Dryland Farming Research Centre
KW	Kilowatts
L_{SV}	Sample Liquor Volume (cm^3)
L_{TV}	Total liquor volume (cm^3)
m	metre; slope of the line
Mc	Gravimetric moisture content (w/w %)
M_{ds}	Mass of oven dry sediment in sample
M_{ds}	Oven dry soil sample (gms).
M_{dsL}	Mass of oven dry sediment in sludge sample
mm	millimetre
MM	Modified Reversible Maresha Prototype plough treatment at all manure levels
MM0	Modified Reversible Maresha Prototype plough without manure treatment
MM1, 2, 3	Modified Reversible Maresha Prototype plough treatment in block 1, 2 or 3
MM_{10}	Modified Reversible Maresha Prototype plough with 10 tonnes manure treatment
M_P	Mass of the wet sample and coring at P pressure suction (gms)
MPa	Megapascals (N/m^2)
M_S	Mass of total oven dry soil (gms)
M_{SC}	Mass of the coring and the oven dry soil (gms)
M_{SL}	Mass of wet sludge in sample

M_{TSL}	the total mass of wet sludge
Mws	Mass of wet soil sample (gms)
PVC	Polyvinyl chloride
PWP	Permanent wilting point
q	Steady state volumetric flow rate (mms^{-1})
r_o	Radius of the sand conduct material (mm)
R/Rw	The "standard count" (R is the count rate in the soil and Rw is thestandard water count rate)
R_C	Clear plot runoff volume (cm^3)
R_{LS}	Clear runoff volume of the liquor and sludge samples.
RS	Conventional Rumptstad mouldboard plough treatment at all manure levels
RS_0	Conventional Rumptstad mouldboard plough without manure treatment
RS1, 2, 3	Conventional Rumptstad mouldboard plough treatment in block 1, 2 or 3
RS_{10}	Conventional Rumptstad mouldboard plough with 10 tonnes manure treatment
RS_{12}	Conventional Rumptstad mouldboard plough at 12 cm tillage depth with 10 tonnes manure
RS_{17}	Conventional Rumptstad mouldboard plough at 17 cm tillage depth with 10 tonnes manure applied
s	Sorptivity ($ms^{-1/2}$)
s	Time in seconds
Sc	Spring compression constant
S_L	Amount of sediment in liquor
SR	Soil surface roughness.
SR	Surface roughness.
t	Time (hour, second)
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
V_θ	Volumetric moisture content
$V\theta_P$	Volumetric water content at P bars of suction pressure (percentage),

VI	Vertical interval
V_{LS}	Volume of liquor in sample the total mass of sediment in sludge
V_S	Volume of the soil sample (cm^3)
V_{TL}	Total volume of original liquor in sample
V_{WS}	Volume of original wet soil sample (cm^3).

ABSTRACT

Soil crusting and hard-setting conditions limit agricultural productivity of most semi-arid lands of Kenya. Hydrological conditions of these soils are negatively influenced by the development and occurrence of soil crusting and hard-setting under the influence of bad tillage implement practices and adverse seasonal rainfall characteristics. The occurrence of soil crusting and hard-setting conditions decrease rainwater infiltration and inversely increases the surface runoff. The reduced rainwater infiltration and high surface runoff induces agricultural soil drought due to reduced water transmittance and consequent storage into the soil profile. The objectives of this study was to investigate the influence of tillage implements and practices on soil and moisture conservation on a crusting and hard-setting (sandy clay loam) Luvisol. This study investigated the hydrological effects of two tillage implement practices with and without farmyard manure on soil erosion and moisture conservation on a crusting and hard-setting (sandy clay loam) Luvisol of the semi-arid Kenya. The experiment was conducted under extreme field conditions of bare land (no test crop) to eliminate any influence of crop cover, over the pertinent hydrological and soil properties. This study took two rainy seasons (short and long rains) with field investigations covering rainfall characteristics, soil surface roughness, shear strength, penetration resistance, bulk density, soil loss, wet soil aggregate stability, surface runoff and soil moisture. Investigations were conducted on 12 micro-plots of two square metres laid-out in a Split-plot in a Randomised Complete Block Design, complemented by a differential tillage depth treatment laid on a Randomised Complete Block Design. The main experimental treatments consisted of farmyard manure (FYM) at 0 and 10 tonnes per hectare for soil amendment. In the 10 (10) farmyard manure per hectare were applied through out for soil amendment. The experimental treatments were two tillage implement practices (minimum tillage -Modified Reversible Maresha Prototype-MRMP, and conventional Rumptstard -RS) and two farmyard manure applications - FYM (0 and10 tonnes ha^{-1}). A complementary tillage depth treatment was introduced during the long rainy season aimed at providing understanding of the effect of tillage depth on soil moisture conservation. The conventional tillage implement was used at 12 cm and 17 cm tillage depth with 10 tonnes per hectare uniform manure application.

The tillage implement practices and manure showed a significant influence on surface runoff, infiltration, soil loss and moisture conservation. The hydrological response of all treatments were influenced by soil crusting and hard-setting. The seasonal rainfall characteristics (amounts, frequency, duration and intensities) and the treatment effects on the soil surface roughness and aggregate stability impacted on the hydrological response. The minimum tillage implement practice reduced soil loss by 19%, surface runoff by 40% and enhanced water infiltration through out the study period. During the second rainy season the minimum tillage steadily enhanced soil moisture conservation due to the furrow depression storage created by the oriented surface roughness of the MRMP. The conventional tillage implement practice initially reduced soil loss, surface runoff and enhanced water infiltration. From mid rainy season however, soil crusting increased soil loss, surface runoff and reduced water infiltration. The treatment response to ten tonnes of manure reduced soil loss by 40%, surface runoff by 39% and enhanced water infiltration through out the study period. The tillage implement practice and manure interaction treatment reduced soil loss by 48%, surface runoff by 68% in the MM and 18% in the RS and enhanced water infiltration through out the study period. The soil moisture conservation response to ten tonnes of manure reduced soil loss by 40%, surface runoff by 39% and enhanced water infiltration through out the study period.

This study has shown that minimum tillage practice and manure application have a greater impact on soil loss, surface runoff and soil moisture conservation in a crusting and hard-setting soils of the semi-arid.

Rainfall intensities of above 75mm per hour has show to influence total soil loss of 66% and runoff water of 40%

During the second rainy season the minimum tillage steadily enhanced soil moisture conservation due to the furrow depression storage created by the oriented surface roughness of the MM

The results obtained showed some significant changes in the hydrological related properties and soil management treatments. The tillage oriented surface roughness, soil aggregation, soil and runoff losses and moisture; changed with rainfall events and soil management practices. FYM and MRMP tillage practices compared to their control of no-manure and RS reduced runoff by 39% and 40% and soil loss by 40% and 36% respectively. Soil moisture conservation was however, not improved until about mid-season (short-rains). Deep tillage (RS_{17}) on the other hand showed a 60% improvement at a 17 cm soil depth over the 12 cm tillage depth (RS_{12}) and was highly significant at 5% probability level.

This study has shown that tillage implement (MRMP) practice and incorporation of farm yard manure (FYM) on a crusting and hard-setting soil is a potential soil and water conservation tool that provides protection even when erosive forces are severe. It has also revealed that, application of un-decomposed manure and MRMP; do not immediately improve moisture retention. Deep tillage that incorporates FYM beyond 12 cm depth can enhance improvement in soil moisture conservation.

1. INTRODUCTION

1.1 General Background

The Arid and Semi-arid lands (ASAL) occupies about 80% of Kenya's total landmass of which 20% is semi-arid and the rest is arid. The (ASALs) of Eastern Kenya suffer from innumerable crop failures due to land degradation, insufficient rainfall for the crops grown in the area. This area, experiences annual rainfall variability coupled with low and erratic storms of high intensities and short duration and annual evapotranspiration exceeding the annual rainfall. In addition, there are high water losses due to high runoff arising from the prevailing soils, which are hardsetting, compacting and surface sealing types, that culminates into low rainfall infiltration rates. Low infiltration rates, ultimately gives rise to high soil and nutrient losses due to high surface runoff generated. Crop production is therefore, further affected by recurrent droughts that result into soil moisture deficits and loss of soil productivity due to.

Semi-arid soils of Machakos, though diverse are predominantly Luvisols and Acrisols (FAO/UNESCO classification, 1974). Vertisols and Planosols dominate the low lying areas. Luvisols and acrisols have a clay content ranging from 10 to 20% and exhibit very strong surface sealing and crusting properties. The prominent clay minerals are kaolinites and Illites (Gicheru and Ita, 1987).

Generally the organic matter content of these soils is very low, thus when exposed to erosive rainstorms, they readily experience surface ponding and erosion with corresponding reduction in infiltration capacity. Due to the presence of unstable sub-soils, any exposure of such soil horizons to concentrated run-off water flows causes severe rill and gully erosion. Planosols behave similarly based on their dispersive soil properties coupled with their high clay content in the sub-soil horizon. The management of these soils therefore requires minimum disturbance of the sub-soil horizon. Vertisols on the other hand are predominantly low in organic matter but high in montmorillonitic clay (50-60%) and therefore undergo pronounced shrinkage during drying. They are therefore hard when dry and sticky when wet.

This study on the influence of tillage practice on erosion and moisture retention of a hardsetting soil was conducted at the Katumani National Dryland Research Centre (KNDRC), an ASAL area situated in the Central Division of Machakos District, Eastern Province.

The high runoff water losses normally occur at the beginning of the rain season when rainfall amounts and intensities are high. This also leads to soil moisture deficit at the crop maturity stage, and causes high water stress. It is common to have drought spells within the rain-season and this further exacerbates the moisture stress.

The mean annual temperatures range from 17° C to 34°C characterized by high annual and biannual fluctuations. These fluctuations result in maximum heating during sunshine hours and maximum heat loss at night leading to high soil moisture losses. This situation is worsened by low water vapour conditions for cloud formation and low relative humidity (50% to 70% - at 06.00 hours) falling to between 36% and 40% at midday. The wind speed can be as high as 120-127 km per day in January to March.

1.2 Relevancy of the Study

Though drought can be mitigated through irrigation, and runoff water harvesting, the low level of technological development in the area limits their applicability. In-situ rainwater conservation is thought to be the most appropriate measure for water conservation in rain-fed semi-arid crop production. In-situ rainwater conservation, however, can only be effectively practised under proper soil surface management practices, attainable through the use of appropriate tillage equipment and practice. These tillage practices should open up the soil surface, incorporate soil amendments and leave a covered and rough soil surface to enhance rainfall infiltration. Thus, it is not enough to examine methods of preventing soil erosion without investigating what leads to erosion and how some tillage equipment and depths with farmyard manure application would influence runoff and enhance soil moisture conservation.

A study of the effect of tillage practices and manuring on some soil hydraulic properties would facilitate better understanding and development of appropriate and effective soil and water management practices. This would enhance the understanding of how a cohesive soil responds to tillage and residue management. Spatial and temporal variations in infiltration, surface runoff, erosion and soil moisture storage due to these treatments were to be observed during the short and long rains seasons.

The physical, chemical and biological conditions of crusting soils largely determines their productivity. The physical condition drives the hydrological system, while the biochemical conditions determine the soil nutrient retention and availability. However, these soil properties and conditions vary with time and management options. They are also dependent on the duration of prevailing weather conditions, particularly rainstorms and seasonal droughts. For example the long dry spell between the end of the long-rains (May) and beginning of short-rains (October) results in soil hardening which limits any early land preparation efforts. This results in delayed field operations. The conditions described call for serious considerations of both inter-seasonal and intra-seasonal changes in the soil physical and hydrologic properties.

The physical and biochemical conditions of the soil, though subject to time variations could also be influenced by some soil surface management systems. These management systems include tillage options, mulching, manure application, cropping and livestock management.

This study deals with the farmer's land holding, whose productivity is constrained by a vicious cycle characterized, by unsustainable land use patterns. In order to provide a sustainable and appropriate mitigation against seasonal agricultural drought, understanding of the farmer's problems is essential. Essential also is to understand the dynamic processes of the physical system in question, analysis and consideration of the functional relationships of the prevailing pertinent variables.

Initially high infiltration rates of cultivated soils undergo rapid decline due to soil compaction, crusting and surface sealing. Soil tillage practices are therefore used to circumvent these problems.

Research in tillage methods and their effects on rainwater harvesting and moisture retention is highly needed, and especially so for Kenyan ASAL areas.

Although the introduction of early maturing, drought tolerant crops has significantly improved crop performance in ASAL areas, crop yield levels are still low due to moisture stress.

Most of the erosion oriented research carried out in Machakos has focused largely on the analysis of runoff and erosion, without much regard to their influence on soil moisture and soil physical properties. Moreover, these analyses have necessarily tended to be restricted in capacity to deal with the processes that vary markedly both in time and space. Very little information is available on the influence of surface soil management on erosion and moisture retention for crop production. The need to study the processes involved in the soil surface hydrological and erosion system and its consequent soil moisture storage dynamics is essential.

1.3 Objectives and Scope of the Study

The overall objective of this study was to establish the effects of tillage implements and practices, organic matter and rainfall properties on soil and moisture conservation of a crusting Luvisol.

1.3.1 Specific Objectives

3 To monitor and relate the effects of tillage implements and practices, and farm yard manure application on:

  3.14 Infiltration, surface runoff and soil loss

  3.15 Soil moisture conservation.

  3.16 Soil aggregate stability

4 To monitor and relate the effects of shallow and deep tillage on soil moisture conservation.

5 To make recommendations on further investigation areas in soil and water management in semi-arid areas with crusting soils.

1.3.2 Scope of the Study

In trying to evaluate the effects of tillage practices and farmyard manure application on erosion and moisture retention of a crusting soil, this study focused on two areas: -

1) Rainfall properties (intensity, amounts and distribution),

2) Soil physical properties (erosion and soil properties comprising of surface roughness, soil moisture conservation and release, bulk density, soil aggregate stability, shear and penetration resistance) as influenced by tillage implements and depth of tillage. This study was carried-out over short and long rain seasons of 1994/95.

1.4 The Study Area

This research study was conducted in a Semi arid environment on a site at the Katumani National Dry land Farming Research Centre, Machakoes, Kenya. The area is located 9 km south of Machakos town and is roughly located by longitude 37° 14′E and latitude 01° 35′s. It lies at an altitude of 1600m above sea level (Gicheru and Ita, 1987).

In the study area, cultivated fields are generally low in soil cover, and hence cumulative runoff relates closely with cumulative soil erosion. The intense rainfall occurring at the beginning of the season can generate very high runoff volumes and soil loss that consequently, hampers agricultural production. Soil erosion is a consequence of increased surface runoff, resulting in soil moisture deficits and decreased soil productivity. Erosion first causes reduced fertility which in turn results in less biomass production and, consequently, poor surface cover and soil macro-faunal activity. This gives rise to a compacted and or crusted soil surface, which culminates in a reduced infiltration, increased runoff and soil loss, increased soil moisture deficits and further reduction in soil fertility. The application of tillage operations for soil surface amelioration, unfortunately renders these soils bare and highly prone to erosive forces. This is most critical early in the season. During this period, the raindrop impact results in loss in soil aggregation, clay eluviation, soil surface sealing, crusting, low infiltration and high generation of surface run-off. In this environment therefore, it is imperative to develop appropriate tillage practices that not only aim at seedbed preparation but also at erosion control; maintenance of soil water stable aggregates and rainwater conservation.

2. REVIEW OF LITERATURE

2.1 Background

The proper management of natural resources in an already resource-poor farming system and environment such as that of semi-arid Machakos is essential for maintaining or increasing food production. Natural resources such as soil, water and nutrients, require proper soil management to satisfy a desirable economic and sustainable level of production. Proper soil management also requires timeliness of field operations, which heavily depend upon tillage power requirements, and availability of suitable implements. Selection of such a desirable conservation management system must satisfy several requirements among which are the control of surface runoff and enhancement of soil moisture.

A desirable conservation farming system that would satisfy the above is hard to come by, as the systems that provide acceptable erosion control may not necessarily be the best for controlling runoff, restricting movement of nutrients, or crop production. Moreover, specific management practices that comprise a system, vary considerably within methods used for tillage; crop residue management and fertilisation (Kilewe and Ulsaker, 1984). Among these soil management practices, proper tillage is found to optimize soil conditions for seed germination, seedling emergence, and subsequent growth of crops (Singh et al., 1993).

Desirable conservation farming systems require the understanding of sustained use of soil resources and their interactions. Sustainable use of resources as reviewed by Lal (1993) depends on a multiple of interacting factors (see Figure 2.1). Notable among these factors are:- soil stability; soil resilience, and soil quality attributes which to a large extent, depend on tillage systems and soil surface management. The type and intensity of tillage, source of power and the magnitude of vehicular traffic on soil are found to set in motion processes that affect organic matter oxidation; soil aggregate stability and soil compaction among others. These processes may affect soil attributes and sustainability of land use (Babalola and Opara-Nadi, 1993; Lal, 1993).

These interactive effects impact on management decision making, especially concerning the choice of tillage methods, land-use, and farming or cropping system.

2.2 Tillage

Tillage as defined by many (Lal, 1977; Unger, 1984 and Singh et al., 1993) is the mechanical manipulation of the soil environment for improved soil conditions that affect plant growth and production. Tillage practices under sustained agricultural production thus, optimize soil conditions for seed germination, seedling emergence, establishment and subsequent growth of crops. Tillage has shown marked influences on soil hydraulic characteristics, surface runoff and to some extent, soil bio-chemical practices particularly organic matter cycling (Singh et al., 1993). Tillage if not well managed can be responsible for a major part of soil structure deterioration as reported by many researchers and farmers (Lal, 1993; Larson et al., 1988; Benites and Ofori, 1993).

The adverse effects of tillage on soil structure are as a result of enhanced organic matter oxidation when exposed at the soil surface; mechanical dispersion due to compacting and shearing action of implements and raindrops impact. The consequences are soil erosion and loss of water and less obvious, the reductions in transmission and storage of air and water, by sealing both at the soil surface and at the plough sole.

Tillage however when properly timed can produce suitable physical conditions of crumb structure in which case its operations should coincide with the friable range of soil consistency (Baver et al., 1972). M'arimi (1977), recognized the crucial role tillage plays in semi-arid Kenya as the first step in rainwater conservation. Unger (1984) affirms the above and envisages tillage practices as adequate soil and water conservation tools requiring complementary practices only on lands of increasing slope and climatic limitations. The other related tillage practices include contour farming, terracing, strip cropping, basin listing, crop-rotation, and use of cover crops.

Judicious tillage application in the face of differing views, should therefore, aim at controlling land degradation (Unger, 1984); while providing conducive plant root environment and plant development. In a semi-arid setting, tillage practices need to be geared towards increased soil moisture conservation while curbing soil and runoff losses (Muchiri and Gichuki, 1982).

Tillage objectives for sustained agricultural production under this environment therefore must aim at optimizing the soil-water-plant environment. To achieve this, tillage must accomplish a number of tasks that aim at altering the physical conditions of the soil. Among these tasks as supported but Muchiri and Gichuki (1982) are to:-

- Produce a cloddy surface to increase surface roughness and micro-depressions which in turn would enhance infiltration, reduce runoff and soil loss.
- Loosen the tillage layer to reduce bulk density and hence increase water holding capacity, permeability, root penetration and proliferation.
- Deep plough when necessary, to increase the soil and rooting depth through the breaking of the underlying hard-pan, consequently enhancing soil water holding capacity.
- Adopt contour and ridge farming to increase infiltration opportunity time and hence, control runoff and soil loss *by* increasing additional surface retention storage.
- Maintain a good soil structure through incorporation of adequate organic matter to enhance the soil's capacity to absorb water and facilitate formation of water stable aggregates that would increase and preserve soil structure and pore stability.
- Provide an adequate seed bed for seed germination.

2.2.1 Tillage Practices in Eastern Kenya

Due to the heavy tropical storms and slopy nature of the land, the semi-arid environment in Eastern Kenya, has tillage done on the contour especially on terraced fields. Land preparation in both cases is constrained by soil type (strength) and limited by the type of equipment, and availability of funds. Due to the hardsetting nature of this soil, land forming practices are not efficiently accomplished. Mitigating against erosion and soil moisture deficiencies therefore requires the contribution of agricultural mechanization in order to realize adequate land forms and timeliness of tillage operations.

Tractor ploughing where applicable is carried out during the dry season, between harvesting and the next planting. However, tractor mechanization has had very little impact in Machakos, due to its high cost. Maintenance problems, lack of spare parts, sharp increases in prices and charges of tractors and fuel exacerbates the use of tractors (Muchiri and Gichuki, 1982).

Ox-mechanization has been heavily and successfully adopted in this environment. In Machakos District, Starkey (1988) reported over 80 per cent of farmers using draft animals. However, lack of proper dryland tillage tools limits the efficient utilization of oxen and the corresponding human power sources. Ox-cultivation using the mouldboard plough, though reported to be inappropriate by Muchiri and Gichuki (1982), is the major form of primary and secondary tillage in Machakos District. Traditionally, ox-ploughing is undertaken at the on set of the rains when the ground is soft and easy to work (M'arimi, 1977). Land preparation for easy dry planting needs soil manipulation at harvest time when the soil is still moist and there is still sufficient feed for the oxen. Generally a ploughed field in the study area consists of ridges and furrows due to the absence of secondary tillage operations like harrowing. Since harrowing and even weed control is carried out with a plough especially in maize fields, ridges are further rebuilt at weeding time (M'arimi, 1977). Soil and water management are enhanced when these operations are carried-out along the contour.

2.2.2 Effect of Tillage on Soil Structural Stability

In the Tropics, soil degradation, decrease in actual and potential soil productivity is a major threat to agricultural sustainability and environmental quality owing to mis-management of land resources. This problem has been caused by high demographic pressure, shortage of prime agricultural land, harsh environments, and resource poor farming systems (Lal, 1993).

Soil characteristics upon which agricultural productivity pivots are soil structure and its stability, porosity and pore size distribution, effective rooting depth, water retention and transmission properties, soil reaction, total and plant available nutrient reserves within the rooting depth, soil organic matter content and its interaction with soil flora and fauna. Soil quality and resilience, however, is also affected by degradation and restoration processes (Lal, 1993) as shown in Figure 2.1.

Soil structural stability hydraulically determines the rate at which water can enter into the soil, as well as the resistance of soil particles to detachment by rainfall impact and subsequent compaction and or the removal in surface runoff. Soil structure relates to soil erodibility in two ways: firstly through particle detachment and secondly through the washing of the detached smaller particles of clay and silt into the courser pores of existing structure. This causes a decrease in the soil's hydraulic conductivity and infiltration.

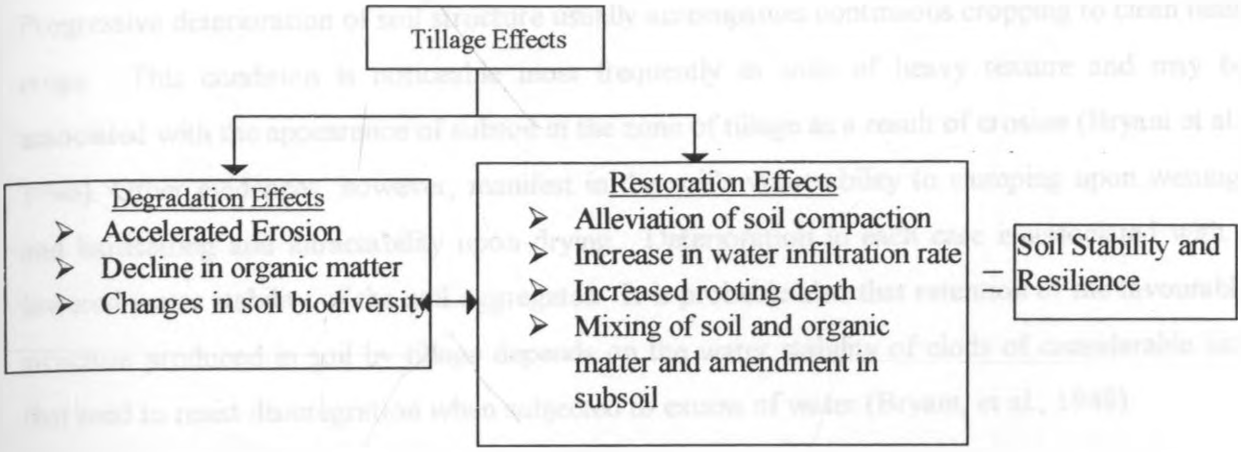


Figure 2 1 Tillage effects on soil resilience as influenced by soil restoration and degradation (adopted from Lal, 1993).

Soil stability therefore, refers to the susceptibility of soil to change under natural or human induced perturbations (Kay, 1992). Soil structural characteristics determine not only the hydrologic characteristics of the soil but also control many of the important plant growth processes. Also of importance in soil management is soil resilience as it marks the soil's ability to recover to the antecedent state following degradative perturbation or change of land use. The recovery may follow a hysterecal path, which may only be possible if the soil is not degraded beyond a critical level (Lal, 1993; Shaxon, 1993). Lal (1993) affirms that soil is not a renewable resource within the time span relevant to one or even several human generations due to the extremely slow rate of renewal.

Soil tillage and residue management alter the proportion and size distribution of water stable aggregates and their stability, quality and quantity of soil organic matter and decomposition rate. Also altered are the proportion and size distribution of water retention and transmission properties, and cycles of major nutrients (Babalola and Opara-Nadi, 1993; Bryant et al., 1948, Kay, 1990). The persistence of the characteristics of the seedbed, and its susceptibility to crust formation and erosion, relate to characteristics such as wet aggregate stability and dispersible clay content (Kay, 1990).

Progressive deterioration of soil structure usually accompanies continuous cropping to clean tilled crops. This condition is noticeable most frequently in soils of heavy texture and may be associated with the appearance of subsoil in the zone of tillage as a result of erosion (Bryant et al., 1948). Other evidences, however, manifest in the soil's vulnerability to slumping upon wetting, and hardsetting and intractability upon drying. Deterioration in each case is associated with a lowered water stability of the soil aggregates. It is probable also that retention of the favourable structure produced in soil by tillage depends on the water stability of clods of considerable size that tend to resist disintegration when subjected to excess of water (Bryant, et al., 1948).

Tillage operations play an important role in the dynamic processes governing soil degradation, resilience and quality. Tillage as shown in Figure 2.1 above, when properly used is an important restorative tool that can alleviate soil related constraints in soil productivity (Lal, 1993, Unger, 1984). Improperly used, however, tillage can set in motion a wide range of destructive processes (Benites and Ofori, 1993; Lal, 1993). Among these processes is deterioration in soil structure; accelerated erosion; depletion of soil organic matter and soil nutrients, disruption in cycle of water; carbon and major nutrients. Agricultural soil requires a good soil structure for good aeration, good water holding and release capacities, and higher resistance to surface crusting and erosion.

The soil aggregate stability size and distribution of a tilled soil and the soil surface roughness created by tillage plays an important role in influencing hydrological phenomena and erosion processes. A higher proportion of unstable soil aggregates or single granules at the soil surface increases susceptibility to surface crust formation and reduction in infiltration. Soil surfaces of low surface roughness usually develop dense surface crusts over a large area; while in more uneven surface, crusts are mainly formed in depressions (Larson, 1962).

Many researchers to establish the resulting soil structural conditions have investigated the effect of tillage practice on soil structure. These investigations extended to the determination of relationships between the resulting soil structural differences and the soil type, management systems and other crop requirements. Broone (1976) observed that aggregate size of soil under tillage is considerably larger, and generally homogeneous, especially aggregates of less than 0.3 mm diameter. Under intensified cultivation, Osborne et al. (1978) observed some significant deterioration in soil structure.

Soil structure is therefore one of the most dynamic soil properties, amenable to changes by tillage operations. The effects of tillage on soil degradation include rapid decline in soil organic matter content (Hudson, 1987; Unger, 1984). This is as a result of an increase in mineralization rate, decrease in aggregation and stability of aggregates, disruption in continuity of macro-pores reduction in soil bio-diversity and inactivity of soil macro-fauna like earthworms and termites.

Thus tillage influences directly or indirectly:- (i) soil cementing agents such as clay and organic matter and microbial products, (ii) mixing and inversion which alter the arrangement of soil particles and (iii) many soil structural attributes such as aggregate size distribution, porosity and pore size distribution, and soil aeration (Babalola and Opara-Nadi, 1993).

Similar to the upland soils of West Africa (Babalola and Opara-Nadi, 1993), the soils of Eastern Kenya, are course-textured in the surface horizons and are coupled with low organic matter content a condition that influences the magnitude of changes in soil structure induced by tillage.

Charreau and Nicou (1971) and Nicou (1974) showed that tillage improved the massive structure of crust-prone soils of West African semi-arid regions. However, due to the instability of the soil aggregates the soil structure improvement was temporal and such repeated tillage may lead to severe degradation. Soil amelioration through the use of farmyard manure improved soil aggregate stability (Biamah, et al., 1994).

2.2.3 Effect of Tillage on Rainwater Conservation

It is theoretically possible to retain moisture from rainfall in-situ by suitable forms of soil and water management practices. In the semi-arid regions where precipitation is deficient, tillage systems and related practices for conserving water are highly desirable for enhancing infiltration and soil water storage for subsequent use by crops (M'arimi, 1977; Unger, 1984).

In the semi-arid areas of Eastern Kenya the first month (30 days) of the rains (season) is the most reliable (Docker, 1961). It has been shown too, that during this period heavier storms are the norm rather than the exception compared to the highlands (Fisher, 1977d; Ann, 1973). Most of the rain water therefore, is likely to get lost as runoff during any one season (M'arimi, 1977). A number of bio-physical processes occur during this time of heavy storms, which have direct or indirect impact on the amount of rain water entering and being stored in the soil against runoff. The same is true of soils being detached, slackened, sealed, crusted and/or eroded.

Enhancement of soil moisture storage can be achieved by employing tillage practices that enhance rainwater infiltration and suppress subsequent evaporation. In order to enhance soil moisture, there is need to maintain soil surface conditions necessary for rapid infiltration and the removal of soil profile layers that restrict water penetration with consequent reduction in surface runoff. Considerable reduction in evaporation losses can be attained through deeper storage of water within the root zone and by improving the micro-climate at the soil-air interface.

The improvement of the micro-climate is attainable through maintenance of mulch to intercept or reflect incoming radiation, provide surface roughness to reduce wind speed, and prevent high soil temperatures (Unger, 1984). The applicability of this kind of mulch, is however, quite limited in semi-arid environments of Kenya.

The relative predominance of any one of these bio-physical and chemical factors including the effect of the slope influences the amount of water entering the soil for storage or lost as runoff.

The fate of rain water received during the rain season in this environment where rainfall is limiting can be visualized, in a form of a simplified water balance model, in relation to soil moisture storage as:-

$$S = P - R - D - E$$

Where:

S is the change in soil moisture storage;

P is the rainfall as recorded in a rain-gauge;

R is runoff;

D is deep percolation (beyond the effective rooting depth);

E is evapo-transpiration or evaporation.

Evapo-transpiration is productive and largely inevitable, while deep percolation in such a rainfall limited environment is negligible. Thus runoff remains the important and unproductive mode of water loss, which can be substantially high under high rainfall intensities. This is further exacerbated by capping conditions present in the semi-arid and arid areas of Eastern Kenya (Ann, 1973; Mbuvi and Weg, 1975).

2.2.4 Effect of Tillage Practise on Infiltration, Erosion and Water Retention

Prospects for irrigation are limited in semi-arid Eastern Kenya but potential is reported to exist for improving water supply to crops through better management of the soil surface that reduce runoff water losses (Keating et al., 1990) and improve water retentivity. Keating et al. (1990) proposed retention of surface residues or topographical modification of the soil surface (e.g. tied-ridging) to reduce runoff. Soil amelioration through application of farmyard manure can lead to increased wet aggregate stability, and decreased susceptibility to crust formation and hence improved hydraulic soil properties (Tisdall et al., 1978).

Soil surface management modifies surface storage capacity, infiltration and susceptibility of soil to detachment (Okwach et al., 1990). Larson (1962) in his paper on tillage requirements for corn maize, showed that tillage improved the infiltration of soils, though improvement was short-lived. Generally these soils quickly settle into a dense compacted medium under the influence of raindrop impact. Under certain circumstances, tillage implements compact soil particularly under the plough share and smear or puddle soil when cultivation operations are conducted in the plastic soil state (Singh et al., 1993). More serious is the decrease in soil infiltrability through increased rate of organic matter oxidation (Baeumer, 1970), with its consequent soil structure decline. The effects of the reduction in soil organic matter are manifested in the deterioration of soil physical condition resulting in surface seals, crusts and hardpans, which culminate in accelerated soil erosion even on gentle slopes (Larson, 1962).

In the effort to reduce the adverse effects of conventional tillage operations, conservation tillage is being advocated. Conservation tillage conserves soil and water by preserving porosity; minimising particle detachment, and retaining mulch cover on the soil surface.

Any practice or factor that stabilizes soil aggregates indirectly increases water infiltration into the soil. The effects of conventional tillage, though temporary improve the soil's hydraulic properties, reduce aggregate stability and cohesion of the soil mass and thereby increase the potential of soil loss. Conservation tillage however, favours development of stable soil aggregates. Improvements in hydraulic properties have been reported by Kayombo and Lal, (1993), under the influence of conservation tillage in which over a long period infiltration rates were maintained at high levels.

2.2.4.1 Effect of Tillage Depth on Infiltration and Water Retention

Deep tillage to beyond 20 centimetres has been advocated to be beneficial only under conditions of dense impervious soil layers in which a long lasting and profitable results of good physical conditions are created (Unger, 1984). In another research in an ASAL environment, Babalola and Opara-Nadi (1993) found deep tillage to have had an influence on the amount of rainwater entering the soil profile, through increased infiltration.

Unger, (1984) and Freebairn et al. (1993) separately, argued that deep tillage effects on most cultivated soils are usually temporal, giving high initial water infiltration and storage but reverting to the original condition upon repeated wetting.

The findings of Singh, et al. (1993), showed that deep tillage decreased bulk density and penetration resistance with a proportionate increase in soil micro-pores and hence the soil profile water storage. Further studies by Reddy et al. (1977) and Chaudhary et al. (1985) found also that reduction in the bulk density of the soil induced deep and prolific root growth of crops, resulting in better utilization of stored water in the profile.

Investigations on deep tillage have therefore shown to be variable (Freebairn et al., 1993; Hudson, 1987). Possible reasons advanced for the different water conservation and yield responses to depth of tillage:- soil differences, initial water contents, type and time of tillage, environmental conditions and crops grown (Unger, 1984).

These variable results therefore, point to the fact that deep tillage should only be used where a soil layer exists, which clearly impedes water and root movement (Freebairn et al., 1993).

2.2.4.2 Effects of Tillage and Surface Roughness on Infiltration and Erosion

Surface configuration of the soil is determined by the geometric design and manner of movement of tillage equipment through the soil. The soil clods that become broken, lifted, shattered and resettled during tillage operations result in a tillage-induced-surface roughness (Mwendera, 1992) which relates closely to depth of tillage. Tillage surface roughness created with the use of primary tillage implements creates rougher and less dense surface (Freebairn et al., 1993).

Burwell, et al. (1966) was cited as having recognised two types of surface roughness produced by tillage (Mwendera, 1992), consisting of oriented and random roughness. Oriented roughness consists of furrows and ridges formed by tillage implements while random roughness (RR), is made-up of irregular peaks and depressions formed by soil clods.

Oriented roughness when on the contour gives rise to depression storage which together with random roughness influences infiltration of rainfall (Burwell and Larson, 1969). Surface roughness can trap water and thus increase infiltration. Cooke (1985) and Freebairn et al., (1990) found that the absence of surface roughness associated with no-till systems can generate higher runoff compared to tilled soil in some circumstances (Freebairn et al., 1993). Johnson et al. (1979) working on simulated rainfall studies, reported an increase in infiltration with a corresponding decrease in soil erosion under rough cloddy surfaces compared to smoother surfaces.

Mwendera (1992) observed that oriented surface roughness can create sufficient depression storage on the contour by enhancing storage of excess rainfall, allowing more opportunity time for infiltration and increasing hydraulic head. Babalola and Lal (1993) reported that in some shallow soils, tied ridging can be effective for conserving water.

The effectiveness of random roughness on the other hand is dependent upon soil aggregate stability, which in turn depends upon organic matter content. Unger (1984) reported that organic matter content influenced soil aggregation and thus soil susceptibility to erosion. Chaney et al. (1984) found that organic matter was the main constituent responsible for the stability of aggregates in the 26 British soils investigated. However, organic agents as classified by Tisdall and Oades (1982) affected soil aggregation in varying duration from transient, temporary to persistent. Thus, total organic matter content alone may not be sufficient to explain variations in aggregate stability (Chaney et al., 1984).

Soil with low organic matter, however, is liable to have poor structure and low water retentivity conditions which are conducive to further soil degradation. A positive relationship between the percentage of water-stable aggregates and soil organic matter levels is reported to exist (Chaney et al., 1984). Wischmeir and Mannering (1965) reported favourable effects of increasing quantities of organic residues in the soil which consequently reduced runoff and increased infiltration.

Unger (1984) looking at the importance of soil organic matter with respect to water infiltration found a stabilising effect on soil aggregates and improvement of soil structure. Stable aggregates resist dispersion; consequently minimizing surface soil sealing due to rain drop impact. Unsealed soil surfaces permitted greater infiltration of water than sealed surfaces.

2.2.4.3 Effect of Soil Amendments on Infiltration, Runoff and Erosion

Surface ground cover is reported to be the most effective among agronomic and engineering practices in erosion control, improvement of infiltration; preservation of soil moisture and regulation of soil temperature (Mirtskhoulava, 1981; Hudson, 1987). Surface mulch, dead or alive, produced in-situ or brought from outside improve the hydraulic properties of a soil. In soils that are prone to crusting and compaction, mulch improves water infiltration (Lawes, 1961; Lal et al., 1980b), by absorbing raindrop energy and reducing aggregate disruption and surface crusting, (Freebairn and Wockner 1986). Mulch, also increases soil-water storage in the root zone and improves crop performance especially in soils that have low nutrient reserves and are prone to frequent drought stress (Lal, 1975).

Kayombo and Lal (1993) observed that gradual replacement of a forest canopy by continuos ground cover, as provided by a crop residue mulch, would arrest the rate of deterioration of soil quality and maintain productivity. At Katumani, Kenya, work by Kilewe (1987) showed that 3 tonnes per hectare maize stover, applied as mulch and providing over 50% cover, significantly reduced runoff and soil loss. Kilewe (1987) concluded that mulch application was the best conservation practice for this region.

Hudson (1987) cites successful use of vegetative mulch in the semi-arid south west USA (Stuart et al., 1985); in India (Yadav, 1974); and in dry land Savannah of Nigeria (Bonsu, 1985). In semi-arid Eastern Kenya however, a number of constraints make vegetative mulch impractical. This stems from the fact that high population pressure on land compels preservation and feeding of crop residues to livestock. The above is exacerbated by the low level of production, nitrogen lock-up, disease and pest problems; and lack of implements that can plant or drill through the mulch. Moreover, the organic mulches are liable to rapid oxidation due to high temperatures (Hudson, 1987).

Young (1989) advances the use of agroforestry pruning as a source of mulch. This however, still requires a lot of research bearing in mind the availability of the agroforestry mulch and that if planted in or around crop fields they may pose a severe tree and/or crop competition for moisture.

It is therefore difficult to maintain a productive mulch layer in this socio-economic and environmental setting. Under this situation the most practical means of obtaining soil amelioration is through kraal composting of farmyard manure with the use of crop stover and trash and its' subsequent application to crop land.

Farmyard manure therefore is the most important organic amendment in this area and repeated applications can lead to increased wet aggregate stability of soils (Tisdall et al., 1978) and decreased susceptibility to crust formation (Becker and Kainz, 1983).

Application of manure plays a major role in the improvement of both the physical properties such as structural stability and infiltration rates; and chemical fertility of soils (Kay, 1990, Probert, et al., 1990). For the resource-poor subsistence farmers of the semi-arid areas of Machakos, the principal source of nutrients that is available for their crops is farmyard manure produced on their farm holdings (Probert, et al., 1990). Its use provides a means of recycling nutrients and where animals have access to forage outside the crop lands, it is a means of collecting nutrients from surrounding areas.

This organic manure when incorporated in the soil through appropriate tillage practices improves the soil nutrient status; ensures development of a good stable structure with better infiltration of rainwater. Consequently, the above benefit reduces runoff and improves root penetration, nutrient and water retention. A healthy environment for crop growth is thus enhanced, providing good crop cover in a short time. A well structured soil on the other hand would be inherently more stable and less likely to breakdown under cultivation and is better able to resist erosion at the critical time of early crop development.

2.3 Effects of Soil Physical Properties on Soil Erosion

2.3.1 Soil Hardsetting

Hardsetting processes though not known with certainty appear to be related to a reduction in aggregate stability that is often associated with cropping under conventional tillage (Ley, et al., 1989). Mullins et al. (1987) in their hypothesis, cited mobilisation of fine materials due to slacking, dispersion and their redistribution upon drying as a possible mechanism of hardsetting development. Soil management unsuitable to the environment can also trigger a hardsetting tendency even on non hardsetting soil. Soil management systems coupled with the soil type and climate, in particular rainfall and its sequential events before and during crop development is found to influence the incidence and severity of hardsetting conditions.

A hardsetting soil condition therefore, refers to the condition of soils that dry and set to a hard structureless mass of high mechanical impedance. These soils are difficult to cultivate until the soil profile is moistened enough. Mullins et al. (1990) reports that even when moistened hardsetting soils harden sufficiently upon drying to even impede seedling emergence. Associated also with the hardsetting condition is the high soil resistance to root proliferation, poor aeration under wet conditions, crusting with a consequent poor seedling emergence.

In addition to the above, hardsetting problems constrain timely land preparation, impede infiltration and consequently increase runoff and soil loss. Chan (1995) remarks that one major agronomic limitation of these soils is their marked increase in soil strength over very narrow water content changes within the plant availability range of soil-water potentials (-100 kPa to -1mPa). The effect results in poor root growth and crop yields.

Soil structural deterioration due to hardsetting can be minimized through application of soil management systems that aim at minimising soil disturbance and maintenance of a high level of organic matter content. Since the short rain season is the most reliable growing season in the study area, delay in land preparation and planting after waiting for sufficient moistening of the soil can cause high losses in yields. Cultivation of dry, hard soils unfortunately, is constrained by high draft power requirement which is rarely available in these areas. Moreover, high power equipment used under dry conditions leads to big clod formation; requiring secondary tillage operations. Preparation of a fine tilth on the other hand may lead to pulverizing the seedbed making it prone to surface sealing and crusting, and consequently, the generation of high runoff (Tisdall and Adem, 1986).

2.3.2 Soil Surface Sealing and Crusting

One of the main characteristics of soils in ASALs is their tendency to form surface seals on exposure to raindrop impact (McIntyre, 1958), or by spontaneous slackening and breakdown of soil aggregate during wetting (Hillel, 1960) or when in water (Moore, 1981). Increased surface soil sealing and crusting leads to a decreased gaseous diffusion; infiltration; seedling emergence; induce runoff and/or erosion that culminates in induced soil drought (Morin et al., 1981, Smiles et al., 1988).

Soil surface crusting is a highly complex and dynamic process affected by soil properties, soil surface conditions and the nature of hydrologic events (Römkens et al., 1990). Soil surface sealing occurs as a structural degradation of thin layer that ranges in thickness from a few millimetres to as much as 3 cm at the soil surface during a rainfall or irrigation event. This thin layer is generally composed of fine soil and clay colloidal particles, bound together by surface tensional forces.

Under simulated rainfall studies, Tackett and Pearson (1984) found that crusts develop a dense surface skin or seal, about 0.1 mm thick with well-oriented clay particles. Beneath this was a layer, 1 to 3 mm thick where the larger pore spaces were filled by finer washed-in material.

During rainstorms, raindrops disperse, compact and transport soil particles (Morgan, 1986). Soil structure formed on cultivation even under optimum moisture conditions is reported as being characterized by loose aggregation with up to 20 and 30 per cent of soil materials in non aggregated state (Kowal, 1972). Early in the season, a gradual deterioration of aggregate structure of the soil surface takes place owing to the raindrop impact (Lawes, 1961), and the kinetic energy of the moving water (Kowal, 1972). The result of this process is the formation of a dispersed and compact soil surface layer with high bulk density; penetration resistance and shear stress.

Surface sealing and crusting have important consequences in hydrological processes and crop environment. Whereas surface soil sealing is primarily important in erosion and hydraulic processes, crust formation affects plant emergence and soil aeration. In some cases, however, the significance of crusting is obscured by more conspicuous soil loss processes such as inter-rill, gully and mass movement.

Surface sealing and crusting decreases infiltration rates and hydraulic conductance, consequently, increasing surface runoff and erosion. Skaggs (1982) in his infiltration study found a drastic reduction in infiltration from about 6.4 cm /h to about 2 cm per hour in 8 minutes due to the formation of surface sealing. Similar studies carried out by Baumhardt et al. (1992) found similar results on the determination of the effect of chisel tillage, furrow diking and surface crusting on infiltration. Crusts and formation of surface seals due to raindrop impact decreased infiltration and eliminated the effect of chisel tillage in increasing infiltration.

The effect of soil surface sealing and crusting on runoff and soil loss depended on the rate of surface seal and crust formation. Soil surface sealing and crusting is found to enhance surface runoff and rill erosion in certain cases while in others the opposite was true. Poesen and Govers (1985) in their study found that surface sealing and compaction decreased the amount of raindrop detached material, sediment concentration in inter-rill runoff and soil loss. Moreover, they found out that raindrop detachment was more on cultivated plots as against the surface sealed ones. Nonetheless sealed plots had more soil lost due to rill runoff. Similar observations were confirmed by Barber et al., (1979); Cai et al. (1985).

Epstein and Grant (1967) in their study of soil losses and crust formation as related to some physical properties found that soil loss increased to a maximum during the first 10 minutes and thereafter decreased. Runoff on the other hand remained constant after sometime. These changes in runoff and soil loss were attributed to surface sealing.

Surface sealing and crusting is prevented by the provision of a cushion of coarse organic matter, either living or dead, on the soil surface to break the impact of the falling raindrop (Donahue, 1961). The condition of soil surface is found to be more influential in regulating water intake and reducing crust formation than soil type, slope or soil moisture content. Cropping systems that include sod forming or cover crops are thus desirable for reducing surface sealing and crusting. However, incorporation of organic matter and tillage helps enhance infiltration, though their effects may be short lived.

2.3.3 Soil Bulk Density

Bulk density of a soil (dry basis) is the ratio of the mass of dry soil solids to its total volume. The mass of the soil solids is taken as the oven-dry constant mass at 105°C (Landon, 1991). Bulk density measurements provide a guide to soil compaction and porosity as indicators of the extent of root penetration and soil aeration in different soil horizons.

Bulk density values vary considerably with moisture content, particularly those of fine - textured soils, thus wherever possible sampling should be taken at or near field capacity (Landon, 1991). Moreover, bulk density of a particular field site varies due to some natural or tillage imposed operations. There is a lateral and vertical variability in bulk density resulting from changes in landscape. This includes such factors as soil texture, organic matter content, soil structure and the effects of past management practice including tillage.

Soil bulk density undergoes temporal variation after imposition of a tillage operation. The variations could be caused by a number of factors, like slumping during periods of excessive wetness and to soil setting in response to desiccation and or the kinetic energy associated with raindrop impact. With time, bulk density at the same depth may decrease due to the loosening action exerted by roots or animal activities.

The range defining the optimum bulk density for plant growth is reported to be unknown for most soils (Cassel, 1982). However, under natural compacting soils, high bulk densities of 1.49-1.55 gcm^{-3} were reported in Tanzania (Northwood and Macartney, 1971). Low bulk densities of 1.28-1.58 gcm^{-3} were reported at Katumani, Kenya (Biamah, 1994) and as high as 1.7-1.8 gcm^{-3} in Botswana (Willcocks, 1981) and Zambia (Gill and Lungu, 1988) at 0-10 cm depth. In the immediate soil surface, high bulk density is attributed to capping caused by raindrop impact (MaCartney et al., 1971; Willcolks, 1981)

Kayombo et al. (1985) cites the study undertaken by Nicou and Charreau (1985) in which the fine sandy soils of West Africa exhibited high bulk densities similar to those of Botswana. In a similar study carried out by Ibanga et al. (1980), West African sandy soils with low content of organic matter and silt, became extremely hard during the dry seasons, even when clay contents were rather low. Biamah, et al. (1994) reports similar results of higher bulk densities at dry soil conditions, with as high as 1.58 g cm^{-3} in zero tillage compared to the 1.46 g cm^{-3} in the 10 tonnes per hectare of farmyard manure treatment.

2.3.4 Mechanical Soil Impedance

Mechanical impedance as equated to the mechanical soil resistance to a penetrometer can be expressed in terms of a cone index (CI). The CI is defined as the force required to push a metal cone into the soil divided by the basal area of the cone.

Mechanical impedance is found to be related to clay mineralogy and soil physical properties such as bulk density, texture, structure, water content, and percentage organic matter. Mechanical impedance measurements, gives an integrated index of the soil compaction, moisture content, texture, and type of clay mineral; and thus provides information on soil strength and compaction, and other conditions (Braver et al., 1972). Tillage operations, therefore affect mechanical impedance by effecting changes in the above factors.

CI measurements are used to assess mechanical impedance differences as affected by different tillage operations in a given soil. The CI is reported to be a more sensitive indicator of soil amelioration than bulk density as the latter is sensitive mainly to pore volume and relatively insensitive to fracture plane or planes of weakness (Voorhees, 1983). Moreover wetting and drying, can ameliorate a compact soil by creating fractures or micro-cracks.

Penetrometer resistance however, is quite sensitive to soil-water content and bulk density (Voorhees, 1983). The decrease in CI therefore can be attributed to (1) the actual amelioration of compacted soil or (2) may merely reflect variation in soil water content at the time of sampling. Due to the dependency of the CI upon bulk density and soil moisture, it is imperative that supporting bulk density and soil moisture data be collected (Cassel, 1982; Voorhees, 1983).

In naturally compacting soils, high soil strength can be exhibited without any tillage imposition. Undisturbed soil in Botswana registered a penetration resistance of 8 MPa or greater at 0-10 cm depth (Willcocks, 1981). According to Taylor et al. (1966), mechanical resistance of such magnitude is nine times higher than the 0.9 MPa suggested as limiting the ability of roots to penetrate the soil.

Resistance to penetration measured on a Luvisol (FAO/ UNESCO classification, 1974) at Katumani, Kenya, showed variation to both tillage and soil amendment treatments. CI was found to be least in a 10 tonne per hectare farmyard manure treatment and highest under zero tillage (Biamah et al., 1994).

The shear strength of the soil on the other hand is characterised by its maximum internal resistance to the movement of its particles (Baver et al., 1972). The vane type shear meter however measures the cohesive components of shear strength apart from the frictional component. Soil strength usually increases with an increase in cohesive soil (Chaudhary et al., 1985).

In soils that develop surface sealing and crusting; shear strength becomes a measure of their development. Biamah et al., (1994), found that shear strength under the zero tillage treatment remained relatively higher that under hand hoe tillage, 5 tonnes per hectare and 10 tonnes per hectare manure treatments. Though seasonal variations in shear strength were observed, they were of low magnitude as compared to variations in bulk density and soil moisture. The trend in shear strength was found to increase or reduce with similar bulk density changes.

2.3.5 Soil-water Infiltration and Transmission

Infiltration is the passage of water through all or part of the soil surface into the soil profile (Landon, 1991). Water transmission on the other hand is the farther downward movement of the water into the lower soil horizons.

Understanding of the phenomenon of water infiltration and transmittance enables effective estimation of the amounts of runoff originating from precipitation on a given soil or land condition. The results obtained thereof can therefore be applied more confidently to design against and solve problems of both arable, rangeland and watershed management areas (Landon, 1991; Mutreja, 1986).

In Nigeria, long-term tillage studies indicated that infiltration rate declined with cultivation (Lal, 1985). In Lal's investigations, the cumulative infiltration at 2 hours for no-tillage and ploughed watersheds decreased from 77 cm and 65 cm in 1976 to 12 cm and 5 cm in 1980, respectively. The dramatic decline was attributed to the structural collapse and elimination of "transmission pores" caused by soil compaction and vehicle traffic. Ploughed watershed showed more compaction compared to the no-tillage treatment, and more prone to surface sealing and crusting development. Measurements in infiltration capacity in 1979 showed superiority in no-till plots compared to the ploughed ones at the level of 10.4 cm h^{-1} in the no-till and 3.8 cm h^{-1} in the ploughed plots.

In Northern Nigeria, Lawes (1961) found that tillage-induced infiltration rate was modified by the presence or absence of mulch. In similar studies Babalola and Opara-Nadi (1993) and Lal (1983) also found that, no-till soils with crop residue mulch maintained a higher infiltration rate than bare plough-till soils. Okwach (1995) also found that infiltration rate was higher for the mulched plots compared to the bare fallow and low cover plots. Biamah et al. (1994) also found bare zero-tillage inappropriate for the soil conditions of Katumani, as it led to a lot of runoff due to soil surface sealing and crusting while hand-hoe tillage with farmyard manure application enhanced infiltration rate and reduced runoff.

2.3.6 Soil Moisture Retention Characteristics

Soil water retention like other soil hydraulic properties are influenced by soil physical properties. These properties include among others, bulk density, organic matter content, porosity, pore size distribution, continuity and stability of pores, as well as soil strength and crusting. Alteration of these physical soil properties through tillage thus influences the soil moisture conservation (Babalola and Opara-Nadi, 1993). Tillage practices increase surface roughness through the creating surface retention and providing the opportunity time for infiltration and subsequent soil moisture storage.

Intensive tillage in the semi-arid regions of Nigeria has shown to improve soil-water retention and crop water use in contrast to humid and sub-humid regions. This condition arises from the long dry season that induces the consolidation of crusted and compacted surface (Adeoye, 1982) necessitating the use of tillage to increase soil water acceptance and reduce surface runoff (Babalola and Opara-Nadi, 1993). In this environment therefore, plough-till and tie-ridging are recommended for the reduction of runoff (Babalola and Opara-Nadi, 1993; Benites and Ofori, 1993; Singh, et al., 1993) and enhancement of infiltration.

In a similar study at Katumani, Machakos, M'arimi (1978) found that tied ridges had higher soil moisture contents compared to minimum tillage and conventional tillage on a sandy clay soil (Chromic Luvisol, FAO/UNESCO Classification, 1974). Minimum tillage stored the least amount of soil moisture. To the contrary Gicheru (1990) investigating the effect of conventional tillage, tied ridging and crop residue mulching on soil moisture conservation under marginal rainfall (750 mm) conditions reported that tie-ridged plots had the least amount of soil moisture and crop performance. This experiment was however, undertaken on a clay soil (Ferric Acrisol, FAO/UNESCO Classification, 1974) at a slope of 2%. This performance of the tied ridges was attributed to lack of runoff impounded and high evaporation water losses from increased an surface area. Tie-ridged plot performance, nonetheless, could have arisen from stress early in the season arising from low infiltrability of the clay soil coupled with bare ground cover and high evaporative losses' in-addition to the increased surface area.

In another tillage study in Nigeria, Lal (1985), observed that water retention at 0.01 MPa metric potential increased from 14.7 % to 17.5 % in the no-till treatment after 6 years, but decreased from 17.7 % to 13.8% in the continuous mechanised farming treatment ploughed at 0-10 cm depth. In the fifth year of mechanised cultivation the available water-holding capacity, expressed as the difference between moisture retention at 0.01 MPa and at 1.5 MPa increased from 9.3 % to 17.3% under no-tillage and from 9.6 % to 16.2% under ploughing. The increase in available water-holding capacity with cultivation was attributed to changes of transmission to retention-size pores.

Naturally, compacting soils of the upland have been found to adversely affect the soil water retention and available water-holding capacity. Kayombo and Lal (1993) cite some findings of research carried out in the semi-arid West Africa; where, water content in the soil surface ranged from 8 % to 15% at 0.03 MPa and 2 % to 7% at 1.5 MPa. Soil water retention in the subsoil, is usually higher and reflects the increasing clay content with depth. Hulugalle (1990) in Burkina Faso, found that soil water content of an Alfisol at 0.03 MPa was 19% and 24% at depth of 30 cm and 60 cm respectively.

Willcocks (1984) in Botswana, observed that water retention at 0.01 MPa and 1.5 MPa was 13% and 5% respectively, at 0-25 cm depth of a Luvisol/Cambisol. Available water-holding capacity of such soils was classified as low (Kayombo and Lal, 1993).

The total porosity of a soil however, can be decreased by the presence of a subsoil gravel concentration and thus the available water holding capacity of soils (Babalola and Lal, 1977). The effects of short-term droughts are exacerbated by these low water-holding characteristics.

2.4 Rainfall Properties

Rainfall is the most limiting factor affecting agricultural productivity coupled with high evapo-transpiration demands. The annual rainfalls for Machakos range from 500 to 800 as per the records of 1953 to 1973, which was considered marginal (Dowker, 1961; Nadar, 1984). The rainfall is characterised by high fluctuations, with more annual values below the mean value than above it (Hudson, 1987), posed severe land use limitations. Extreme conditions do occur whereby in wet years excessive erosion and flush floods are prevalent; while in most seasons, rainfall is inadequate.

Rainfall occurring in the ASALs, though low and erratic, are intense and of short duration, with about 70% of the most erosive rainstorms occuring immediately after on set of the rains. It has also been shown that the most reliable rains fall in the first 30 days of the rain season (Dowker, 1961). Consequently, most rainwater can be lost during the first month of rains during any one season (M'arimi, 1977). This culminates in soil moisture deficit and crops start drying at flowering or immediately afterwards (M'arimi, 1977). Such crops could therefore be carried to maturity if a good shower comes at such a time or rainwater is conserved in-situ against loss from runoff and evaporation.

The nature of an individual storm: its intensity, duration and timing determine the partitioning of rainfall between infiltration, surface runoff and evaporation. In-turn, this influences the way the rainwater becomes available as soil moisture or leads to surface soil erosion (Rowntree, 1988).

The principal characteristics of rain that affect runoff and erosion are intensity and duration; distribution of rainfall and storm frequency (Beasley et al., 1984). Runoff and soil erosion in semi-arid areas are reported to be associated with Hortonian overland flow in which the infiltration capacity of the soil must be exceeded before runoff can take place (Rowntree, 1987). This condition, however, is reported to be satisfied only under sufficient depth and intensity of rainfall. Stocking and Elwell (1976) found that 12.5 mm was a reasonable minimum depth before a storm can generate runoff. Any rainfall depth below 12.5 mm therefore was found unsuitable to be included in the storm Erosivity calculations. Rowntree (1988) however, used 10.0 mm as a convenient cut-off point between runoff and non-runoff producing storms.

Intensive work on the development of Erosivity indexes that best correlate with soil loss has been undertaken by among others Wishmeier (1959), Stocking and Elwell (1973), Hudson (1981), Kilewe and Ulsaker (1984), Lal (1976). Wishmeier (1959) devised the EI_{30} index, which is a compound index of kinetic energy and the maximum 30-minute rainfall intensity (I_{30}). However, Morgan (1988), suspected its validity for tropical rains of high intensity, couple with its assumption that erosion occurs even with light rainfall intensities. Hudson (1981), referring to his 1965 research findings in Zimbabwe found that erosion was almost entirely caused by rain falling at intensities greater than 25 mm per hour. However, reworking the data reported by Hudson (1981) showed that, this data when expanded over larger number of plots gave the EI_{30} to be the better Erosivity index than KE>25. In the above determination however, the EI_{30} was modified to exclude storms less than 12.5 mm and the minimum 5-min intensity greater than 25 mm per hour (Stocking and Elwell, 1973a). Stocking and Elwell (1973) also found the use of EI_{30} to be limited to bare soil conditions. However, those of sparse and dense plant covers, better correlation with soil loss was found using maximum 15 and 5-min intensities respectively.

The EI_{30} index is however, the standard universal soil loss equation erosivity index, where applicability has not proved uniformity world-wide (Kilewe and Ulsaker,1984). An alternative erosivity index, Hudson (1981) use is the KE >25, that sums up the kinetic energy received in the time increments when the rainfall intensity equals or exceeds 25 mm per hour. When applied to data in Zimbabwe, the KE>25 was found to be more appropriate compared to the EI_{30}.

Another index developed by Elwell (1977), is the Soil Loss Estimator for Southern Africa (SLEMSA) model. This model uses the seasonal kinetic, the total energy content of all rainfall events as the erosivity index called to predict mean annual soil loss from sheet erosion. Using the AI_{30} index, Lal (1976) found it a better predictor of soil loss and runoff than either EI_{30} or KE>25. The AI_{30} is the product of total rainfall amount (A) and peak 30-min storm intensity (I_{30}).

Kilewe and Ulsaker (1984) found that rainfall amount to be one of the best erosivity factors, having a coefficient of determination (r^2) of 0.66. Morgan (1986) and Kilewe and Ulsaker (1984) citing Roose (1973), working in Ivory Coast, reported soil loss to have been significantly related to rainfall amount and total kinetic energy (E) with an r^2 of 0.64. When Kilewe and Ulsaker (1984) related total kinetic energy to rainfall amount for the storms of Katumani, they found an r^2 of 0.97. This high r^2 indicated that nearly all the variations in total energy can be accounted for by rainfall amount. They also found that storm-runoff (RO) was the best single variable erosive factor with an r^2 of 0.71. Kilewe and Ulsaker (1984) further found that the KE>25 index was not as efficient as Hudson (1981) reported to be in Zimbabwe.

Kilewe and Ulsaker found that the four compound factors involving rainfall variables only (EI_{15}, EI_{30}, AI_{15}, AI_{30}), all produce good results, with r^2 ranging from 0.62 to 0.73. Regression computation of the EI_{30} and AI_{30} was also found to have an r^2 of 0.992 while that of the EI_{30} and rainfall amount (A) revealed a relationship of an r^2 of 0.902. Thus the rainfall amount was found to be a good estimator for EI_{30}.

2.5 Mechanization

As a developing country, Kenya's mechanization has drown some attention to problems of the majority smallholder farmers as tracterization has only assisted large scale farmers who are commercially orienyed. Mechanization in a developing country like Kenya aims at operating a labour intensive; capital and foreign exchange saving strategy (Mutebwa, 1979) in order to develop and achieve sustainable tillage systems. It is for this reason, that intermediate technology based methods have a good chance for prosperity in Machakos District as well as other semi-arid areas. Draft animal utilisation accompanied by improved animal draft power packages for tillage will go a long-way in fulfilling the above aims.

Hand tool mechanization in Machakos was observed to be constrained by labour shortage during peak periods (tillage and weeding), high energy requirements, associated drudgery and availability of appropriate tools (Muchiri and Gichuki, 1982).

An intermediate level lying between the extremes of hand techniques and tractors with its applied equipment, based on animal draft power would be more appropriate (Mutebwa, 1979). Moreover, this offers a good alternative in Machakos, where excess land is available to support draft animals (Muchiri and Gichuki, 1982).

Draft animal power and performance, is found to be dependent on a number of factors like, the animal type, design of implement, type and condition of the soil, training condition of the animals and the nature of field operations (Mrema and Hatibu, 1989). The efficient use of draft animals is also hindered by nutrition and disease.

Draft animal use in Machakos is currently restricted to ploughing, an operation frequently undertaken in only two months a year. This restriction has severe implications on the investment in draft animals in both time and resources. Training of draft animals for other operations such as weeding would therefore increase the overall farm profitability and output against draft animal investment.

2.5.1.1 Animal Drawn Tillage Implements available in Kenya

A number of equipment for small-holder semi-arid agriculture has been made available through several years of research and development. The Ministry of Agriculture through Rural Technology Development Centres and the University of Nairobi, Department of Agricultural Engineering have been instrumental in this research and development.

2.5.1.2 Animal Drawn Mouldboard Ploughs

The widely used animal-drawn tillage equipment in Kenya is the convential victory mouldboard plough (Kahumbura, 1992; Muchiri and Gichiki, 1982). This plough is now being manufactured locally, though originated from United Kingdom and was earlier manufactured in, India.

When good quality steel is used, Victory plough is light and popular with farmers. This plough is used in a range of tillage operations from land preparation, ridging, furrow opening for seed planting, inter-row weeding, soil spreading and harrowing.

However, this implement requires high draft power, particularly when soils are dry and hard (Kahumbura, 1992). The other implement being promoted through the Netherlands supported draft animal power and development project in the Department of Environmental and Biosystems Engineering, University of Nairobi is the Rumptstad manufactured mouldboard plough shown in Plate 2.1. This plough is named after the Rumptstad Commercial Manufacturer of Agricultural Equipment in the Netherlands.

Plate 2.1 The Winding Bottom Conventional Rumptstad Mouldboard Plough

There are two types of the Rumptstad mouldboard ploughs in Kenya (the Cylindrical bottom and the Winding bottom). These ploughs work just like the victory and the Bukura MK 11 ploughs, but showed a better performance manifested in their better inversion and less specific resistance (Ndogo, 1992).

These ploughs make clear furrows, as they continually turn soil into each previous furrow, covering weeds and surface trash. The degree of inversion depends on the cohesion of the soil and the depth of tillage. These ploughs generally lessen ground cover (mulch) on the soil surface and thus expose soil to erosive storms early in the season. Soil inversion in semi-arid environments increase the rates at which soil moisture is lost and humus is decomposed. Moreover, a fine till makes the soil prone to both wind and water erosion.

2.5.1.3 Animal Drawn Chisel Plough

The chisel plough which is made up of a triangular share with, about 8 to 10 cm working width, operates like a ripper. While with the conventional mouldboard plough, animal energy is used in turning over the soil, chisel ploughs break the soil without inversion and thus cut deeper into the hard soil crusts in order to facilitate better rainwater infiltration at minimum draft (Kahumbura, 1992; Muchiri and Gichuki, 1982). However, Figueroa and Mburu (1984) found this implement unsuitable due to failure to maintain a straight line.

2.5.1.4 Animal Drawn Desi Plough

The Desi plough is adopted from the Indian Sub-continent and is also extensively used in parts of the Middle East and Sub-Sahara Africa. The original plough consisted of a wooden beam with a metal tip for breaking the ground. The modified plough, however, uses a metallic frame construction. During the dry season, the traditional Desi plough may be used for shallow (2-5 cm) tillage operations to keep the seedbed free from weeds while spreading the mulch for moisture conservation.

The biggest weakness in this system is reported to include lack of protection from soil erosion and failure to break the subsurface pans which impede root development and rain penetration.

2.5.1.5 The "Maresha" Plough

The traditional Ethiopian "Maresha" plough shown in Figure 2.2 below is a wooden plough which has a sharply pointed metallic tip and a metallic hook hinged to the handle of the plough. Two flat wooden wings are fitted by the hook to the handle and by a steel pin to the beam on the other side of the implement. This plough basically scratches the soil, lifts and slightly turns it equally on either side of the plough leaving a furrow and two small ridges behind (Starkey, 1988).

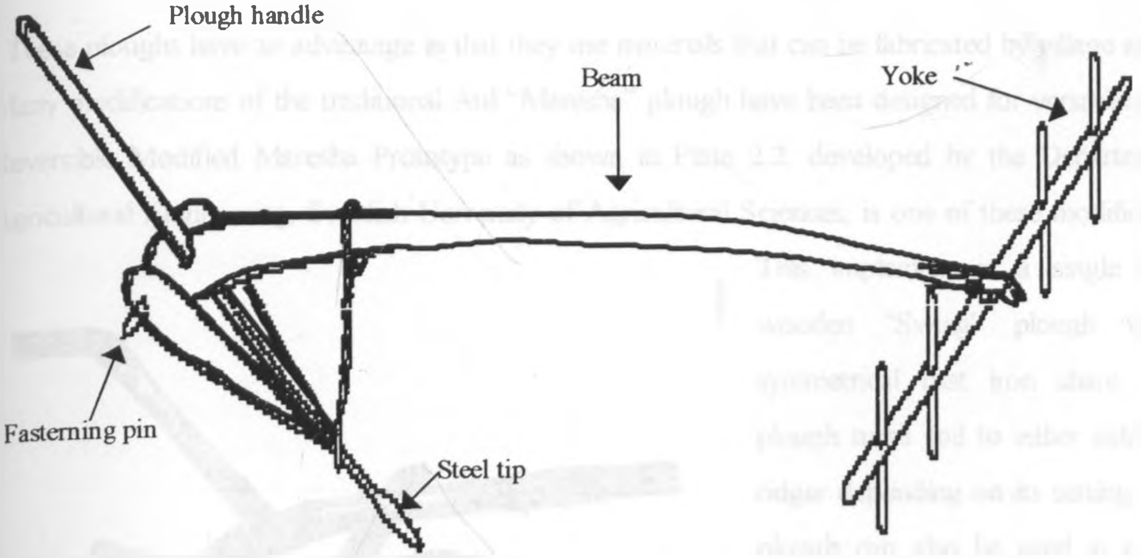


Figure 2 2 The Ethiopian Traditional Maresha Plough.

The traditional Ethiopian "Maresha" achieves weed control and seedbed preparation through a series of cultivation (at least three times) each at an angle to the other (Starkey, 1988). Repeated cultivation, disturbs most of the soil leading to a harrowing effect. Secondly, the symmetrical nature of the Ethiopian "Maresha" plough design makes it unsuitable for use in soil and water conservation activities that require soil to be thrown to one side such as contour bunding, bed or crop ridge formation.

The above adverse effects and limitations led to the development of the Reversed Maresha type ploughs. The modified types are basically conventional maresha ards, fitted with wings or mouldboards, and use a flexible chain rather than a long beam between the body of implement and the yoke.

These ploughs have an advantage in that they use materials that can be fabricated by village artisans. Many modifications of the traditional Ard "Maresha" plough have been designed for versatility. The Reversible Modified Maresha Prototype as shown in Plate 2.2, developed by the Department of Agricultural Engineering, Swedish University of Agricultural Sciences, is one of these modifications. This implement is a single handle wooden "Swing" plough with a symmetrical cast iron share. This plough turns soil to either side like a ridger depending on its settings. The plough can also be used in a single sided mode, as was the case in the experiment.

Plate 2. 2 The Reversible Modified Maresha Prototype Plough

Both the original and the developed Reversible Modified Maresha Prototype (MM) ploughs are being tested for local suitability by the Department of Environmental and Biosystems Engineering, University of Nairobi.

The MM modifications on the conventional "Maresha" were in principle, similar to those carried out by the International Livestock Centre for Africa (ILCA). These modifications were directed not only at improving the draft but also at controlling soil movement. The other modification done by ILCA was the ability to shape the top soil into broad beds and furrows for drainage of excess surface water from heavy clay soils.

The MM plough basically, strip tilled by opening a furrow and slightly inverting the soil, forming one or two ridges on either side depending on the setting. These ridges were formed on the untilled strip and thus soil disturbance was only in the furrows. Evaluation of the performance of some tillage equipment undertaken at Katumani in 1982 and 1984 are shown in Table 2.1.

Table 2.1 Evaluation of Some Tillage Equipment at Katumani, 1982 and 1984

Parameter	Muchiri, 1981		Figueroa and Mburu, 1984	
	Desi plough	Chisel plough	Desi plough	Chisel plough
Average draft (kg)	183.0	98.0	95	100
Depth of tillage (cm)	9.3	7.1	11	15

Muchiri (1982) used the Sine Hoe T-tool-frame system, while Figueroa and Mburu (1984) adapted the same tillage components to the Bukura Mark 11 tool-frame and obtained a lower draft. The difference in draft requirement was attributed to the toolframe weight of the Sine Hoe T-tool-frame (27 kg) and the Bukura Mark 11 tool-frame (14 kg).

3. RESEARCH METHODOLOGY

3.1 Research Study Area

This research study was conducted in a Semi arid environment on a site at the Katumani National Dry land Farming Research Centre, Machakoes, Kenya. The area is located 9 km south of Machakos town and is roughly located by longitude 37° 14′E and latitude 01° 35′s. It lies at an altitude of 1600m above sea level (Gicheru and Ita, 1987).

According to Sombroek et al., (1982) this centre falls under Agro-ecological zone IV which is classified as semi-humid to semi-arid. The rainfall distribution is bimodal occurring in two distinct peaks separated by a dry season of two to four weeks as shown in Figures 4.7 & 4.8. The mean annual rainfall is 711 mm. The long-rains occur during the months of March to May with a peak of about 147 mm in April. The short rains fall in the months of late October or early November to December with a peak of about 164 mm in November.

The short rain season is usually followed by very erratic convective rains in January and February that sometimes marks the onset of the long-rains (as was the case in 1995 season when it fall in February) or even late January (Kilewe, 1987). This therefore, makes it difficult to plan for the long rains which at the same time, is generally unreliable. There is a tendency for the short rains to be more reliable and heavy though short when compared to the long rains.

The mean annual temperature range varies from 17 to 34°c with the mean maximum and minimum temperatures of 24.9 and 13.7°c respectively (Kilewe, 1987). Temperatures are characterised by high annual and biannual fluctuations. These fluctuations result in maximum heating during sunshine hours and maximum heat loss at night leading to high soil moisture losses. This situation is worsened by low water vapour conditions for cloud formation. The relative humidity ranges from 50% to 70% at 06.00 hours and falls to between 36% and 40% at midday.

The dominant soils of the centre are the Luvisols, both chromic and orthic, with fluvisols, lithosols and vertisols as minor intrusions developed from an undifferentiated quartzo-feldsphathic gneisses of the Basement System Complex (Gicheru and Ita, 1987). The experiment was conducted on a sandy clay loam soil (Chromic luvisol, FAO/UNESCO Classification, 1974) that corresponds to Alfisols (USDA Classification). The soil structure was weak to moderate, medium, sub-angular blocky. This soil consisted of a strongly weathered, well drained, deep to very deep, dark red to dark reddish brown, friable clay. The clay content increases with depth (see Table 5.1) with a gravely stone line waving between 90 to 150 cm. The soil has a tendency for hardsetting, sealing and crusting under intense rainfall.

3.2 Characterization of the Soils at the Experimental Site

Augering was done up to the hard gravelly lining for depth determination and soil sampling for the determination of various soil physico-chemical soil properties. Soil samples were collected at the research site from representative locations of both the Runoff and the Complementary moisture plots (see section 3.3.2). Each plot was sampled (disturbed and undisturbed soil samples) at depths of 0-20, 20-40, 40-60, 60-80, 80-100, 100-120 cm. Undisturbed soil samples were taken to help determine the before ploughing soil bulk density and its corresponding soil moisture content. The disturbed soil samples collected in the upper 30 cm depth were for the determination of the initial soil bulk density and soil moisture content immediately after ploughing and setting of the experiment.

Three representative, disturbed samples collected randomly from each tilled block (see Figures 3.1 and 3.2) were used for organic matter content and soil textural characterization. The soil textural classification was made following the mechanical analysis using the hydrometer method. The soil classification was adopted after Gicheru and Ita, (1987) whose detailed soil pit profile description was obtained from a representative pit dug about 80m away from the experimental site.

Field infiltration and hydraulic conductivity tests at the site were conducted using a disc permeameter while soil moisture determination was carried out using a calibrated Neutron Probe. Neutron Probe access tubes were installed in each auger hole for the soil profile moisture characterisation up to 120 cm depths.

Selected soil physical and chemical properties of the experimental site are given in tables 3.1 and 3.2. The soil bulk density, organic matter and soil textural composition at the site were examined down the soil profile. Bulk density of the soil ranged from 1530 kg/m^3 in the top 20 cm to 1350 kg/m^3 in the 100-120 cm horizons. Bulk density reduced with depth. Similar results were reported by Kilewe and Ulsaker (1984) and Biamah et al. (1994). More information on bulk density and its variation is discussed under Section 4.5.4. The organic matter content was very low, decreasing with depth, ranging from 1.2% at the surface to 0.6% at the 100-120 cm soil horizon. Investigation on individual plots' residual organic matter content showed no statistical differences at 5% probability. The sand content like organic matter content and bulk density decreased with depth from 70% to 57% in the 0-20 cm and 100-120 cm soil horizons respectively. The clay content on the other hand increased with depth, ranging from 23% to 37% in the upper 20 cm and the lower 100-120 cm soil horizons respectively.

Table 3.1 Soil Properties at the Experimental Site.

Soil profile Depth (cm)	Bulk density kg/m^3	% matter content	Soil textural composition			Soil Textural Class
			% Sand 2.00-0.05	% Silt 0.05-0.002	% Clay <0.002 mm	
0 – 20	1530	1.2	70	7	23	Sand Clay Loam
20 – 40	1470	1.2	66	8	26	Sand Clay Loam
40 – 60	1490	0.9	60	7	33	Sand Clay Loam
60 – 80	1410	0.8	60	5	35	Sand Clay
80 - 100	1360	0.8	59	6	35	Sand Clay
100 - 120	1350	0.6	57	6	37	Sand Clay

The soil exhibited a sandy clay loam texture composition changing gradually with depth to sandy clay at the 60-120 cm horizons.

The soil water release characteristics (tables 3.2 and 3.3) show a gradual increase of soil moisture with depth. The increase of moisture with depth is well explained by the increase in clay content and decrease in bulk density with depth and thus increase in specific surface area and total porosity.

Table 3.2 Profile Soil-Water Release Characteristics Data

Profile depth (cm)	Percentage volumetric moisture content										
	Suction (pF)										
	0	2	2.5	2.7	3	3.5	3.7	3.8	4	4.2	Average
0-20	37	27	22	20	18	16	14	14	14	13	20
20-40	35	30	26	24	22	21	19	18	18	17	23
40-60	38	33	29	27	23	21	19	18	18	17	24
60-80	41	36	30	27	25	23	20	20	19	19	26
80-100	39	34	30	28	25	23	21	20	20	19	26

The resultant soil-moisture curves of such soils give rise to a sigmoid form, with the horizontal displacement principally reflecting texture, while the shape relates more to structure (Kowal, 1970).

Table 3.3 Profile Soil water Holding Capacity

Profile depth (cm)	Percentage volumetric moisture content		
	Field capacity	Wilting point	Available water
0-20	22.4	13.5	8.9
20-40	26.0	17.4	8.6
40-60	29.0	17.3	11.7
60-80	30.2	18.9	11.2
80-100	31.0	19.8	11.2

3.3 Experimental Design, Layout and Treatment

Figures 3.1 and 3.2 below, shows the field experimental layout and design. During the short rains (1994), the experimental layout and design covered only the runoff experimental tillage practices (figure 3.1), while during the long rains investigations were extended to include the complementary (differential) tillage depth experimental unit (figure 3.2).

3.3.1 Experimental Design and Lay out

The runoff experimental design was a Split-plot with three replications. The runoff investigations were conducted on 12 micro-plots of two square metres (2 m^2), with manure treatment laid-out in a Split-plot design superimposed over a Randomized Complete Block Design plough type. The runoff experiment consisted of two tillage implements:- the Conventional Rumptstad (RS) and Modified Reversible Maresha Prototype (MM) tillage practices and manure application. This experiment therefore, had four main treatments, namely two tillage types at two levels of farmyard manure.

The runoff experimental unit was laid out on a general slope of 8.5 % with plot slopes ranging from 7.5 % to 15.5 %, (Figures 3.1 and 3.2).

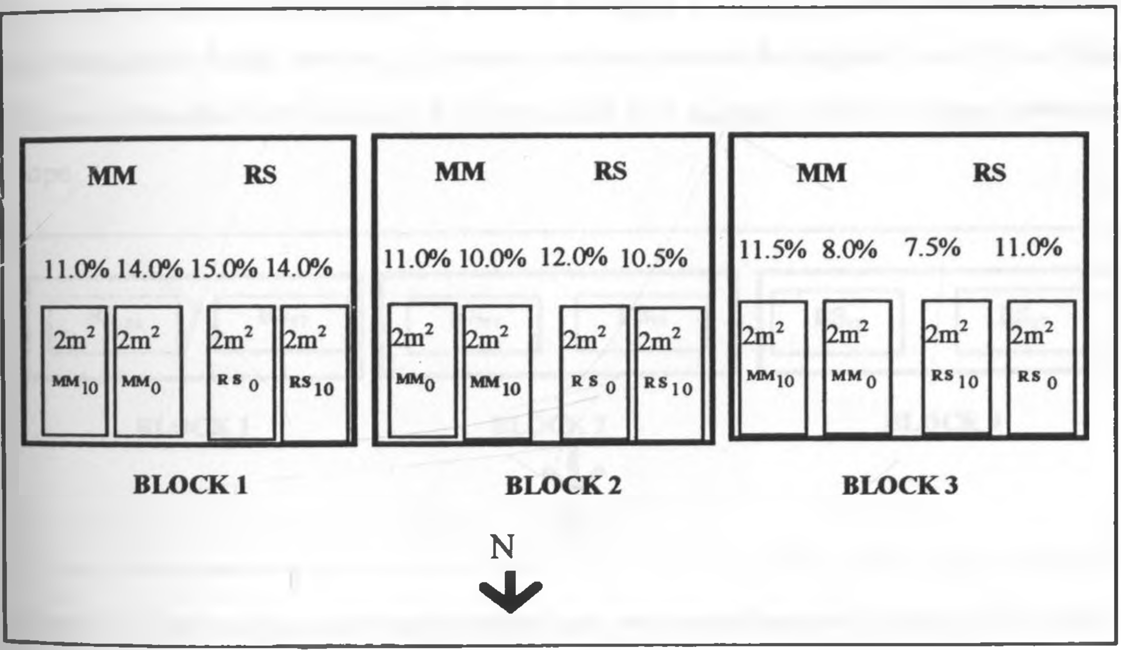


Figure 3. 1 Runoff experimental unit showing plot layout, and percent slopes.

Layout Legend:

The complementary experiment comprised of two differential tillage depths (12 cm and 17 cm) with the use of the Conventional Rumptstad plough in a Randomized Complete Block Design with three replications. This experiment was set up in order to deepen our understanding of the effect of tillage depth on soil moisture:

Treatment RS_0	Conventional Rumptstad mouldboard plough without farmyard manure applied.
Treatment RS_{10}	Conventional Rumptstad mouldboard plough with 10 tonnes per hectare farmyard manure applied.
Treatment MM_0	Modified Reversible Maresha Prototype (strip tillage) plough without farmyard manure applied.
Treatment MM_{10}	Modified Reversible Maresha Prototype (strip tillage) plough with 10 tonnes per hectare farmyard manure applied.

In addition to the runoff experiment laid out in Figure 3.1 above, a complementary experimental unit was added during the long rain season and sited above the original runoff plots (Figure 3.2). This unit consisted of 6 plots of 24 m^2 (4 m wide by 6 m long) with the longest side across the slope.

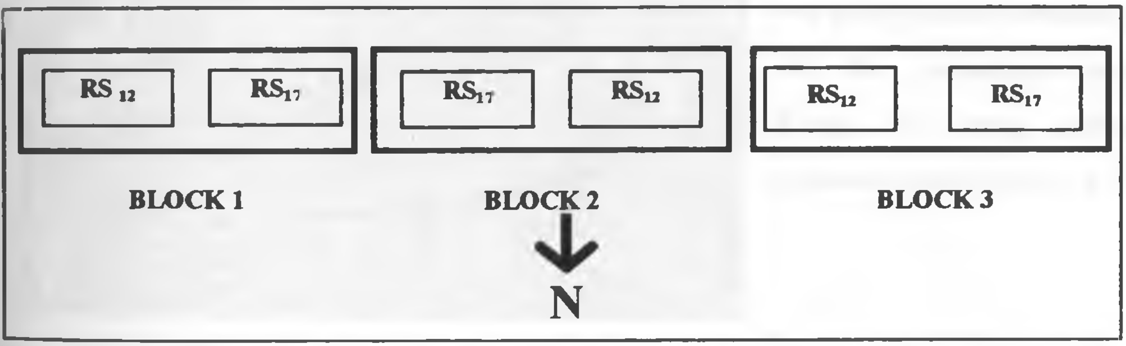


Figure 3.2 The complementary experimental units with runoff and soil moisture plot layouts.

Layout Legend:

Treatment RS_{12}	12 cm tillage depth with Conventional Rumptstad mouldboard plough with 10 tonnes per hectare farmyard manure applied.
Treatment RS_{17}	17 cm tillage depth with Conventional Rumptstad mouldboard plough at 10 tonnes per hectare farmyard manure applied.

3.3.2 Tillage Operations

Research site pre-season land preparation was undertaken using a mouldboard tractor drawn plough to a 25-30 cm plough depth. This operation created a uniform soil tillage depth and soil's surface roughness (Gebresenbet and Kaumbutho, 1994). The conventional tillage operation was done using a Conventional Rumptstad Mouldboard Plough (winding bottom) up to an average ploughing depth of 12 cm.

The conservation tillage on the other hand was undertaken with the use of the Modified Reversible Maresha Prototype (MM) plough (see Plate 3.1) to the depth of depth of 8 cm. The strips that were being tilled were about 20 cm apart, separated by an untilled strip. The tilled strip was basically a furrow from which soil was inverted to the covering of the untilled strip.

Two adjacent plots (i.e. MM_{10} and MM_0) were treated as a unit under one plough main treatment (MM). All the parameters monitored during the study period are discussed under Section 3.5.

Figure 3. 3Conservation tillage plot showing the resultant tillage surface configuration of the Modified Maresha Prototype Plough (Katumani Research Site).

In order to eliminate any influence of vegetative cover on the pertinent hydrologic and soil properties coupled with space limitations plots had no test crop and were hand weeded. In all cases, ploughing was carried out approximately on the contour

3.3.3 Soil Amelioration.

The soil amelioration for soil physico-chemical improvement was undertaken with the use of farmyard manure, that consisted of cow-dung and crop residue collected from the Katumani Dryland Agricultural Research Centre's night paddock. This was air dried and applied by broadcasting before ploughing, for complete incorporation into the soil.

In the runoff experimental units the ten tonnes per hectare of manure was applied in one sub-unit of each tillage plot. The other remaining sub-unit of the same tillage type was left without any manure and therefore was a control treatment. In the complementary (differential tillage depth) experimental unit, manure was applied at a uniform rate of 10 tonnes per hectare.

Farmyard manure was applied in order to reduce surface sealing and crusting; and surface runoff (Biamah et al., 1994). Due to the prevalence of livestock in the area, farm yard manure was found appropriate for soil amendment and building up soil organic carbon.

Application of farmyard manure in amounts of approximately 5-15 tonnes per hectare is reported to be a reasonable range for maintenance of soil fertility in rain fed dry land farming in most African countries (Chakraboty T., 1989). 10 t/ha is therefore a reasonable mid way the recommended range for use in this study. Similarly, Grimes and Clarke, 1962 in a trial at Matunga, in Kenya found no significant differences between the 7.5 t/ha/annum and 22.5 tonnes/ha per annum every third year in maize sorghum, cassava and sweet potatoes grown in rotation.

3.4 Experimental Procedure

This experiment was conducted under natural rainfall conditions and over 2 rain seasons, short rains 1994 and long rains 1995. While both field and laboratory measurements were carried out, the bulk of the experimental parameters were monitored in-situ. The relevant soil physico-chemical properties like bulk density, antecedent soil moisture and organic matter content were determined just before plots were subjected to any treatment. These were sampled for subsequent comparisons with experimental measurements.

Immediately after the on-set of the rains, two ox-drawn tillage implements were used to plough the site as per the experimental layout and design (see Figures 3.1 and 3.2). The experiment was supported with the collection of daily rainfall records from the KNDRC meteorological station covering the period from 1956 to 1994.

The KNDRC meteorological station was 600 m away from the experimental site and thus was assumed to be close enough to be representative of the site's rainfall records. Weekly averages were compiled covering the long-term rains seasons and basic rainfall data analysis carried out.

Similarly, the experiment seasons' rainfall was collected for the short rains 1994 and long rains 1995, analysed separately, compared between the different stations, and related to the long-term weekly averages.

3.5 Experimental Materials and Methods

3.5.1 Tillage Depth

In the runoff experimental unit, tillage depth measurements were done using a potentiometer based ground wheel an attachment of a tillage power logging (computer-based) equipment. In the complementary (differential tillage depth) experimental unit, however, tillage depth was measured manually with a steel rule. With the help of a straight edge positioned on the original soil surface, the height of the rule from the furrow bottom, to the cross-line of the straight edge was measured as the tillage depth.

3.5.2 Seasonal Rainfall

3.5.2.1 Calibration of Rain-gauges

The two rain gauges used in the recording of the on-site rainfall had slightly blunt edges, thus required calibration against a standard one. Figure 3.3 shows the calibration of the two rain gauges. The regression equations from the two graphs were then used to calibrate the recorded rainfall amounts.

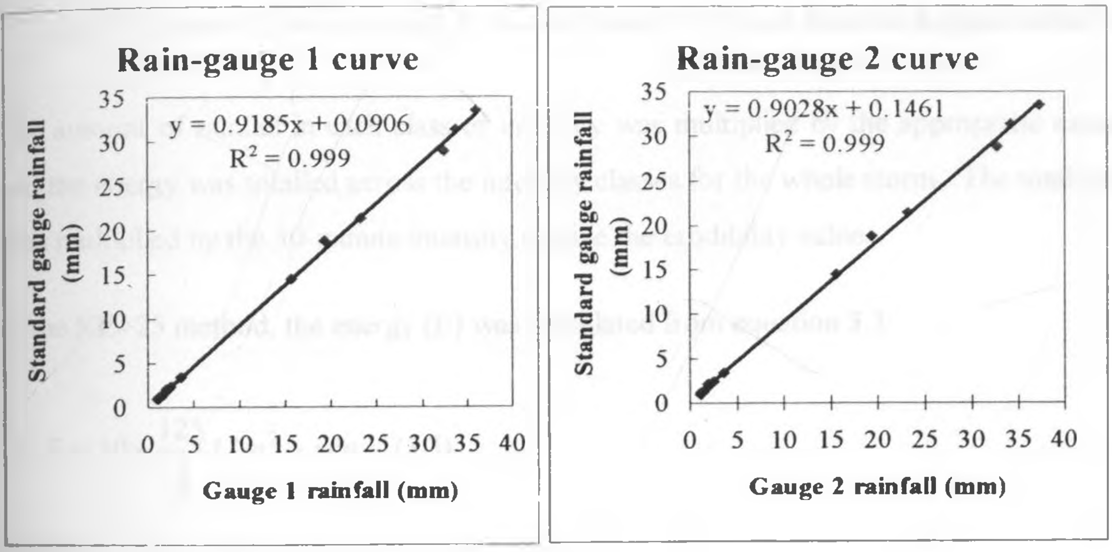


Figure 3. 4 Calibration Curves of Rain-gauges

3.5.2.2 Seasonal Rainfall Measurements

The two rain gauge average rainfall amounts were recorded daily at 9.00 hours from two non-recording rain gauges placed 100 m apart. Another set of two rain gauges located 600 m and 100 m from the runoff plots provided long historical data for testing and relating to that of the experimental season, and logged rainfall data for rainfall Erosivity determination respectively.

Computations were made similar to Hudson (1981) whereby, the EI and KE>25 erosivity determination were calculated from, using the amount of rain which fell at a particular rate of intensity. Classes of rainfall intensity ranges of 0-25, 25-50, 50-75,>75 mm per hour were made and rainfall energy (E) values for the EI calculated from equation 3.1:-

$$E = 11.9 + 8.7 \log I \; J/m^2 - mm \qquad (3.1)$$

Where:

I = average rainfall intensity (mm/h)

$$EI = \frac{E \times I_{30}}{1000} kJ - mm/m^2 - h \qquad (3.2)$$

Where:

E = rainfall energy as in equation 4.1 above,

I_{30} = Maximum 30-minute rainfall intensity (mm/h), derived from the logged rainfall records.

The amount of rainfall in each class of intensity was multiplied by the appropriate energy value, and the energy was totalled across the intensity classes for the whole storm. The total energy was then multiplied by the 30-minute intensity to give the erodibility value.

In the KE>25 method, the energy (E) was calculated from equation 3.3:

$$E = 30 - \frac{125}{I} J/m^2 - mm \qquad (3.3)$$

Where:

I = average rainfall intensity (mm/h)

In the KE>25 the 0-25 mm/h intensity was however, omitted from the calculation and the index was simply the total energy of the remainder.

Weekly, monthly and yearly averages for the long term and experimental seasons were run and a paired t-test performed for variability test at 95% probability level.

3.5.3 Runoff and Sediment Collection

3.5.3.1 Runoff and Sediment Collection Equipment

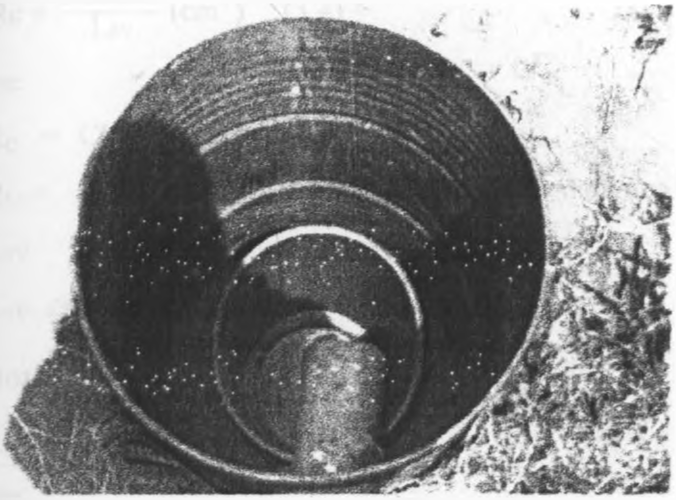
The runoff collection equipment used in this experiment consisted of metal sheet borders (1 m x 2m) open at the collection side. The sheet boarders were installed around 2 m² plot sizes and were connected to sediment and runoff collection systems (see Plates 3.2, 3.3 and 3.4).

Plate 3. 1 Runoff and sediment collection assembly.

The collection system consisted of a collection trough exposed in Plate 3.3, PVC pipe for conveying the runoff and sediment from the plot to the sedimentation tank as shown hanging in the drum in Plate 3.4. The sediment collector was provided with a lead (the part facing upwards in Plate 3.3), to prevent collection of direct rainfall (from outside monitored plot).

Plate 3. 2 Sediment and runoff collector assembly connected to the runoff plot

The sedimentation tank comprised of a 200 litre metallic drum with a 20 litre plastic bucket inside it (Plate 3.4).



A 20 litre capacity bucket was placed inside the drum directly below the inflow spout to the drum as the receiving tank to facilitate easy manual sampling and cleaning up after rainstorms.

Plate 3. 3 Sediment and runoff collection tank comprising of a metallic drum, plastic bucket and PVC pipe spout.

3.5.3.2 Runoff and Soil Loss

On a rain storm event basis, runoff and soil loss were monitored. Due to non-automated rainfall and runoff system, storm events were recorded and summed up for the whole day according to the 9 a.m. meteorological observance time.

The amount of runoff and soil loss was determined by Volumetric and gravimetric methods. The runoff and sediment collected from the plots were sampled for sediment load whilst the liquor and sludge samples under went a standard gravimetric analysis for quantification.

The suspended sediment loaded runoff volume (liquor), however, was determined in the field with the help of a graduated bucket and cylinder, after the liquor was separated from the sludge. Representative liquor was sampled in a known volume container and taken to the lab for the determination of sediment.

The liquor was then left for 24 hours to settle and then clear water was carefully decanted and volume measured to obtain the clear runoff volume in the samples. The total clear runoff volume was obtained from equation 3.4:

$$Rc = \frac{R_{LS} \times L_{TV}}{L_{SV}} (cm^3) \quad (3.4)$$

Where:

R_C = Clear plot runoff volume (cm^3)

R_{LS} = Clear runoff volume of the liquor and sludge samples.

L_{TV} = Total liquor volume (cm^3)

L_{SV} = Sample Liquor Volume (cm^3)

The total sediment was obtained from equation 4.5:

$$SR = S_L + S_{SL} \quad (3.5)$$

Where:

S_L was the amount of sediment in liquor = $\frac{M_{ds} \times V_{TL}}{V_{LS}}$ (*gms*) (3.6)

Where:

M_{ds} = The mass of oven dry sediment in sample.

V_{TL} = The total volume of original liquor in sample.

V_{LS} = The volume of liquor in sample.

S_{SL} was the total mass of sediment in sludge = $\frac{M_{dSL} \times M_{TSL}}{M_{SL}}$ (gms) (3.7)

Where:

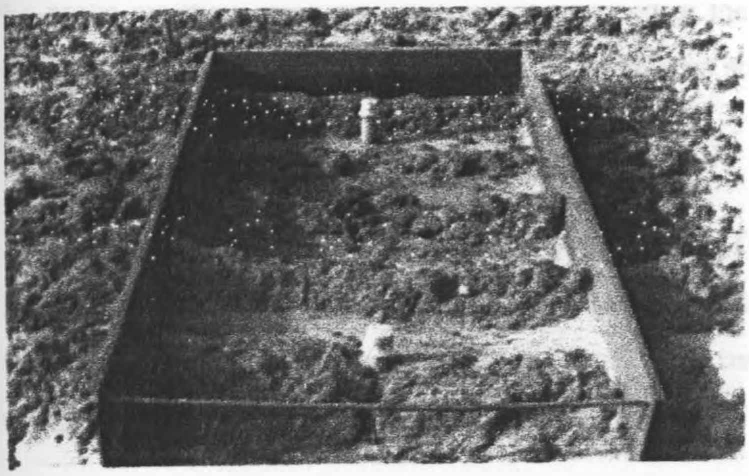
M_{dSL} = The mass of oven dry sediment in sludge sample.

M_{TSL} = The total mass of wet sludge.

M_{SL} = The mass of wet sludge in sample.

3.5.4 Soil Moisture Content

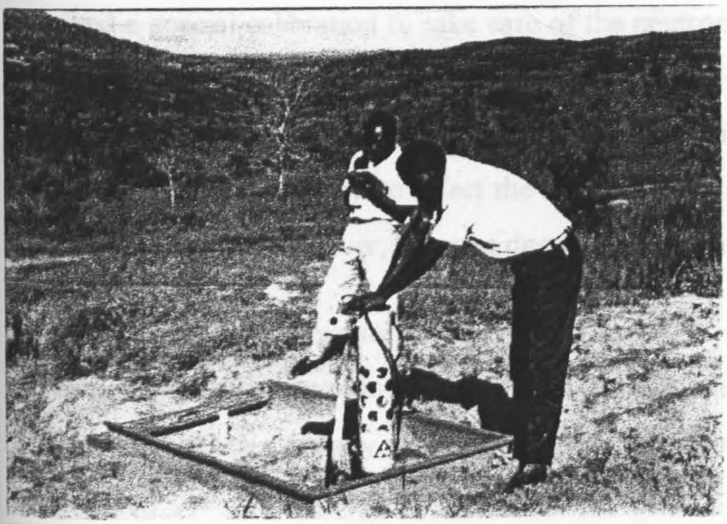
3.5.4.1 Neutron Moisture Probe



For the soil moisture measurements, aluminium access tubes of an inner and outer diameter of 48 mm and 50 mm respectively were installed two in each runoff plot, positioned at 30 cm from each plot end (see Plate 3.5).

Plate 3. 4 Runoff plot showing installation positions of the access tubes at the Katumani Research

The complementary plots, however, had only one access tube positioned in the middle of the plot. Installation of the access tubes was at a depth of 130 cm or to the maximum possible soil depth depending on the soil profile. The depths of access tubes varied between 90 and 150 cm due to the occurrence of stones and hardpans.



The neutron probe equipment shown held against the access tube in Plate 3.6 was used to determine the profile soil moisture on a weekly basis and twice a week during dry spell periods.

Plate 3. 5 Neutron moisture probe placed on an access tube at the Katumani Research

This was done by lowering the probe in the access tubes to successive measurement depths of 15, 30, 45, 60, 75, 90, 105, 120 cm, by means of a cable.

The probe moisture measurements were determined in the runoff and differential tillage depth plots. A standard neutron moisture probe whose neutron source was a Radium and Americium-Beryllium mixture was used.

3.5.4.2 Calibration of the Neutron Probe and Moisture Content

The calibration of the Neutron Probe for soil moisture measurements was carried out under both wet and dry conditions. Three readings per depth were read within a variation of 10 units and averaged to represent the particular depth's mean count rate.

The calibration access tubes were installed outside but between the runoff experimental plots and were left in the ground for three weeks before use to ensure that the soil around them had settled. The calibration curves obtained represented the regression calculations of the known-volume soil cores determined by the gravimetric measurements against their corresponding probe counts per depth of monitoring in the access tubes.

Calibration was done for the profile depths of 15, 30, 45, 60, 75, 90, 105, and 120 cm in two ranges; 15-25, 25-75 and 75-120 cm. This calibration was necessary as the 10-25 cm depth required a special calibration to take care of the neutrons which were permitted to escape to the atmosphere due to its nearness to the soil surface. The 25 - 75 cm and 75 - 120 cm soil depths were also calibrated separately, due to the presence of iron and manganese concretions (Biamah et al., 1994) that are known to affect the count readings (Lal, 1975). Out of the 30 access tubes installed in the plots however, 24 went deeper than 90 cm while 6 went only up to 90 cm.

The gravimetric soil moisture of the core soil samples were laboratory determined from depths corresponding to the mean probe readings. The regression curves were drawn and the count rate of the probe (R) was linearly related to the volumetric moisture content (θ) of the soil as noted in Figure 3.4.

3.5.4.3 Soil Moisture Neutron Probe Calibration Curves

Figure 3.4 shows the soil moisture neutron probe calibration curves of the site for the 25-75 cm and 75-120 cm profile ranges. These two calibrations were necessitated by the accumulation of iron and manganese concretions below 75 cm soil horizons.

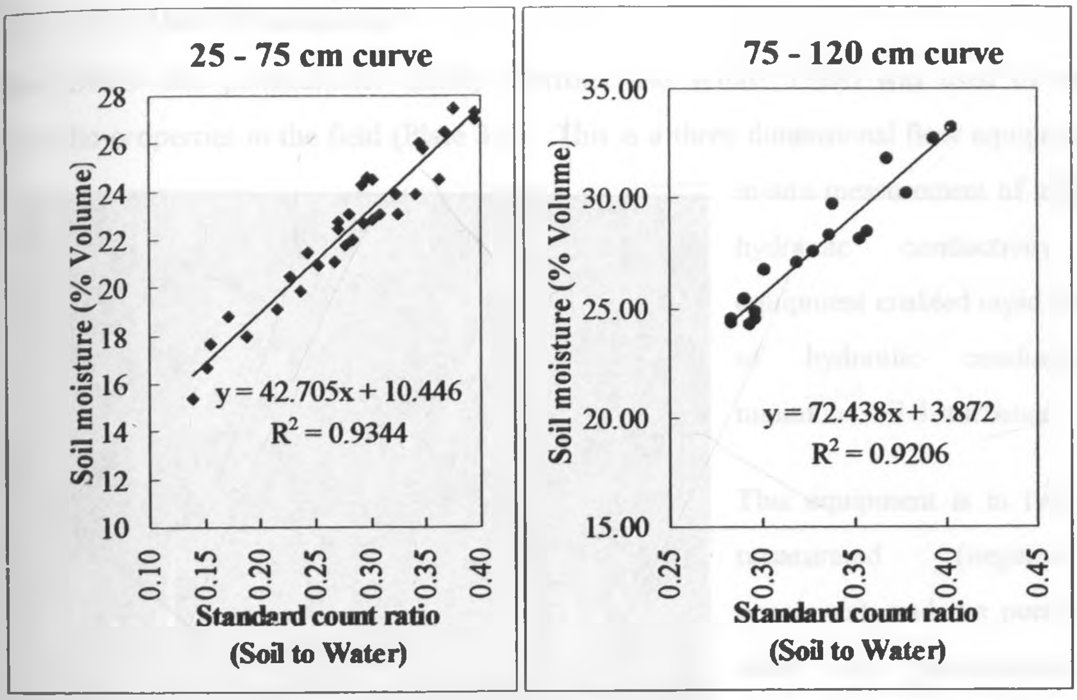


Figure 3. 5 Neutron Probe Calibration Curves (25 - 75; 75 - 120 cm depths).

3.5.4.4 Gravimetric Moisture Content

Monitoring of soil moisture was done at two levels: the top soil 0-10 cm and the 10-120 cm depth at which gravimetric and Neutron probe measurements were undertaken respectively, covering the 1994 short rains and 1995 long rains. Like in the calibration, three readings per depth were taken within a variation of 10 units and averaged to represent the particular depth's mean count rate.

Three (3) soil samples were collected along the outer border of each runoff and complementary moisture plot for moisture determination. The samples were weighed immediately after sampling and after oven drying at 105^0 C for 24 hour, and the moisture content determined.

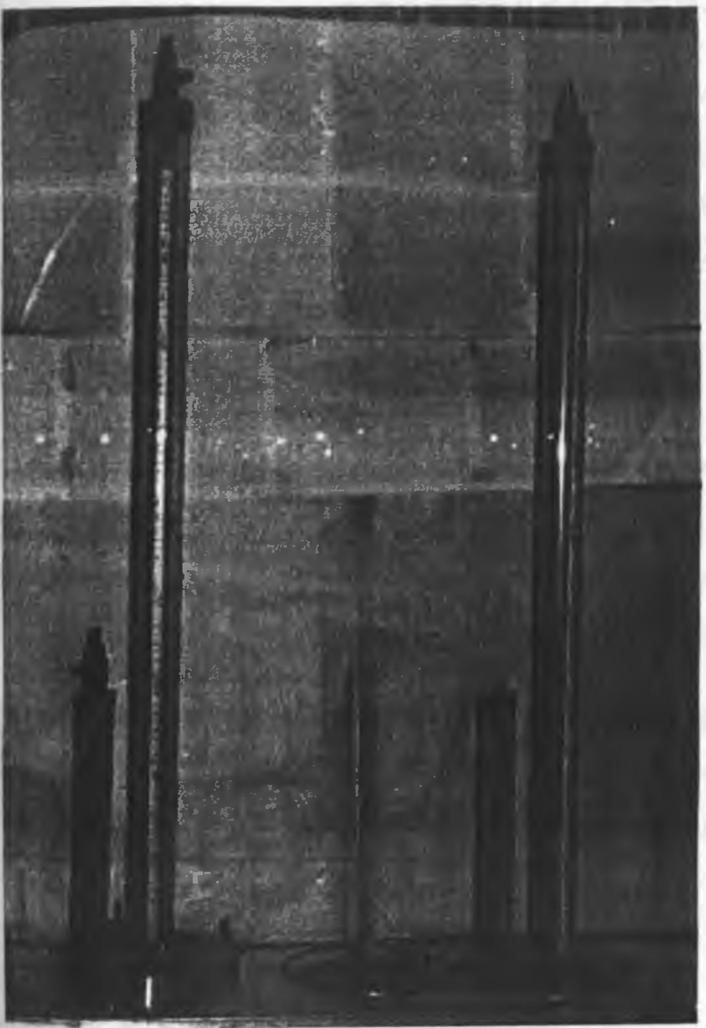
3.5.5 Hydraulic Conductivity

3.5.5.1 The Disc Permeameter

The CSIRO disc permeameter facility (Perroux and White, 1988) was used to measure soil hydraulic properties in the field (Plate 3.7). This is a three dimensional flow equipment used for in-situ measurement of infiltration and hydraulic conductivity. This equipment enabled rapid measurement of hydraulic conductivity with minimum soil disturbance.

This equipment is in two types: the unsaturated (negative water potentials), and the ponded (positive head disc permeameter). The unsaturated disc permeameter was the one used in the experiment.

The disc permeameter was chosen for use due to its relatively rapid measurements, robustness, ease in use, and its ability to characterise the sorptivity, hydraulic conductivity (White, et al., 1992).



(a) ponded **(b) unsaturated**

Plate 3. 6 Disc Permeameter used in surface soil hydraulic measurements.

Calibration of the disc permeameter reservoirs using the available water at the site was done and applied in the hydraulic conductivity determination.

3.5.5.2 Hydraulic Conductivity.

Hydraulic conductivity measurements were conducted under un-saturated conditions using the disc permeameter shown in Plate 3.7 above.

Monitoring effort concentrated on the surface soil conductance since it was the most limiting factor due to surface sealing and crusting. However, the long period of running the conductivity at every location permitted characterization of the whole profile conductance.

Measurements were carried out at a potential of negative 40 mm. Scale increments at constant time interval of one and two minutes for sorptivity and steady water flow states were used. Recording after the sorptivity stage was done interruptedly till steady flow was reached at which 10 measurements were taken.

3.5.6 Soil Water Release Characteristics

The water-holding capacity and soil water release characteristics of each runoff and differential tillage depth plot as influenced by its particular treatment were measured in the lab with the use of the pF-meter. The pF-meter used in the laboratory for soil-water release characteristic determination was the 15 bar ceramic plate Extractor CAT NUMBER 1500.

Due to time and equipment limitation, only the first season's samples were processed together with those from the differential tillage depth. Undisturbed soil samples were collected from both runoff and differential tillage depth plot sites and used in the determination of the soil moisture release characteristics.

The difference between water held at 0.3 bars (pF 2.5) and permanent wilting point 15 bars (pF 4.2), was designated available water capacity of the soil. Similarly the difference between the soil moisture at any particular time, from that of the permanent wilting point was considered as available water.

3.5.7 Water Stable Aggregate Stability.

Three replicate samples were collected from all treatment plots at the start and end of each rain season for the soil's water stable aggregate stability. The samples were passed, through 4.75 and 2 mm sieves with the portion remaining on the 4 75 mm and that which passed through the 2 mm discarded. From the clods retained on the 2 mm sieve, 25 gm was placed on top of a set of immersed sieves, of 1, 0.5 and 0.25 mm openings with the 2 mm sieve placed to barely touch the water to allow for capillary soaking for 10 minutes.

After ten (10) minutes the sieves were then fixed on a VIBRO type, TAMSON Retsch test sieve shaker (serial No. 10549025) with a wet sieving attachment set to run at 35 revolutions per minute. Water from a constant head apparatus 30 cm above the top sieve was then turned on to give a fine spray on the sample and then the shaker was switched on for 10 minutes. The test was conducted according to Kemper, (1965) and Hillel, (1980).

3.5.8 Soil Bulk Density.

The bulk density of the runoff and complementary moisture plots, as well as those of the moisture probe calibration sites were determined from the undisturbed core samples using a core sampler. Bulk density monitoring was done at the beginning and end of the short rain (first season), but due to limited data it was found necessary to increased to fortnightly during the long rain (second season). Two soil samples per location at a time were collected and soil bulk density determined.

3.5.9 Soil Texture.

The soil textural classes and distribution for site characterisation were determined in the lab with the use of the hydrometer method. Three representative locations, one per Block had disturbed soil samples collected and analysed for soil particle distribution.

3.5.10 Soil Organic Matter.

The organic matter content was determined using the standard Walkley - Black dichromate method. The organic matter content for site characterization was obtained from the same sample as that for particle size distribution.

Apart from the site soil characterization, soil samples were collected from each plot site for the determination of the initial organic matter status of the experimental plots. Soil sampling was done just before farmyard manure treatment application. Pre-treatment sampling was taken in order to establish the residual organic matter content to act as a basis for comparison across treatments. A multiple conversion factor of 1.73 was applied to convert the organic carbon to per cent organic matter.

3.5.11 Micro Relief Meter and Surface Roughness Measurements

3.5.11.1 Micro Relief Meter

The Micro Relief Meter used in this experiment was a modified version of the one used by Kuipers (1957) as shown in Plates 3.8 and 3.9. It consisted of a 120 by 25.5 cm mainframe with a board made by joining 5 cm wide and 2 cm thick aluminium bars. A hollow needle screw mounted locking bar was placed across the middle of the frame.

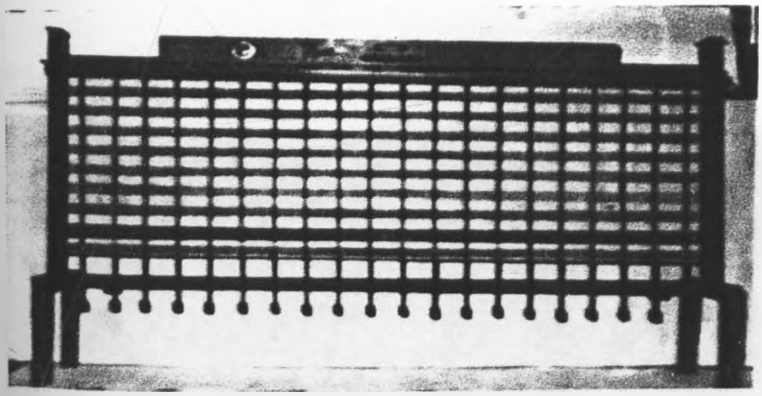


Plate 3. 7 Micro Relief Meter

Both the frame and the bar had twenty needle holes in place, through which twenty small pins were allowed to slide freely. These twenty pins are covered at the bottom with pieces of rubber tubes to provide support against penetrating into the soil. A reference level was marked on the board for horizontally aligning the locking bar.

At the ends of the frame were fixed two stands that supported and helped in horizontal levelling of the equipment. By means of a spirit-level, the frame was placed horizontally above the soil surface, fixed by the two stands at the end of the frame, which was being pressed into the soil. Each measurement resulted into 20 figures, a column each corresponding to one position of the frame. The distribution of this figure was a measure of the surface roughness. This distribution was composed of three components; the clods and soil aggregate, the furrows and the differences in height present before tillage or an inclination of the soil surface to the frame.

3.5.11.2 Soil Surface Roughness Measurements

Determination and monitoring of the soil's oriented surface roughness was carried out with the use of a surface relief meter (Figure 3.12). Micro relief consisted of ridges and furrows as well as the macro-structure of the soil. Measurements were carried out on a weekly basis to obtain a measure of the soil surface variability from tillage, through to the end of each rain season.

Measurements per treatment plot were taken perpendicular to the ridges and furrows as in Plate3.9. Since the length of monitoring depended on the length of the rain season a total of 9 and 18 sets of readings for the short and long rains respectively were obtained, three per plough type and per monitoring day.

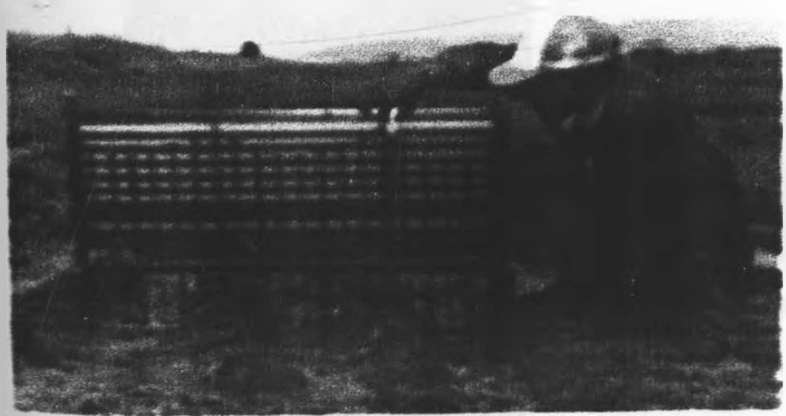


Plate 3. 8 Micro relief measurement with the use of the Micro Relief Meter

Measurements were conducted at random within each plough treatment area. Each measurement consisted of 20 points along a distance of one meter, making a total of 540 height readings per plough treatment.

The three sets of measurements per treatment plot were averaged to give the standard deviation and thus the soil surface roughness was obtained with the use of equation:

$$SR = 100 \log \sigma \qquad (3.8)$$

Where:

SR = The surface roughness

σ = The standard deviation per the treatment plot readings

3.5.12 Shear Vane

The Pilcon Direct Recording Hand Vane Tester (Plate 3.10) shear vane was used in the determination of soil shear strength of the treatment plots on a fortnightly basis with all measurements taken along with soil moisture measurements. Three replications per treatment were taken and analysis.

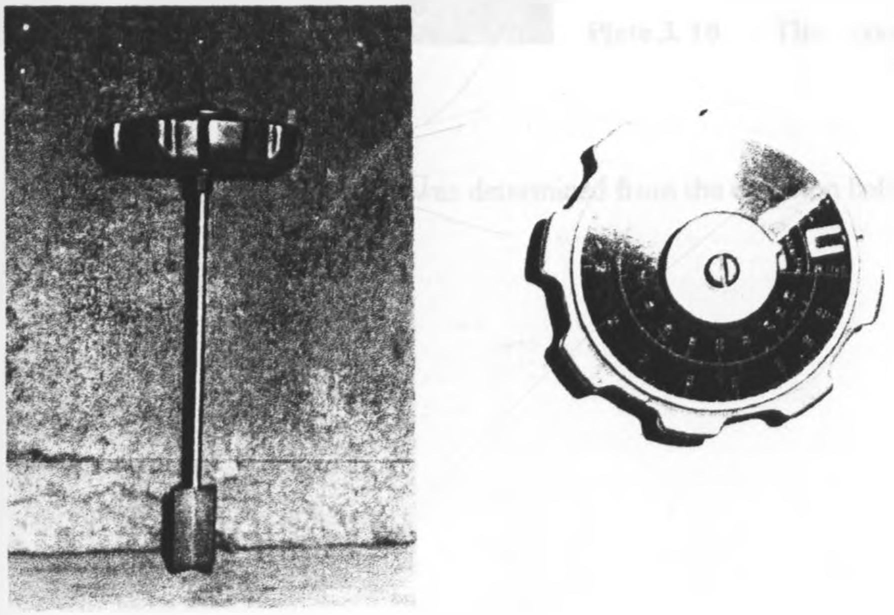


Plate 3. 9 Shear Vane Apperatus

3.5.13 Penetration Resistance

3.5.13.1 Hand Penetrometer

A hand cone penetrometer Type 1B, from Eijkelkamp Equipment (Plate 3.11) for measurement of top soil layer (0–10 cm)penetration resistance was used in this study whenever the penetrogragh (Figure 3.16), was not available due to logistical problems.

Two cone sizes were used in the experiment depending on the soil hardness (i.e. 0.25 cm^2 and 0.5 cm^2), with a range of three compression springs (50N, 100N, 150N). the choice of a cone and compression spring depended on the expected penetration resistance. However, the compression spring was 150N widely used in the investigations.

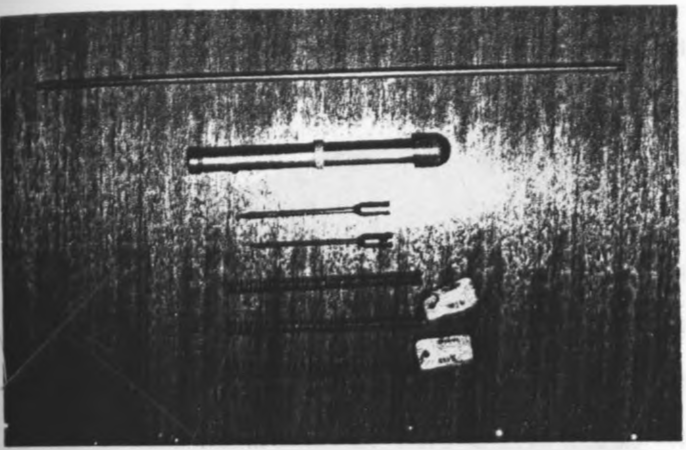


Plate 3. 10 The cone penetrometer unit

The hand cone, penetration resistance (CI) was determined from the equation bellow:

$$CR = CS \times \frac{Sc}{Ac} \quad (3.9)$$

Where:-

CI = Cone resistance (N cm^{-2})
CS = Compression of spring (cm)
Sc = Spring compression constant
A_C = Area of the cone (cm^2)

3.5.13.2 Stiboka Penetrograph

The Stiboka penetrograph (an Eijkelkamp Equipment) shown in Plate 3.12 was used to produce a graph (diagram) representing the core resistance in relation to penetration depth. The depth measuring range was up to 80 cm, based on the recording of the compression of the calibrated spring, while at the same time the driving roller moved the recording card proportionally. This study however, concentrated on the upper 10 cm soil depth.

Plate 3. 11 The Eijkelkamp Stiboka Penetrometer

This instrument was provided with four cones of 1, 2, $3\frac{1}{3}$ and 5 cm^2 used depending on the anticipated range of soil resistance. The Stiboka Penetrograph on the other hand was used to produce a diagram that reflected the cone resistance in relation to penetration depth of 80 cm. The compression of the calibrated spring was recorded, while the driving roller moved the recording card proportionally.

Penetration resistance was then read against depth. The maximum resistance; encountered in the depth ranges of 0-10, 10-25, 25-40, 40-55, 55-70 and 70-80 were recorded.

3.5.14 The Site Slopes

3.5.14.1 Line Level

The site and plot slopes were measured using a line level instrument as shown in Figure 3.5 below. Slope measurements of the site were carried out across and down the slope per each block. The runoff plots were measured individually by placing the two line level pegs down-slope at up and lower inside edges of the plot borders. Depending on the positioning of the border, furrow or ridge positions might have affected the slopes of the individual plots.

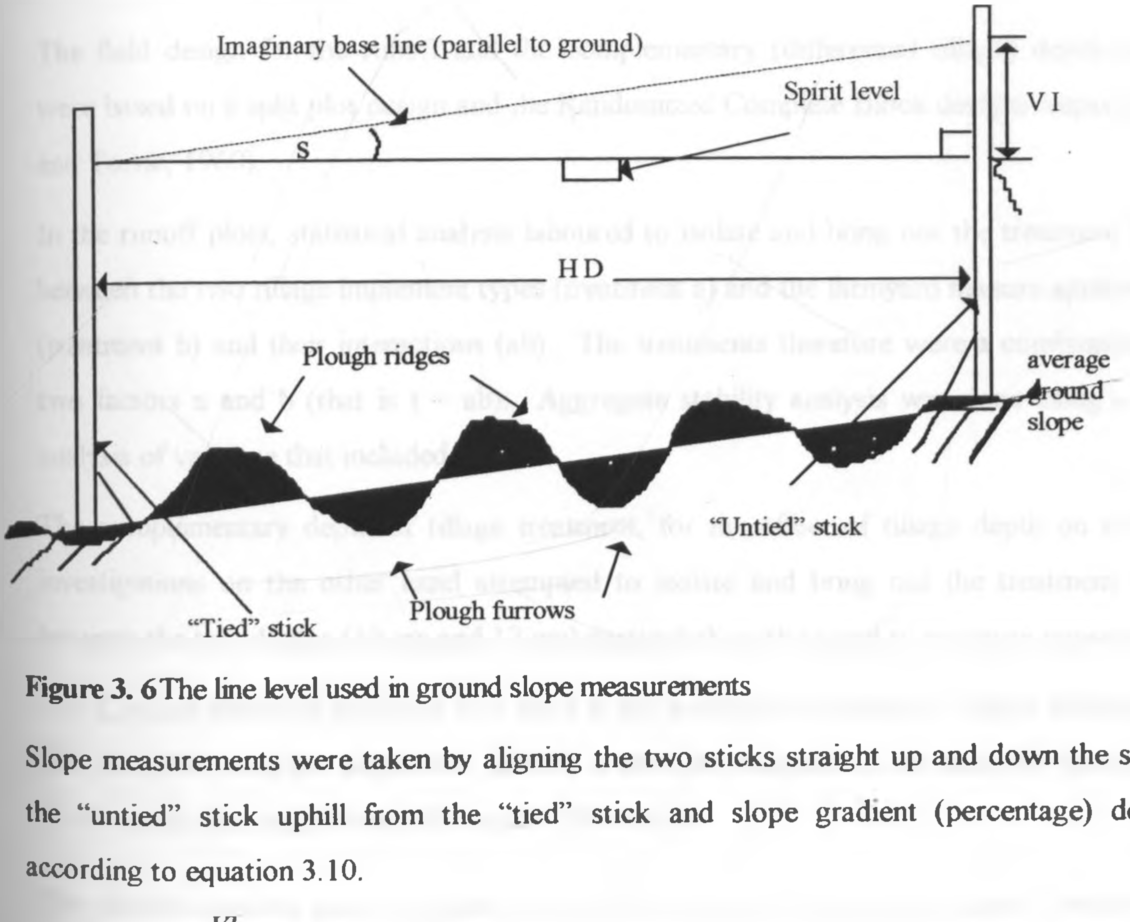


Figure 3. 6 The line level used in ground slope measurements

Slope measurements were taken by aligning the two sticks straight up and down the slope with the "untied" stick uphill from the "tied" stick and slope gradient (percentage) determined according to equation 3.10.

$$\% S = \frac{VI}{HD} \times 100 \quad (3.10)$$

Where:

% S = the per cent slope

VI = the vertical interval

HD = the horizontal distance

3.5.14.2 Land Slope

The main slope of the research site was found to be 8.5% ranging from 7.2 to 10% with a cross slope of about 1.3%. Figure 5.1a shows the individual run-off plot slope percentages that ranged from 7.5% to 15.5%. Blocking reduced the experimental treatment plots' slope effect to an average of 13.6% (11 to 15.5%); 11% (10.5 to 12%) and 9.5% (7.5 to 11.5%) in Blocks 1, 2 and 3 respectively.

3.6 Analysis of Data

The field design for the runoff and the complementary (differential tillage) depth experiments were based on a split plot design and the Randomized Complete Block designs respectively (Steel and Torrie, 1960).

In the runoff plots, statistical analysis laboured to isolate and bring out the treatment differences between the two tillage implement types (treatment a) and the farmyard manure application levels (treatment b) and their interactions (ab). The treatments therefore were a combination of these two factors a and b (that is t = ab). Aggregate stability analysis was done using a three way analysis of variance that included time.

The complementary depth of tillage treatment, for the effect of tillage depth on soil moisture investigations on the other hand attempted to isolate and bring out the treatment differences between the two depths (12 cm and 17 cm) particularly with regard to moisture conservation.

The Co-Stat statistical software was used in the analysis of variance (CoHort Software, 1990). The Duncan's multiple range test allowed a multiple comparison between the treatment means with a single least significant difference (LSD) value.

The rainfall erosivity was correlated and regressed against soil loss and runoff, while the rainfall data was analyzed using the t-test at 5% probability to determine if there were any significant differences between the weekly averages of the long-term and the experimental year. The current year's rainfall data for the recording and the non-recording rain-gauges were similarly analyzed for their significant differences

4. RESULTS AND DISCUSSION

4.1 Soil Hydrological Characteristics

4.1.1 Soil Moisture Release Characteristics

Tables 3.2 and Figures 4.1 and 4.2 show the site soil water release characteristics (pF curves) for the runoff and the complementary (differential) tillage depth treatments. The curves have taken a sigmoid form, with the horizontal displacement principally reflecting texture, while the shape relates more to structure. In such non-swelling soils the soil water release characteristics reflect the pore-size distribution. Any given point on the curve therefore, represent a moisture content at which pores of larger than the corresponding equivalent diameter will be air filled and those smaller will be water filled. Figure 4.1 shows the profile water release characteristics under the influence of the plough implement type and plough implement-manure interaction treatments. The water retention under manure treatment has shown to be more than that without manure.

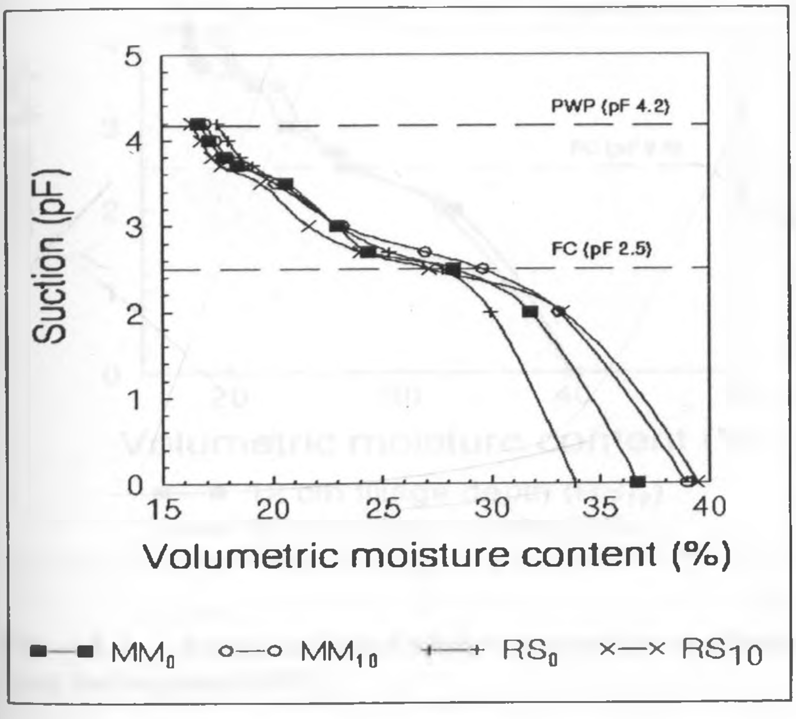


Figure 4. 1 Average soil water release characteristics as influenced by plough implement and manure treatment interaction, during the short rains (1994/95).

Figure 4.1 shows that at less than pF 2 (0.1 bar) suction the MM and RS with 10 tonnes per hectare FYM application responded similarly and were higher than their controls. This could have been influenced by the manure treatment. At field capacity (pF 2.5), however, the MM with 10 tonnes manure surpassed the rest. This could have been due to the less tillage (soil disturbance) and the corresponding resultant soil aggregate stability.

Figure 4.2 shows the profile water release characteristics under the influence of the complementary (differential) tillage depth treatments under the influence of 10 tonnes farmyard manure application. Under the differential tillage depth treatments, water release above field capacity showed to be the same but thereafter the 17 cm tillage depth maintained higher moisture content over the 12 cm depth. This could be explained by the incorporation of FYM and clay from lower soil horizon and thus an increase in the specific surface area.

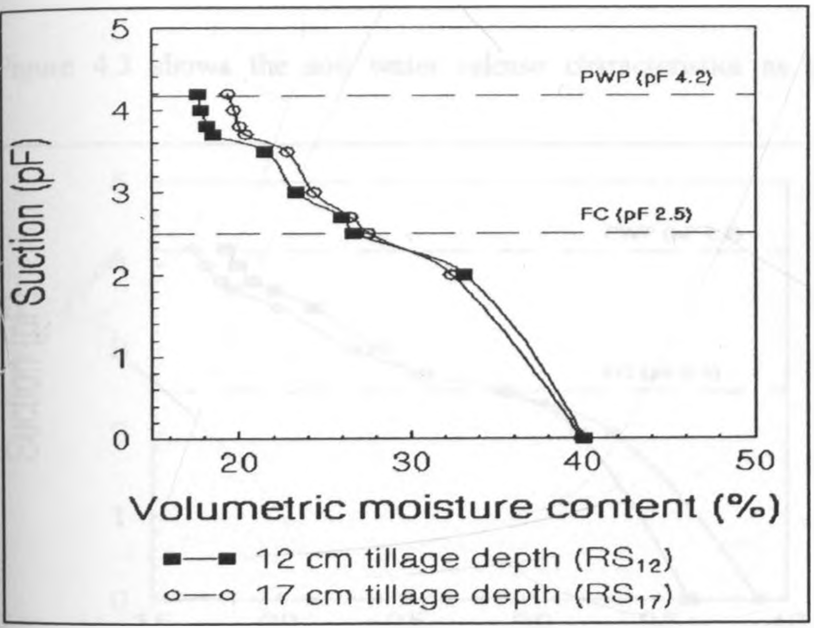


Figure 4. 2 Average soil water release characteristics as influenced by differential tillage depth, during the long rains (1995).

Table 4.1 shows treatment soil water release characteristics for the runoff and differential tillage depth (RS_{12} and RS_{17}) treatments. The measured water content across treatments of each depth was appreciable in the lower compared to the higher suction ranges.

The differences in the moisture content in the lower suction range could be attributed to structural and organic matter content differences. The smaller variation at the higher suction is explained by the fact that water content here is related to soil texture, which is fairly uniform.

Table 4.1 Treatment soil water release characteristics data

Treatment	Percentage volumetric moisture content											
	Suction (pF)											
	0	2	2.5	2.7	3	3.5	3.7	3.8	4	4.2	Average	Available water
MM$_0$	37	32	28	25	23	21	19	18	17	17	24	12
MM$_{10}$	39	33	30	27	23	20	19	18	17	17	24	13
RS$_0$	34	30	28	25	23	20	19	19	18	18	23	10
RS$_{10}$	40	34	28	25	22	20	18	18	17	17	24	11
RS$_{12}$	40	32	25	24	22	20	18	17	17	17	23	9
RS$_{17}$	40	32	27	26	24	23	20	20	20	19	25	8
Average	38	32	28	25	23	21	19	18	18	17	24	10

Figure 4.3 shows the soil water release characteristics as influenced by farmyard manure treatment. As was expected the 10 tonnes per hectare farmyard manure (10 FYM) treatment held more water that was released more slowly above field capacity than the 0 FYM. However, this water above field capacity was loosely held and thus was easily lost to drainage.

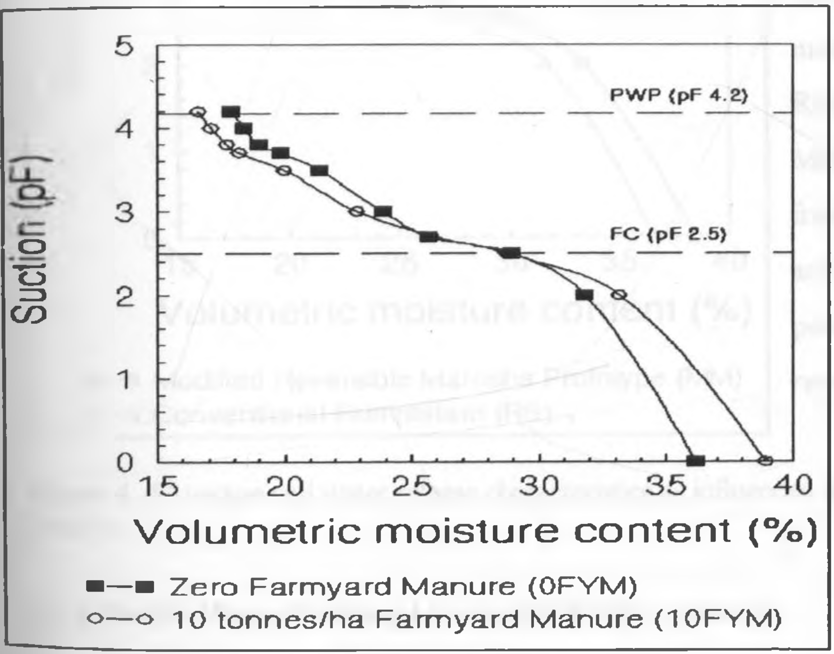


Figure 4. 3 Average soil water release characteristics as inflenced by farmyard manure 1994/95.

Under field condition however, this water would be lost not only through drainage but through evaporation also. This partly explains why the field soil water under the manured treatments (see section 4.4) was almost always below the non-manured treatments. Improved capillary water movements due to manure could have also influenced this trend.

Below the field capacity however, there was more available water under the 10 FYM than the 0 FYM. Moisture content released ranged from 18% to 36% under 0 FYM and 16.5 % to 39.2 % under 10 FYM at permanent wilting and at saturation respectively.

At field capacity, water held was however, the same under both treatments, with more water released, under 10 FYM at permanent wilting point.

Figure 4.4 shows the soil water release characteristics as influenced by the plough implement type treatment. The Modified Reversible Maresha Prototype (MM) plough implement showed to hold more water throughout the monitored suction levels and held more water than the Conventional Rumptstad (RS) plough implement. Moisture content released ranged from 16.5% to 36.8 % under RS and 17.5% to 38.5 % under MM at permanent wilting and at saturation respectively.

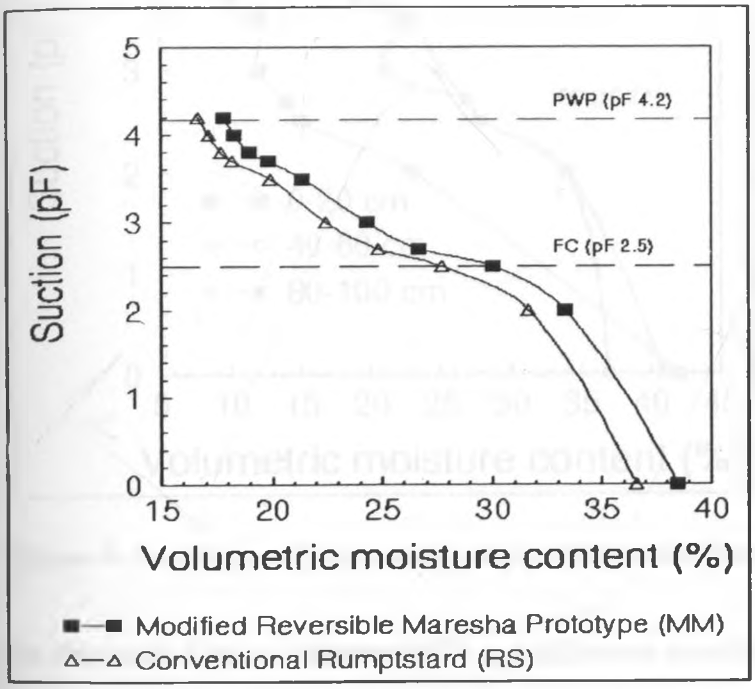


Figure 4. 4 Average soil water release characteristics as influenced by plough implement type, 1994/95.

4.1.2 Profile Water Holding (Available Water) Capacity

Table 4.1 shows the profile water holding capacity of the experimental site. Soil moisture content per se however, is of limited value, since the measured moisture in the soil at any moment is not necessarily available to the growing crop. The moisture at field capacity (pF2.5), or at permanent wilting point (pF4.2) is not utilized by the crop. Available water capacity would therefore, be the appropriate measure to use as an index of the ability of a soil to store water and sustain plant growth during dry spells. Available water capacity is therefore the amount of water between the field capacity and the permanent wilting points, expressed in volumetric percentage or in millimetres of water for a given depth of soil.

Figures 4.5 and 4.6 shows the profile water release characteristics per soil profile depth range as influenced by depth of tillage and 10 tonnes' manure application. As discussed under section 4.1.2 and as shown in Table 3.2 the soil's water holding capacity increased with depth (Figures 4.5 and 4.6).

Soil moisture retention is shown to be influenced more by higher clay content down the profile depth as opposed to tillage practice and manure application.

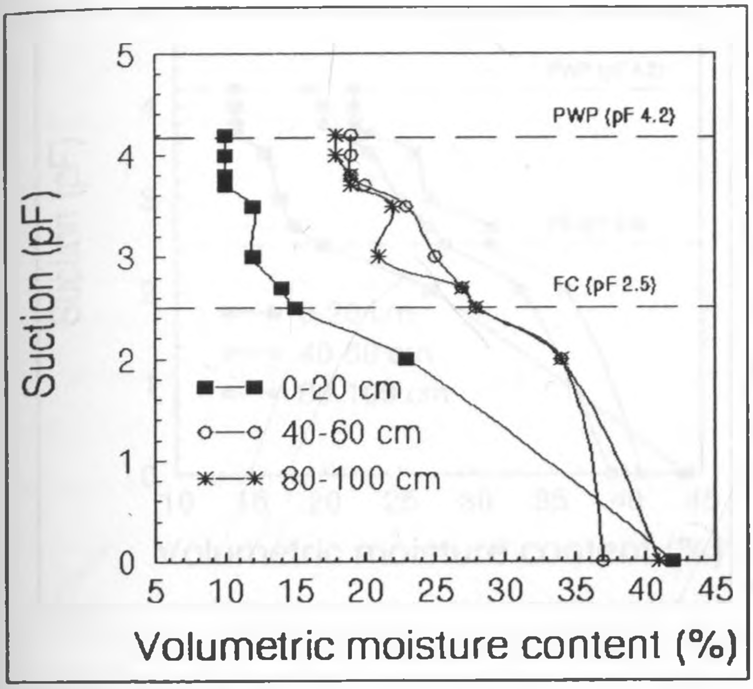


Figure 4. 5 Average soil water release characteristics as influenced by the 12 cm depth of tillage.

As shown in Table 3.2 above, there is a difference in water retention of 6% between the top 20 cm depth (where manure and plough implement treatments were applied) compared to that at 60 to 100 cm depth. Examination of Table 4.1 also shows that tillage practice and farmyard manure application improved the soil moisture characteristics by only 1%. The availability of soil moisture however, has shown to be positively influenced by tillage practices and farmyard manure as shown in Figures 4.3 and 4.4 than clay content down the profile.

Retained water at field capacity and the permanent wilting point like the general water release characteristics increased with depth, ranging from 24% to 31% and 14% to 19% respectively at the upper and lower profile horizons. The upper 20 cm depth had 2% available soil moisture compared to the depth immediately below, signifying the influence of surface management on soil moisture availability. The soil profile below the 60 cm depth showed a 1% reduction in available water capacity, possibly due to the presence of petroplinthite (murram) detected during soil sampling and high clay content. This trend is similar to that obtained by Kilewe and Ulsaker (1984), at the same site.

Under the 17 cm tillage depth treatment, however, the 80-100 cm soil profile maintained higher moisture content over the 40-60 cm profile as shown in Figure 4.6. This could have been due to the higher clay content in the lower soil depth profile. Generally, the 17 cm tillage was better in water holding and poor in water release than the 12 cm tillage depth.

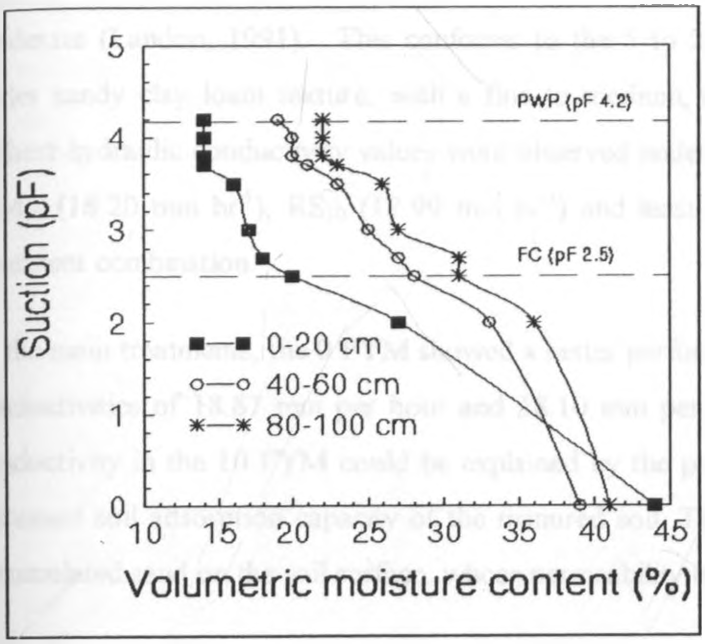


Figure 4. 6 Average soil water release characteristics as influenced by the 17 cm depth of tillage.

This could be explained by the incorporation of farmyard manure and clay brought up from the lower soil horizon and thus an increase in the specific surface area.

In the 12 cm tillage depth treatment, water release except at saturation was not much different for the 40-60 cm and 80-100 cm profiles (see Figure 4.5). This may reflect the transient argillic nature of these semi-arid Luvisols.

4.1.3 Soil Hydraulic Conductivity

Hydraulic conductivity measured under unsaturated conditions showed that MM_O had better conductance compared to the MM_{10} treatment combination. The RS, on the other hand showed that manure treatment enhanced unsaturated hydraulic conductivity. Due to poor working conditions of the ponded disc permeameter, the saturated hydraulic conductivity measurement was not determined.

The hydraulic conductivity ranged from 15.55 to 22.0 mm per hour, classified as slow to moderate (Landon, 1991). This conforms to the 5 to 20 mm per hour hydraulic conductivity under sandy clay loam texture, with a fine to medium, sub-angular blocky soil structure. The highest hydraulic conductivity values were observed under MM$_0$ (22.20 mm hr^{-1}) followed by the MM$_{10}$ (18.20 mm hr^{-1}), RS$_{10}$ (17.99 mm hr^{-1}) and least was the RS$_0$ (15.55 mm hr^{-1}), for the treatment combination.

In the main treatments, the 0 FYM showed a better performance than the 10 FYM with hydraulic conductivities of 18.87 mm per hour and 18.10 mm per hour respectively. The lower surface conductivity in the 10 FYM could be explained by the presence of the smaller soil colloids and increased soil adsorption capacity of the manured soil. The non-manured soil on the other hand accumulated sand on the soil surface, whose permeability is high.

In the plough implement type treatment, MM was observed to have had a higher hydraulic conductivity compared to the RS with values of 20.2 mm per hour and 16.77 mm per hour respectively.

As reflected in Figure 4.29, the MM$_{10}$ under dry conditions, showed higher shear strength compared to the MM$_0$, indicating cohesiveness and thus impediment to water flow. These results, thus show that water movement in this type of soil and environment could be influenced more by saturated than unsaturated hydraulic conductivity.

4.2 Seasonal Rainfall Variability and Distribution

4.2.1 Seasonal rainfall amount, duration and distribution

The daily rainfall data for the 1994/95 is shown in Appendix 1.1. During the experimental period recorded, storm rainfall ranged from 1.1 mm to 67.8 mm; 0.3 mm to 32.5 mm, with standard deviations of 16.2 mm and 9.0 mm during the short rains (1994) and long rains (1995) 36 respectively. The highest monthly rainfall amounts were received in November (297.9 mm) and

March (151.4 mm), for the short and long rains respectively (Figures 4.7 and Tables 4.2 and 4.3). This rainfall is about twice (1.9 times) the 38 year long-term average of 155.4 mm and 79.0 mm for the same months. Moreover, though the short rains' monthly maximum corresponded with the long-term average maximum, the long-term average maximum differed. The long-term average maximum of 143.5 mm occurred in April during which only 66.3 mm was received during the study period.

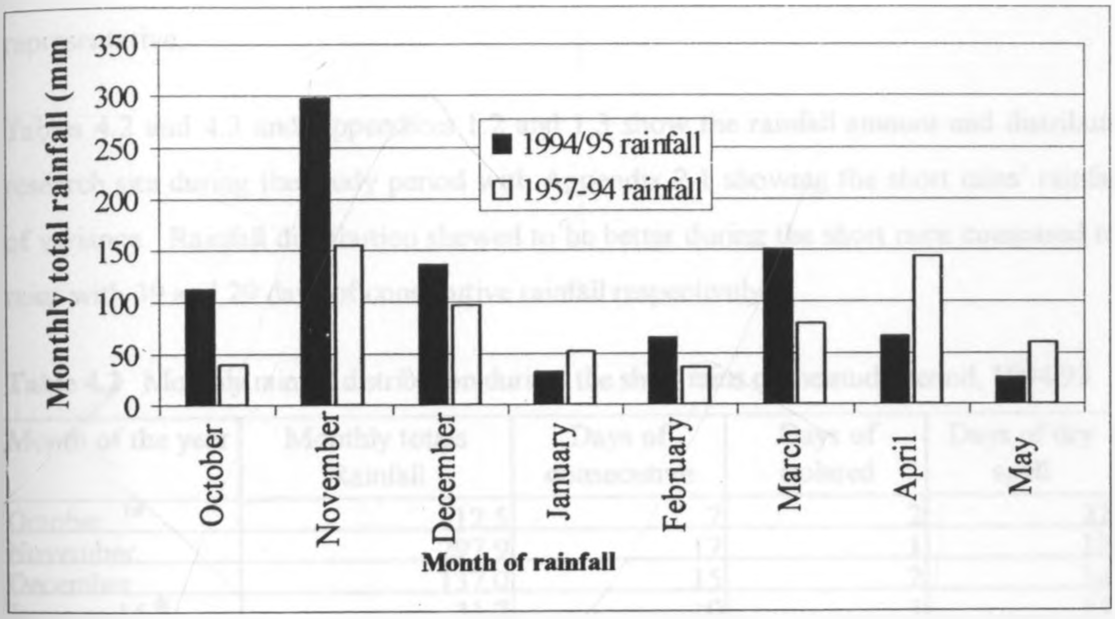


Figure 4. 7 Comparison of seasonal (1994/95) with the long-term (38 years record) rainfall distribution

During the experimental period, a total of 888.0 mm was recorded as against 663.2 mm average totals over a 38 year long-term period. The study period, therefore had 1.34 times more rain than the long-term average. The recorded storm duration, during the experimental short rains period ranged from 7.8 minutes to 571.2 minutes, with rainfall amounts of 0.1 mm and 41.6 mm respectively.

During the short rains period (October to January) a total of 579.1 mm was recorded and was 1.68 times higher than that of the long term average (343.9 mm). During the long rains period however, the total rainfall of 308.7 mm was 0.97 times that of the long-term average rainfall (319.3 mm).

4.2.1.1 Rainfall events, amount and distribution

The long-term rainfall record (38 years) shows a minimum total annual rainfall of 156 mm in 1958 and as much as 875.8 mm in 1961 for the short rains. The long rains total rainfall, however, has had as little as 55.4 mm in the year 1984 and as much as 556.9 mm in 1990, (see Appendix 1.4). This high variation thus makes effective planning difficult. The t-Test for the long term (1957-94) and the short-term (1994/95) rainfall periods showed no significant difference (see Appendix 2.1) between them. The soil and hydrological response to rainfall effect would therefore, considered representative.

Tables 4.2 and 4.3 and Appendices 1.2 and 1.3 show the rainfall amount and distribution at the research site during the study period with Appendix 2.1 showing the short rains' rainfall analysis of variance. Rainfall distribution showed to be better during the short rains compared to the long rains with 39 and 29 days of consecutive rainfall respectively.

Table 4.2 Monthly rainfall distribution during, the short rains of the study period, 1994/95

Month of the year	Monthly totals Rainfall	Days of consecutive	Days of isolated	Days of dry spell
October 1st	112.5	7	2	22
November	297.9	17	1	12
December	137.0	15	2	14
January 16th	31.7	0	3	13
Total rainfall	579.1			
Span of days		39	8	61
Span of rainfall days in the season 108				

During the study period the onset of rains were advanced. The short rains effectively started on the 13\10\94 during the 41st Julian week whereas normally effective rains do not start until after 21 of October (the 42nd Julian week). The long rains on the other hand had its onset advanced from mid-March to mid-February (the 6th Julian week).

Table 4. 1 Monthly rainfall distribution during, the long rains of the study period, 1994/95.

Month of the year	Monthly totals Rainfall (mm)	Days of consecutive rainfall	Days of isolated rainfall	Days of dry spell
February 9 th	64.8	7	0	13
March	151.4	11	2	18
April	66.3	6	5	19
May 18th	26.3	5	2	11
Total rainfall	308.9			
Span of days		29	9	61
Span of rainfall days in the season 99				

The highest number of rainfall events in any one month was recorded in November (18), and March (13) during the short and long rains respectively (Tables 4.2 and 4.3). The highest occurrence during the study period was in November as compared to the 1992/93 record of January with 23 events (Biamah et al., 1993). The lowest occurrence was recorded in January (3 events), with the rest of the other months as: October (9), December (17), February (7), April (11) and May (7).

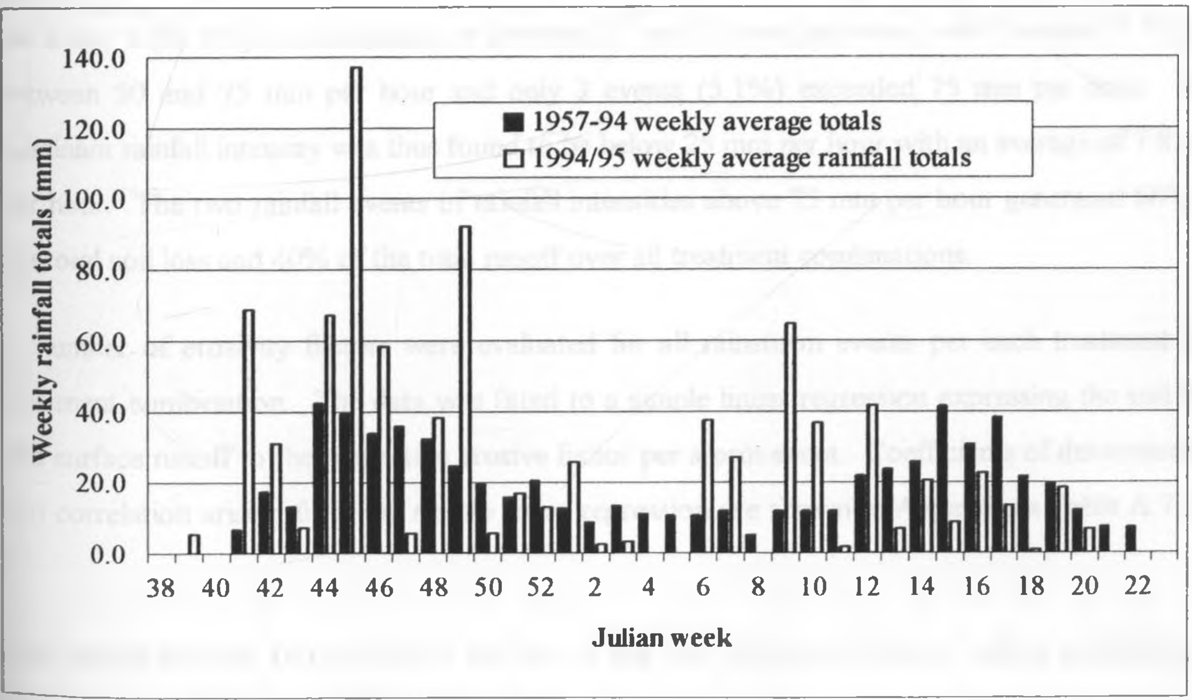


Figure 4. 8 Long-term and 994/95 season's total weekly rainfall distribution

The longest dry spell from onset to end of rains occurred in April (19) followed by March (18), all during the long rains. Coupled with the low rainfall amounts during any rainfall event, these dry spells worsened the soil moisture availability throughout the vegetative, floral and ear-initiation (with the greatest draught sensitivity) stages, (Nadar, 1984). The advance of the long rains during the study period affected the normal rainfall distribution by effecting an early rainfall retreat from 22nd to the 20th Julian week (Figure 4.8).

Rainfall steadily decreased from April to 18th May (20th Julian week) as compared to the long-term when it goes to the end of the 22nd Julian week (Figure 4.8). This shows the erratic nature of the rainfall of this area and conforms to the observation by Stewart (1980) and Stewart and Hash (1982), that effective rainfall for maize production at Katumani is strongly correlated with the date of the on-set of the long rains compared to the short rains periods.Rainfall Intensity and Erosivity

4.2.2 Rainfall intensity and erodibility

During the study period, out of the 39 storm events, 25 (64.1%) had intensities less than 25 mm per hour, 9 (23.1%) had intensities of between 25 and 50 mm per hour, with 3 events (7.7%) of between 50 and 75 mm per hour and only 2 events (5.1%) exceeded 75 mm per hour. The dominant rainfall intensity was thus found to be below 25 mm per hour with an average of 7.8 mm per hour. The two rainfall events of rainfall intensities above 75 mm per hour generated 66% of the total soil loss and 40% of the total runoff over all treatment combinations.

A number of erosivity factors were evaluated for all rainstorm events per each treatment and treatment combination. The data was fitted to a simple linear regression expressing the soil loss and surface runoff to the respective erosive factor per storm event. Coefficients of determination and correlation arising from the simple linear regression are shown in Appendices Table A.7 and 8.

The rainfall amount (A) proved to be one of the best Erosivity factors, with a coefficient of determination (r^2) ranging from 0.56 to 0.78.

Analysis of rainfall characteristics has shown that this soil is highly susceptible to rainfall erosion when the ground has not been protected. Secondly, prediction of Erosivity in this environment is shown to be possible from regression equations using rainfall amounts in localities without automated rain gauges. Available rainfall data is therefore adequate for prediction of Erosivity and hence provides data in planning erosion control measures.

4.2.3 Rainfall and runoff responses to tillage

4.2.3.1 Rainfall, runoff and soil loss responses to tillage treatments Short Rains Period, 1994/95.

Figures 4.12, 4.13, and 4.14 shows the rainfall-infiltration response to tillage type and manure treatment interaction, manure and plough implement treatments respectively. The first seven storms and all the storms of the second (long rains) produced no runoff and thus infiltrated into the soil. During the short rains period, infiltration under all treatments showed a gradual decline with time at the same rainfall amount (see Appendix 2.2). This was attributed to the tendency of the soil to reach saturation as the rain season advances coupled with the decline in soil aggregate stability (aggregate structure). The gradual structural deterioration consequently reduced infiltration and increased runoff. The gradual structural deterioration is further explained by the increase in shear strength as shown in Figures 4.29, 4.30, and 4.32, and reduction in oriented surface roughness reflected in Figures 4.27, 4.28, and 4.29.

In the plough implement and manure treatment, the MM_{10} had the highest infiltration amount with an average of 22.8 mm under the MM_{10} followed by RS_{10} (20.2 mm), MM_o (19.8 mm), and RS_o (19.5 mm). Considering all the rainfall events throughout the season, the rainfall infiltration was highly significant within treatments and their interactions (see Appendix Table A.18).

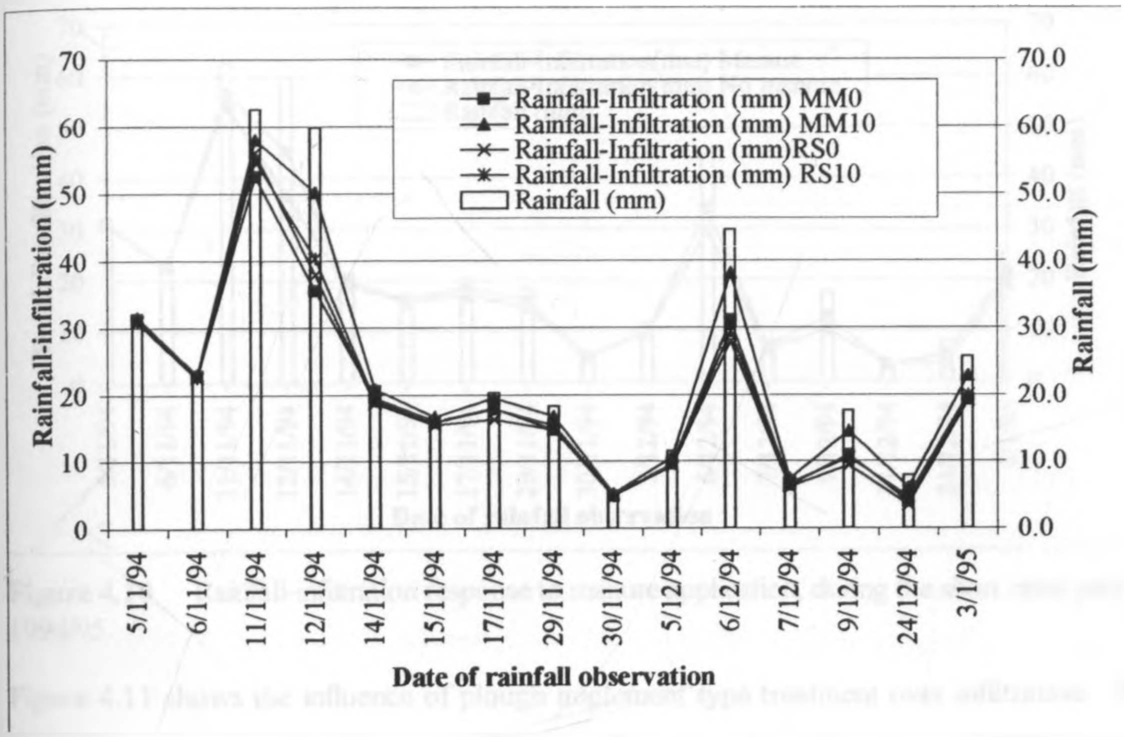


Figure 4. 9 Rainfall-infiltration response to tillage and manure application, during the short rains period, 1994/95.

Rainfall infiltration however, declined with time (see Figure 4.9) and the increase in percentage and runoff response to rainfall amount (see Appendix 1.6 and Figure 4.12 respectively). These effects were also attributed to the development of surface sealing and crusting that led to gradual deterioration of aggregate stability.

The farmyard manure (FYM) soil amendment treatment was highly significant in its influence on infiltration and runoff (see Appendices 2.2 and 2.3). The 10 tonnes farmyard manure (10 FYM) had 10.3 mm while the zero tonnes farmyard manure (0 FYM) had 9.9 mm average infiltration. Figure 4.10 shows the infiltration response to manure application. At the beginning of the season there were no treatment differences in infiltration and runoff losses, till high rainfall amounts were received which reduced the surface depression storage and soil structural conditions. The 10 FYM was greater than the 0 FYM throughout the season, though the response declined with time as reflected in Appendix 1.6 for runoff. Here again infiltration was influenced by rainfall amounts.

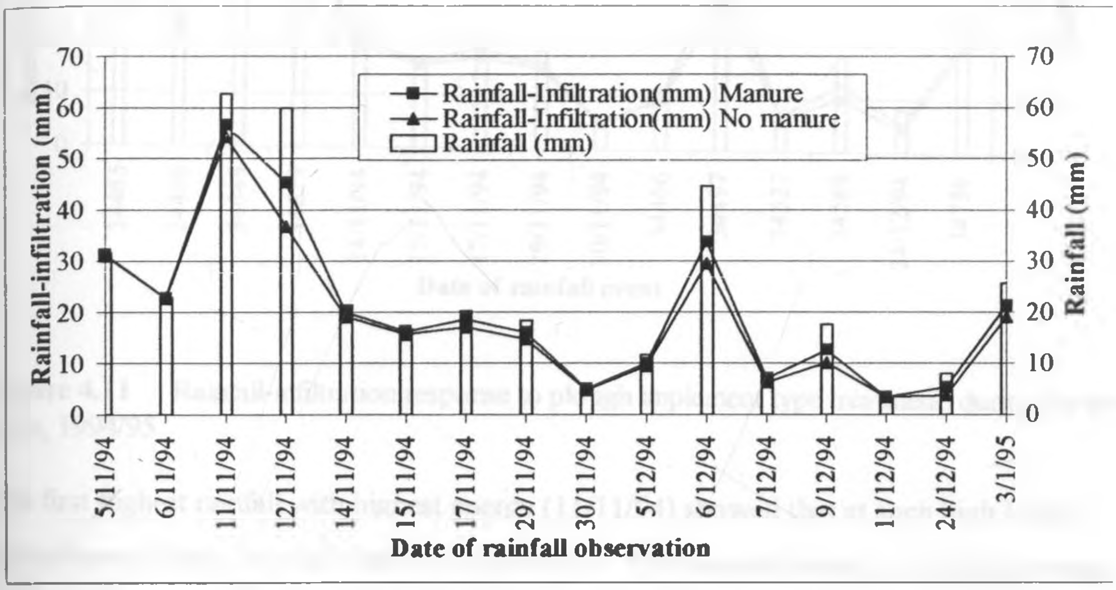


Figure 4.10 Rainfall-infiltration response to manure application, during the short rains period, 1994/95.

Figure 4.11 shows the influence of plough implement type treatment over infiltration. With time the effect of the Modified Reversible Maresha Prototype plough implement (MM) showed to be highly significant compared to the Conventional Rumptstad plough implement (RS) with infiltration averages of 10.3 mm and 9.8 mm respectively.

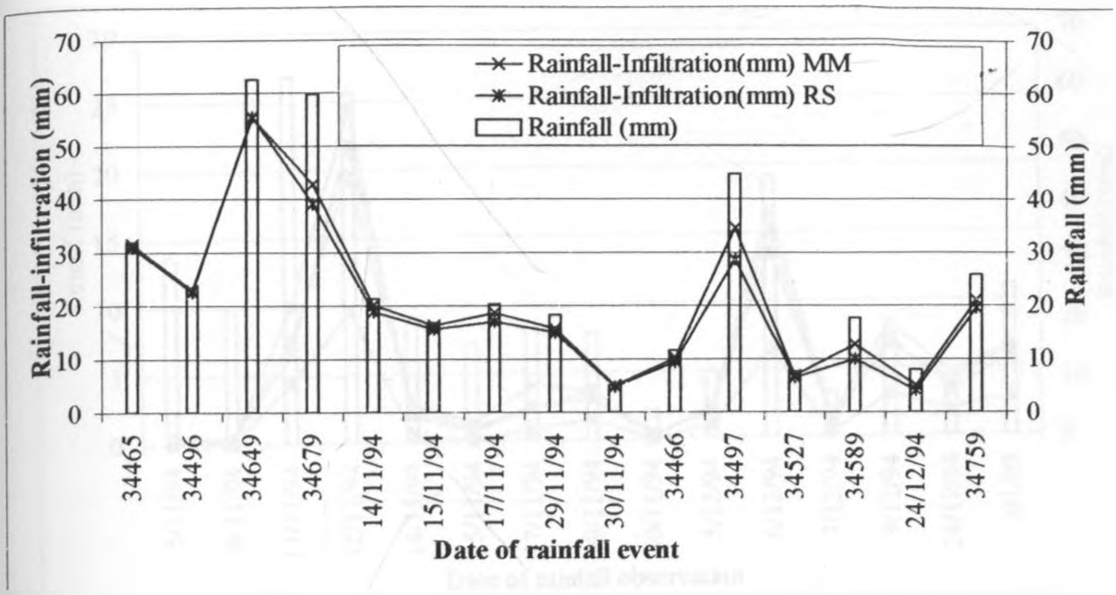


Figure 4.11 Rainfall-infiltration response to plough implement type treatment, during the short rains, 1994/95

The first highest rainfall with highest energy (11/11/94) showed that at such high levels, conventional tillage responds better to infiltration. This was attributed to the higher water absorptive surface area with high random roughness under conventional tillage.
The MM, however, being a strip-till had its surface roughness limited to oriented roughness whose depression storage once filled, overflows (see Appendices 1.13 and 1.14).

4.2.3.2 Rainfall, infiltration and runoff response due to tillage and manure treatments during the short rains period, 1994/95

Figures 4.12 and 4.13, shows the runoff water(mm) as influenced by the plough implement type and plough implement/manure application treatments. The percent rainfall-runoff response, though varying with type of treatment and storm characteristics, increased with time.

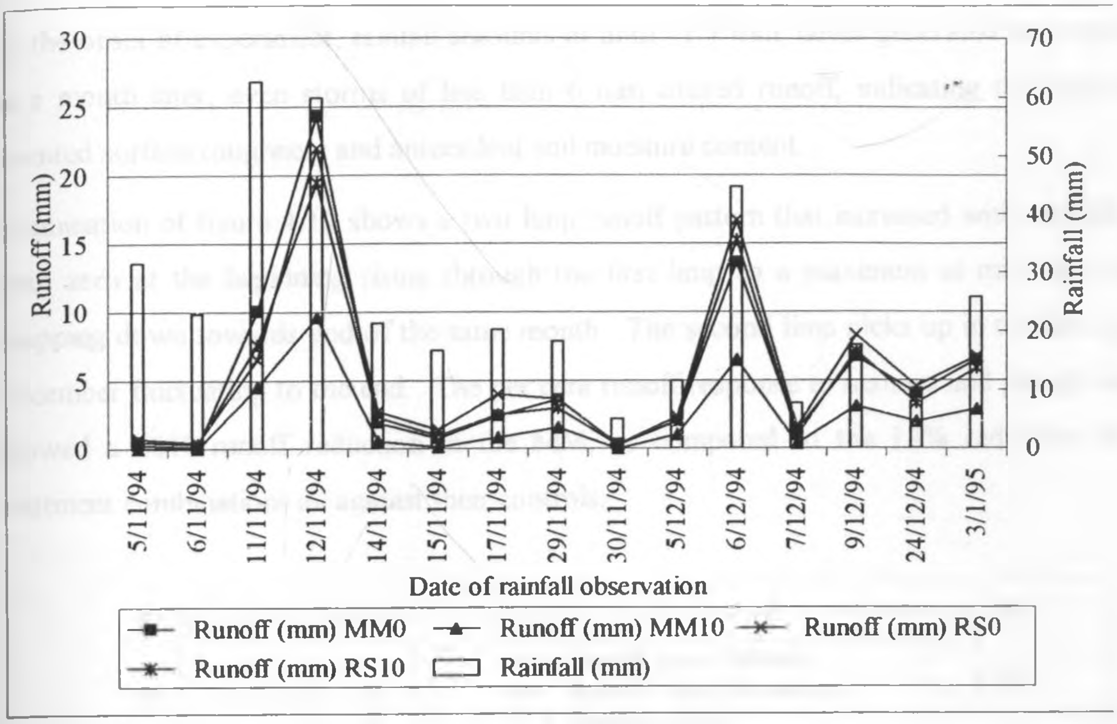


Figure 4.12 Runoff response due to tillage equipment and manure interaction, during the short rains period, 1994/95.

At the onset of experiment, rainfall amounts of unto 11.7 mm, never generated any runoff where as a month later, even storms of less than 6 mm caused runoff, indicating the importance of oriented surface roughness and antecedent soil moisture content.

Examination of figure 4.12 shows a two limp runoff pattern that increased with rainfall amount, from zero at the beginning rising through the first limp to a maximum at mid November and dropping down towards end of the same month. The second limp picks up in the first quarter of December fluctuating to the end. The per cent runoff response to manure and plough implement showed a 68% runoff reduction in the MM, as compared to the 18% reduction in the RS treatment combinations all against their controls.

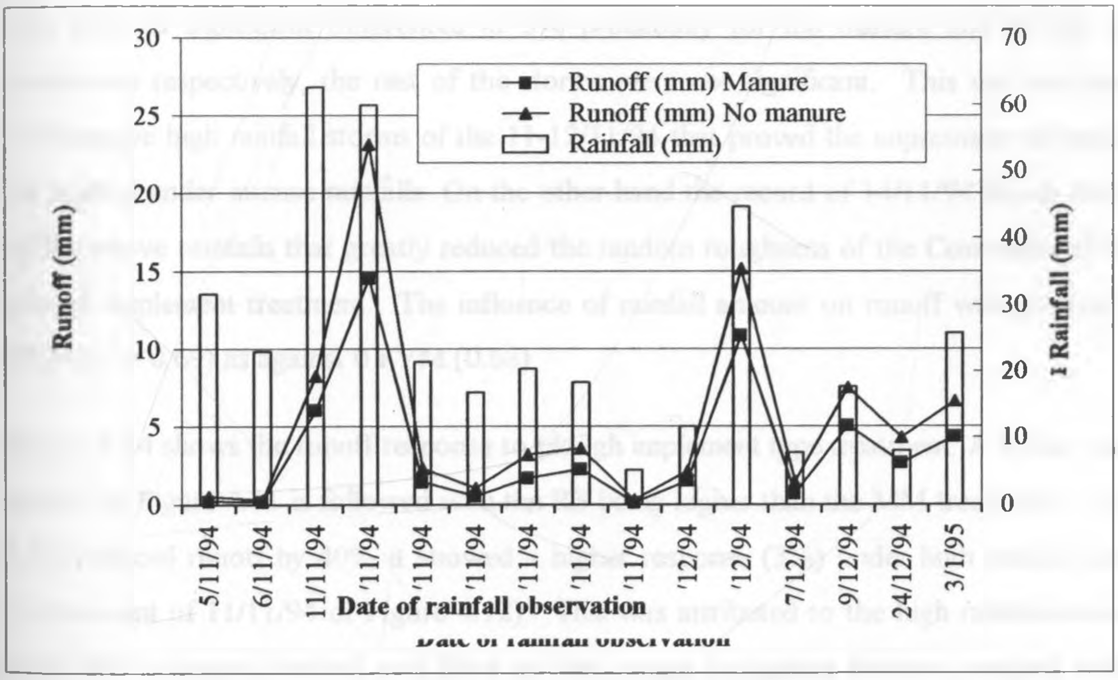


Figure 4.13 Runoff response to manure application, during the short rains period, 1994/95.

Figure 4.13 shows the runoff response to farmyard manure (FYM) application, during the short rains period, 1994. A similar runoff trend as in Figure 4.9 is followed, with manure treatment reducing runoff by 39% (see Appendix 1.6). The runoff response to farmyard manure treatment was significantly different with 0 FYM (1.9) and 10 FYM (1.2 mm). Farmyard manure and plough implement type interaction also showed to be significantly different with MM (1.8) and RS (1.3 mm as shown in Appendix 2.3).

A similar runoff trend as that of Figure 4.11 is followed with the RS being higher than the MM treatments. On a storm basis, out of 39 storms received from the onset of the experiment during the short rains period, 15 produced runoff. Except for the storm of 12/11/94 and that of 14/11/94 that showed significant differences at 5% probability for the manure and plough implement treatments respectively, the rest of the storms were not significant. This was attributed to the consecutive high rainfall storms of the 11-12/11/94 that proved the supremacy of manuring over its control under intense rainfalls. On the other hand the record of 14/11/94 shows the aftermath of the above rainfalls that greatly reduced the random roughness of the Conventional Rumptstad plough implement treatment. The influence of rainfall amount on runoff was greatest in the 10 FYM ($r^2 = 0.69$) as against 0 FYM (0.68).

Figure 4.14 shows the runoff response to plough implement type treatment. A similar runoff trend as that of Figure 4.11 is followed with the RS being higher than the MM treatments. Though the MM reduced runoff by 40% it showed a higher response (3%) under high rainfall amount (see storm event of 11/11/94 of Figure 4.12). This was attributed to the high rainfall amounts (62.6 mm) that saturated the soil and filled up the plough implement furrows coupled with its high rainfall kinetic energy (1364 Jm^{-2}). High rainfall kinetic energy caused soil compaction and particle detachment consequently plough implement furrows were silted-up causing reduction in detention storage. This storm consisted of two individual storms totalling to five hours and fifty-six minutes duration with the last phase having intensities above 75 mm hr^{-1}.

The influence of rainfall amount on runoff was greatest under the MM plough implement type with a correlation coefficient of ($r=0.70$) as against RS ($r=0.66$). The I_{30} coefficients of determination (r^2) against runoff were 0.52 (MM), 0.49 (10 FYM), 0.49 (0 FYM) and 0.47 (RS). In the treatment combinations the r^2 showed to be higher in MM_o (0.51), followed by the MM_{10} (0.50), RS_{10} (0.49) and the least was the RS_0 (0.46). Appendix 2.3 clearly shows that runoff treatment response is significantly different between the implement types and in their interactive effect with the farm yard manure.

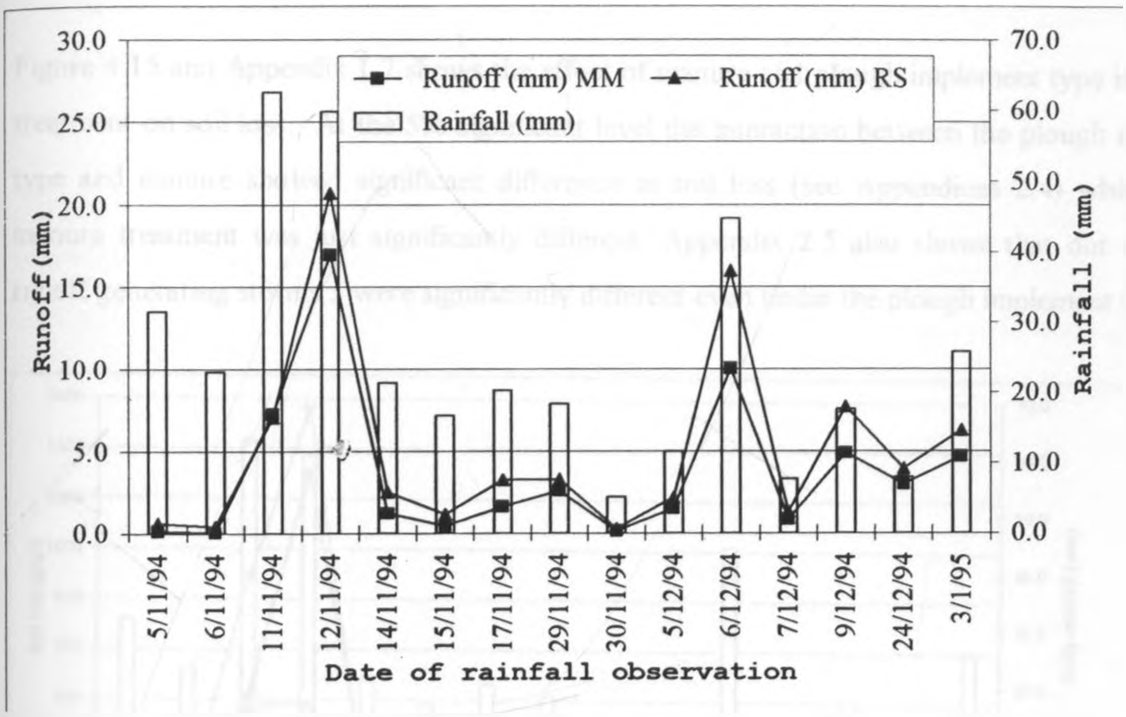


Figure 4.14 Runoff response to plough implement type treatment, during the short rains period, 1994/95.

The rainfall erosivity analysis has shown rainfall amounts, to be the best simple estimator of runoff with a coefficient of determination (r^2) of 0.98 and an r of 0.99 (with an $E = 21.1144\ A - 33.66$) as shown in Appendix 1.8 and 1.9)

4.2.3.3 Soil loss response to tillage and manure application.

Soil loss just like runoff, was influenced by tillage practice through the modification of soil surface configuration and application of manure. Tillage tool marks on the contour provided random and oriented surface roughness that gave rise to a reduced runoff that consequently led to reduced soil loss.

Figure 4.15 and Appendix 1.7 shows the effect of manure and plough implement type interaction treatment on soil loss. At the 5% significant level the interaction between the plough implement type and manure showed significant difference in soil loss (see Appendices 2.4) while that of manure treatment was just significantly different. Appendix 2.5 also shows that out of the 15 runoff generating storms 3 were significantly different even under the plough implement type.

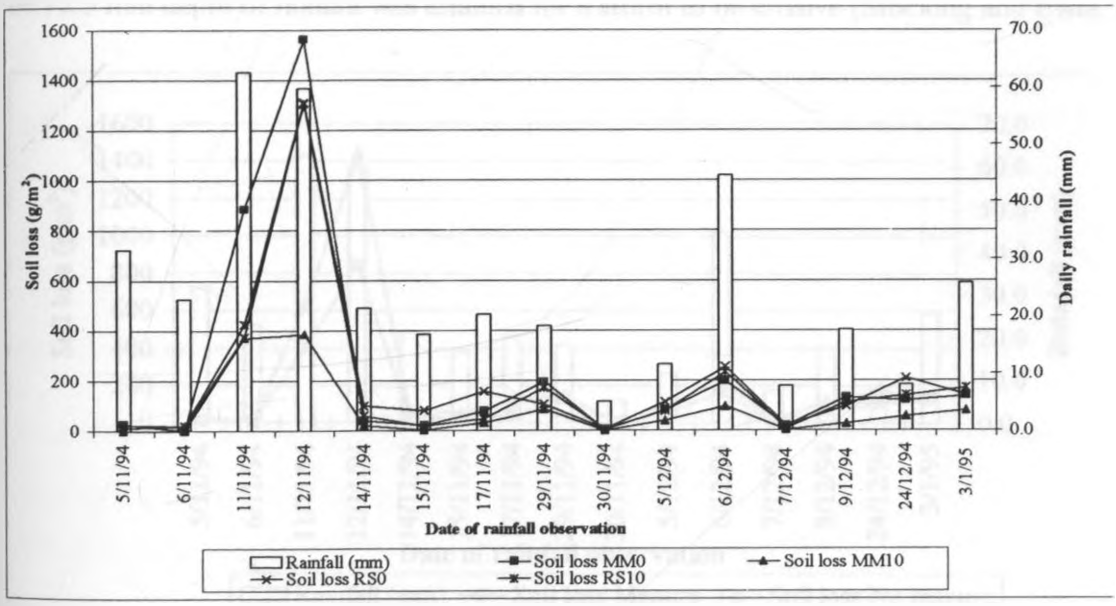


Figure 4.15 Treatment combination effect on soil loss during the short rains period, 1994/95.

During the short rains period, soil loss amounted to 3.5, 3.0, 2.8 and 1.2 kg/m^2 under MM$_0$, RS$_0$, RS$_{10}$ and MM$_{10}$, respectively. The 12/11/94 highest rainfall had a devastating effect on the MM$_0$, treatment due to overflow from the oriented surface roughness. The soil loss coefficient of variation (CV) showed to be influenced by the antecedent soil moisture condition and the amount of erosive rainfall (see Appendix 1.2).

The manure and plough implement interaction reduced soil loss by 66% in the Modified Reversible Maresha Prototype (MM) plough implement compared to only 7% in the Conventional Rumptstad (RS) plough implement over their respective non-manure treatment controls (see Appendix 1.7). The MM$_{10}$ was 48% lower in soil loss compared to the RS$_{10,}$ while the manure sub-treatment gave a 40% reduction in soil loss compared to the control with the MM tillage practice reduced soil loss by 19% compared to the RS.

The initial seven (7) rainstorms immediately after land preparation were less than 12 mm of rainfall each and never produced any runoff and soil loss and thus conformed to the Hortonian overland flow as described by Rowntree, (1987). This condition was satisfied when a minimum of 12.5 mm depth of rainfall was attained for a storm to be erosive (Stocking and Ewel, 1976).

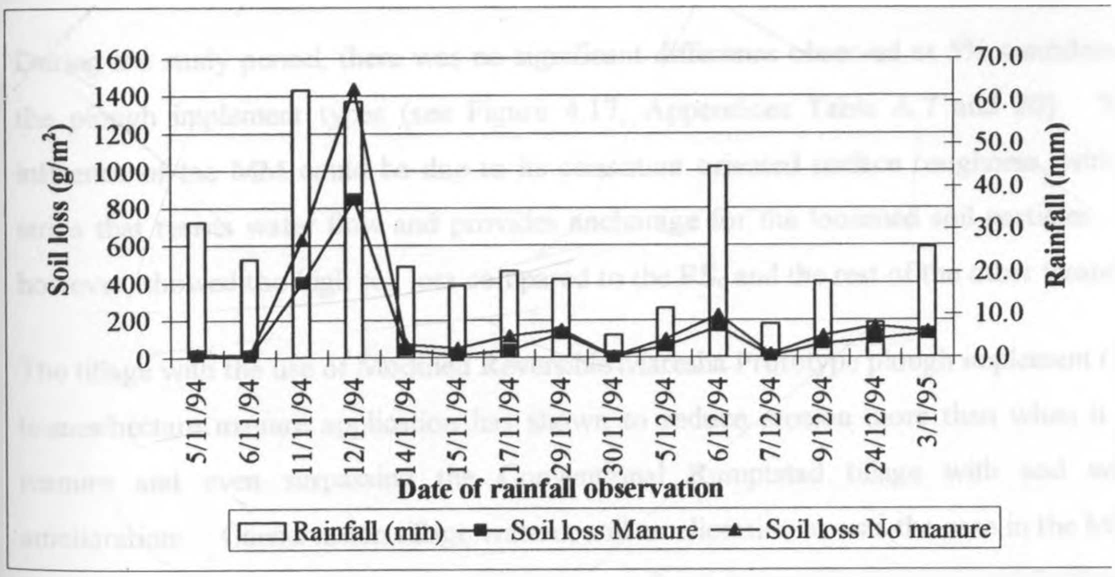


Figure 4.16 Manure treatment effect on soil loss during the short rains period, 1994.

Figure 4.16 shows the manure treatment effect on soil loss during the short rains period, 194/95. The total soil loss amounting to 2.01 and 3.25 kg m^{-2} were observed under 10 FYM and 0 FYM respectively. Manure treatment reduced soil loss by 39% signifying the necessity of manure incorporation into the soil on one hand and the better interactive capacity of MM and manure over the RS and manure.

The soil loss showed to be highly correlated to surface runoff ($r= 0.88$), followed by EI_{30} (0.87), KE>25 (0.85), E (0.82), rainfall (0.79), I_{30} (0.69) and least was duration of rainfall (0.56). This therefore shows that runoff is the most important single erosivity factor and its control would go a long way in reducing soil and nutrient losses in surface water. High rainfall amounts, coupled with high kinetic energy has equally shown to be very important in soil loss and thus good crop cover is imperative for soil loss mitigation.

In the interaction treatment, the highest r^2 was found to be between soil loss and KE>25 (0.88) followed equally by AI_{30} and EI_{30} (0.84), all under MM_{10}, followed by MM_0 with r^2 of 0.82 for EI_{30}, 0.81 (runoff), 0.80 (KE>25). The best r^2 for RS_0 and RS_{10} were 0.75 under the influence of runoff.

During the study period, there was no significant difference observed at 5% confidence level, in the plough implement types (see Figure 4.17, Appendices Table A.7 and 20). The overall influence of the MM could be due to its consistent oriented surface roughness, with non-tilled strips that resists water flow and provides anchorage for the loosened soil particles. The MM_0 however, showed too high soil loss compared to the RS_0 and the rest of the other treatments.

The tillage with the use of Modified Reversible Maresha Prototype plough implement (MM) at 10 tonnes/hectare manure application has shown to reduce erosion more than when it is without manure and even surpassing the Conventional Rumptstad tillage with and without soil amelioration. Conservation tillage without soil amelioration as was the case in the MM_0 and yet soil was partly loosen makes most of the loosened soil vulnerable to erosion under highly erosive conditions and once the micro-relief is filled up by water and runoff is generated.

The Conventional Rumptstad tillage and manure interaction treatment on the other hand showed to have reduced soil loss more than the Modified Reversible Maresha Prototype plough implement without soil amelioration.

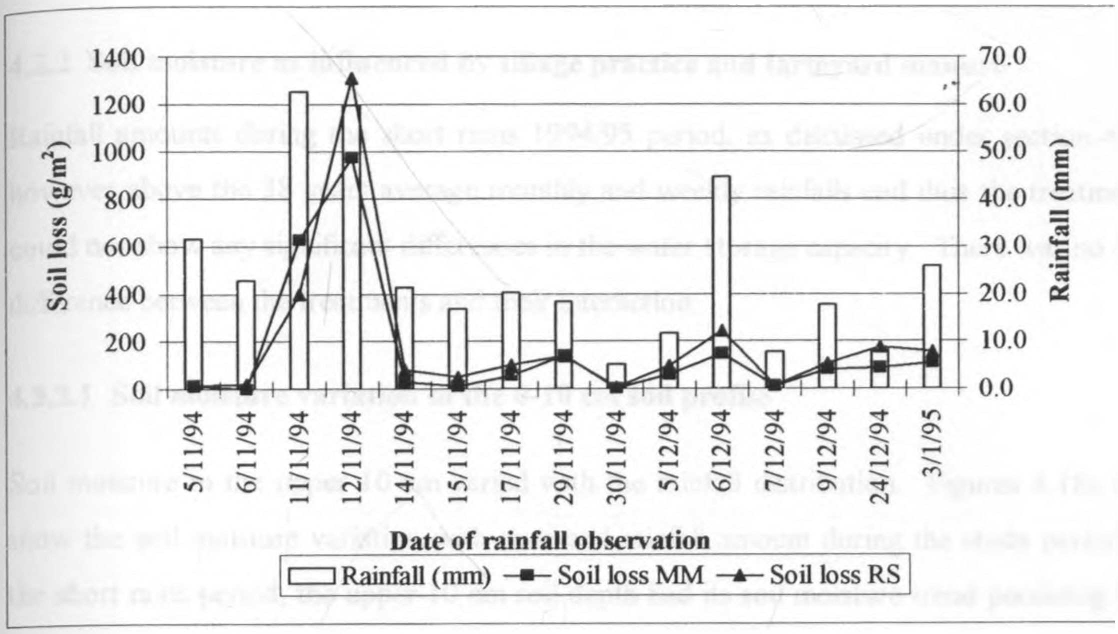


Figure 4.17 Plough implement type treatment effect on soil loss during the short rains period, 1994

4.2.4 Rainfall, runoff and soil loss responses to tillage treatments during the Short Rains Period, 1994/95.

During the long rains period, there was no significant amount of rainfall generating runoff and hence no data generated on soil loss as all the water infiltrated into the soil.

4.3 Treatment effect on Soil Moisture and Water Conservation

4.3.1 Treatment effect on soil moisture content and availability

Water in the soil is retained largely by surface tension, therefore its availability to plants does not correspond to the measured water content per se, but to the suction force, which plant roots, exert in maintaining transpiration requirements. Figures 4.18 to 4.21 and Appendices 1.10 to 1.12 show the total water storage and available water content (underlined) in MM for the respective soil-profile depths of 10 and 90 cm under the tillage practice and 10, 30, 60, and 90 cm for the differential tillage depth treatment and the rainfall received between the observation dates.

4.3.2 Soil moisture as influenced by tillage practice and farmyard manure

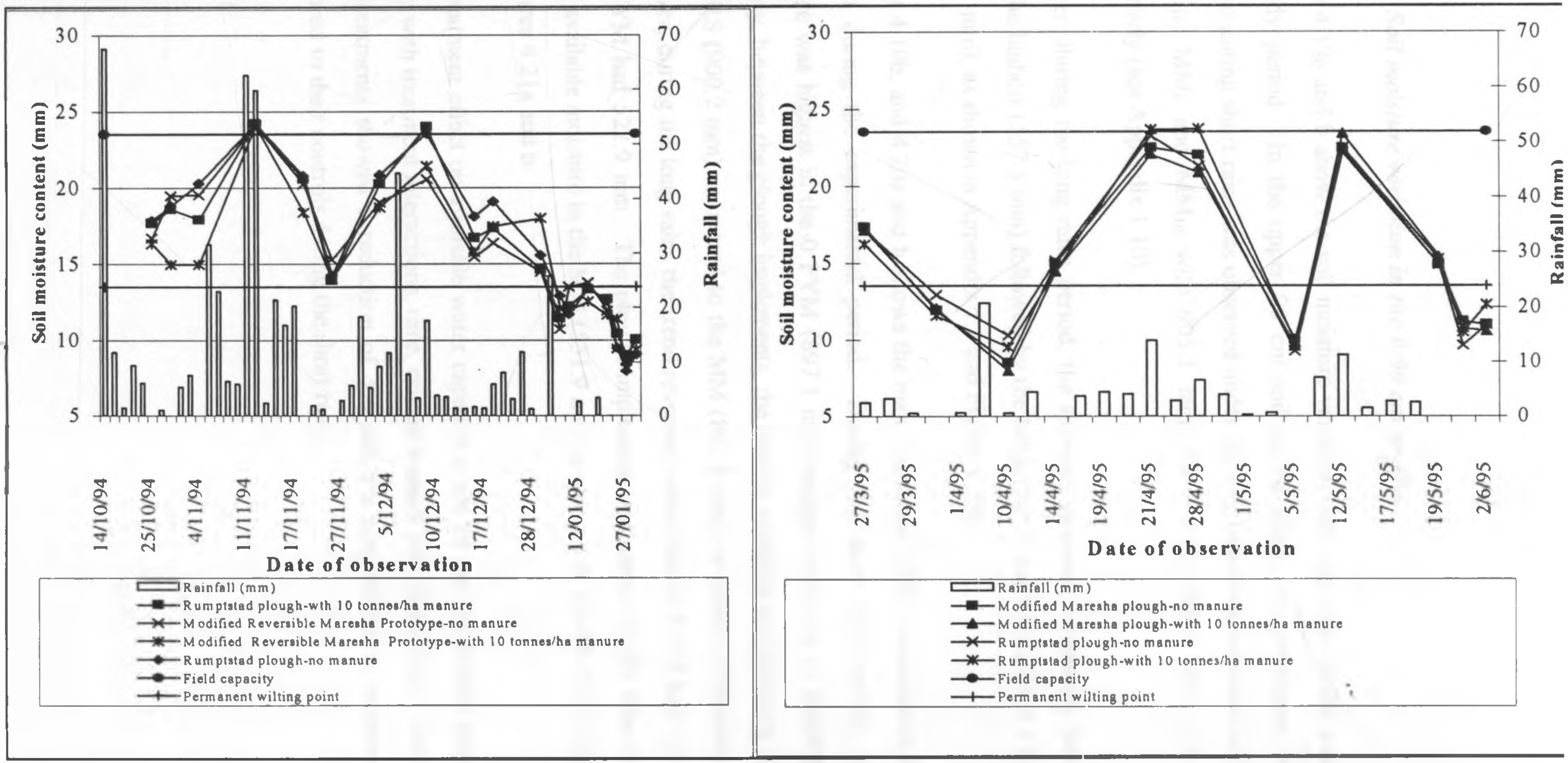
Rainfall amounts during the short rains 1994/95 period, as discussed under section 4.2.1 were however above the 38 years average monthly and weekly rainfalls and thus the treatment effects could not show any significant differences in the water storage capacity. There was no significant difference between the treatments and their interaction.

4.3.2.1 Soil moisture variation in the 0-10 cm soil profile

Soil moisture in the upper 10 cm varied with the rainfall distribution. Figures 4.18a and 4.18b show the soil moisture variation with time and rainfall amount during the study period. During the short rains period, the upper 10 cm soil depth had its soil moisture trend persisting above the permanent wilting point reaching field capacity in mid-November and coinciding with the maximum rainfall. All treatment combinations followed almost the same trend (see Figure 4.19a). However, during the long rains period, the onset of rains occurred with the conventional rains of February, thus moisture measurements lagged behind the rainfall events.

In both cases, the highest moisture content was in the RS (45.6 mm and 19.9 mm), main treatment followed by 0 FYM (41.4 mm and 18.4 mm), 10 FYM (35.0 mm and 18.4 mm) and MM (31.8 mm and 17.05 mm) during the short and long rains respectively. The 10 FYM treatment however, improved to match-up with 0 FYM during the long rains. This was attributed to the state and the properties of the manure after decomposition during the short rains and thus the soil structure and water holding capacity was improved.

In the 0-10 cm depth range therefore, the RS treatment proved superior in moisture storage capacity over the rest. Throughout the rain seasons, soil moisture kept on fluctuating following wetting due to rainfall and drying due to dry spells.


(a) Short rains period, 1994/95

(b) Long rains ,period, 1995

Figure 4.18 Plough implement type and manure interaction effect on soil moisture content as influenced by rainfall in the upper 10 cm soil profile.

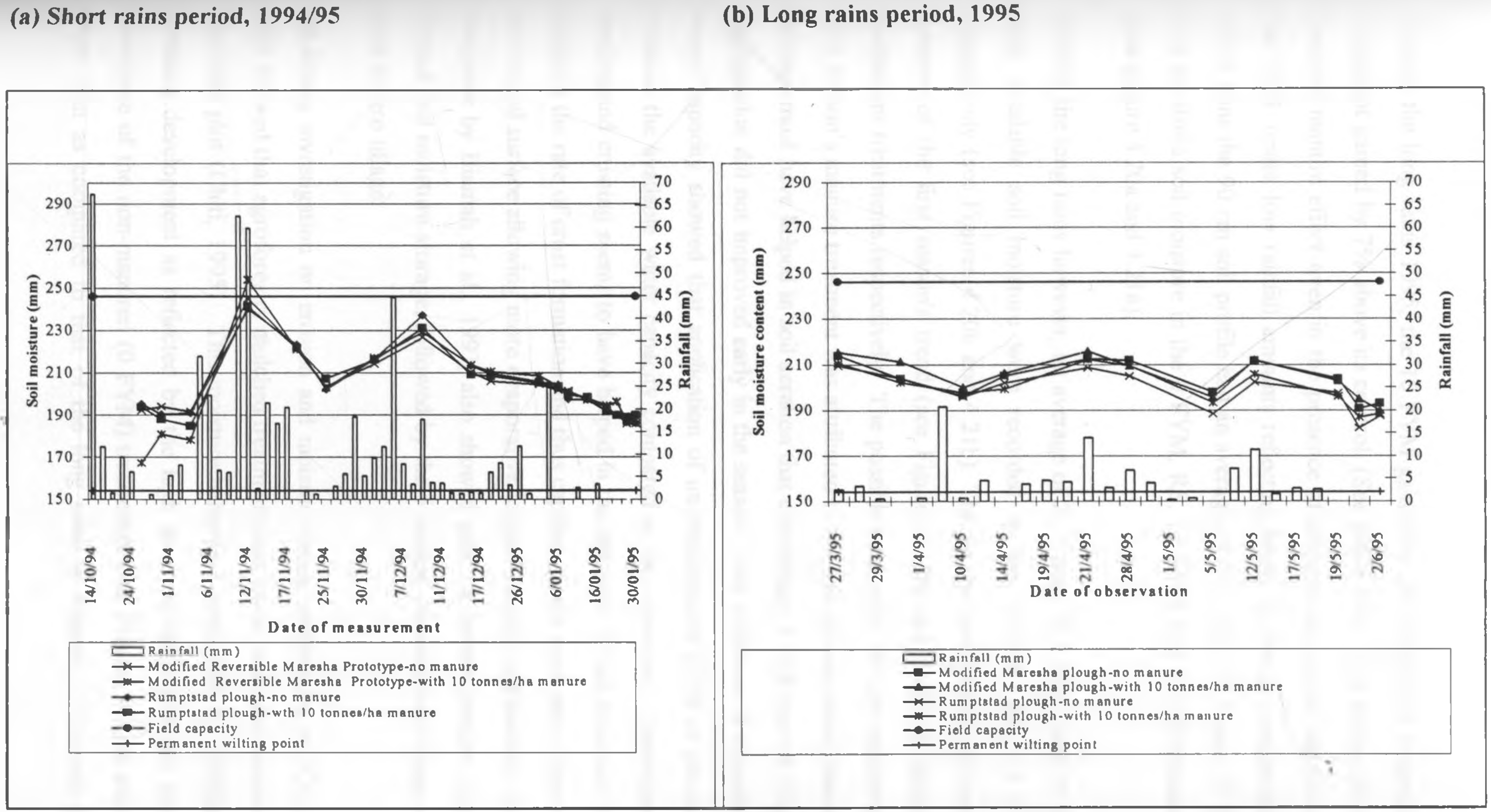
4.3.2.2 Soil moisture variation in the 0-90 cm profile

Figures 4.19a and b show the soil moisture variation with time and rainfall amount during the study period. In the upper 90 cm soil profile depth, the maximum available soil moisture during short rains was observed under the RS_0 treatment combination followed by the RS_{10}, MM_0 and MM_{10} with 905.1 mm, 895.3 mm, 889.0 mm, and 876.5 mm respectively (see Appendix 1.10).

However, during the long rains period, the situation reversed completely with the MM_{10} being the highest (557.3 mm) followed by the MM_0 (545.6 mm), RS_{10} (505.7 mm) and RS_0 (501.2 mm), as shown in Appendix 1.1 and Figure 4.19b.

Figures 4.19b, and 4.20a and b shows the main treatment effects on available soil moisture content during the experimental period. During the short rains period, available soil moisture was highest in the 0 FYM (897.1 mm) compared to the 10 FYM (885.9 mm). Similarly, between the plough implements, the highest available soil moisture was observed in the RS (900.2 mm) compared to the MM (882.8 mm) as shown in Figures 4.21a and b. However, during the long rains the trend reversed, where the 10 FYM had 531.5 mm while the 0FYM had 522.9 mm. The plough implement treatments on the other hand showed higher available moisture in the MM (551.9 mm) compared to the RS (503.7 mm) as shown in Figures 4.21a and b.

The treatment effect on available water capacity in the 90 cm soil profile therefore, varied greatly with treatment interactions, time, rainfall amount and distribution. The 10 FYM and MM treatments showed a reduction of 3% and 6% respectively in moisture availability compared to their controls during the short rains.



(a) Short rains period, 1994/95

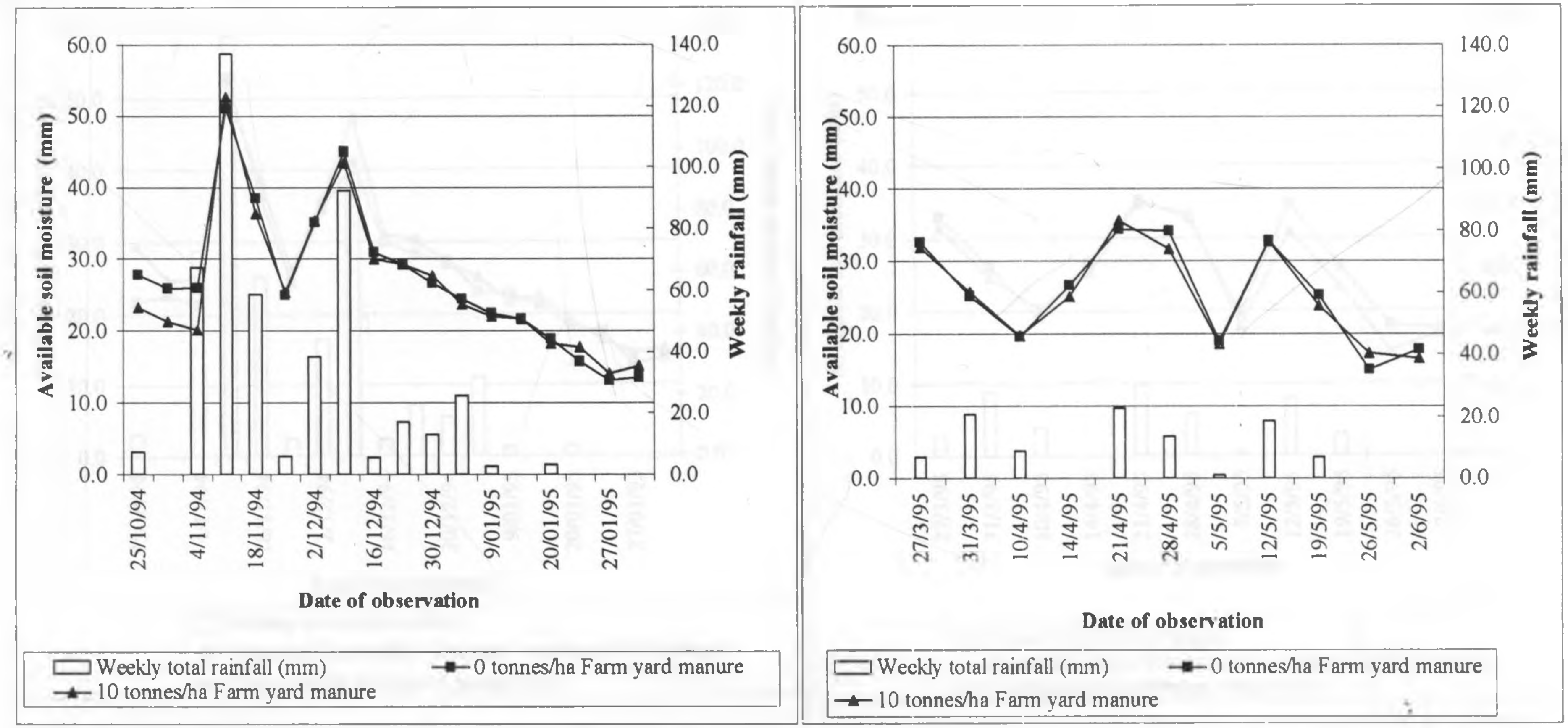
(b) Long rains period, 1995

Figure 4.19 Plough implement type and manure interaction effect on soil moisture content as influenced by rainfall in the upper 90 cm soil profile during the 1994/95 and 1995, rains period.

During the long rains 1995, the 10 FYM gained by 2% against its control while the MM treatment gained by 7% above its control. (See Table 4.4). This shows the contribution of residual manure effect even in the presence of non-rotted manure and the contribution of the MM, under low rainfall amounts reflecting better hydraulic conductance. During the short rains the 90 cm soil profile had an average of 27.3 mm, 27.8 mm, 26.5 mm, and 26.0 mm available soil moisture in the 0 FYM, RS, 10 FYM and MM treatments respectively, (see Figure 4.20a and 4.21a).

During the long rains however, an average of 25.7 mm, 26.2 mm, and 25.3 mm, and 24.8 mm, available soil moisture were recorded in the 0 FYM, RS, 10 FYM and MM respectively (see Figures 4.20b and 4.21b). The second season thus showed a gain and a reverse of the first season's trend (see Figures 4.20b and 4.21b in manure and plough implement treatments respectively. The possible reason for the low moisture content in the first season's manure treatment was attributed to the use of non-rotted manure. Non-rotted manure must have helped in soil aeration that encouraged a high rate of evaporation, while aggregation did not improved early in the season. The influence of manuring on available water capacity showed that application of un-decomposed FYM at the onset of rainfall reduces the available water capacity compared to non-manured. Development of surface sealing and crusting seems to have helped in the retention of soil moisture. Manuring thus reduced the rate of crust formation and thus capillary pores were more open and continuous to the soil surface allowing more evaporative losses. Graphs representing the soil moisture response by Biamah et al., 1993, also showed that 10 tonnes manure treatment had the lowest soil moisture storage, followed by the 5 tonnes, conventional tillage and the highest was in zero tillage.

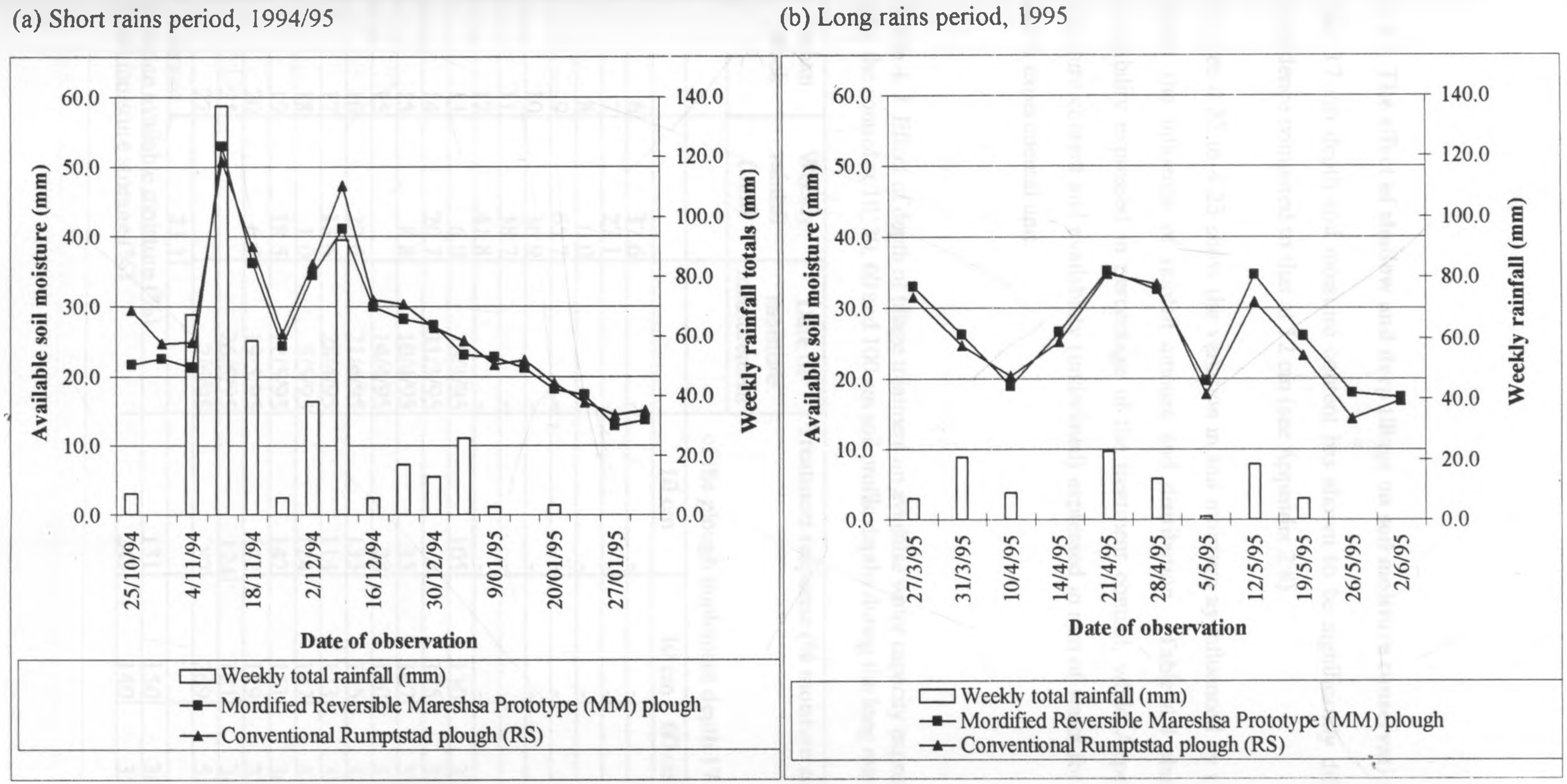
Mulching investigation on erosion and moisture being undertaken at ICRAF, Machakos, also showed that agroforestry mulched treatments had lower moisture contents compared to the bare plot (Chiti, 1995). This moisture behaviour could only be explained by the soil crusting development as reflected by the high shear strength and top layer penetration resistance of the non-manured (0 FYM) treatments (see Figures 4.31A and 4.39A) of the short rain as compared to that of the long rains in Figures 4.31b and 4.39b). Crust development therefore helped in reducing evaporation losses through curtailing of the continuity of capillary pores.



(a) Short rains period, 1994/95

(b) Long rains period, 1995

Figure 4.20 Manure effect on availability of soil moisture (mm) as influenced by rainfall in the upper 90 cm soil profile.


(a) Short rains period, 1994/95

(b) Long rains period, 1995

Figure 4.21 Plough implement type effect on the availability of soil moisture (mm) as influenced by weekly rainfall in the upper 90 cm soil profile.

4.3.3 The effect of shallow and deep tillage on soil moisture conservation

The 17 cm depth soil moisture content has shown to be significantly different at 5% level of confidence compared to that at 12 cm (see Appendix 2.8).

Figures 4.22 to 4.25 show the variation in soil moisture as influenced by tillage depth treatment under the influence of rainfall amount and distribution. Table 4.4 shows the soil moisture availability expressed in percentage of the treatment control, while Appendix 2.12 shows soil moisture content and availability (underlined) expressed in mm of water for the differential tillage depth experimental unit.

Table 4. 2 Effect of depth of tillage treatment on available water capacity expressed as a percentage over the control at 10, 30, 60 and 100 cm soil profile depths during the long rains period, 1995.

Julian week	Weekly rainfall (mm)	Date of moisture measurement	Treatment response (% moisture conservation)			
			of the plough implement depth 17 cm against			
			10 cm	30 cm	60 cm	100 cm
6	37.6	-	-	-	-	-
7	27.1	-	-	-	-	-
8	0.0	-	-	-	-	-
9	65.7	-	-	-	-	-
10	36.9	-	-	-	-	-
11	38.7	-	-	-	-	-
12	41.8	-	-	-	-	-
13	6.9	28/3/95	105	130	324	124
14	20.7	31/3/95	4	175	357	127
15	8.8	10/4/95	35	147	356	140
15		14/4/95	28	110	316	111
16	22.6	21/4/95	135	135	327	130
17	13.6	28/4/95	114	133	337	135
18	1.0	5/5/95	124	147	374	123
19	18.5	12/5/95	142	161	368	141
20	6.9	19/5/95	542	119	331	113
21		26/5/95	124	121	369	113
22		2/6/95	87	269	510	145
Average	23.1					
Average available moisture (%)			131	150	361	128
Total moisture storage (%)			245	140	352	127

The Conventional Rumptstad plough implement at 17 cm tillage depth (RS_{17}) treatment proved to be superior over the Conventional Rumptstad at 12 cm tillage depth (RS_{12}) treatment.

4.3.3.1 Soil moisture variation in the 0-10 cm profile

Figure 4.22 shows the variation in soil moisture in the upper 10 cm profile during the long rains period, 1995. In both tillage depth treatments, soil moisture showed high fluctuation following the wetting and drying phases of the 10 cm soil profile with the RS_{17}. showing a quicker response to rainfall amount.

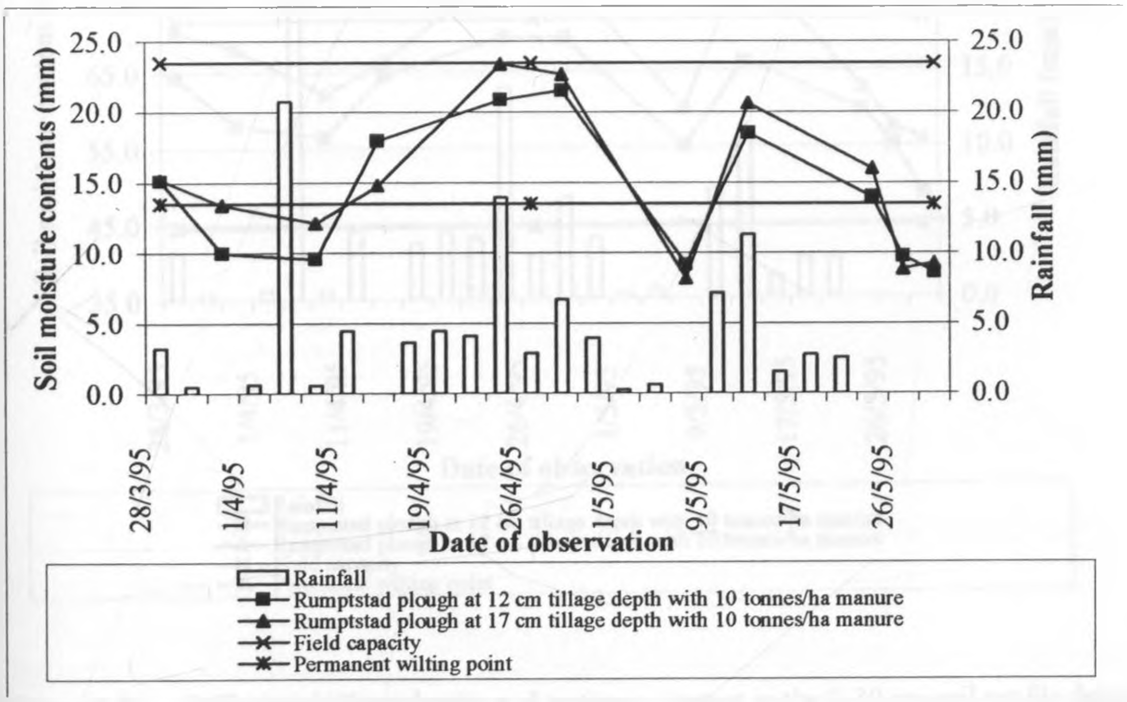


Figure 4.22 Differential tillage depth's soil moisture content in the 0-10 cm soil profile depth, during the long rains period, 1995.

The RS_{17} treatment improved the water retention and availability by 2.4 times that of the RS_{12} tillage, with 15.9 mm against 6.5 mm total available water under RS_{17} and RS_{12} respectively, except once when the RS_{17} barely reached field capacity, all the observations persisted below field capacity.

4.3.3.2 Soil moisture variation in the 0-30 cm soil profile

Figure 4.23 shows the soil moisture variation in the upper 0-30 cm profile depth as influenced by rainfall amount and distribution during the long rains period, 1995. The soil moisture trend shows to be far better than that of the upper 10 cm profile depth. Though soil moisture fluctuations were observed, their occurrence was well above the permanent wilting point.

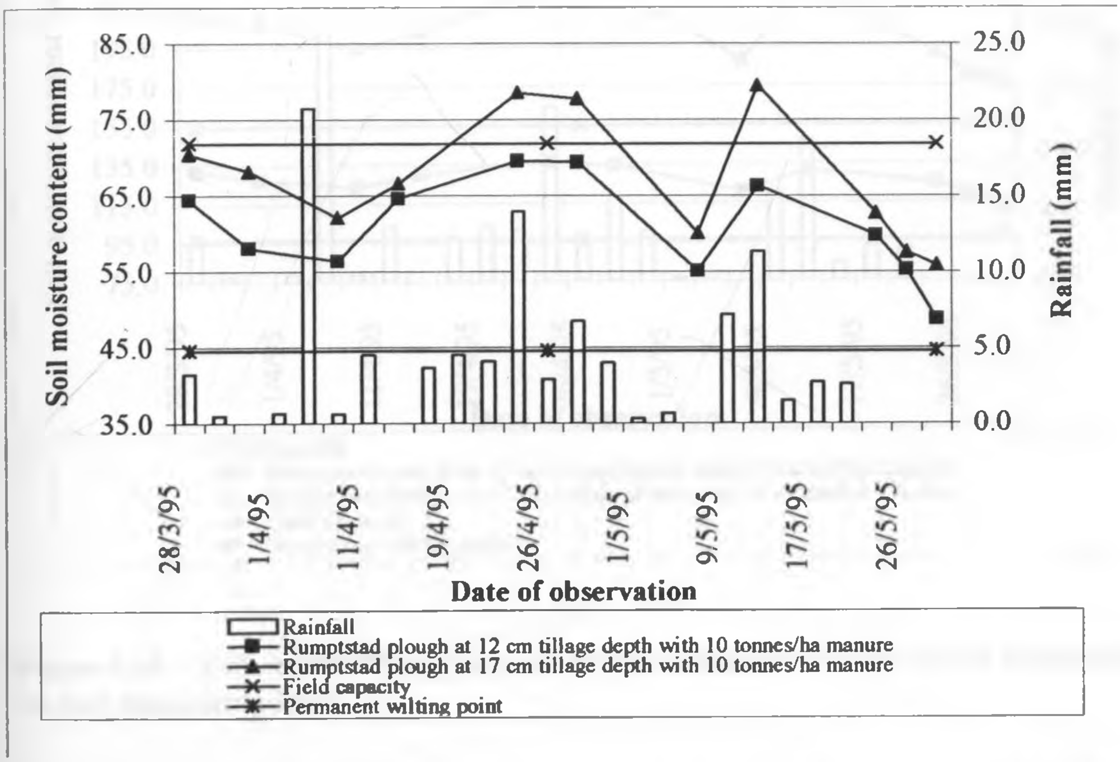


Figure 4.23 Differential tillage depth's soil moisture content in the 0-30 cm soil profile depth, during the long rains period, 1995.

The three storms of 15.0 mm (21/4/95), 6.7 mm (28/4/95) and 11.3 mm (12/5/95) enabled to replenish and/ or sustain the soil moisture above the field capacity in case of the RS_{17} treatment. The RS_{12} treatment, however, never reached field capacity. The RS_{17} showed to be 1.4 times that of RS_{12} in water storage and availability with 249.5 mm and 178.1 mm of available water under RS_{17} and RS_{12} respectively (see Appendix 1.12).

4.3.3.3 Soil moisture variation in the 0-60 cm profile

Figure 4.24 shows the soil moisture content in the upper 0-60 soil depth profile as influenced by tillage depth and rainfall amount and distribution. The soil moisture trend though similar to that under the upper 30 cm shows a smoother moisture storage variation.

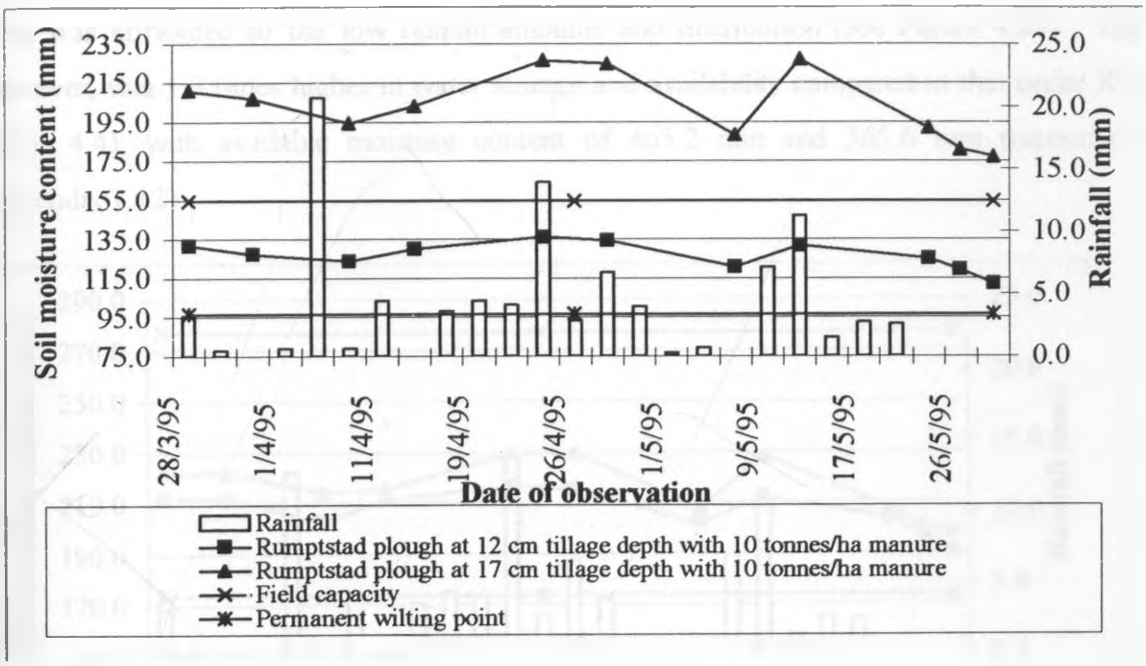


Figure 4.24 Differential tillage depth's soil moisture content in the 0-60 cm soil profile depth, during the long rains period, 1995.

The total available moisture in the upper 60 cm profile under the RS_{17} was 3.5 times that under RS_{12} and was above field capacity throughout the monitoring period (see Table 4.4). The RS_{12} treatment on the other hand was below the field capacity throughout the study period. The total available water was found to be 1171.9 mm under RS_{17} and 333.2 mm under the RS_{12} treatments (see Appendix 1.12).

4.3.3.4 Soil moisture variation in the 0-100 cm profile

Figure 4.25 shows the soil moisture content in the upper 0-100 soil depth profile as influenced by tillage depth and rainfall amount and distribution.

In the 0-100 cm soil profile depth, soil storage never reached field capacity in both treatments. This was attributed to the low rainfall amounts and distribution (see Figure 4.25). The RS_{17} however, was 1.3 times higher in water storage and availability compared to that under RS_{12} (see Table 4.4); with available moisture content of 465.2 mm and 365.6 mm respectively (see Appendix 1.12).

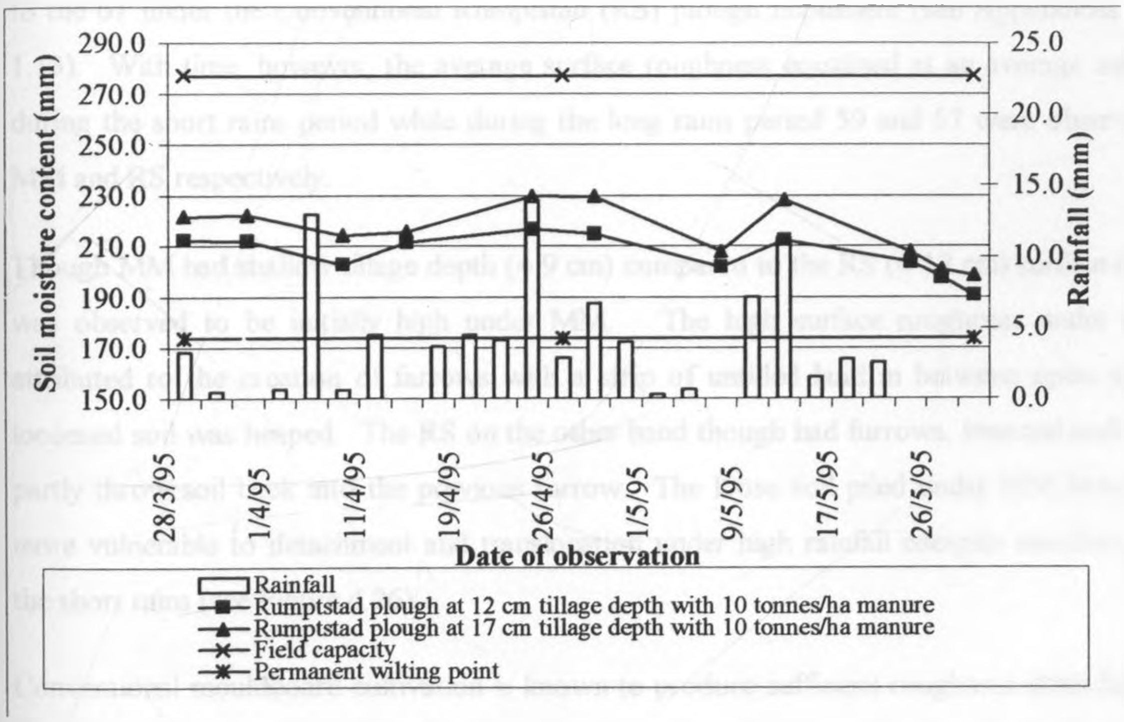


Figure 4.25 Differential tillage depth's soil moisture content in the 0-100 cm soil profile depth, during the 1995, long rains.

Effect of tillage depth on soil moisture conservation was greater between the 30 and 80 cm soil profile horizon for the RS_{17} as compared to that of RS_{12}. Deeper tillage depth has shown to be statistically highly significant compared to the normal tillage depth of 12 cm (see Appendix 2.8).

A built-up of a soil moisture of above the field capacity through out the observation period was observed in deep tillage (17 cm) compared to shallow tillage at the 60 soil profile with 838 mm available water. This water could be available to plants through capillary or a further drainage down the soil profile.

4.4 Soil Surface Physical Conditions

4.4.1 Soil surface roughness

The highest surface roughness index immediately after tillage operations during the short rains was under the Modified Reversible Maresha Prototype (MM) plough implement (65) as compared to the 61 under the Conventional Rumptstad (RS) plough implement (see Appendices 1.13 and 1.13). With time, however, the average surface roughness equalised at an average index of 40 during the short rains period while during the long rains period 59 and 57 were observed in the MM and RS respectively.

Though MM had shallow tillage depth (≈ 9 cm) compared to the RS (≈ 12 cm) surface roughness was observed to be initially high under MM. The high surface roughness under MM was attributed to the creation of farrows with a strip of untilled land in between upon which, the loosened soil was heaped. The RS on the other hand though had furrows, inverted soils and thus partly throw soil back into the previous furrow. The loose soil piled under MM however, was more vulnerable to detachment and translocation under high rainfall energies manifested during the short rains (see Figure 4.26).

Conventional mouldboard cultivation is known to produce sufficient roughness immediately after tillage operations (M'arimi, 1977, Stein et al., 1982). This initial rough surface condition created considerable surface storage and exposed large surface areas to rainwater, enhancing infiltration, consequently reducing runoff (see Figure 4.14). This initial surface roughness is essential in the retention of rainwater that accounted for 60% and 54% of the short and long rains, 1994/95, falling in the first 30 days from the on-set of rains. This follows the observation by Doker (1961) in which he noted that the most reliable rains fall in the first 30 days of a rains.

During the study period, the first 30 days generated soil loss amounting to 66 per cent (see Appendix 1.6). Fisher (1978) observed that 70 per cent of erosive storms in the study area occur in the first month of the rains. During this period crop canopy barely cover planting stations. This calls for soil surface management that provides surface water retention and infiltration, if soil and water are to be conserved early in the season. However, as the seasons progressed, clods were being broken and oriented roughness arising from ridges and furrows diminished. This was attributed to the sediment deposits and washing into the furrows of soil from the ridges. Complementary to the above was the washing-in of clay and silt particles into the coarser pores by rain-splash and runoff that together resulted into reduced surface storage and infiltration.

Figures 1.26 to 1.28 and Appendices 1.13 to 1.15 show the oriented surface roughness index for the periods of the short and long rains and the differential tillage depth measurements respectively. These figures show the variation of the oriented soil surface roughness marked by a decrease with time and rainfall amount.

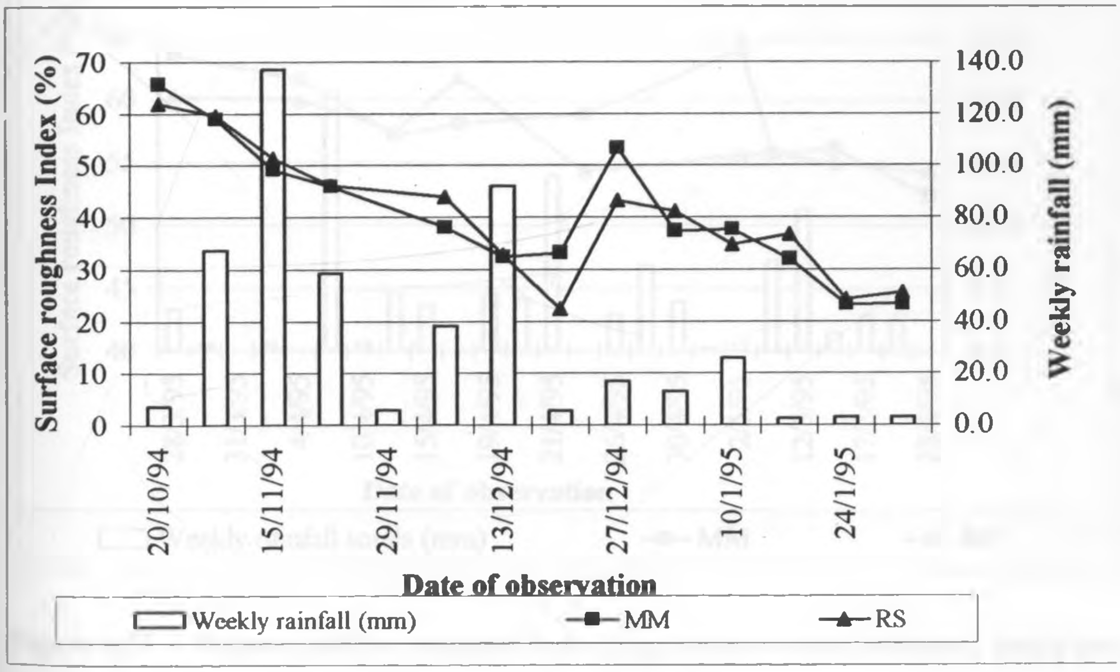


Figure 4.26 Oriented surface roughness Index (Log of the standard deviation), during the short rains period, 1994/95.

Figure .4.26 though gives a declining trend in the surface roughness with time; it does not show a uniform decline. A closer look at Figure 4.26 shows that around the 27/12/94 surface roughness increased instead of reducing arising from the limitations of the relief-meter in continuous monitoring, of the soil surface relief with the equipment placed in different positions at a time. The nature of the equipment is such that every setting has to be levelled an act which in itself disturbed the area of measurement as its legs would have to be pushed into the soil. Random sampling thus could not bring out the expected results.

Surface irregularities were observed to be caused by plough implement, runoff water, scouring and deposition along furrows with time. During the rains season micro-relief across the main plots were observed to influence the direction of water flow that resulted into more damage in portions of runoff accumulation and deposition in some parts. Highly eroded surfaces (rill erosion) thus would show high surface roughness compared to deposition areas. Also true is that where uniform surface erosion takes place, surface roughness is reduced and surface smoothened.

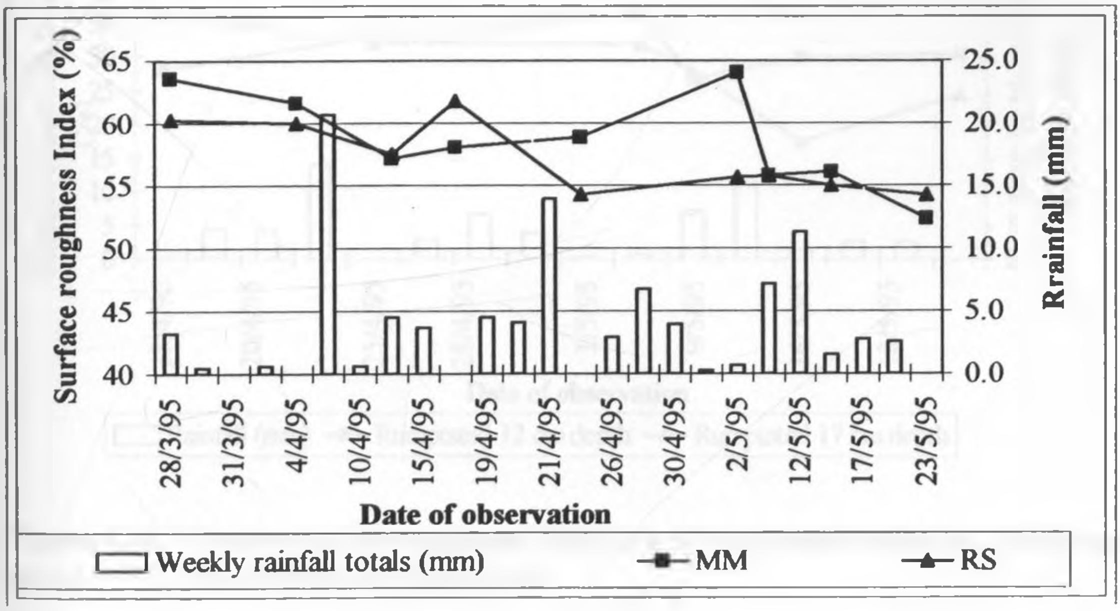


Figure 4.27 Oriented surface roughness Index (Log of the standard deviation), during the long rains, 1995.

Generally water movement was observed to be from the middle of the main plot area surrounding runoff plots towards the runoff plots. Since these plots have been in use for long, uniformity plough implementing could not even the surface well enough; this enabled water to damage more around the runoff plots compared to the middle of the plot. In this case continuous surface roughness monitoring required a reference point per plot rather that random sampling if a satisfactory surface roughness was to be attained.

Appendix 1.13 shows that MM started with a higher surface roughness of 66 as compared to the RS of 62. However, towards the end most of the MM furrows became silted up and thus had less roughness 23 compared to RS of 26. On the whole, the average surface roughness for both plough implements was the same (40). This shows that surface roughness depends more on the type of equipment rather than on the depth of tillage. Appendix 1.12 and Figure 4.27 show the long rains surface roughness index. A similar trend to that of the short rains period was observed, except this time around, there was less erosive rainfall. However, MM had a higher a average index of 59 compared to the RS 57.

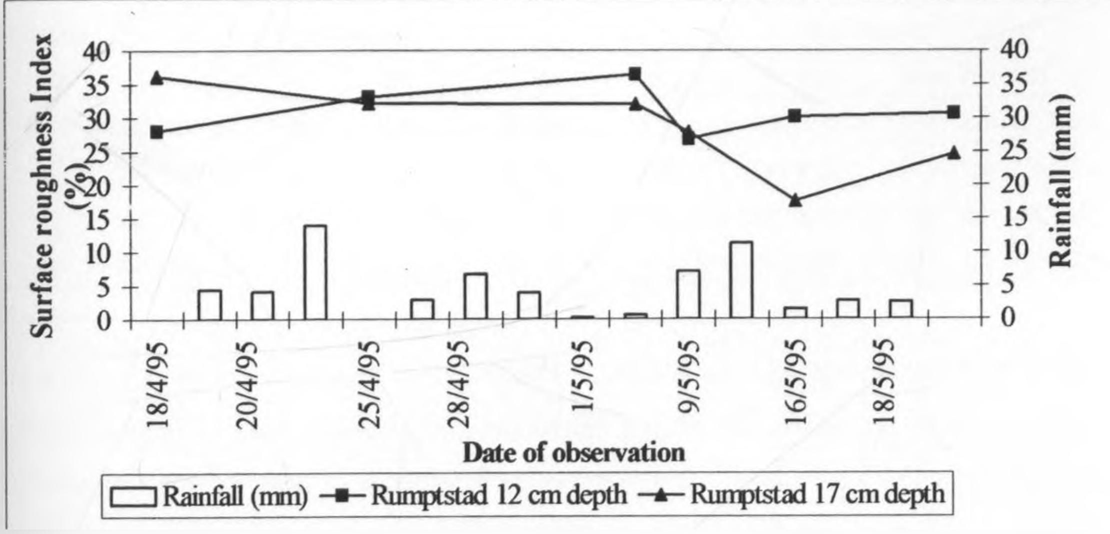


Figure 4.28 Oriented surface roughness Index (Log of the standard deviation), during long rains period, 1995, for the differential tillage depth.

Appendix 1.15 and Figure 4.28 show the oriented surface roughness index as observed in the Conventional Rumptstad, differential tillage depth treatment. Initial surface roughness showed to be higher under deep tillage (36) compared to the shallow tillage (28). However, random sampling problems again manifested here where surface roughness increased in the 12 cm

Rumptstad tillage depth (RS_{12}) compared to the 17 cm Rumptstad tillage depth (RS_{17}), resulting in a higher average index under RS_{12} (31) against RS_{17} (28)

Initial surface roughness showed to be higher under deep tillage (36) compared to the shallow tillage (28). The higher initial surface roughness under RS_{17} could have contributed to the higher soil moisture observed in Figures 4.22 to 4.25. Although the surface roughness was reduced by end of season, due to rainfall impact and runoff, rainwater was retained early in the season under erosive storms.

4.4.2 Soil structural stability

Tables 4.5a and b show the treatment combination effect on percentage aggregate soil stability distribution under wet sieving conditions, for the short and long rains respectively. Generally, aggregate stability showed to be higher at 2.0 mm diameter and decreased through the 0.5 mm and below. This trend means that once the bigger aggregates disintegrated in the presence of transport power, soil loss is enhanced. Secondly, disintegration of soil aggregate results into surface seal and crusting, on one hand and clogging of soil pores on the other.

Table 4.3 Per cent aggregate stability ("drop" wet sieving).

(a) Short rains period, 1994/95

Treatment	Per cent aggregate stability distribution							
	Early short-rains (1994/95)				End short-rains (1994/95)			
	Sieve size (mm)							
type	2.00	1.00	0.50	0.25	2.00	1.00	0.50	0.25
MM_0	13.43	1.33	2.82	10.18	9.40	1.12	4.69	10.62
MM_{10}	18.78	1.06	5.30	7.67	12.62	1.28	6.70	10.61
RS_0	12.97	1.09	4.09	8.92	9.78	1.04	5.16	10.39
RS_{10}	24.11	1.22	2.86	7.43	15.64	1.42	6.15	9.41

(b) Long rains period, 1995

Treatment	Per cent aggregate stability distribution							
	Early long-rains (1995)				End long-rains (1995)			
	Sieve size (mm)							
type	2.00	1.00	0.50	0.25	2.00	1.00	0.50	0.25
MM_0	9.36	1.28	3.69	10.58	9.18	1.03	2.58	11.33
MM_{10}	21.65	1.25	5.20	10.29	20.83	1.30	3.92	11.18
RS_0	9.33	1.38	6.03	12.75	11.24	1.27	2.89	11.97
RS_{10}	18.61	0.91	7.14	12.38	19.70	1.25	3.53	13.25

Table 4.6 shows the summary of the treatment percentage aggregate stability over the range of sieves above 0.25 mm diameter. The average percentage stable aggregates in the treatment combination ranged from 34% in the RS_{10} to 25% in RS_0 and 38% (RS_{10}) to 23% (RS_0) during the short and long rains respectively. Manure and time interaction was significant at 5% probability, while plough implement and time, manure and plough implement as well as manure, plough implement and time showed no statistically significant difference (see Appendix 2.9). The average percentage aggregate stability under MM_{10} and MM_o was 32% and 27% during the short rains period, with 38% and 23% during the long rains period, respectively.

Table 4.4 Summary of the treatment percentage aggregate stability (wet sieving), during, 1994/95 period

Treatment type	Aggregate stability (%) through 2.00, 1.00, 0.50 & 0.25 mm sieve diameters							
	Short-rains (94)			Long-rains (95)			Rate of structural degardation	
	Early	End	Average	Early	End	Average	Short-rains (94)	Long-rains (95)
MM$_0$	27.76	25.82	26.79	24.90	24.12	24.51	6.97	3.13
MM$_{10}$	32.81	31.21	32.01	38.39	37.24	37.81	4.90	2.99
RS$_0$	25.67	23.86	24.77	23.59	22.78	23.19	7.06	3.41
RS$_{10}$	35.62	32.62	34.12	39.05	37.73	38.39	8.41	3.38

Generally, a higher rate of structural deterioration was observed under the Conventional Rumptstad tillage with manure (RS$_{10}$). The RS$_{10}$ treatment had 8.41% compared to the 7.06% under RS$_0$ during the short rains possibly due to some residual effect of the previous season's manure application. During the long rains however the RS$_{10}$ (3.38%) showed a reduction compared to the RS$_0$ (3.41). The Modified Reversible Maresha Prototype without manure (MM$_0$) was higher in structural deterioration than that with manure (MM$_{10}$) in both seasons. The MM$_0$ had a rate of deterioration of 6.97 and 3.13% while MM$_{10}$ had 5.90 and 2.99% during the short and long rains respectively.

The total aggregate stability response tc manure treatment was higher in the manured compared to the non-manured plots with a mean of 36% and 25% respectively (see Appendix 2.9). This conforms to the soil loss response shown under Section 4.2.4.3, and reduced rainfall-runoff response under section 4.2.4.2. The observed aggregate stability showed to be slightly higher than those reported by Biamah et al. (1994) of 26%. This could have been attributed to the residual effect of manure from the previous treatments. Soil that had no manure application, thus showed a higher breakdown of soil aggregates. The plough implement treatment response to aggregate stability showed no significant difference though MM showed to be slightly higher than the RS (see Appendix 2.9).

Table 4.7 shows the proportion of soil water stable aggregate of less than 0.5 mm diameter. Using the proportion of soil in water stable aggregates of less than 0.5 mm as the best indicator of erodibility (Bryan, 1974, Rai et al., 1954) the above results show that MM$_0$ treatment combination was more erodible; followed by RS$_0$, RS$_{10}$ and least was MM$_{10}$.

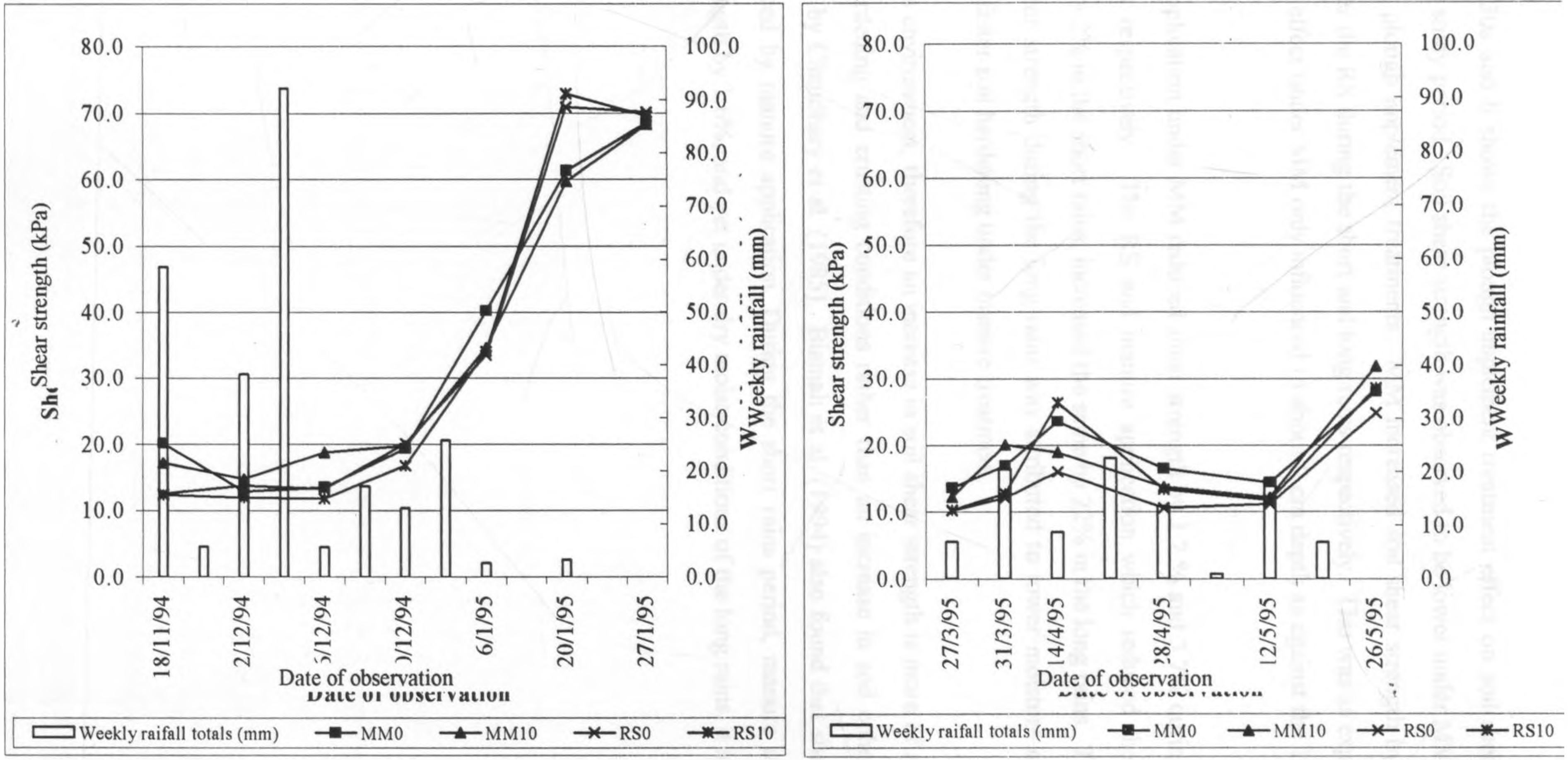
Table 4.5 Proportion of soil in water stable aggregates less than 0.5 mm, 1994/95

Treatment type	Per cent aggregate stability distribution less than 0.5 mm			
	Short-rains (1994/95)		Long-rains (1995)	
	Early	End	Early	End
MM$_0$	82	85	86	87
MM$_{10}$	75	79	72	74
RS$_0$	82	84	83	85
RS$_{10}$	72	77	73	76
0FYM	82	84	84	86
10FYM	73	78	73	75
MM	79	82	79	81
RS	77	80	78	80

The manure treatment response however, showed the 0 FYM to be highest with an average of 84% and 10 FYM to be lowest with an average of 75%, while with the plough implements, the MM was the highest (80%) and the RS (79%) was the lowest. Thus, non-manured soils showed a higher breakdown of soil aggregates into smaller aggregates or primary particles in contrast to the manured (Kay, 1990, Probert, et al., 1990). The plough implement type on the other hand showed that the effect of minimum tillage on water stable aggregates in the short-term is negligible, unless combined with soil amendments.

4.4.3 Soil shear stress and surface crusting strengths

Throughout the study period, soil shear strength increased with moisture stress (see Figures 4.29, 4.30, 4.31 and 4.32). The interaction of the plough implement and manure under the influence of rainfall properties has shown to reduce soil shear strength. Shear strength reduced by 1.2% in the Modified Reversible Maresha Prototype plough implement with manure and 2.0% under Conventional Rumptstad plough implement with manure, compared to their controls (see Figure 4.29, and Appendices 1.16 and 1.17). Though fluctuations were noticed throughout the season the average shear strength during the short rains was highest in the MMo (33.7 kPa), followed by RSo (33.5 kPa).



(a) Short rains period, 1994/95

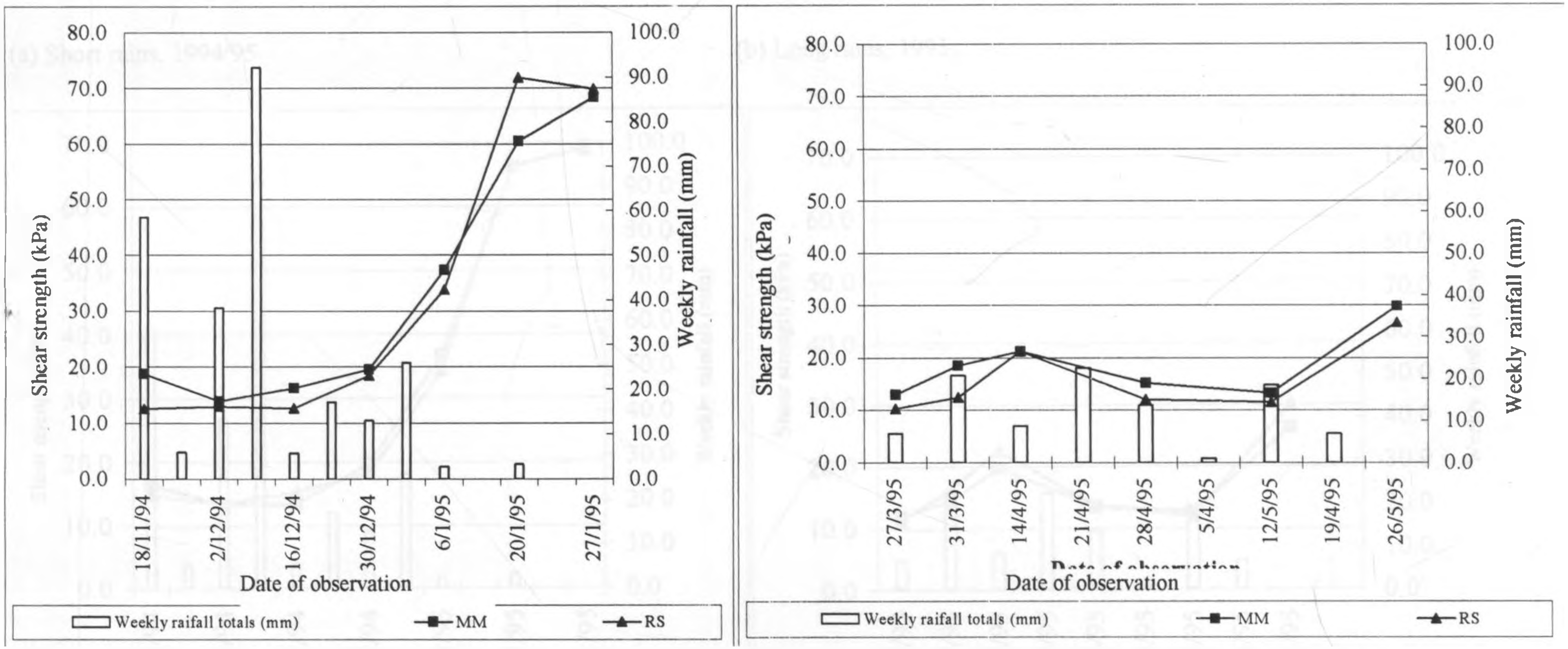
(b) Long rains period, 1995

Figure 4.29 Interaction treatment effects on seasonal shear strength.

Figures 4.30a and b shows the plough implement treatment effect on soil shear strength, during the study period. Soil shear strength was observed to be lower under MM compared to the RS plough implement treatments. MM increased soil shear strength by 1.1% and 17.8% over the RS during the short and long rains respectively. This was as expected since the tillage effect under MM only influenced to about 9 cm depth as against the 12 cm depth under RS.

Manure application under MM reduced shear strength by 1.2 % and 3.7% during short and long rains respectively. The RS and manure application which reduced the soils hear strength by 2% in the short rains, increased the same by 22% in the long rains. The increase in soil shear strength during the long rains was attributed to lower moisture content that enhanced faster soil hardening under manure treatment.

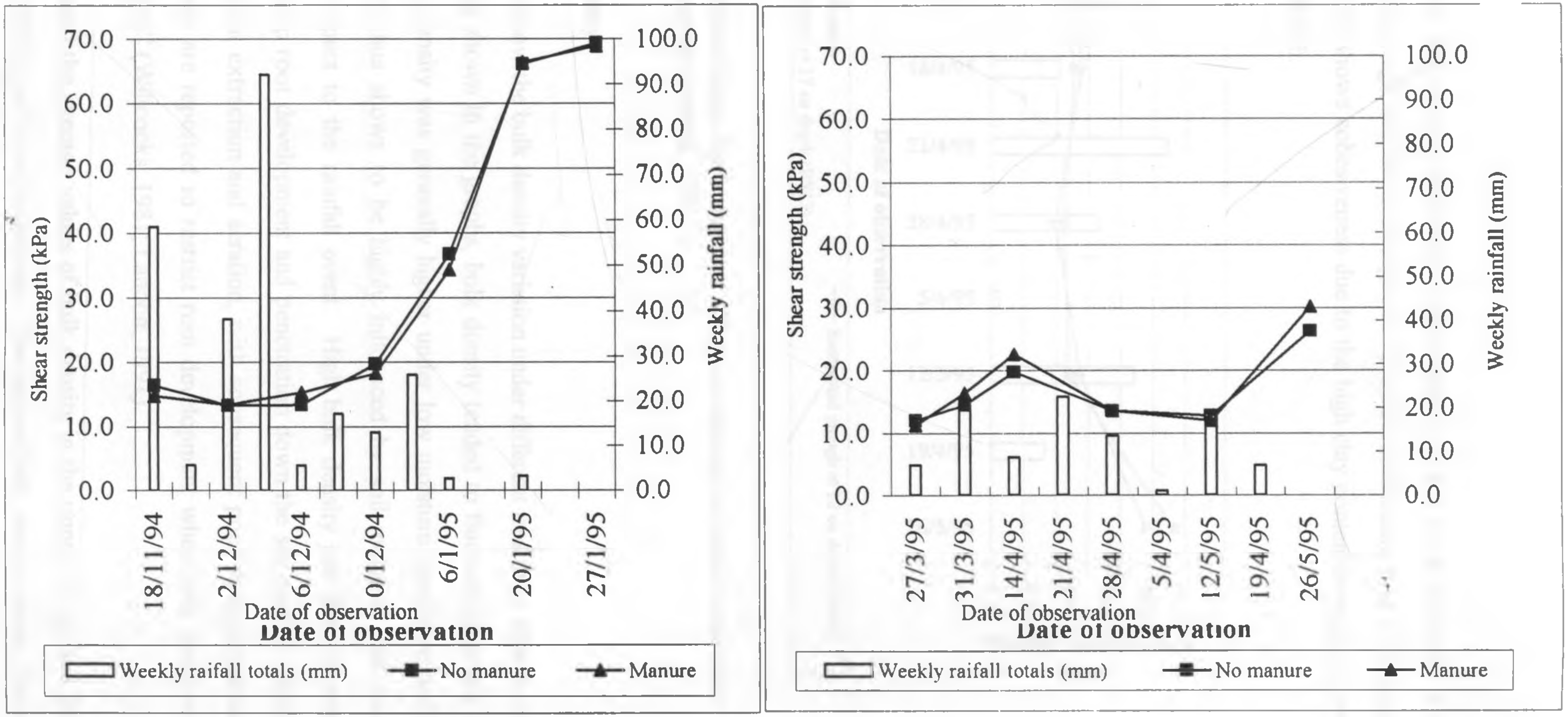
Under this environment, therefore an increase in soil shear strength is more of an indicator of soil hardening and crusting conditions rather than an increase in soil cohesiveness as suggested by Chaudhary et al. (1985). Biamah et al. (1994) also found that shear strength was reduced by manure application. During the short rains period, manure reduced soil shear strength by 1.6%, and yet under dry moist-conditions of the long rains, it increased by 1%.



(a) Short rains, 1994/95.

(b) Long rains, 1995.

Figure 4.30 Plough implement type treatment effects on seasonal shear strength



(a) Short rains, 1994/95

(b) Long rains, 1995

Figure 4.31 Farmyard manure treatment effects on seasonal shear strength.

Figure 4.32 shows the influence of differential tillage depth on soil shear strength. The 17 cm tillage depth had average soil shear strength of 13.6 kPa amounting to a 1.5% increase (see Table 5.13b). This shows cohesiveness due to the high clay content brought to the top surface from 17 cm depth.

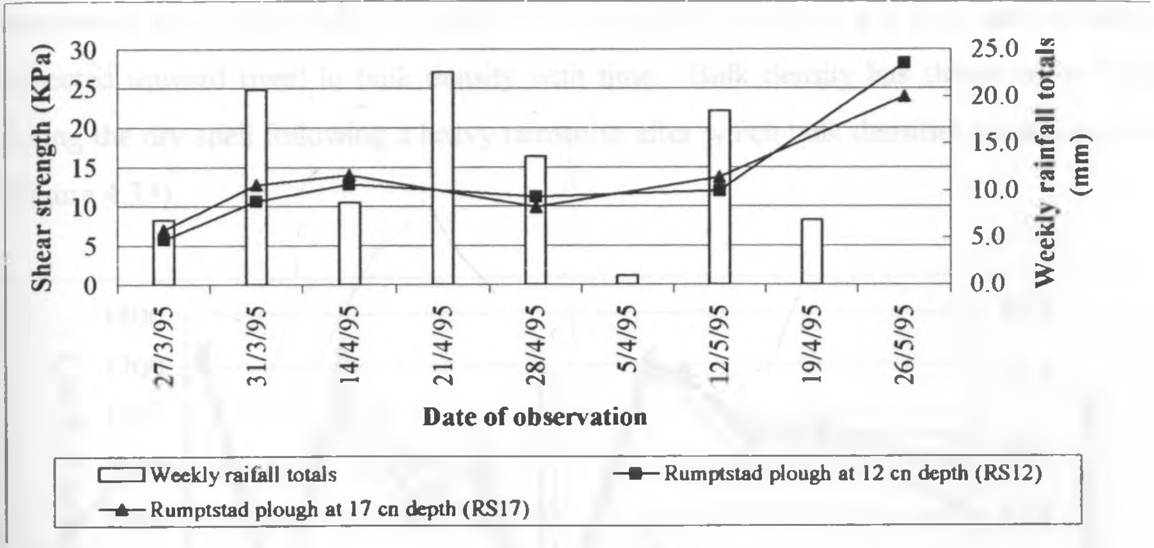


Figure 4.32 Differential tillage depth treatment effects on seasonal variation in soil shear strength during the long rains period, 1995.

4.4.4 Soil bulk density

Figures 4.33 to 4.36 show the bulk density variation under different treatment effects during the study period. As shown in the graphs, bulk density tended to fluctuate inversely with soil moisture. Bulk density was generally higher under low moisture conditions and vice versa. Bulk density thus shows to be highly influenced by soil moisture and time of measurement with respect to the rainfall event. High bulk density just like penetration resistance impedes crop root development and penetration down the soil profile leading to poor water and nutrient extraction and aeration, with consequent poor crop performance. Sandy and loamy soils are reported to restrict root development when bulk densities are greater than 1600 kg m^{-3} (Willcocks, 1981; Landon, 1991).

During the study period the average values of bulk density in the upper 10 cm soil profile was lower than the 1600 kg m^{-3} in all treatments. The highest bulk density during the study period was observed under the MM$_o$ treatment combination with a mean of 1510 kg m^{-3} followed by MM$_{10}$ (1500 kg m^{-3}). Others were: 1460 kg m^{-3} in RS$_0$ and 1450 kg m^{-3} RS$_{10}$.. The bulk density coefficient of variability was 13% with no statistical significance between treatment combinations.

The removal of surface crust by erosion and moisture fluctuations were assumed to have maintained bulk densities in the upper 10 cm profile fluctuating and thus camouflaging an expected upward trend in bulk density with time. Bulk density has shown to be highest during the dry spell following a heavy rainstorm after which bulk densities tended to reduce (Figure 4.33).

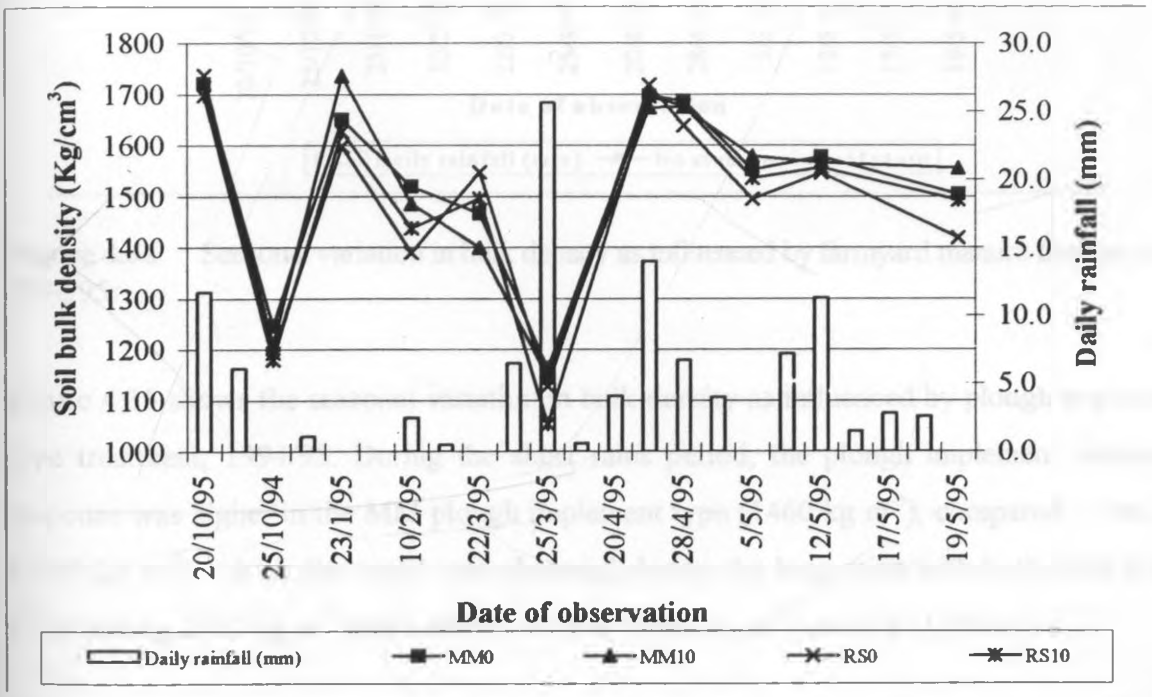


Figure 4.33 Seasonal variation in the treatment combination on bulk density, 1994/95.

Bulk density trend did not follow that of penetration resistance, due to the mode of sampling whereby in bulk density measurement sampling was being done at about 7 cm depth. The 7 cm depth is normally below the soil surface crust that would normally be registered under penetration resistance measurements.

Figure 4.34 shows bulk density response to farmyard manure (FYM) application. During the study period, manure application showed to have had no significant effect on bulk density with the 0 FYM (1430 kg m^{-3}), and the 10 FYM (1420 kg m^{-3})

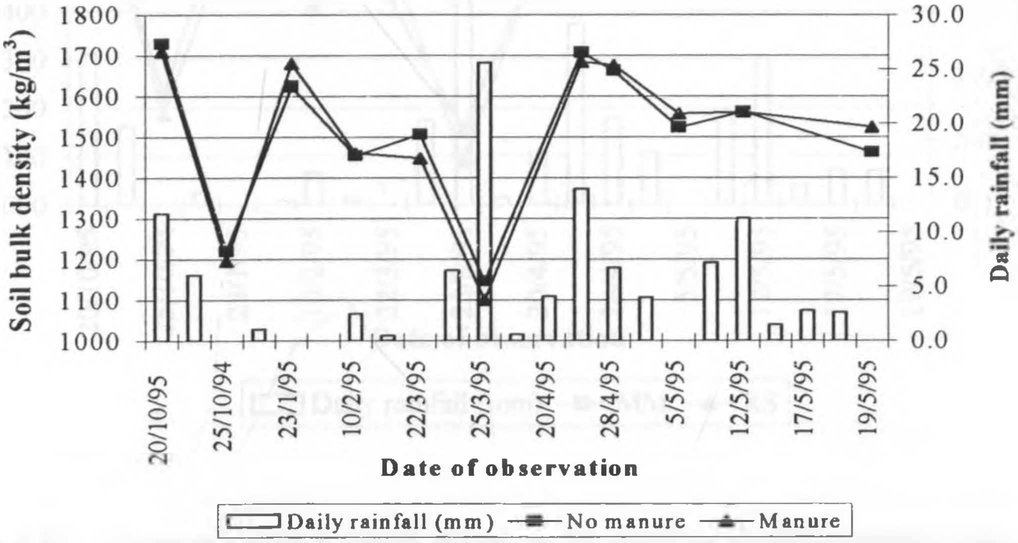


Figure 4.34 Seasonal variation in bulk density as influenced by farmyard manure treatment, 1994/95.

Figure 4.35 shows the seasonal variation in bulk density as influenced by plough implement type treatment, 1994/95. During the short rains period, the plough implement treatment response was higher in the MM plough implement type (1460 kg m^{-3}), compared to the RS (1390 kg m^{-3}). A similar trend was observed during the long rains with both MM and 0 FYM having 1520 kg m^{-3} followed by 10 FYM (1490 kg m^{-3}) and RS (1480 kg m^{-3}).

In both seasons, manure applications showed no statistical significance, in the plough implement treatments. However, manure applications during the short-rains were significant. The coefficient of variation was found to be 13% in both seasons. The change in bulk density before and after tillage operations was significantly different at 1% probability with 1720 and 1210 kg m^{-3} before and after tillage for short rains. The long-rain's tillage operations changed bulk density from 1480 to 1120 kg m^{-3} before and after tillage respectively, giving a statistical difference at 5% probability.

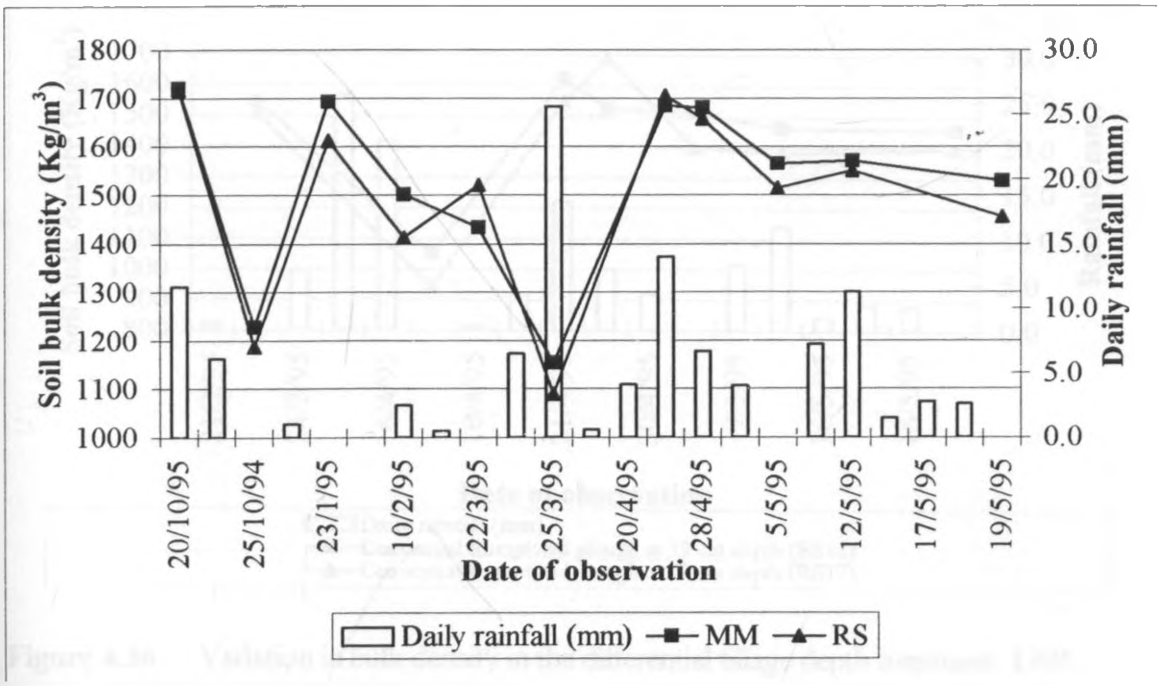


Figure 4.35 Seasonal variation in bulk density as influenced by plough implement type treatment, 1994/95.

Figure 4.36 shows variation in bulk density in the differential tillage depth treatment. The differential tillage depth showed higher bulk density under the shallow tillage depth (12 cm) of 1440 kg m^{-3} compared to 1360 kg m^{-3} under deep tillage (17 cm). There was no significant difference among the blocks, but the bulk density was significant at 5% probability between the treatments and highly significant with time with a coefficient of variation (CV) of 15%.

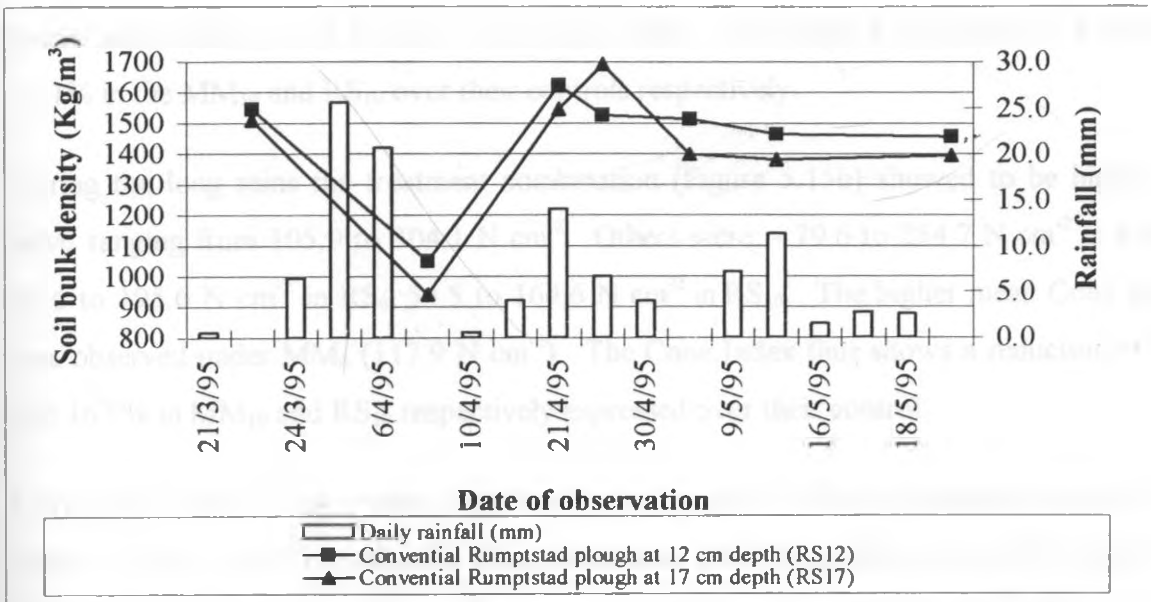


Figure 4.36 Variation in bulk density in the differential tillage depth treatment, 1995.

The 17 cm tillage depth manifested lower bulk density due to a higher clay content that was inverted to the soil surface. The change in bulk density between the time before and after tillage operations was highly significant with a coefficient of variation (CV) of 24%.

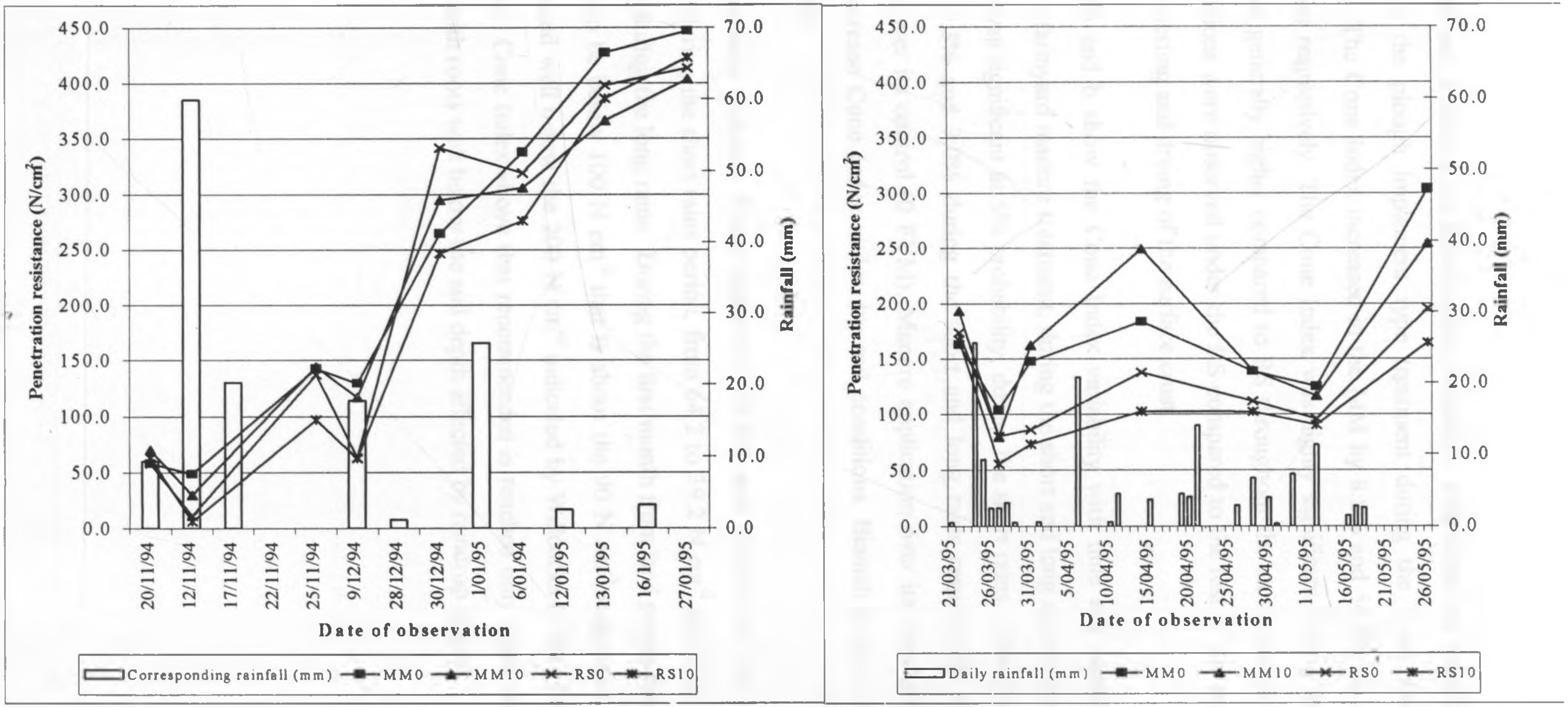
4.4.5 Variation in soil penetration resistance and surface crusting

The soil's mechanical impedance was measured in terms of penetration resistance and is shown in Figures 4.37a and b, Figures 4.38a and b, Figures 4.39a and b. In all the graphs, the first observation point represents the penetration resistance expressed as Cone Index (N/cm^2) on the day but before land preparation, except for the differential tillage depth treatment. The treatment combinations for the short rains are shown in Figure 4.37a. The Cone Index observed during the short rains ranged from 48.8 to 446.7 N cm^{-2} and from 29.8 to 403.3 N cm^{-2} in the Modified Reversible Maresha Prototype plough implement without (MM$_0$) and with (MM$_{10}$) manure respectively.

For the Conventional Rumptstad plough implement, penetration resistance ranged from 11.3 to 413.3 N cm^{-2} and 6.1 to 422.7 N cm^2 in the treatment without (RS$_0$) and with (RS$_{10}$) manure respectively. The highest mean Cone Index was observed in the MM$_0$ (256.8 N cm^{-2}), followed by RS$_0$ (240.5 N cm^{-2}), MM$_{10}$ (237.3 N cm^{-2}) and the least was found under RS_{10} (213.7 N cm^{-2}). The Cone Index thus shows a reduction of 3.6% and 11.1% in the MM_{10} and RS_{10} over their controls respectively.

During the long rains the treatment combination (Figure 5.15b) showed to be highest in MM_0 ranging from 105.9 to 304.1 N cm^{-2}. Others were: - 79.6 to 254.7 N cm^{-2} in MM_{10}, 80.6 to 195.6 N cm^{-2} in RS_0, 54.5 to 164.6 N cm^{-2} in RS_{10}. The higher mean Cone Index was observed under MM_0 (117.9 N cm^{-2}). The Cone Index thus shows a reduction of 1% and 16.9% in MM_{10} and RS_{10} respectively expressed over their control.

During the 1994/95, short rains, the Cone Index response to main treatment showed to be highest (248.6 N cm^{-2}) in the zero farmyard manure (0 FYM), followed by 247.0 N cm^{-2} in the Modified Reversible Maresha Prototype plough implement (MM). The others were: - Conventional Rumptstad plough implement (RS) with Cone Index of 227.1 N cm^{-2}, and the least was under the ten tonnes farmyard manure treatment (10 FYM) with Cone Index of 225.5 N cm^{-2}. During the long rains the highest Cone Index was observed under MM (167.0 N cm^{-2}) followed by 0 FYM (142.5 N cm^{-2}), 10 FYM (132.5 N cm^{-2}) and the least was now in the RS (108.0 N cm^{-2}).


(a) Short rains period, 1994/95.

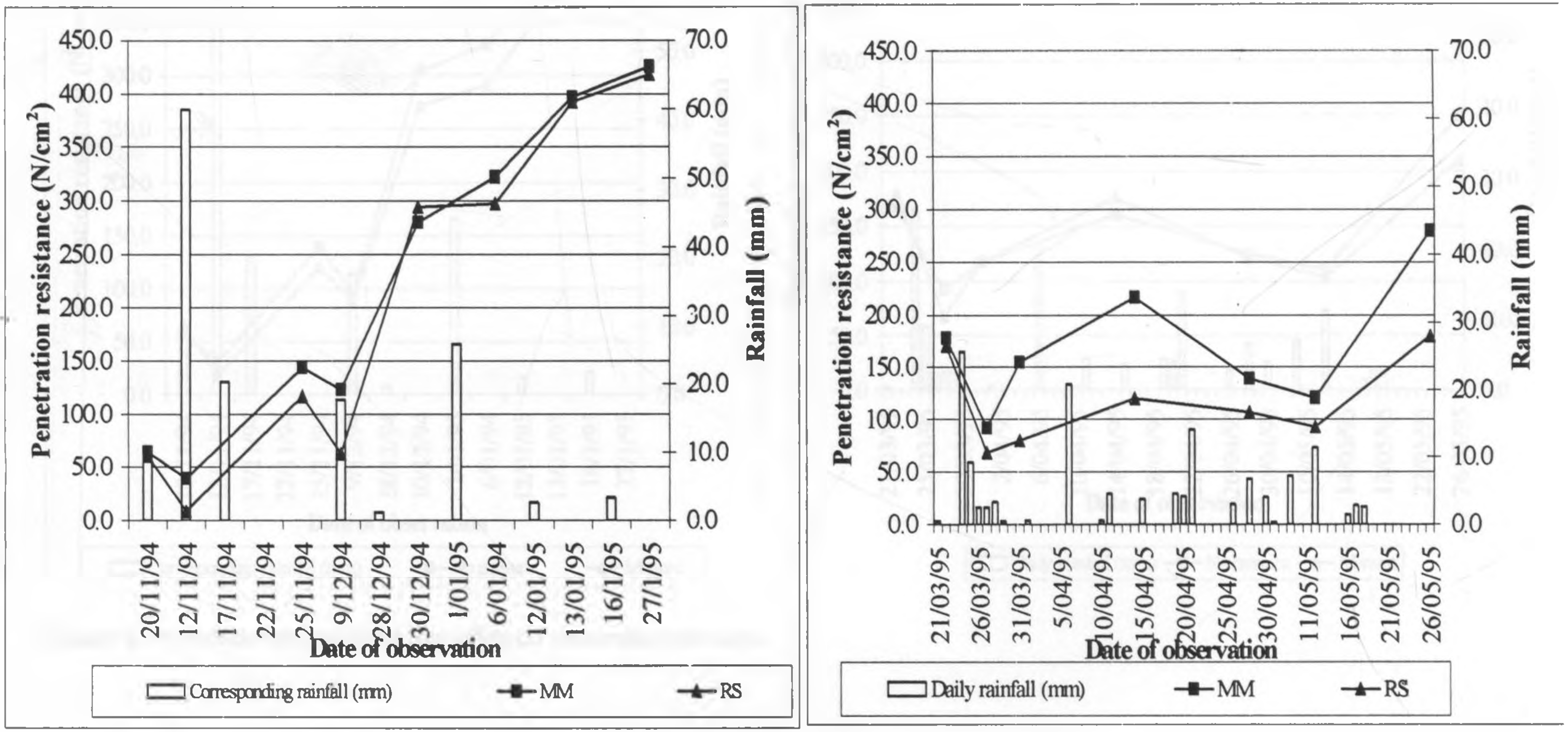
(b) Long rains period, 1995.

Figure 4.37 Plough implement and manure treatment interaction's effect on penetration resistance.

Figures 4.38a and b shows the Cone Index variability with time and rainfall amount as influenced by the plough implement type treatment during the short and long rains respectively. The Cone Index increased in the MM by 8.8% and 54.6% during the short and long rains respectively. The Cone Index was highly significant during the long rains. The MM was generally higher compared to RS throughout the study period. High Cone Index fluctuations were observed under the RS compared to the rest of the treatments as a result of the wetting and drying of the surface crust.

Figures 4.39a and b show the Cone Index variability with time and rainfall amount as influenced by farmyard manure treatment, during the short and long rains respectively. The Cone Index was significant at 5% probability, during the short rains. The Cone Index was reduced by 9.3% and 7.0% during the short and long rains respectively with 10 FYM applications over its control (0 FYM). Manure application over its control (0 FYM) has shown to increase Cone Index under dry soil conditions. Biamah et al. (1994) reported similar results.

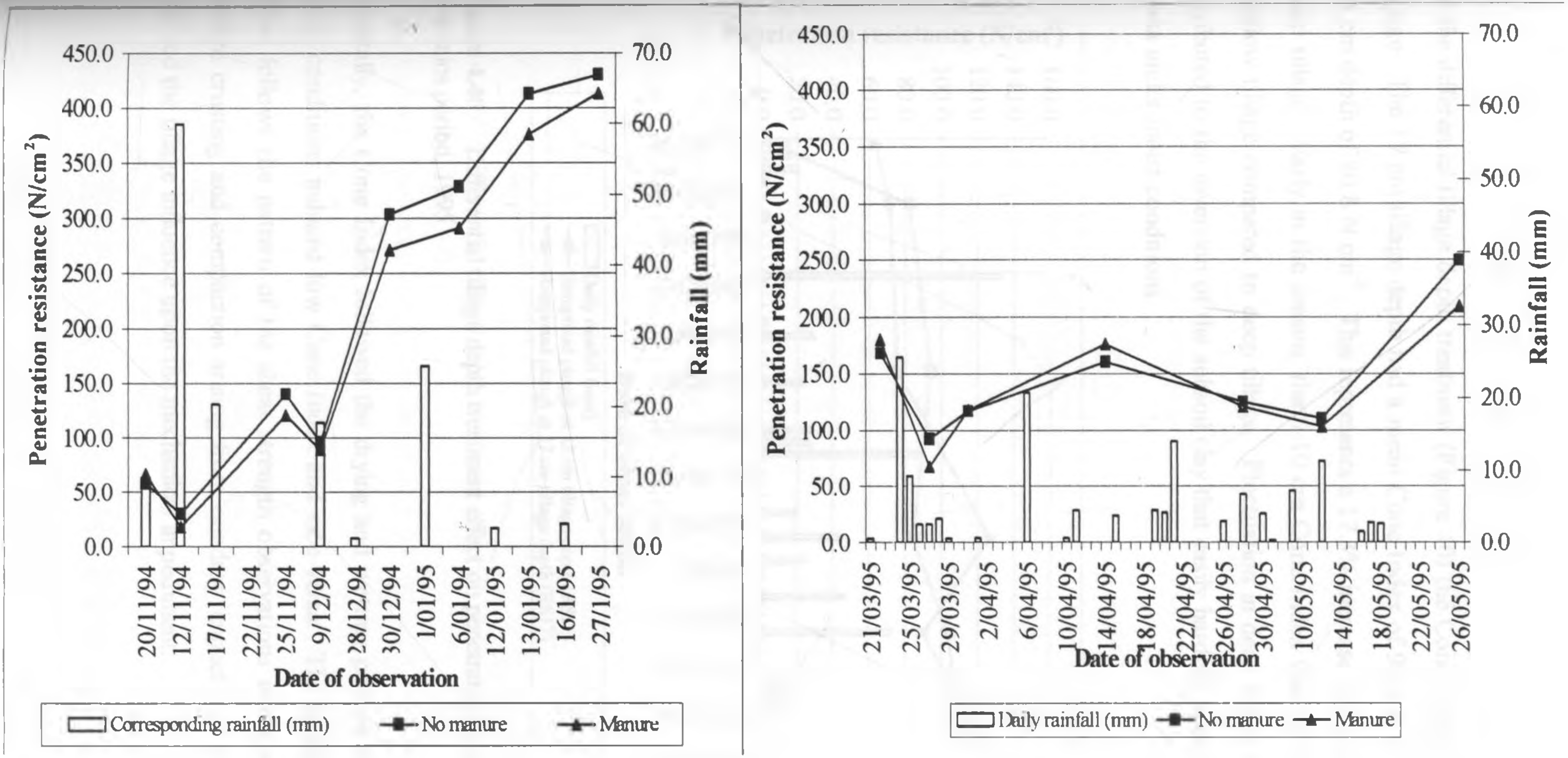
Tillage operations reduced Cone Index by 38.9% and 85.6% in the MM and RS respectively during the short rains period, from 64.2 to 39.2 N cm^{-2} and 60.6 to 8.7 N cm^{-2} respectively during the long rains. During the first month from land preparation Cone Index was shown to be below 100 N cm^{-2} that is about the 90 N cm^{-2} suggested limit for root penetration and well below the 200 N cm^{-2} indicated by Willcocks (1981) for reduction of crop growth. Cone Index above that recommended is reached only when the crop is well established with roots well below the soil depth affected by raindrop impact.



(c) Short rains period, 1994/95.

(d) Long rains period, 1995.

Figure 4.38 Plough implement type treatment effect on penetration resistance.


(e) Short rains, 1994/95.

(f) Long rains, 1995.

Figure 4.39 Farmyard manure treatment effect on penetration resistance.

In the differential tillage depth treatment (Figure 40) the Cone Index increased with deep tillage. The 17 cm tillage depth had a mean Cone Index of 98.8 N cm^{-2} compared to the 12 cm depth of 80.8 N cm^{-2}. This represents a 17.3% increase in Cone Index arising from deep tillage. Early in the season, the 0-10 cm Cone Index was significantly reduced by shallow tillage compared to deep tillage. Fluctuation in deep tillage of Cone Index was attributed to the inversion of the subsoil clay that easily hardens under dry spells and vice versa under moist conditions.

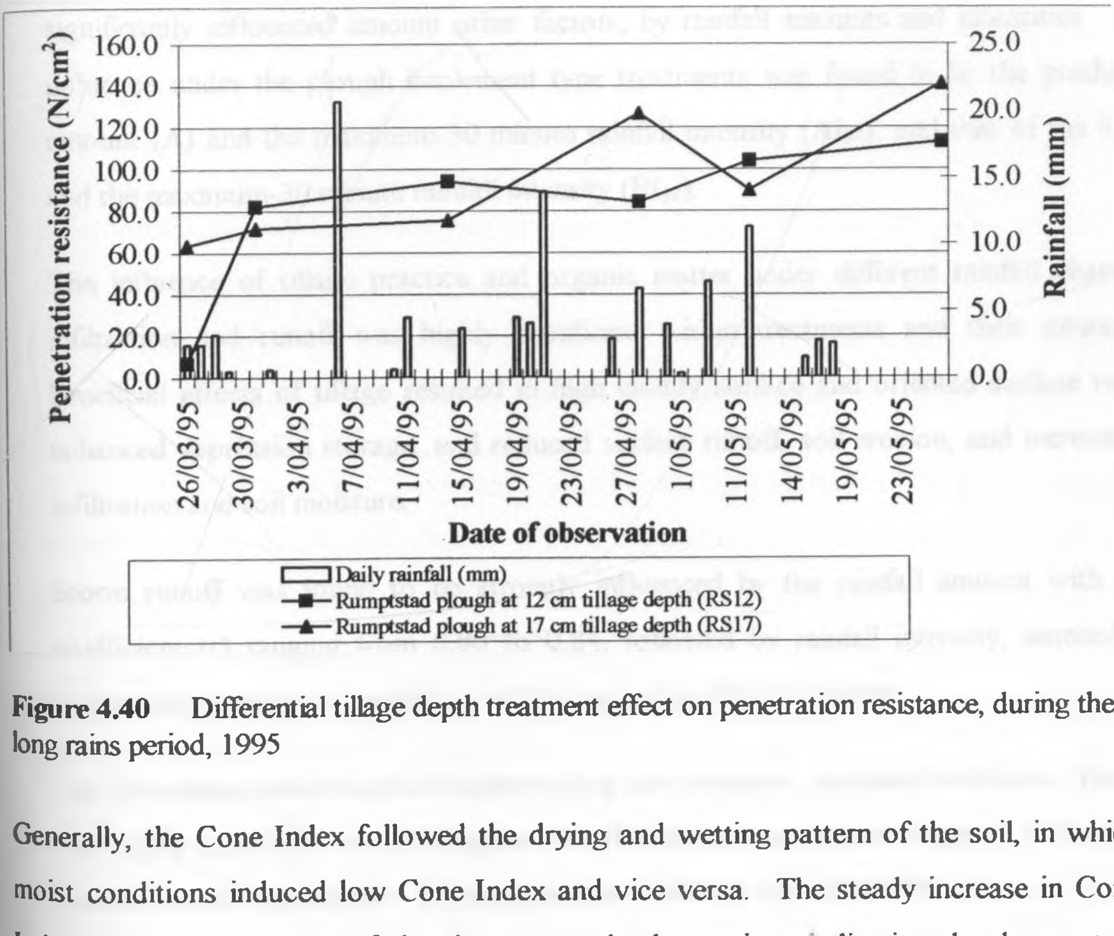


Figure 4.40 Differential tillage depth treatment effect on penetration resistance, during the long rains period, 1995

Generally, the Cone Index followed the drying and wetting pattern of the soil, in which moist conditions induced low Cone Index and vice versa. The steady increase in Cone Index follows the pattern of the shear strength observations indicating development of surface crusting and compaction arising from raindrop impact and soil settlement. This reduced the tillage influence upon the mechanical impediment.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This experiment has shown that tillage implements and practices, organic matter and rainfall properties on soil and moisture conservation on a crusting Luvisol.

5.1.1 Influence of tillage implements and practices, farmyard manure application on:

5.1.1.1 Infiltration, surface runoff, soil loss and soil moisture.

This research has shown that soil loss on an Aluvisol of the ASALs of Eastern Kenya is significantly influenced amount other factors, by rainfall amounts and intensities. The greatest influence under the plough implement type treatments was found to be the product of rainfall amount (A) and the maximum-30 minute rainfall intensity (AI_{30}), and that of the kinetic energy and the maximum-30 minute rainfall intensity (EI_{30}).

The influence of tillage practice and organic matter under different rainfall characteristics on infiltration and runoff was highly significant within treatments and their interactions. The beneficial effects of tillage resulted in high cloddy surface and oriented surface roughness that enhanced depression storage, and reduced surface runoff, soil erosion, and increased rainwater-infiltration and soil moisture.

Storm runoff was found to be strongly influenced by the rainfall amount with a correlation coefficient (r) ranging from 0.80 to 0.84, followed by rainfall intensity, antecedent moisture content and duration of rainfall as well as the soil surface conditions.

The percentage runoff-rainfall treatment response however, increased with time. Runoff response was highly significant with the highest runoff under no manure as compared to the 10 tonnes' per hectare manure application. Manure treatment reduced runoff by 39%.

Runoff response to plough implement type and manure interaction treatment impacts runoff reduction of 12% in the Modified Reversible Maresha Prototype tillage and farmyard manure compared to its control and 10% less than that of Conventional Rumptstad Mouldboard with farmyard manure. The Conventional Rumptstad Mouldboard with farmyard manure on the other hand was able to reduce runoff by only 3%compared to its control. The Modified Reversible Maresha Prototype tillage reduced runoff by 40%.

Runoff response to plough implement treatment was also significant with the least runoff in the Modified Reversible Maresha Prototype tillage compared to that of the Conventional Rumptstad Mouldboard. The Modified Reversible Maresha Prototype tillage reduced runoff by 40%.

Modified Reversible Maresha Prototype tillage and application of manure gives a better control of runoff than the Conventional Rumptstad Mouldboard and the non-manure treatments. Under high rainfall amounts however, the Modified Reversible Maresha Prototype tillage practice can yield high runoff due to overflows from its oriented surface roughness as compared to the random roughness created by the Conventional Rumptstad Mouldboard tillage under similar treatment.

Over the experimental period tillage practice with farmyard mature interaction gave a significance difference in soil loss at the 5% confidence level. The Modified Reversible Maresha Prototype tillage with manure interaction reduced soil loss by 66% compared to the control whilst the Conventional Rumptstad Mouldboard with manure reduced soil loss by only 7%.

In the main treatments the zero tonnes' manure was higher than the 10 tonnes' manure, while the plough implement type the Conventional Rumptstad Mouldboard had more soil loss than the Modified Reversible Maresha Prototype tillage. Manure effected a 39% reduction in soil loss over the non-manure treatments, while in the plough implement type the Modified Reversible Maresha Prototype tillage reduced soil loss by 24% over the Conventional Rumptstad plough implement.

5.1.1.2 Soil Moisture Conservation

Results of the soil moisture conservation as influenced by tillage practice and farmyard manure treatment as monitored throughout the short and the long-rains had no significant difference.

During the short-rains period the manure application did not improve the soil moisture conservation over the non-manured, similarly in the plough implement type the Modified Reversible Maresha Prototype tillage did not improve soil moisture conservation over the

Conventional Rumptstad Mouldboard. During the long-rains however, manure had the highest available soil moisture compared to its control while in the plough implement treatments the Modified Reversible Maresha Prototype tillage was higher than that under Conventional Rumptstad Mouldboard tillage.

Seasonal soil moisture variations were more pronounced in the upper 10 cm depth than in the 0-90 cm soil profile. The reverse in the seasons' moisture status reflects the importance of the state of farmyard manure in soil moisture conservation for early water retention benefits. In the plough implement types the results showed that long-term use of Modified Reversible Maresha Prototype tillage as a minimum tillage improves soil water retentivity and availability.

The situation under crop cover could, however, been different due to the fact that in the long run raindrop impact and soil surface evaporation could have been reduced by crop canopy. Secondly, high evaporation from the manure treatment arising from improved soil structure and capillary action, could have negatively influenced the amount of soil moisture conservation.

5.1.1.3 Soil aggregate stability

There was a very high significant difference at 5% confidence level in water soil aggregate stability with farmyard manure application compared to its control. All treatments however, experienced a reduction in soil aggregation at the end of the two rain seasons.

Using the proportion of "water stable aggregates" of less than 0.5 mm diameter as the erosivity indicator, the soil tilled with the use of the Modified Reversible Maresha Prototype tillage without manure was found to be the most erodible. These results showed that soils void of organic matter when subjected to raindrop and soil moisture conditions under go higher break-down of soil aggregates into smaller or primary particles as compared those with manure.

Though not significantly different the Modified Reversible Maresha Prototype tillage improved soil aggregation compared to the Conventional Rumptstad Mouldboard tillage practice. This goes to emphasize the importance of organic matter in the soils. Secondly, it goes to show that tillage practice requires a longer observational period than the two seasons in order to obtain effective data.

5.2 Effect of shallow and deep tillage on soil moisture conservation

In the tillage depth soil water conservation monitoring, the 17 cm tillage depth was significantly different at 5% confidence level as compared to that of 12 cm depth. The best soil depth profile that showed the highest significant difference was the 0-60 cm, where Conventional Rumptstad Mouldboard tillage at 17 cm depth had 3.5 times that under the Conventional Rumptstad Mouldboard tillage at 12 cm depth. The 0-100 cm profile depth had an improvement in soil moisture of up to 1.3 times in favour of deep tillage.

This investigation has shown that deep tillage effect on soil moisture conservation is statistically highly significant compared to the normal tillage depth of 12 cm. Though this research covered only one rainfall season, results are quite promising in that, the deep tillage has proved to improve soil moisture storage and availability 2.4 times compared to the normal tillage depth under the same manure type and application. Since a crop can use retained soil water to a depth of 30 to 60 cm beyond its root range, deep tillage would, therefore go a long-way in improving soil water conservation for enhanced crop production.

5.3 Recommendations on soil and water management in semi-arid areas with crusting soils

5.3.1 Use of Farmyard Manure in Soil and Water Conservation

Since investigation in the application of farmyard manure has shown some remarkable improvement on the soil's physical conditions, and the resultant increase in rainwater infiltration, reduction in the soil loss, its wide adoption can lead to some significant improvement in crop performance and food security. Moreover, composting and the return to the soil farmyard manure for maintaining soil fertility in this environment and socio-economic set-up is not only feasible but economical also. It is therefore recommended that farmers should be:-

1. Encouraged to seriously adopt periodic farmyard manure application as an integral farm management practice for the improvement and maintenance of the soil's aggregate stability.
2. Advised to use well decomposed manure for in-situ rainwater conservation. However, the commonly available farmyard manure found in the area is the un-decomposed type, whose use has shown to lag the soil's response to moisture conservation enhancement. This situation is due to high soil water conductance without a corresponding improved water holding capacity. It is therefore recommended that, non decomposed farmyard manure should be incorporated into the soil at the end of the rainy season; around harvesting time. Post-harvest manure incorporation, would enhance the manure decomposition before the planting time or should be placed in the field in heaps a month before the rains. This will also reduce the temporal shortage of available nitrogen to the crop in the early development stages.
3. Further research is required to investigate the residual effect of manure application on crop, soil and water management with the hope of establishing the frequency of application.

5.3.2 Tillage practices in soil and water conservation

Since tillage directly influences rainwater infiltrating into the soil, runoff and soil loss, and the amount of water stored in the soil, tillage practice that is most effective in enhancing infiltration should be adopted. From the performance of Modified Reversible Maresha Prototype tillage and the Conventional Mouldboard Rumptstad plough implements the later has shown to be the most promising of the two tillage implements and their interaction with manure application. It is recommended that:-

1. The use of Modified Reversible Maresha Prototype implement could be adopted to start with for ridging on the contour at weeding time following a shallow conventional tillage operation.
2. Where farmers deep ploughed their fields at post-harvest time this plough implement can be used to ridge on the contour to impound water early in the season.
3. In order to establish the suitability of this implement for primary tillage operations further research is required to investigate its compatibility with the currently used planting system of placing seed behind the plough implement and the effect of the early weed infestation observed. Also to be investigated is the influence of strip tillage on penetration resistance and its effect on crop growth.
4. There is need to investigate the effect of surface sealing and crusting on soil moisture conservation and crop production in the semi-arid environment.

5.3.3 Tillage depth in water conservation

1. Since the deep tillage and farmyard manure treatment has shown a high potential in in-situ rainwater conservation, its' adoption by farmers will mitigate soil drought and improve crop yields. Due to high draught power requirement for deep tillage, ploughing could be carried out at post-harvest time to take advantage of the residual soil moisture and the healthier draught animal condition. Post-harvest tillage would also facilitate the incorporation of the non decomposed manure.

2. Since deep tillage is a promising in-situ rainwater conservation tillage practice further research is required to investigate its effect on soil loss, since it exposes the unstable subsurface soil to the surface.

5.3.4 Soil and water conservation planning

The linear relationship established between the product of rainfall energy (E) and its 30-minute intensity (I_{30}), enables the prediction of rainfall erosivity from rainfall amounts. This prediction facilitates soil loss estimation in places without rainfall intensity data and thus aids soil and water conservation planning.

The tillage investigations have shown that in the Modified Reversible Maresha Prototype plough implement with 10 tonnes' farmyard manure application the use of physical conservation structures would only be necessary as a precautionary measure against the high rainfall amounts and intensities at slopes lower than 9%. The design of soil and water management strategies should therefore emphasize on soil surface management system that would not only incorporate manure but would also aim at less soil disturbance feasible through strip-tillage. Conventional Rumptstad Mouldboard plough implement with 10 tonnes' farmyard manure application has shown to be far much better than without manure and even much better than the Modified Reversible Maresha Prototype plough implements without manure. Therefore the later two if ever used must be supported with adequate physical conservation structures for erosion control.

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Appendices 1: Rainfall, erosion parameters and soil moisture.

Appendix 1. 1 Rain-gauges' calibration and the recorded rainfall data, 1994/95.

a) Short-rains' period

Date of	Rainfall amount (mm)					
			Calibrated		Average	
rainfall observation	Gauge 1	Gauge 2	Gauge 1	Gauge 2	(mm)	Comments
01/10/94	-	-	-	-	5.4	Standard gauges used
12/10/94	-	-	-	-	1.	(50 to100m away)
13/10/94	-	-	-	-	67.8	"
19/10/94	-	-	-	-	8.5	"
20/10/94	-	-	-	-	11.	"
22/10/94	1.6	1.3	1.6	1.3	1.4	Calibrated data
23/10/94	9.9	10.4	9.1	9.5	9.3	"
24/10/94	6.2	6.9	5.8	6.4	6.1	"
27/10/94	1.3	1.0	1.3	1.0	1.	"
1/11/9	5.7	5.7	5.3	5.3	5.3	"
2/11/94	8.3	7.8	7.7	7.2	7.5	"
5/11/94	34.9	34.2	32.1	31.	31.6	"
6/11/94	25.0	25.3	23.0	23.0	23.0	"
7/11/94	6.7	7.0	6.3	6.5	6.4	"
8/11/94	6.0	6.7	5.6	6.2	5.9	"
11/11/9	65.6	71.7	60.3	64.9	62.6	"
12/11/9	66.6	64.6	61.2	58.5	59.9	"
13/11/9	2.6	2.4	2.4	2.3	2.4	"
14/11/9	23.7	23.0	21.8	20.9	21.4	"
15/11/9	18.4	18.2	17.0	16.6	16.8	"
17/11/9	22.4	22.0	20.7	20.0	20.3	'
21/11/9	1.9	1.8	1.9	1.8	1.8	"
22/11/94	1.2	1.2	1.	1.2	1.2	"

b) Long-rains' period

	Rainfall amount (mm)					
Date of			Calibrated		Average	
rainfall event	Gauge 1	Gauge 2	Gauge 1	Gauge 2	(mm)	Comments
9/2/95	18.9	18.4	17.4	16.7	17.	
10/2/95	18.8	18.7	17.4	17.0	17.2	
11/2/95	3.5	3.6	3.3	3.4	3.4	
12/2/95	9.0	9.9	8.3	9.0	8.7	
13/2/95	1.5	1.3	1.5	1.3	1.4	
15/2/95	13.6	13.6	12.6	12.4	12.5	
16/2/95	4.7	5.0	4.4	4.7	4.5	
3/3/95	35.5	34.9	32.7	31.7	32.2	
4/3/95	34.6	36.5	31.9	33.1	32.5	
9/3/95	31.0	27.9	28.6	25.3	27.0	
10/3/95	4.2	3.5	3.9	3.3	3.6	
11/3/95	7.0	6.6	6.6	6.1	6.3	
15/3/95	1.9	1.8	1.9	1.8	1.8	
21/3/95	0.5	0.4	0.6	0.5	0.5	
24/3/95	6.9	7.0	6.4	6.5	6.5	
25/3/95	28.2	27.8	26.0	25.3	25.6	
26/3/95	9.7	10.2	9.0	9.4	9.2	
27/3/95	2.7	2.6	2.6	2.5	2.5	
28/3/95	3.4	3.5	3.2	3.3	3.3	
29/3/95	0.4	0.4	0.4	0.6	0.5	
1/4/95	0.6	0.5	0.7	0.6	0.6	
6/4/95	22.7	22.5	21.0	20.5	20.7	
10/4/195	0.6	0.5	0.6	0.6	0.6	

Appendix 1. 1 Continuation

Date of rainfall event	Rainfall amount (mm) Gauge 1	Gauge 2	Calibrated Gauge 1	Gauge 2	Average (mm)	Comments
27/11/94	2.9	3.1	2.7	2.9	2.8	"
28/11/94	6.3	5.8	5.9	5.3	5.6	"
29/11/94	20.2	19.8	18.6	18.	18.3	"
30/11/94	5.6	5.4	5.3	5.1	5.2	"
2/12/94	9.9	9.9	9.2	9.0	9.1	"
5/12/94	12.8	12.5	11.	11.	11.	"
6/12/94	49.5	48.3	45.6	43.8	44.7	"
7/12/94	8.4	8.3	7.9	7.7	7.8	"
8/12/94	3.2	3.7	3.0	3.5	3.3	"
9/12/94	19.5	19.0	18.0	17.3	17.7	"
10/12/94	4.1	3.8	3.9	3.6	3.7	"
11/12/9	3.8	3.5	3.6	3.3	3.5	"
14/12/94	1.5	1.3	1.5	1.3	1.4	"
15/12/94	1.7	1.0	1.6	1.0	1.3	"
16/12/94	1.7	1.6	1.6	1.6	1.6	"
17/12/94	1.4	1.3	1.4	1.3	1.3	"
23/12/94	6.6	6.1	6.1	5.6	5.9	"
24/12/94	8.7	8.6	8.1	7.9	8.0	"
25/12/95	3.6	3.1	3.4	2.9	3.2	"
26/12/95	12.8	12.8	11.	11.	11.	"
28/12/94	1.4	1.0	1.4	1.0	1.2	"
3/1/95	27.5	28.9	25.3	26.3	25.8	"
12/1/95	2.8	2.7	2.7	2.6	2.6	"
16/1/95	3.4	3.5	3.2	3.3	3.3	"
Total	527.2	526.2	488.0	481.2	579.1	
Average	12.6	12.5	11.	11.	12.3	

Date of rainfall event	Rainfall amount (mm) Gauge 1	Gauge 2	Calibrated Gauge 1	Gauge 2	Average (mm)	Comments
11/4/95	4.7	4.9	4.4	4.6	4.5	
15/4/95	4.0	3.8	3.8	3.6	3.7	
19/4/95	4.9	4.7	4.6	4.4	4.5	
20/4/95	4.5	4.3	4.2	4.0	4.1	
21/4/95	15.2	15.2	14.	13.9	14.0	
26/4/95	3.2	2.9	3.0	2.8	2.9	
28/4/95	7.9	6.6	7.3	6.1	6.7	
30/4/95	4.3	4.2	4.0	3.9	4.0	
1/5/95	0.2	0.2	0.3	0.3	0.3	
2/5/95	0.7	0.5	0.7	0.6	0.7	
9/5/95	7.4	8.1	6.9	7.5	7.2	
12/5/95	12.2	12.4	11.	11.	11.	
16/5/95	1.6	1.5	1.6	1.5	1.5	
17/5/95	3.0	2.8	2.8	2.7	2.8	
18/5/95	2.8	2.6	2.7	2.5	2.6	
Total	336.6	331.8	312.6	305.1	308.9	
Average	8.9	8.7	8.2	8.0	8.1	

Appendix 1. 2 Seasonal rainfall distribution, 1994/95.

Month Of Year	Dates of rainfall observation	Days of consecutive rainfall	Days of isolated rainfall	Days of dry spells	rainfall (mm)
October	01/10/94		1	10	5.4
	12-13/10/94	2		5	68.9
	19-20/10/94	2		1	20.2
	22-24/10/94	3		2	16.9
	27/10/94		1	4	1.1
November	1-2/11/94	2		2	12.8
	5-8/11/94	4		2	66.9
	11-15/11/94	5		1	163.1
	17/11/94		1	3	20.3
	21-22/11/94	2		4	3.0
	27-30/11/94	4		1	31.9
December					
	2/12/94		1	2	9.1
	5-11/12/94	7		2	92.2
	14-17/12/94	4		5	5.7
	23-26/12/94	4		1	28.8
	28/12/94		1	3	1.2
January					
	3/1/95		1	8	25.8
	12/1/95		1	3	2.6
	16/1/95		1		3.3
Span of days and total rainfall		39	8	59	579.1
Span of rainfall days in the season		106			

Appendix 1. 3 Seasonal rainfall distribution, during the long-rains period, 1995.

Month of year	Dates of rainfall observation	Days of consecutive Rainfall	Days of isolated Rainfall	Days of dry spells	Rainfall (mm)
February	9-13/2/95	5		1	47.7
	15-16/2/95	2		12	17.1
March				2	
	3-4/3/95	2		4	64.7
	9-11/3/95	3		3	36.9
	15/3/95		1	5	1.8
	21/3/95		1	2	0.5
	24-29/3/95	6		2	47.6
April	1/4/95		1	4	0.6
	6/4/95		1	3	20.7
	10-11/4/95	2		3	5.1
	15/4/95		1	3	3.7
	19-21/4/95	3		4	22.6
	26/4/95		1	1	2.9
	28/4/95		1	1	6.7
May	30/4-2/5/95	3		6	5.0
	9/5/95		1	2.0	7.2
	12/5/95		1	3.0	11.3
	16-18/5/95	3			6.9
Span of days and total rainfall		29	9	61	308.9
Span of rainfall days in the season		99			

Appendix 1. 4 Long term period total rainfall (1957-94) for Katumani Meteorological Station.

	Seasonal total rainfall (mm)							
Year	Season of the year		Year	Season of the year		Year	Season of the year	
	Short-rains	Long-rains		Short-rains	Long-rains		Short-rains	Long-rains
1957	341.2	265.1	1970	188	371.2	1983	230	248.7
1958	156	503.8	1971	267.7	277.2	1984	414.1	55.4
1959	209.4	350.6	1972	414.7	197	1985	311.1	552.1
1960	256	295.5	1973	207.1	127.8	1986	342.3	324.5
1961	875.8	164.4	1974	236.6	476.6	1987	199.5	119.4
1962	348	307.7	1975	190.9	190.6	1988	455.1	350.4
1963	782.4	426.2	1976	222.7	154.5	1989	375.2	285.8
1964	276.1	421.2	1977	384.4	532.8	1990	348	556.9
1965	344	160.6	1978	496.6	372.6	1991	331.9	193.7
1966	213.6	347.9	1979	251.7	499.5	1992	602.3	211.5
1967	259.5	453.2	1980	190.8	310.5	1993	209.3	165.1
1968	455.7	518.9	1981	182.4	452.2	1994	579.1	285.7
1969	267.3	209.9	1982	476	262.1	1995	-	308.9

Key: Short-rains is considered to run from October to January.
Long-rains is considered to run from February/march to May.

Appendix 1. 5 Rainfall characteristics during the short-rains period, 1994.

Date of rainfall observation	Rainfall Duration (Minutes)	Manual rainfall amount (mm)	Logged rainfall amount (mm)	Max. I_{30} (mm/h)	AI_{30} (mm^2/h)	Total kinetic energy [J/m^2]	EI_{30} Energy (E x I_{30}) [J-mm/m^2-h]	KE>25 Total K.E.
27/10/94	30	1.1	1	2	2	15	29	0
1/11/94	40	5.3	4.6	8	36.8	88	706	0
2/11/94	66	7.5	7.2	12	86.4	155	1855	84
5/11/94	196	31.6	32.8	24.8	813.44	698	17321	235
6/11/94	299	23.0	22.4	12.8	286.72	397	5085	22
7/11/94	89	6.4	5.6	4.8	26.88	95	455	0
8/11/94	169	5.9	5	3.2	16	71	226	0
11/11/94	356	62.6	59.2	29.6	1752.3	1364	40363	921
12/11/94	399	59.9	60	30.8	1848	1309	40328	750
13/11/94	70	2.4	2	2.4	4.8	28	67	0
14/11/94	354	21.4	20.8	8	166.4	349	2792	16
15/11/94	333	16.8	15.6	5.2	81.12	246	1281	0
17/11/94	305	20.3	19.2	7.6	145.92	325	2472	0
21/11/94	66	1.8	1.6	2	3.2	21	43	0
22/11/94	10	1.2	0.4	0.8	0.32	6	5	0
27/11/94	93	2.8	2.2	1.6	3.52	29	46	0
28/11/94	90	5.6	6	6.8	40.8	103	699	0
29/11/94	220	18.3	17.2	14.4	247.68	321	4616	92
30/11/94	50	5.2	4.2	7.6	31.92	76	574	0
2/12/94	187	9.1	8.6	3.2	27.52	132	423	0
5/12/94	138	11.6	11.2	12.8	143.36	224	2865	110
6/12/94	503	44.7	42.8	15.2	650.56	788	11980	86
7/12/94	147	7.8	6.8	5.2	35.36	81	421	0
8/12/94	91	3.3	3	2.4	7.2	44	105	0
9/12/94	89	17.7	17	26.4	448.8	381	10050	225
10/12/94	113	3.7	3.8	1.6	6.08	55	88	0
11/12/94	28	3.5	2.6	5.2	13.52	48	249	0
14/12/94	18	1.4	1	2	2	16	31	0
15/12/94	19	1.3	0.6	1.2	0.72	9	10	0
16/12/94	14	1.6	1	2	2	17	35	0
17/12/94	4	1.3	0.8	1.6	1.28	17	27	0
23/12/94	54	5.9	5.2	8.4	43.68	96	810	0
24/12/94	277	8.0	8.4	3.6	30.24	119	427	0
25/12/94	18	3.2	3.2	6.4	20.48	68	435	16
26/12/94	94	11.8	11.4	8	91.2	211	1689	48
28/12/94	63	1.2	1	2	2	12	24	0
3/1/95	246	25.8	24.6	11.6	285.36	477	5538	117
12/1/95	20	2.6	2	4	8	37	149	0
16/01/95	23	3.3	3	6	18	37	223	22

Appendix 1. 6 Treatment effects to rainfall-runoff response expressed as a percentage of their controls during the short rains period, 1994/95.

Date of	Rainfall	Per cent				Per cent runoff response to			
						Manure and plough interaction		Manure	Plough
		MM_0	MM_{10}	RS_0	RS_{10}	MM_{10}	RS_{10}	10 tonnes	MM
5/11/94	31.6	1	0	2	2	0	68	50	22
6/11/94	23.0	0	0	2	2	0	85	69	13
11/11/94	62.6	16	7	10	12	45	116	73	103
12/11/94	59.9	41	16	37	33	39	89	63	82
14/11/94	21.4	9	3	13	11	30	84	62	49
15/11/94	16.8	5	1	8	6	17	68	50	39
17/11/94	20.3	12	4	20	12	35	63	52	50
29/11/94	18.3	20	8	20	16	43	82	62	78
30/11/94	5.2	6	0	6	5	0	89	44	53
5/12/94	11.6	17	9	20	17	53	87	71	69
6/12/94	44.7	30	15	37	34	48	91	72	63
7/12/94	7.8	17	5	20	13	28	64	47	66
9/12/94	17.7	38	17	47	40	46	86	68	64
24/12/94	8.0	50	25	57	42	49	74	62	76
3/1/95	25.8	25	11	26	23	45	87	66	75
Average	25.0	21	9	22	19	32	82	61	60
Total (mm)	374.6	77.9	33.0	81.9	71.5	79.9	52.2	55.4	76.7

Appendix 1. 7: Plough and manure treatment effect on soil loss (g/m^2) during the short-rains period, 1994/95.

Date of	Erosive	Soil loss (g/m^2)				Statistical results	
Observation	rainfall (mm)	MM_0	MM_{10}	RS_0	RS_{10}	P (probability)	CV (%)
5/11/94	31.6	26.4	0.0	12.1	22.2	0.13 ns	120
6/11/94	23.0	2.2	0.0	20.1	20.4	0.87 ns	146
11/11/94	62.6	883.6	370.5	374.7	423.7	0.10 ns	54
12/11/94	59.9	1561.8	385.1	1311.7	1306.4	0.25 ns	70
14/11/94	21.4	40.1	20.4	99.8	60.1	0.55 ns	63
15/11/94	16.8	21.7	3.5	80.9	19.7	0.17 ns	126
17/11/94	20.3	78.1	31.8	156.1	47.2	0.46 ns	98
29/11/94	18.3	195.0	85.6	104.0	172.3	0.01 **	66
30/11/94	5.2	3.8	0.0	8.1	6.1	0.74 ns	94
5/12/94	11.6	80.7	40.0	115.0	79.8	0.93 ns	65
6/12/94	44.7	196.5	96.5	254.4	232.8	0.60 ns	63
7/12/94	7.8	19.3	3.3	19.1	8.7	0.69 ns	83
9/12/94	17.7	133.0	28.3	97.2	113.5	0.20 ns	67
24/12/94	8.0	120.1	57.4	210.4	140.6	0.89 ns	54
3/1/95	25.8	136.9	80.5	142.5	170.3	0.35 ns	58
Mean	25.0	233.3	80.2	200.4	188.2	0.25 ns	55
Total (g/m^2)	374.6	3499.1	1203.0	3006.1	2823.6		

Key:

MM_0 is the modified reversible maresha prototype plough with no-manure treatment.

MM_{10} is the modified reversible maresha prototype plough with 10 tonnes manure traetment.

RS_0 is the Rumptstad conventional plough with no-manure treatment.

RS_{10} is the Rumptstad conventional plough with 10 tonnes manure treatment.

Appendix 1. 8 Regression coefficients of the rainfall-soil erosion parameters, during the long rains period, 1994/95.

Treatment or Erosivity factor	Multiple correlation coefficients (MR)													
	Runoff versus Rainfall proprties						Soil loss versus Rainfall proprties							
	I_{30} (mm/h)	EI_{30} [$KJm^{-2}mmh^{-1}$]	Rainfall amount	Total E [J/m^2-mm]	K. E.>25 [J/m^2]	Rainfall duration (minutes)	I_{30} (mm/h)	EI_{30} [$KJm^{-2}mmh^{-1}$]	Rainfall amount	AI_{30} [mm^2h^{-1}]	Total E [J/m^2-mm]	K. E.>25 [J/m^2]	Runoff	Rainfall duration (minutes)
0 FYM	0.71	0.78	0.83	0.82	0.71	0.69	0.69	0.87	0.79	0.87	0.82	0.84	0.89	0.56
10 FYM	0.71	0.78	0.84	0.83	0.71	0.70	0.70	0.88	0.81	0.88	0.84	0.85	0.88	0.57
MM	0.72	0.82	0.84	0.84	0.76	0.68	0.72	0.92	0.82	0.92	0.86	0.91	0.89	0.55
RS	0.70	0.75	0.82	0.81	0.67	0.71	0.66	0.82	0.72	0.83	0.78	0.78	0.89	0.57
Plough and manure interactions														
MM_0	0.72	0.82	0.84	0.84	0.76	0.67	0.71	0.91	0.80	0.91	0.84	0.90	0.90	0.53
MM_{10}	0.72	0.81	0.84	0.84	0.75	0.68	0.73	0.93	0.86	0.93	0.89	0.94	0.86	0.59
RS_0	0.69	0.73	0.80	0.79	0.64	0.71	0.64	0.81	0.75	0.81	0.77	0.76	0.87	0.58
RS_{10}	0.71	0.77	0.83	0.82	0.69	0.71	0.67	0.84	0.76	0.84	0.79	0.80	0.87	0.55
Storm duration Vs	0.54													
Rainfall amounts Vs	0.86	0.92		0.99	0.85									
AI_{30} (mm^2/h)		0.998												

Appendix 1. 9 *Coefficients of determination for the rainfall-soil erosion parameters, during the short rains period, 1994/95.*

Treatment or Erosivity factor	Coefficient of determination (r^2)													
	Runoff versus Rainfall proprties						Soil loss versus Rainfall proprties							
	I_{30} (mm/h)	EI_{30} [$KJm^{-2}mmh^{-1}$]	Rainfall amount	Total E [J/m^2-mm]	K. E.> 25 [J/m^2]	Rainfall duration (minutes)	I_{30} (mm/h)	EI_{30} [$KJm^{-2}mmh^{-1}$]	Rainfall amount amount	AI_{30} [mm^2h^{-1}]	Total E [J/m^2-mm]	K. E.> 25 [J/m^2]	Runoff	Rainfall duration (minutes)
0 FYM	0.49	0.60	0.68	0.66	0.49	0.47	0.46	0.76	0.61	0.76	0.66	0.70	0.78	0.29
10 FYM	0.49	0.61	0.69	0.68	0.49	0.47	0.50	0.77	0.64	0.78	0.69	0.72	0.77	0.31
MM	0.52	0.67	0.70	0.70	0.56	0.44	0.50	0.84	0.67	0.84	0.73	0.83	0.79	0.28
RS	0.47	0.55	0.66	0.64	0.43	0.49	0.42	0.67	0.57	0.67	0.60	0.60	0.75	0.30
Plough and manure interactions														
MM_0	0.51	0.67	0.70	0.70	0.57	0.44	0.49	0.82	0.64	0.82	0.70	0.80	0.81	0.26
MM_{10}	0.50	0.65	0.70	0.70	0.55	0.45	0.52	0.87	0.73	0.87	0.78	0.88	0.73	0.33
RS_0	0.46	0.53	0.64	0.61	0.40	0.49	0.40	0.64	0.56	0.66	0.59	0.56	0.75	0.32
RS_{10}	0.49	0.58	0.68	0.66	0.46	0.48	0.44	0.69	0.57	0.70	0.62	0.62	0.75	0.28
Storm duration Vs	0.27													
Rainfall amounts Vs	0.73	0.84		0.98										
AI_{30} (mm^2/h)		0.997		0.98	0.71									

Appendix 1. 10 *Total* water storage and available water capacity (underlined) in mm of water for 10, 30, 60, and 90 cm soil profile during short-rains period, 1994/95.

Date of	MM$_0$				MM$_{10}$				RS$_0$				RS$_{10}$			
measurement	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm
25/10/94	16.7	69.8	131.8	192.3	16.3	70.2	126.2	167.3	17.9	75.8	140.2	195.2	17.7	74.3	137.6	193
	3.2	25.3	35.4	38.2	2.8	25.7	29.8	13.2	4.4	31.3	43.8	41.1	4.2	29.8	41.2	39
28/10/94	19.5	69.3	131.9	194.0	15.0	62.8	123.9	181.0	18.8	68.6	131.8	190.5	18.6	67.9	130.3	188
	6.0	24.8	35.5	39.9	1.5	18.3	27.5	26.9	5.3	24.1	35.4	36.4	5.1	23.4	33.9	34
4/11/94	19.5	69.1	130.1	191.7	15.0	61.7	121.8	178.3	20.3	70.8	132.6	190.9	17.9	67.9	128.7	186
	6.0	24.6	33.7	37.6	1.5	17.2	25.4	24.2	6.8	26.3	36.2	36.8	4.4	23.4	32.3	32
12/11/94	24.1	85.2	158.9	245.1	24.1	87.7	161.9	253.9	24.2	86.2	161.6	240.2	24.2	85.6	159.4	241
	10.6	40.7	62.5	91.0	10.6	43.2	65.5	99.8	10.7	41.7	65.2	86.1	10.7	41.1	63.0	87
18/11/94	20.2	73.4	142.6	221.7	18.4	70.3	138.6	221.0	20.8	74.8	147.9	223.3	20.6	72.4	143.9	221
	6.7	28.9	46.2	67.6	4.9	25.8	42.2	66.9	7.3	30.3	51.5	69.2	7.1	27.9	47.5	67
25/11/94	15.3	63.0	127.9	203.4	14.0	60.3	125.3	202.9	14.2	61.9	129.2	202.1	13.9	64.8	131.8	207
	1.8	18.5	31.5	49.3	0.5	15.8	28.9	48.8	0.7	17.4	32.8	48.0	0.4	20.3	35.4	53
2/12/94	19.0	71.8	139.4	214.1	18.7	72.9	140.0	216.9	20.8	73.0	143.8	216.4	20.2	72.9	142.4	216
	5.5	27.3	43.0	60.0	5.2	28.4	43.6	62.8	7.3	28.5	47.4	62.3	6.7	28.4	46.0	61
9/12/94	20.5	77.8	148.1	226.7	21.4	76.3	146.2	229.1	23.6	80.6	162.8	237.3	24.0	82.0	154.0	231
	7.0	33.3	51.7	72.6	7.9	31.8	49.8	75.0	10.1	36.1	66.4	83.2	10.5	37.5	57.6	77
16/12/94	15.4	66.0	132.8	210.1	15.8	67.4	135.0	213.6	18.1	69.2	139.0	213.4	16.7	65.3	133.9	209
	1.9	21.5	36.4	56.0	2.3	22.9	38.6	59.5	4.6	24.7	42.6	59.3	3.2	20.8	37.5	54
23/12/94	16.3	65.2	130.1	206.0	17.5	66.1	131.0	210.5	19.1	68.7	136.1	209.6	17.3	66.8	133.7	208
	2.8	20.7	33.7	51.9	4.0	21.6	34.6	56.4	5.6	24.2	39.7	55.5	3.8	22.3	37.3	54
30/12/94	14.5	63.3	129.1	204.4	18.0	65.8	131.7	208.5	15.6	64.7	132.8	205.5	14.6	63.6	131.3	205
	1.0	18.8	32.7	50.3	4.5	21.3	35.3	54.4	2.1	20.2	36.4	51.4	1.1	19.1	34.9	51

Appendix 1. 10 Continuation

Date of	MM_0				MM_{10}				RS_0				RS_{10}			
measurement	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm
06/01/95	10.7	60.8	126.8	201.6	12.1	60.1	126.3	203.4	12.9	63.2	132.6	204.2	11.4	61.1	129.6	202.7
	-2.8	16.3	30.4	47.5	-1.4	15.6	29.9	49.3	-0.6	18.7	36.2	50.1	-2.1	16.6	33.2	48.6
9/01/95	13.5	61.8	126.6	201.5	11.9	58.9	123.7	200.7	11.7	58.2	125.6	197.4	12.2	59.5	126.7	199.5
	0.0	17.3	30.2	47.4	-1.6	14.4	27.3	46.6	-1.8	13.7	29.2	43.3	-1.3	15.0	30.3	45.4
13/01/95	13.8	59.9	123.6	197.0	12.5	58.7	122.7	197.8	13.4	59.9	125.9	197.3	13.3	60.7	126.4	198.4
	0.3	15.4	27.2	42.9	-1.0	14.2	26.3	43.7	-0.1	15.4	29.5	43.2	-0.2	16.2	30.0	44.3
20/01/95	11.9	57.1	119.7	191.6	11.6	55.9	119.6	194.4	12.6	58.2	123.2	193.8	12.7	56.7	121.0	191.2
	-1.6	12.6	23.3	37.5	-1.9	11.4	23.2	40.3	-0.9	13.7	26.8	39.7	-0.8	12.2	24.6	37.1
23/01/95	9.4	54.2	116.4	189.9	11.4	57.0	120.8	196.2	9.5	54.3	119.8	189.8	10.4	54.6	119.0	189.9
	-4.1	9.7	20.0	35.8	-2.1	12.5	24.4	42.1	-4.0	9.8	23.4	35.7	-3.1	10.1	22.6	35.8
27/01/95	8.6	51.8	113.1	185.7	8.1	51.3	113.4	187.0	7.9	51.9	116.1	186.3	9.0	53.8	118.0	188.8
	-4.9	7.3	16.7	31.6	-5.4	6.8	17.0	32.9	-5.6	7.4	19.7	32.2	-4.5	9.3	21.6	34.7
30/01/95	9.3	52.6	114.0	185.9	9.4	52.5	114.6	187.7	9.1	52.6	116.2	185.8	10.0	55.0	119.1	189.9
	-4.2	8.1	17.6	31.8	-4.1	8.0	18.2	33.6	-4.4	8.1	19.8	31.7	-3.5	10.5	22.7	35.8
Totals	278.4	1172.1	2342.8	3662.8	271.2	1156.2	2322.7	3650.3	290.3	1192.6	2417.2	3678.9	284.8	1184.9	2386.9	3669.1
	35.4	371.1	607.6	889.0	28.2	355.2	587.5	876.5	47.3	391.6	682.0	905.1	41.8	383.9	651.7	895.3

Key:

$MRMP_0$ is the modified reverseble maresha prototype plough with no-manure treatment

$MRMP_{10}$ is the modified reverseble maresha prototype plough with 10 tons manure treatment

RS_0 is therumptstard conversional plough with no-manure treatment

RS_{10} is the Rumptstard convertional plough with 10 tons manure treatment

Appendix 1.11: Total water storage and available water capacity (underlined) in mm of water for 10, 30, 60, and 90 cm soil profile during long-rains **period**, 1995.

Date of	MM_0				MM_{10}				RS_0				RS_{10}			
measurement	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm	10 cm	30 cm	60 cm	90 cm
27/3/95	17.3	69.6	139.1	213.9	17.1	69.7	138.4	215.3	17.1	70.4	140.4	209.4	16.2	67.5	137.2	210.5
	3.8	25.1	42.7	59.8	3.6	25.2	42.0	61.2	3.6	25.9	44.0	55.3	2.7	23.0	40.8	56.4
31/3/95	11.9	61.9	128.7	203.7	12.1	64.0	133.3	211.3	13.0	63.8	131.6	203.8	11.6	59.9	128.4	202.0
	-1.6	17.4	32.3	49.6	-1.4	19.5	36.9	57.2	-0.5	19.3	35.2	49.7	-1.9	15.4	32.0	47.9
10/4/95	8.5	56.0	122.6	196.1	8.0	55.2	122.5	199.9	10.3	58.7	125.6	195.8	9.6	57.3	124.7	197.6
	-5.0	11.5	26.2	42.0	-5.5	10.7	26.1	45.8	-3.2	14.2	29.2	41.7	-3.9	12.8	28.3	43.5
14/4/95	15.0	64.4	131.7	205.0	14.5	62.8	130.1	206.1	15.2	65.8	131.3	201.9	14.5	61.9	128.5	199.2
	1.5	19.9	35.3	50.9	1.0	18.3	33.7	52.0	1.7	21.3	34.9	47.8	1.0	17.4	32.1	45.1
21/4/95	22.5	73.1	139.4	212.5	22.0	72.7	140.1	215.8	23.2	73.4	139.0	208.6	23.6	74.2	141.1	212.2
	9.0	28.6	43.0	58.4	8.5	28.2	43.7	61.7	9.7	28.9	42.6	54.5	10.1	29.7	44.7	58.1
28/4/95	22.0	72.2	138.4	211.8	20.9	68.3	134.6	209.2	21.3	70.2	134.8	219.4	23.7	69.1	135.1	209.4
	8.5	27.7	42.0	57.7	7.4	23.8	38.2	55.1	7.8	25.7	38.4	65.3	10.2	24.6	38.7	55.3
5/5/95	10.0	60.0	125.4	197.8	9.6	55.2	121.3	195.5	9.3	56.6	121.0	188.4	9.9	57.8	123.0	193.2
	-3.5	15.5	29.0	43.7	-3.9	10.7	24.9	41.4	-4.2	12.1	24.6	34.3	-3.6	13.3	26.6	39.1
12/5/95	22.4	74.4	139.5	211.6	23.4	72.6	138.3	212.0	22.2	71.7	135.2	202.1	22.5	69.5	134.9	205.7
	8.9	29.9	43.1	57.5	9.9	28.1	41.9	57.9	8.7	27.2	38.8	48.0	9.0	25.0	38.5	51.6
19/5/95	14.9	65.7	131.2	203.7	15.4	62.7	128.7	202.7	14.9	64.0	127.8	197.4	15.3	60.7	126.7	196.0
	1.4	21.2	34.8	49.6	1.9	18.2	32.3	48.6	1.4	19.5	31.4	43.3	1.8	16.2	30.3	41.9
26/5/95	11.2	55.2	118.6	190.6	10.8	57.9	122.2	194.8	9.7	53.4	116.1	182.2	10.5	54.3	118.3	186.8
	-2.3	10.7	22.2	36.5	-2.7	13.4	25.8	40.7	-3.8	8.9	19.7	28.1	-3.0	9.8	21.9	32.7
2/6/95	11.0	57.6	121.8	193.0	10.6	54.4	118.2	189.7	11.0	57.5	120.2	187.4	12.3	56.3	119.9	188.4
	-2.5	13.1	25.4	38.9	-2.9	9.9	21.8	35.6	-2.5	13.0	23.8	33.3	-1.2	11.8	23.5	34.3
Totals	166.8	710.1	1436.6	2239.7	164.3	695.6	1427.6	2252.4	167.1	705.5	1422.9	2196.3	169.6	688.6	1417.8	2200.8
	18.3	220.6	376.2	544.6	15.8	206.1	367.2	557.3	18.6	216.0	362.5	501.2	21.1	199.1	357.4	505.7

Appendix 1. 12 Total water storage and available water capacity (underlined) in mm of water for 10, 30, 60, and 100 cm soil profile of the tillage depth treatment during the long-rains (1995).

Date of	RS12				RS17			
measurement	10 cm	30 cm	60 cm	100 cm	10 cm	30 cm	60 cm	100 cm
28/3/95	15.1	64.4	131.8	212.5	15.2	70.4	210.9	221.5
	1.6	19.9	35.4	38.7	1.7	25.9	114.5	47.7
31/3/95	10.0	58.0	127.4	211.8	13.4	68.2	206.9	222.2
	-3.5	13.5	31.0	38.0	-0.1	23.7	110.5	48.4
10/4/95	9.6	56.4	123.9	202.6	12.1	62.0	194.3	214.2
	-3.9	11.9	27.5	28.8	-1.4	17.5	97.9	40.4
14/4/95	17.9	64.6	130.2	211.5	14.7	66.5	203.3	215.7
	4.4	20.1	33.8	37.7	1.2	22.0	106.9	41.9
21/4/95	20.9	69.6	136.2	216.7	23.4	78.5	226.4	229.6
	7.4	25.1	39.8	42.9	9.9	34.0	130.0	55.8
28/4/95	21.5	69.4	134.5	214.9	22.7	77.7	224.8	229.4
	8.0	24.9	38.1	41.1	9.2	33.2	128.4	55.6
5/5/95	9.2	55.1	120.9	201.7	8.2	60.0	188.1	208.0
	-4.3	10.6	24.5	27.9	-5.3	15.5	91.7	34.2
12/5/95	18.5	66.3	131.9	212.4	20.6	79.5	227.1	228.2
	5.0	21.8	35.5	38.6	7.1	35.0	130.7	54.4
19/5/95	14.0	59.8	125.2	203.9	16.0	62.7	191.8	207.8
	0.5	15.3	28.8	30.1	2.5	18.2	95.4	34.0
26/5/95	9.8	55.3	119.4	197.7	8.9	57.6	181.1	200.9
	-3.7	10.8	23.0	23.9	-4.6	13.1	84.7	27.1
2/6/95	8.6	48.7	112.3	190.7	9.3	55.8	177.5	198.4
	-4.9	4.2	15.9	16.9	-4.2	11.3	81.1	24.6
Totals	155.0	667.6	1393.6	2276.4	164.4	739.0	2232.3	2376.0
	6.5	178.1	333.2	364.6	15.9	249.5	1171.9	464.2

Appendix 1. 13 Wet sieving aggregate stability (%) per plot.

Treatment Type	Wet aggregate stability (%) through 2.00, 1.00, 0.50 & 0.25 mm sieve diameters (dry sieved through a 4.75 mm sieve).			
	Short-rains (94)		Long-rains (95)	
	Early	End	Early	End
MM10	32.81	31.21	38.39	37.24
MM0	27.76	25.82	24.90	24.12
RS0	25.67	23.86	23.59	22.78
RS10	35.62	32.62	39.05	37.73

Appendix 1. 14 Oriented surface roughness Index (Log of standard deviation), during long-rains period, 1995.

Treatment type	Surface roughness (100Log of the Standard deviation)									
	Date of observation									
	28/3 /95	4/4 /95	11/4 /95	18/4 /95	25/4 /95	2/5 /95	9/5 /95	16/5 /95	23/5 /95	Average
Rainfall (mm)	6.9	20.7	8.8	0.0	22.6	13.6	1.0	18.5	6.9	11
MM	64	62	57	58	59	64	56	56	52	59
RS	60	60	58	62	54	56	56	55	54	57

Appendix 1. 15 Oriented surface roughness Index (Log of standard deviation), during long-rains, 1995 for the differential tillage depth.

Treatment type	Surface roughness (100Log of the Standard deviation)						
	Date of observation						
	18/4 /95	25/4 /95	2/5 /95	9/5 /95	16/5 /95	23/5 /95	Average
Weekly total rainfall (mm)	0.0	22.6	13.6	1.0	18.5	6.9	10
Rumptstad 12 cm depth	28	33	36	27	30	31	31
Rumptstad 17 cm depth	36	32	32	28	18	25	28

Appendix 1. 16: Treatment effect on shear strength (kPa) during short rains period, 1994/95

Julian week	Weekly raifall totals (mm)	Date of observation	Shear strength (Kpa) response to treatment							
							Manure level		MM	RS
			MM_0	MM_{10}	RS_0	RS_{10}	0 tonnes	10 tonnes		
46	58.5	18/11/94	20.1	17.2	12.6	12.4	16.4	14.8	18.7	12.5
47	5.8	-	-	-	-	-	-	-	-	-
48	38.2	2/12/94	12.9	14.7	13.7	12.0	13.3	13.4	13.8	12.8
49	92.2	-	-	-	-	-	-	-	-	-
50	5.7	16/12/94	13.5	18.8	13.2	11.8	13.4	15.3	16.1	12.5
51	17.1	-	-	-	-	-	-	-	-	-
52	13.0	30/12/94	19.3	19.7	20.1	16.8	19.7	18.2	19.5	18.4
1	25.8	-	-	-	-	-	-	-	-	-
2	2.6	6/1/95	40.2	34.6	33.5	34.1	36.8	34.3	37.4	33.8
3	3.3	20/1/95	61.3	59.7	70.9	72.9	66.1	66.3	60.5	71.9
3		27/1/95	68.6	68.2	70.1	69.6	69.3	68.9	68.4	69.8
Means	26.2		33.7	33.3	33.5	32.8	33.6	33.0	33.5	33.1

Appendix 1. 17 **Treatment effect on shear strength (Kpa) during the short-rains period (1994/95).**

Julian week	Weekly raifall totals (mm)	Date of observation	Shear strength (Kpa) response to treatment									
							Manure level		MM	RS	RS_{12}	RS_{17}
			MM_0	MM_{10}	RS_0	RS_{10}	0 tonnes	10 tonnes				
13	6.9	28/3/95	13.6	12.2	10.2	10.3	11.9	11.2	12.9	10.3	5.8	7.0
14	20.7	31/3/95	16.9	20.0	12.1	12.7	14.5	16.4	18.5	12.4	10.7	12.8
15	8.8	14/4/95	23.5	18.9	16.0	26.4	19.7	22.6	21.2	21.2	12.8	14.0
16	22.6	-	-	-	-	-	-	-	-	-		
17	13.6	28/4/95	16.5	13.7	10.6	13.3	13.5	13.5	15.1	12.0	11.2	9.9
18	1.0	-	-	-	-	-	-	-	-	-		
19	18.5	12/5/95	14.3	12.1	11.1	11.8	12.7	11.9	13.2	11.5	12.0	13.7
20	6.9	-	-	-	-	-	-	-	-	-		
21		26/5/95	28.0	31.8	24.8	28.5	26.4	30.2	29.9	26.7	28.2	24.0
Mean	12.4		18.8	18.1	14.1	17.2	16.5	17.7	18.5	15.7	13.4	13.6

Key:

MM_0 is the modified reverseble maresha prototype plough with no-manure treatment

MM_{10} is the modified reverseble maresha prototype plough with 10 tonnes manure treatment

RS_0 is theRumptstad conversional plough with no-manure treatment

RS_{10} is the Rumptstad convertional plough with 10 tonnes manure treatment

MM is the modified reversible maresha prototype plough.

RS is the Rumptstad convertional plough treatment

RS_{12} is the Rumptstad convertional plough at 12 cm tillage depth with 10 tonnes manure treatment

RS_{17} is the Rumptstad convertional plough at 17 cm tillage depth with 10 tonnes manure treatment

Appendices 2: Descriptive rainfall statistics and Analysis of Variance for a Split-plot over the Short-rains' (1994/95) erosion parameters.

Appendix 2. 1: **Long-term (1957-94) weekly paired t-Test for Two Sample for Means**

	Long-term rains (1957-94)	***1994/95 rains***
	12.86052632	*25.7856172*
Mean	13.42822904	17.11081171
Variance	161.4339848	862.6533827
Observations	51	51
Pearson Correlation	0.546643475	
Hypothesized Mean Difference	0	
Df	50	
t Stat	-1.059529403	
P(T<=t) one-tail	0.147225213	
t Critical one-tail	1.675905423	
P(T<=t) two-tail	0.294450426	ns
t Critical two-tail	2.008559932	

Appendix 2. 2: Rainfall-infiltration Split-plot Analysis of Variance for the Short-rains (1994/95).

Source	SS	df	MS	F	P	
Subplots						
Main plots						
Blocks	39.18453	2	19.59227			
Rain	68094.2	42	1621.291	639.6310487	0	***
Main Plot Error	212.9171	84	2.534728			
Plough	31.45496	1	31.45496	23.35193152	0	***
plough x rain	169.2334	42	4.029366	2.991371638	0	***
Subplot Error	115.8417	86	1.346996			
manure	53.2745	1	53.2745	32.06873462	0	***
manure x rain	299.0438	42	7.120091	4.285959267	0	***
manure x plough	20.72008	1	20.72008	12.47250965	0.0005	***
manure x plough x rain	161.4549	42	3.844165	2.314005958	0.0001	***
Error	285.7367	172	1.66126			
Total	69483.07	515				
Coef Var (CV)	116					

Duncan's Multiple Range Test

Factor	manure
Error mean square	1.66126
Degrees of freedom	172
Significance level	5%
LSD .05	0.223995

Rank	Trt#	Mean	n	Non-significant ranges
1	2	10.32946	258	a
2	1	9.686822	258	b

Duncan's Multiple Range Test

Factor	plough
Error mean square	1.346996
Degrees of freedom	86
Significance level	5%
LSD .05	0.203138

Rank	Trt#	Mean	n	Non-significant ranges
1	1	10.25504	258	a
2	2	9.76124	258	b

Appendix 2.2: Continuation

Duncan's Multiple Range Test
Factor: Rain
Error mean square 2.534728
Degrees of freedom 84
Significance level 5%
LSD .05 1.292527

Rank	Trt#	Mean	n	Non-significant ranges
1	12	55.433	12	a
2	13	41.058	12	b
3	26	31.683	12	c
4	8	31.225	12	c
5	9	22.775	12	d
6	41	20.308	12	e
7	15	19.525	12	e
8	17	17.866	12	f
9	16	16	12	g
10	22	15.366	12	g
11	39	11.8	12	h
12	1	11.7	12	h
13	29	11.4	12	h
14	25	9.7583	12	i
15	3	9.3	12	i
16	24	9.1	12	i
17	7	7.5	12	j
18	27	6.7333	12	jk
19	10	6.4	12	jkl
20	4	6.1	12	jkl
21	36	5.9	12	klm
22	11	5.9	12	klm
23	21	5.6	12	klm
24	6	5.3	12	klm
25	23	4.9833	12	lmn
26	37	4.5333	12	mno
27	30	3.7	12	nop
28	31	3.5	12	op
29	28	3.3	12	op
30	43	3.3	12	op
31	38	3.2	12	opq
32	20	2.8	12	pqr
33	42	2.6	12	pqrs
34	14	2.4	12	pqrs
35	18	1.8	12	qrs
36	34	1.6	12	rs
37	32	1.4	12	rs
38	2	1.4	12	rs
39	33	1.3	12	rs
40	35	1.3	12	rs
41	19	1.2	12	s
42	40	1.2	12	s
43	5	1.1	12	s

Key: Trt # stands for the treatment number, i.e.
Where: under manure : 1 stands for zero manure application (0 FYM)
: 2 stands for 10 tonnes/ha manure application (10 FYM)
: under ploughs type : 1 stands for Modified Reversible Maresha Prototype plough
: 2 stands for the Conventional Rumptstad Mouldboard plough

Appendix 2. 3: Runoff Analysis of Variance for a Split-plot for the short rains period (1994/95).

Source	SS	df	MS	F	P	
Subplots						
Main plots						
Blocks	39.18453	2	19.59227			
rain	6955.948	42	165.6178	65.33948499	0	***
Main Plot Error	212.9171	84	2.534728			
plough	31.45496	1	31.45496	23.35193152	0	***
plough x rain	169.2334	42	4.029366	2.991371638	0	***
Subplot Error	115.8417	86	1.346996			
manure	53.2745	1	53.2745	32.06873462	0	***
manure x rain	299.0438	42	7.120091	4.285959267	0	***
manure x plough	20.72008	1	20.72008	12.47250965	0.0005	***
manure x plough x rain	161.4549	42	3.844165	2.314005958	0.0001	***
Error	285.7367	172	1.66126			
Total	8344.81	515				
Coef Var (CV)	262					

Duncan's Multiple Range Test	
Factor:	manure
Error mean square	1.66126
Degrees of freedom	172
Significance level	5%
LSD .05	0.223995

Rank	Trt#	Mean	n	Non-significant ranges
1	1	1.857364	258	A
2	2	1.214729	258	B

Duncan's Multiple Range Test	
Factor	plough
Error mean square	1.346996
Degrees of freedom	86
Significance level	5%
LSD .05	0.203138

Rank	Trt#	Mean	n	Non-significant ranges
1	2	1.782946	258	A
2	1	1.289147	258	B

Appendix 2. 4: Continuation

Duncan's Multiple Range Test

Factor	rain
Error mean square	2.534728
Degrees of freedom	84
Significance level	5%
LSD .05	1.292527

Rank	Trt#	Mean	n	Non-significant ranges
1	13	18.84167	12	a
2	26	13.01667	12	b
3	12	7.166667	12	c
4	29	6.3	12	cd
5	41	5.491667	12	d
6	37	3.466667	12	e
7	22	2.933333	12	ef
8	17	2.433333	12	efg
9	15	1.875	12	fgh
10	25	1.841667	12	fgh
11	27	1.066667	12	ghi
12	16	0.8	12	hi
13	8	0.375	12	i
14	9	0.225	12	i
15	23	0.216667	12	i
16	3	0	12	i
17	1	0	12	i
18	18	0	12	i
19	19	0	12	i
20	20	0	12	i
21	21	0	12	i
22	7	0	12	i
23	14	0	12	i
24	24	0	12	i
25	10	0	12	i
26	2	0	12	i
27	11	0	12	i
28	28	0	12	i
29	4	0	12	i
30	30	0	12	i
31	31	0	12	i
32	32	0	12	i
33	33	0	12	i
34	34	0	12	i
35	35	0	12	i
36	36	0	12	i
37	6	0	12	i
38	38	0	12	i
39	39	0	12	i
40	40	0	12	i
41	5	0	12	i
42	42	0	12	i
43	43	0	12	i

Appendix 2. 5: Soil loss Split-plot Analysis of Variance covering the short rains period, (1994/95)

Source	SS	df	MS	F	P	
Subplots						
Main plots						
Blocks	34482.48	2	17241.24			
rain	18270659	42	435015.7	44.56271292	0	***
Main Plot Error	819997.6	84	9761.876			
plough	22179.5	1	22179.5	1.052360243	0.3078	ns
plough x rain	554545.4	42	13203.46	0.626470342	0.9522	ns
Subplot Error	1812532	86	21075.96			
manure	107154.8	1	107154.8	7.047053364	0.0087	**
manure x rain	1164856	42	27734.67	1.823975579	0.004	**
manure x plough	77913.93	1	77913.93	5.124023842	0.0248	*
manure x plough x rain	1238341	42	29484.32	1.939041563	0.0017	**
Error	2615366	172	15205.61			
Total	26718028	515				
Coef Var (CV)	372					

Duncan's Multiple Range Test	
Factor: Manure	
Error mean square	15205.61
Degrees of freedom	172
Significance level	5%
LSD .05	21.42998

Rank	Trt#	Mean	n	Non-significant ranges
1	1	75.64178	258	a
2	2	46.82066	258	b

Duncan's Multiple Range Test	
Factor: Plough	
Error mean square	21075.96
Degrees of freedom	86
Significance level	5%
LSD .05	25.40977

Rank	Trt#	Mean	n	Non-significant ranges
1	2	67.7874	258	a
2	1	54.67504	258	a

Appendix 2. 6: Continuation.

Duncan's Multiple Range Test

Factor: Rainfall (mm)	
Error mean square	9761.876
Degrees of freedom	84
Significance level	5%
LSD .05	80.21223

Rank	Trt#	Mean	n	Non-significant ranges
1	13	1141.258	12	a
2	12	513.1375	12	b
3	26	195.0617	12	c
4	22	139.2383	12	cd
5	41	132.5433	12	cd
6	37	132.0908	12	cd
7	29	92.975	12	de
8	25	78.8725	12	de
9	17	78.29583	12	de
10	15	55.09	12	de
11	16	31.45	12	e
12	8	15.16667	12	e
13	27	12.60083	12	e
14	9	10.6725	12	e
15	23	4.49	12	e
16	11	0	12	e
17	14	0	12	e
18	18	0	12	e
19	19	0	12	e
20	20	0	12	e
21	21	0	12	e
22	4	0	12	e
23	10	0	12	e
24	24	0	12	e
25	2	0	12	e
26	3	0	12	e
27	1	0	12	e
28	28	0	12	e
29	7	0	12	e
30	30	0	12	e
31	31	0	12	e
32	32	0	12	e
33	33	0	12	e
34	34	0	12	e
35	35	0	12	e
36	36	0	12	e
37	6	0	12	e
38	38	0	12	e
39	39	0	12	e
40	40	0	12	e
41	5	0	12	e
42	42	0	12	e
43	43	0	12	e

Appendix 2. 7: Soil erosion Split-plot Analysis of Variance on storm basis for the Short-rains (1994/95).

	Manure level						Plough type						Overall CV (%) (interaction)
	0 FYM		10 FYM				MM		RS				
Date of observation	Mean & non-significant range (g/m^2)	CV (%)	Mean & non-significant range (g/m^2)	Cv %	LSD (.05)	P	Mean & non-significant range (g/m^2)	CV %	Mean & non-significant range (g/m^2)	CV (%)	LSD (0.05)	P	
5/11/94	19.23a	101	11.1a	160	26.78	0.45ns	13.18b	165	17.15a	93	2.102	0.01*	120
6/11/94	11.12a	151	10.22a	155	20.56	0.91ns	1.08a	225	20.27a	86	32.548	0.13	146
11/11/94	629.17a	54	397.11a	40	373.10	0.16ns	627.08a	54	399.2a	39	517.056	0.20ns	54
12/11/94	1436.77a	62	845.75a	74	1203.93	0.24ns	973.47a	102	1309.05a	45	2192.372	0.58ns	70
14/11/94	69.95a	55	40.24a	63	42.10	0.12ns	30.23b	47	79.95a	39	15.817	0.00**	63
15/11/94	51.28a	93	11.62a	131	35.47	0.04*	12.612a	93	50.29a	97	100.778	0.25ns	126
17/11/94	117.1a	81	39.5a	39	107.29	0.12ns	54.69a	408	101.63a	89	232.787	0.48ns	98
29/11/94	149.52a	65	128.96a	73	48.06	0.30ns	140.318a	79	138.16a	58	433.899	0.98ns	66
30/11/94	5.943a	69	3.04a	134	6.68	0.29ns	1.89b	163	7.09a	50	4.814	0.04*	93
5/12/94	97.85a	65	59.9a	57	89.96	0.29ns	60.38a	66	97.36a	59	135.94	0.36ns	65
6/12/94	225.5a	58	164.63a	72	193.25	0.43ns	146.51a	84	243.62a	46	398.634	0.41ns	63
7/12/94	19.2a	55	6.01a	85	18.04	0.11ns	11.27a	106	13.93a	69	10.497	0.39ns	83
9/12/94	115.09a	53	70.87a	84	108.39	0.32ns	80.62a	98	105.33a	41	85.057	0.34ns	67
24/12/94	165.22a	36	98.97a	70	63.39	0.05ns	88.71a	72	175.47a	29	149.576	0.13ns	54
3/1/95	139.68a	57	125.41a	65	109.52	0.74ns	108.73a	60	156.36a	55	240.031	0.48ns	58
Average	216.17a	46	133.83a	59	136.58	0.19ns	156.33a	76	193.67a	38	136.58	0.53ns	55

Appendix 2. 8: Soil moisture Split-plot Analysis of Variance on day of observation basis for the Short-rains (1994/95).

	Manure level						Plough type						
	0 FYM		10 FYM				MM		RS				Overall CV (%) (interaction
Date of observation	Mean & non-significant range (mm)	CV (%)	Mean & non-significant range (mm)	CV (%)	LSD (.05)	P	Mean & non-significant range (mm)	CV (%)	Mean & non-significant range (mm)	CV (%)	LSD (.05)	P	
25/10/94	19.76a1	11	18.48a	15	1.56	0.08ns	18.38b	15	19.86a	11	0.54	0.00**	13
28/10/94	19.60a1	12	18.69b	13	0.69	0.02*	19.07a	14	19.21a	11	1.11	0.64ns	13
4/11/94	19.57a1	12	18.57a	12	1.15	0.07ns	18.83a	14	19.31a	11	1.71	0.35ns	12
12/11/94	24.74a	13	25.26a	14	1.49	0.39ns	25.45a	15	24.55a	11	1.61	0.14ns	13
18/11/94	22.60a1	17	22.26a	20	1.11	0.45ns	22.33a	20	22.52a	17	2.85	0.80ns	18
25/11/94	20.36a	22	20.60a	23	1.39	0.66ns	20.45a	23	20.50a	21	1.61	0.91ns	22
2/12/94	21.86a	16	21.95a	15	1.08	0.82ns	21.90a	15	21.90a	15	1.42	1.00ns	15
9/12/94	23.60a1	19	23.38a	15	1.22	0.65ns	23.12a	16	23.86a	18	2.51	0.33ns	17
16/12/94	21.31a1	19	21.19a	20	1.2	0.80ns	21.31a1	21	21.19a	18	1.54	0.70ns	20
23/12/94	20.98a	19	21.12a	20	1.93	0.85ns	21.02a	21	21.07a	18	1.96	0.93ns	19
30/12/94	20.64a	21	20.90a	22	0.63	0.31ns	20.91a	22	20.62a	21	1.72	0.52ns	21
6/1/95	20.26a1	25	20.14a	26	0.97	0.72ns	20.14a	26	20.26a	24	2.22	0.84ns	25
9/1/95	19.95a	24	20.02	25	1.46	0.90ns	20.19a	25	19.79a	25	2.45	0.55ns	25
13/1/95	19.67a	22	19.88a	23	0.89	0.54ns	19.17a	23	19.83a	22	0.51	0.42ns	23
20/1/95	19.14a	24	19.24a	25	1.21	0.84ns	19.24a	25	19.14a	25	0.88	0.69ns	25
23/1/95	18.86a	28	19.14a	27	0.96	0.45ns	19.19a	27	18.81a	27	1.04	0.26ns	27
27/1/94	18.40a	30	18.69a	30	0.85	0.41ns	18.57a	30	18.52a	30	0.57	0.75ns	30
30/1/95	18.45a	28	18.74a	28	1.12	0.52ns	18.55a	29	18.64a	27	0.27	0.27ns	29
Average	20.57a1	18	20.5a	19	0.83	0.82ns	20.45a	19	20.62a	17	0.91	0.31ns	13

Appendix 2. 9: Main experimental soil moisture Split-plot analysis of variance on date of measurement basis for the long-rains (1995).

	Manure level						Plough type						
	0 FYM		10 FYM				MM		RS				Overall
Date of observation	Mean & non-significant range (mm)	CV (%)	Mean & non-significant range (mm)	CV (%)	LSD (.05)	P	Mean & non-significant range (mm)	CV (%)	Mean & non-significant range (mm)	CV (%)	LSD (0.05)	P	CV (%) (interaction)
27/3/95	21.29a	17	21.48a	19	1.26	0.70ns	21.62a	19	21.14a	17	2.89	0.55ns	18
31/3/95	20.36a	23	20.60a	25	0.79	0.45ns	20.69a	25	20.26a	24	1.08	0.23ns	24
10/4/95	19.43a	28	19.62a	31	1.14	0.67ns	19.48a$_2$	32	19.57a	28	0.89	0.69ns	30
14/4/95	20.45a1	19	20.33a	21	1.04	0.77ns	20.62a	21	20.17a	19	1.90	0.41ns	20
21/4/95	21.50a	16	21.79a	16	1.56	0.64ns	21.83a	16	21.45a	15	0.72	0.15ns	16
28/4/95	21.19a	15	21.29a	19	0.99	0.80ns	21.33a	17	21.14a	17	1.61	0.66ns	17
5/5/95	19.17a	26	19.41a	27	1.39	0.66ns	19.57a	28	19.00a	26	2.91	0.49ns	27
12/5/95	21.14a	13	21.29a	17	1.30	0.78ns	21.57a	15	20.86a	15	2.15	0.29ns	15
19/5/95	20.10a1	19	20.05a	20	1.28	0.92ns	20.41a	20	19.74a	19	3.16	0.46ns	20
26/5/95	18.60a	26	18.95a	26	1.95	0.64ns	19.21a	26	18.33a	26	1.18	0.09ns	30
2/6/95	18.93a1	25	18.86a	25	1.23	0.88ns	19.05a	26	18.74a	23	2.72	0.67ns	25
Avarage moisture	20.21a	19	20.33a	20	1.09	0.77ns	20.51a	20	20.03a	19	1.57	0.32ns	29

KEY: #a1 stands for soil moisture under 0 FYM greater than that of 10 FYM.
a2 stands for soil moisture under MM greater than that of RS.

Appendix 2. 10: Tillage depth soil moisture analysis of variance under a randomised complete block design on observation date basis the Long-rains (1995).

	Differential tillage depth				
Date of Observation	**Tillage depth**		**LSD 0.05**	**P**	**CV (%)**
	12 cm Mean & non-significant range (mm)	17cm _Mean & non-significant range (mm)			
28/3/95	21.38a	22.38a	1.36	0.14ns	20
31/3/95	21.13b	22.46a	0.99	0.11*	26
14/4/95	21.50a	21.62a	1.42	0.86ns	28
10/4/95	20.46b	21.58a	0.91	0.02*	21
28/4/95	23.08a	22.17a	0.93	0.05ns	16
5/5/95	19.42b	21.50a	0.52	0.00***	16
12/5/95	22.13a	22.54a	1.07	0.43ns	28
21/4/95	23.29a	21.92b	0.81	0.00**	16
19/5/95	20.38a	21.17a	0.90	0.08ns	21
26/5/95	19.00b	20.88a	0.76	0.00***	27
2/6/95	18.33b	20.71a	0.74	0.00***	29
Avarage moisture	**20.88b**	**21.71a**	**0.56**	**0.01****	**20**

Appendix 2. 11: Aggregate stability, three way analysis of variance split-plot over the study period.

Source of variation	SS	df	MS	F	P
Subplots					
Main plots					
Blocks	156.17	2	78.09		
time	61.24	3	20.41	1.3	.3591 ns
Main Plot Error	94.58	6	15.76		
plough	0.33	1	0.33	0.03	.8576 ns
plough x time	1.14	3	0.38	0.04	.9888 ns
Subplot Error	77.37	8	9.67		
manure	1391.82	1	1391.82	103.65	.0000 ***
manure x time	145.94	3	48.65	3.62	.0362 *
manure x plough	27.33	1	27.33	2.04	.1729 ns
manure x plough x time	4.59	3	1.53	0.11	.9506 ns
Error	214.86	16	13.43		
Total	2175.38	47			
C.V.	23				

Duncan's Multiple Range Test
Factor: manure
Error mean square = 13.428549367 Significance level = 5%
Degrees of freedom = 16 LSD .05 = 2.2425409772

Rank	Trt#	Mean	n	Non-significant ranges
1	2 (ten tonnes)	35.6	24	a
2	1 (zero tonnes)	24.8	24	b

Duncan's Multiple Range Test
Factor: plough
Error mean square = 9.6718307119 Significance level = 5%
Degrees of freedom = 8 LSD .05 = 2.0702548079

Rank	Trt#	Mean	n	Non-significant ranges
1	1 (MM)	30.3	24	a
2	2 (RS)	30.1	24	a

Duncan's Multiple Range Test
Factor: time
Error mean square = 15.762930786 Significance level = 5%
Degrees of freedom = 6 LSD .05 = 3.9660773823

Rank	Trt#	Mean	n	Non-significant ranges
1	3 (early long-rains)	31.5	12	a
2	4 (end long-rains)	30.5	12	a
3	1 (early short-rains)	30.5	12	a
4	2 (end short-rains)	28.4	12	a