Evaluation of soil erosion in the Harerge region of Ethiopia using soil loss models, rainfall simulation and field trials

by

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ACRONYMS AND ABBREVIATIONS USED

ACRU	Agricultural Catchments Research Unit
ANOVA	Analysis Of Variance
ASA	American Society of Agronomy
ASAE	American Society of Agricultural Engineering
AU	Alemaya University
BD	Bulk Density
CEC	Cation Exchange Capacity
CSSA	Crop Science Society of America
ESP	Exchangeable Sodium Percentage
FAO	Food and Agriculture Organization
IAHS	International Association of Hydrological Sciences [formerly International Association of Scientific Hydrology, Netherlands]
IITA	International Institute for Tropical Agriculture
IR	Infiltration Rate
ISCO	International Soil Conservation Organization
ISCW	Institute for Soil, Climate and Water
MOA	Ministry Of Agriculture
MOMS	Modular Optoelectronic Multi-Wavelength Scanner
NH_4OAC	Ammonium Acetate
OC	Organic Carbon
ODU	Old Dominion University [Norfolk, Virginia, US]
RUSLE	Revised Universal Soil Loss Equation
SADC	Southern African Development Community
SADCC	Southern African Development Coordination Conference
SAS	Statistical Analysis System
SCRP	Soil Conservation Research Project
SFSCDD	Community Forest and Soil Conservation and Development main Department
SLEMSA	Soil Loss Estimation Model for Southern Africa

SSSA	Soil Science Society of America
UNEP	United Nations Environmental Program
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WSA	Water Stable Aggregates

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Abstract

Accelerated soil erosion is one of the major threats to agricultural production in Ethiopia and the Harerge region is not exceptional. It is estimated that about 1.5 billion tones of soil is being eroded every year in Ethiopia. In the extreme cases, especially for the highlands, the rate of soil loss is estimated to reach up to 300 t $ha^{-1}yr^{-1}$ with an average of about 70 t $ha^{-1}yr^{-1}$ which is beyond any tolerable level. The government have made different attempts to avert the situation since 1975 through initiation of a massive program of soil conservation and rehabilitation of severely degraded lands. Despite considerable efforts, the achievements were far bellow expectations.

This study was aimed at assessing the effect of some soil properties, rainfall intensity and slope gradients on surface sealing, soil erodibility, runoff and soil loss from selected sites in the Harerge region, eastern Ethiopia, using simulated rainfall. Soil loss was also estimated for the sites using Soil Loss Estimation Model for Southern Africa (SLEMSA) and the Universal soil Loss Equation (USLE). Moreover, the effectiveness of various rates and patterns of wheat residue mulching in controlling soil loss was also evaluated for one of the study sites, (i.e. Regosol of Alemaya University), under both rainfall simulation and field natural rainfall conditions.

For most of the erosion parameters, the interaction among soil texture, slope gradient and rainfall intensity was significant. In general however, high rainfall intensity induced high runoff, sediment yield and splash. The effect of slope gradients on most of the erosion parameters was not significant as the slope length was too small to bring about a concentrated flow. The effect of soils dominated by any one of the three soil separates on the erosion parameters was largely dependent on rainfall intensity and slope gradient.

The soils form the 15 different sites in Harerge showed different degrees of vulnerability to surface sealing, runoff and sediment yield. These differences were associated with various soil properties. Correlation of soil properties to the erosion parameters revealed that aggregate stability was the main factor that determined the susceptibility of soils to sealing, runoff and soil loss. This was in turn affected by organic carbon content, percent clay and exchangeable sodium percentage (ESP). Soils with relatively high ESP such as those at Babile (13.85) and Gelemso (7.18) were among the lowest in their aggregate stability (percent water stable aggregates of 0.25 –2.0mm diameter); and have highest runoff and sediment yield as compared to other soils in the study. Similarly, most of those soils with relatively low ESP, high organic carbon content (OC%) and high water stable aggregates such as Hamaressa, AU (Alemaya University) vertisol and AU regosol were among the least susceptible to sealing and interrill erosion. Nevertheless, some exceptions include soils like those of Hirna where high runoff was recorded whilst having relatively high OC%, low ESP and high water stable aggregates.

Both the SLEMSA and USLE models were able to identify the erosion hazards for the study sites. Despite the differences in the procedures of the two models, significant correlation (r = 0.87) was observed between the values estimated by the two methods. Both models estimated higher soil loss for Gelemso, Babile, Karamara and Hamaressa. Soil loss was lower for Diredawa, AU-vertisol and AU-Alluvial all of which occur on a relatively low slope gradients. The high soil loss for Babile and Gelemso conforms with the relative soil erodibility values obtained under rainfall simulation suggesting that soil erodibility, among others, is the main factor contributing to high soil loss for these soils. The difference in the estimated soil losses for the different sites was a function of the interaction of the various factors involved. Though the laboratory soil erodibility values were low to medium for Hamaressa and Karamara, the estimated soil loss was higher owing to the field topographic situations such as high slope gradient.

SLEMSA and USLE showed different degrees of sensitivities to their input variables for the conditions of the study sites. SLEMSA was highly sensitive to changes in rainfall kinetic energy (E) and soil erodibility (F) and less sensitive to the cover and slope length factors. The sensitivity of SLEMSA to changes in the cover factor was higher for areas having initially smaller percentage rainfall interception values. On the other hand, USLE was highly sensitive to slope gradient and less so to slope length as compared to the other input factors.

The study on the various rates and application patterns of wheat residue on runoff and soil loss both in the laboratory rainfall simulation and under field natural rainfall conditions revealed that surface application of crop residue is more effective in reducing soil loss and runoff than incorporating the same amount of the residue into the soil. Likewise, for a particular residue application method, runoff and soil loss decreased with increasing application rate of the mulch. However, the difference was not significant between 4 Mg ha^{-1} and 8 Mg ha^{-1} wheat straw rates suggesting that the former can effectively control soil loss and can be used in areas where there is limitation of crop residues provided that other conditions are similar to that of the study site (AU Regosols). The effectiveness of lower rates of straw (i.e. less than 4 Mg ha^{-1}) should also be studied. It should however be noted that the effectiveness of mulching in controlling soils loss and runoff could be different under various slope gradients, rainfall characteristics and cover types that were not covered in this study.

Integrated soil and water conservation research is required to develop a comprehensive database for modelling various soil erosion parameters. Further research is therefore required on the effect of soil properties (with

special emphasis to aggregate stability, clay mineralogy, exchangeable cations, soil texture and organic matter), types and rates of crop residues, cropping and tillage systems, mechanical and biological soil conservation measures on soil erosion and its conservation for a better estimation of the actual soil loss in the study sites.

Keywords: Erosion models, Infiltration rate, mulching, rainfall intensity, rainfall simulator, runoff, sediment yield, SLEMSA, slope gradient, soil properties, splash, surface sealing, texture, USLE, water stable aggregates

INTRODUCTION

It is widely recognized that accelerated erosion is one of the major factors responsible for soil degradation (Dudal, 1982; Kovda, 1983; Lal, 1990; 1994; Piccolo et al., 1997). Mismanagement, neglect and exploitation can ruin the fragile resource and become a threat to human survival (Lal and Pierce, 1991). Brown et al. (1990) estimated that the world could be losing 14 million tons of grain output because of environmental degradation, mainly due to soil erosion. According to Dudal (1981), the rate of agricultural degradation world wide by soil erosion and other factors is leading to an irreversible loss in productivity in about six million hectares of fertile land a year. Buringh (1981) estimated the annual global loss of agricultural lands due to soil erosion to be about 3 million hectares. Crop productivity is reduced to zero or becomes uneconomic because of soil erosion or erosion induced degradation on about 20 million hectares every year (UNEP, 1991) in the world. According to Kovda (1983), soil erosion has destroyed about 430 million hectares of productive lands since the beginning of settled agriculture. Human induced soil degradation has affected 24 % of the inhabited land area of the world. The values for the individual continents range from 12% in North America, 18% in South America, 19% in Oceania, 26 % in Europe, 27% in Africa and 31% in Asia (Oldeman, 1991-92).

Despite a wide recognition of accelerated erosion as a serious global problem, assessing the dimensions like: the magnitude, extent and the rate of soil erosion and its economic and environmental consequences precisely and reliably however, is still difficult (Lal, 1988, 1994). Besides, the readily available information in the literature is often based on reconnaissance surveys and extrapolations based on sketchy data.

Ethiopia has a total surface area of 111.8 million hectares; of which 60 million hectares are estimated to be agriculturally productive. Out of the estimated agriculturally productive lands, about 27 million hectares are significantly eroded, 14 million hectares are seriously eroded and 2 million hectares have reached the point of no return; with an estimated total loss of 2 billion m^3 of top soil per year (Fikru, 1990; Sertsu, 2000). According to the Soil Conservation Research Project (SCRP, 1985) of Ethiopia, the rate of soil loss in extreme cases ranges from 0 to 300 t $ha^{-1}yr^{-1}$ with an average loss (observed from SCRP experiments conducted in six different agro-climatic regions namely Maybar, Gununo, Hunde Lafto, Andit Tid, Anjeni and Dizi) of 70t $ha^{-1}yr^{-1}$, which is beyond the concept of any tolerable soil loss. This SCRP project also estimated that about 1.5 billion tones of soil are eroded away every year in Ethiopia.

The Ethiopian government first recognized the impact of soil degradation after the 1973-74 famine. Since then, it initiated a massive program of soil conservation and rehabilitation in the highly degraded areas (Hurni, 1985) which involved the mobilization of peasant associations and the involvement of over 30 million peasant workdays per year. Reports indicate that, between 1975 and 1989, terraces were built on 980000 hectares of cropland; 208000 hectares of hillside terraces were constructed and 310000 hectares of highly denuded lands were revegetated (Kruger et al., 1996). Yet these achievements are far bellow expectations, and despite considerable efforts, the country is still losing an appreciable amount of precious topsoil annually.

Sustainable soil management systems must be developed to reduce further degradation and restore the productivity of the eroded land. Lal and Pierce (1991) suggested that the scientific community must develop agricultural technology to: (a) reduce input while maximizing economic returns, (b) decrease soil degradation, (c) minimize risks of pollution of natural waters and environments, (d) restore productivity of degraded land and (e) maintain productive capacity of existing land by preserving a soil's life support processes.

Two soil conservation approaches, the barrier approach and the cover approach, have been developed and are in use world wide to control soil loss by water erosion (Young, 1989). Soil conservation methods including terraces, channels (bunds) and stonewalls as well as semi-permeable structures like grass strips and hedgerows are used as barriers to obstruct runoff and sediment carried with it. The cover approach usually involves use of plant materials and others like stones, plastics and industrial wastes, to obstruct raindrops beating of the soil surface and reduce the flow volume and velocity of runoff.

Although the two approaches are not alternative but complementary (Hudson, 1984), the fact that most of the physical or mechanical structures like terraces and channels that involve land shaping and manipulation, are expensive (Rodriguez, 1997) and time consuming (Tripathi and Singh, 1993) and deserve careful thought and planning, makes the use of the cover approach very important under farmers' conditions. Surface mulching with crop residues is found to be one of the most cost effective means of erosion control (Shelton et al., 1995).

Therefore, this study emphasizes on some factors affecting soil erodibility; estimates erosion hazard using some empirical soil loss models; and evaluates the role of different rates and patterns of surface cover materials (mulches) on control of erosion.

The specific objectives are outlined below:

- To assess the erodibility of some soils of Harerge, eastern Ethiopia, under laboratory rainfall simulation and relate erodibility to the physico-chemical properties of the soils.
- To study the effect of soil texture on seal formation, infiltration, runoff and soil erosion under different rainfall intensities on various slope gradients.
- To predict soil loss in the study areas using the SLEMSA and USLE models and correlate the predicted soil loss and measured soil erodibility.
- To study the effect of surface application and incorporation of different rates of crop residues on seal formation, infiltration, and runoff and soil loss under different rainfall intensities using laboratory rainfall simulation.
- To investigate the role of rates and application methods of straw mulches on runoff and soil loss from field plots using natural rainfall.

To achieve the above objectives, the research involved a preliminary survey of the study sites and soil sampling. Erodibility of the soils collected from the different areas of the region was assessed in the laboratory under rainfall simulation. The effect of some soil properties, slope and rainfall intensity on soil surface sealing and erosdibility was also evaluated. Moreover, soil loss was estimated for the various study sites using the USLE and SLEMSA models. The role of various rates and application methods of straw mulches on soil erosion control was assessed under both laboratory rainfall simulation and natural rainfall in field experimental plots.

CHAPTER 1

LITERATURE REVIEW

1.1 Soil erosion mechanisms and processes

Soil erosion by water starts when raindrops strike the bare soil surfaces. It involves the detachment and transportation of soil particles (Tripathi and Singh, 1993; Unger, 1996; Barthes et al., 2001) followed by deposition (Barthes et al., 2001). Therefore, the fundamental erosion processes are detachment by raindrop impact and flow, displacement by raindrop impact, transport and deposition by flow (Foster, 1990). Detachment processes remove soil particles from the soil mass producing sediment while transport processes move sediment from its point of origin.

The main mechanisms of detachment are the disintegration of aggregates by slaking, cracking, dispersion and shearing by raindrop impact and runoff (Barthes *et al.*, 2001). Slaking results from compression of air trapped inside rapidly wetted aggregates (Yoder, 1936 as quoted by Barthes *et al.*, 2001); cracking results from differential swelling and shrinkage; dispersion results from the reduced cohesion between wetted colloidal particles (Le Bissonnaise, 1996). Shearing as well as transport by splash and runoff depend largely on kinetic energy of raindrops and runoff, but also on properties of the soil itself (Casenave and Valentin, 1989 cited by Barthes *et al.*, 2001). As runoff increases according to the slope length, its shearing and transport capacities also increase, and erosion evolves from sheet erosion to more severe rill erosion (Roose, 1996).

1.2 Soil surface sealing and crusting

Surface sealing refers to the re-organization of the surface soil layer during a rainstorm and crusting is the hardening of the surface seal as the soil dries out (Morgan, 1995). Different mechanisms are involved in surface sealing. This include pore filling due to transport of fine particles into the pore spaces; particle deposition and reorientation and raindrop compaction with consolidation upon subsequent drying (West et al., 1992). Bajracharia and Lal (1999) also indicated that development of surface seal and crust involved several overlapping, parallel processes including: (a) mechanical disruption of soil aggregates by raindrop impact and slaking; (b) filling of inter-aggregate voids in surface layer of aggregates and clay illuviation; (c) raindrop compaction and rearrangement of particles in the seal layer; (d) smoothing and lowering of the surface 3-5 mm soil layer; and (e) drying and consolidation resulting in a cemented, rigid structural crust a few millimetres thick.

Soil crusting, a common phenomenon occurring in most cultivated soils in many regions of the world has major implications for agricultural production because of its effects on soil hydrological properties, erosion and crop establishment (Bajracharia and Lal, 1999). It results from the drying and hardening of surface seals, which form upon physical and chemical disruption and reorientation of soil aggregates and primary soil particles when exposed to rain or irrigation water (Bradford and Huang, 1992; Shainberg and Levy, 1996).

Rapid drop in infiltration rates of soils which was observed during rainstorms were mainly due to crust formation on the soil surface (Aarstad and Miller, 1981). Crusts are characterized by increased soil surface strength and density that leads to reduced porosity due to change in pore size distribution and infiltration capacity thereby leading to high runoff and erosion rates (Box and Bruce, 1996; Shainberg and Levy, 1996).

1.3 Effect of soil texture on sealing and erosion

Soil texture seems to be the most important soil variable influencing surface sealing (Mannering, 1967). Soil particle size distribution and the relative proportions of the various soil separates affect soil crusting. Lutz, (1952) as cited by Bradford and Huang, 1992, indicated that crusts can form on soils of any texture except coarse sand with an extremely low silt and clay contents. High clay contents generally favour aggregation and reduce crust formation although composition of the clay mineralogy and exchangeable cations will modify these generalizations (Van der Watt and Valentin, 1992). They indicated that medium textured (< 20% clay) soils are usually more susceptible to crusting. In a comparison of the sealing intensity of 8 binary mixtures, Poesen (1986) demonstrated that the soil texture most prone to sealing consists of approximately 90% sand and 10% silt and clay. In another report, Tackett and Pearson (1965) also indicated that crusts form more readily on sandy loam soils than clay loam but soils with high silt contents are even more susceptible. In an experiment involving the influence of silt and clay content on seal formation, on five soils (<20 mm aggregates), increasing silt content from 51 to 84 % while decreasing clay content from 45 to 8 % resulted in a 70 % increase in the surface strength and a 300% decrease in infiltration for a sand content <10% (Bradford and Huang 1992).

1.4 Effect of slope gradient on runoff and soil loss

Apart from slope length that was not included in the treatments of this study, slope gradient is one of the important factors affecting soil erosion by water. At low slopes, due to the low overland flow velocities, detachment or removal of soil particles from the soil surface in to the water layer is due to rainfall detachment alone (Stern, 1990). Furthermore, at low slope gradients, particles are splashed in to the air in random directions unlike the case with steeply sloping surfaces where preferential down-slope splash occurs (Watson and Laflen, 1985). However, as slope gradient increases, the ability of overland flow alone to entrain and transport sediments rises rapidly until the entrainment by the surface flow becomes the dominant mechanism contributing to the sediment transport (Stern, 1990). Runoff velocity and the effective depth of interaction between surface soil and runoff increases with increase in slope steepness (Sharpley, 1985). In the early version of the USLE, soil erosion was predicted as a power function of slope gradient (Fox and Bryan, 1999). Some researchers, for instance (Zingg, 1940; McCool *et al.*, 1987) indicated that soil erosion increases exponentially with increase in slope gradient. This relationship is indicated in equation 1.1 after Zingg (1940).

$$\mathbf{E = aS^b} \qquad (1.1)$$

Where, E is soil erosion, S is slope gradient (%) and a and b are empirical constants. The value of b usually ranges from 1.35- 2.0. The other relationship between erosion and slope gradient for inter-rill erosion is given by (McCool et al., 1987)

$$\mathbf{E = a \sin^{b} Q + C} \qquad (1.2)$$

Q is the slope angle in degrees
a, b, C are empirical constants.

However, even if the effect of slope gradient on erosion is well recognized, several studies indicated that the power relationship between slope gradient and soil loss over predicts interrill erosion rate by as much as two or more times (Torri, 1996; Fox and Bryan, 1999), and the relationship is better described as linear or less than linear.

1.5 Effect of rainfall intensity on runoff and soil loss

Soil loss is closely related to rainfall partly through the detaching power of raindrops striking the soil surface and partly through the contribution of rain to runoff (Morgan, 1995). This applies particularly to erosion by overland flow and rills for which intensity is generally considered to be the most important rainfall characteristics.

If rainfall intensity is less than the infiltration capacity of the soil, no surface runoff occurs and the infiltration rate equals the rainfall intensity (Horton, 1945) as cited by Morgan (1995). If the rainfall intensity exceeds the infiltration capacity, the infiltration rate equals the infiltration capacity and the excess rainfall forms surface runoff.

The effect of rainfall intensity on infiltration rate and runoff is modified by other soil characteristics like water content and soil texture. According to Morgan (1995), when the soil is unsaturated, the soil matric potential is negative and water is held in the capillaries due to the matrics suction. Hence, under unsaturated conditions, sands, which normally have low levels of capillary storage, may produce runoff very quickly although their infiltration capacity is not exceeded by the rainfall intensity. Since rainfall intensity partly controls hydraulic conductivity, increasing the rainfall intensity may cause conductivity to rise so that, although runoff may have formed rapidly at relatively low rainfall intensity, higher rainfall intensities do not always produce greater runoff (Morgan, 1995). This mechanism explains the reason why infiltration rates sometimes increase with rainfall intensities (Nassif and Wilson, 1975). This increase in infiltration capacity with increased intensity was also reported by Bowyer- Bower (1993) who found that, for a given soil, infiltration rate was higher with higher rainfall intensities because of their abilities to disrupt surface seals and crusts which otherwise keep the infiltration rate low.

1.6 Soil erosion impacts

1.6.1 Soil physical properties

Progressive soil erosion increases the magnitude of soil related constraints for crop production. The constraints can be physical, chemical or biological. Among the important soil physical constraints for crop production exasperated by erosion include: reduced rooting depth, loss of soil water storage capacity (Schertz et al., 1984; Kilewe, 1988; Ebeid et al., 1995; Sertsu, 2000), crusting and soil compaction and hardening of plinthite (Lal, 1988). Erosion also results in loss of clay and colloids due to preferential removal of fine particles from the soil surface (Fullen and Brandsma, 1995). The loss of clay influences soil tilth and consistency. Exposed subsoil is often of massive structure and harder consistency than the aggregated surface soil (Lal, 1988).

Development of rills and gullies may change the micro-relief that may make mechanized farming operations difficult. Another physical effect of erosion concerns the management and timing of farm operations. Achieving a desired seedbed with friable tilth necessitates a delay in ploughing until the soil is adequately watered (Lal, 1988).

1.6.2 Soil chemical properties

Erosion reduces the fertility status of soils (Morgan, 1986; Williams et al. (1990). Soil chemical constraints and nutritional disorders related to erosion include: low CEC, deficiency of major plant nutrients (N, P, K,) and trace elements (Lal, 1988; Fullen and

Brandsma, 1995). Massey et al., (1953) reported an average loss of 192 kg of organic matter, 10.6 kg of N and 1.8 kg of exchangeable K per ha on a Winsconsin soils with 11% slope. Sharpley and Smith (1990) reported that the mean annual loss of total P in runoff from P fertilized watersheds is equivalent to an average of 15 %, 12 %, and 32 % of the annual fertilizer P applied to wheat, mixed crop and grass, and peanut - sorghum rotation practices respectively. Various workers (Massey *et al*., 1953; Lal, 1975) have also reported extensive loss of N in eroded sediments. Based on the nutrient contents and ranges of soil losses in the highlands of Ethiopia, Sertsu (2000) estimated the annual nutrient losses due to erosion to be in the range of 36 to 429 kg ha^{-1} of N, 0.412 to 5 kg ha^{-1} of the available P and 1.4 to 17 kg ha^{-1} of the exchangeable K.

1.6.3 Productivity

Quantifying the effects of soil erosion on crop yields is a complex task because it involves the assessment of a series of interactions among soil properties, crop characteristics, and the prevailing climate. The effects are also cumulative and often not observed until long after accelerated erosion begins (Lal, 1988). Furthermore, the magnitudes of erosion’s effect on crop yields depend upon soil profile characteristics and management systems. Crop yield, an integrated response to many parameters is difficult to relate under field conditions to any individual factor. It is, therefore, difficult to establish a one-to-one, cause and effect relationship between rates of soil erosion and erosion induced soil degradation on the one hand and crop yield on the other (Lal, 1988).

Despite all these, it is well known that soil erosion can reduce crop yields through loss of nutrients, structural degradation and reduction of soil depth and water holding capacity (Timilin *et al*., 1986; Lal, 1988). In Ethiopia, the average crop yield from a piece of land (1.2 t ha^{-1} for cereals, 0.6 t ha^{-1} for pulses and 0.5 t ha^{-1} for oil crops) is very low according to international standards mainly due to soil fertility decline that is associated with removal of topsoil by erosion (Sertsu, 2000). The loss of economy due to reduced agricultural production resulting from the effect of soil erosion has been estimated on average to amount to 600 million Birr (Ethiopian currency per year; 8.56 Birr ≈ 1US$ in 2003). In addition to reduced grain yield, erosion also increases crop production costs (Lal, 1988; Sertsu, 2000). Improved technology may however, mask the effect of lost fertility and water storage capacity making the effects difficult to quantify (Schertz *et al*., 1984, Lal, 1988).

Generally, fertility and soil structure can be restored through management practices that include addition of plant nutrients and crop rotation. However restoration of water holding capacities and soil depth is not economically feasible. In rain-fed agronomic systems, yield reduction due to changes in these characteristics can be permanent (Frye et al., 1982)

Loss of production in eroded soil further degrades its productivity, which in turn accelerates soil erosion. The cumulative effect observed over a long period of time may lead to irreversible loss of productivity in shallow soils with hardened plinthite or in soils that respond only to expensive management and to additional inputs (Lal, 1988).

1.6.4 Off-site effects of soil erosion

Among the most important offsite effects of erosion include: siltation of reservoirs, crop failure at the low-lying areas due to flooding, pollution of water bodies due to the various chemicals brought by the runoff from the different areas. Several studies reported the significance of the off -site effects of erosion on land degradation (e.g. Wall and van Den, 1987; Lo, 1990; Robertson and Colletti, 1994; Petkovic et al., 1999; Suresh et al., 2000)

Surface rainwater washes away materials that originate from fertilizers and various biocides (fungicides, insecticides, herbicides and pesticides, etc.) which are applied in ever increasing doses with the result that they reappear in greater quantities in the hydrosphere polluting and contaminating the water environment (Zachar, 1982; Intarapapong et al., 2002; Verstraeten, and Poesen, 2002; Withers, and Lord, 2002). It is estimated that in some regions, upon 40% of this matter is carried into the rivers. This is also true for industrial fumes that increasingly pollute the soil surface from where they are carried by the flow in to watercourses. Owing to chemical pollution of water mainly by organic matter from farm fields, a rapid eutrophication takes place in waterways (Zachar, 1982; Zakova et al., 1993; Lijklema, 1995).

Problems associated with sediment accumulation in the low-lying areas are recognized in Ethiopia. For instance, the reduction in hydroelectric power production at the Koka reservoir in the year 2002 was ascribed to siltation (Nyssen et al., 2003). It is estimated that 18 x 10^6 tonnes of sediments enter into the reservoir from a catchment of approximately 4050km^2 (Shahin, 1993 as quoted by Nyssen, 2003). The Atbara, Blue Nile and White Nile sub-basins are considered to be the main sources of sediment deposition in the Aswan High Dam (Fahmy, 1998, Nyssen, 2003). Lake Alemaya, which is closer to Alemaya University, is also drying due to siltation problem.

1.7 Soil erosion models

Models are simplifications of realities (Morgan, 1995). Modeling soil erosion is the process of mathematically describing soil particle detachment, transport and deposition on land surfaces (Nearing et al., 1994). Erosion models can be used as predictive tools for assessing soil loss, conservation planning, soil erosion inventories and project planning. Moreover they can be used as tools for understanding erosion processes and their impacts (Nearing et al., 1994).

A wide range of models that differ in terms of their data requirement for model calibration and use, complexity and processes considered are available for use in simulating sediment and pollutant transport (Merritt et al., 2003). These models are basically categorized into three types namely empirical or statistical, conceptual and physically based (Morgan, 1995, Nearing et al., 1994, Merritt et al., 2003). The distinction between these models is somewhat subjective as there is no sharp difference among them.

1.7.1 Empirical models

Empirical model are based primarily on observations and are usually statistical in nature. They are based on inductive logic, and generally are applicable only to those conditions for which the parameters have been calibrated (Nearing et al., 1994, Merritt et al., 2003). The primary focuses of the empirical models have been in predicting average soil loss although some extensions to sediment yield have been developed (Williams, 1975 as quoted by Nearing et al., 1994). Empirical models are generally based on the assumption of stationarities that is, it is assumed that the underlying conditions remain unchanged for the duration of the study period. They are not event responsive and ignore the process of rainfall- runoff in the catchments being modeled. They make no inferences as to the processes involved at work. However, as they can be implemented in situations with limited data and parameter inputs, empirical models are frequently used in preference to the more complex models and are particularly useful as first step in identifying sources of sediment and nutrient generations (Merritt et al., 2003). Among the commonly used empirical erosion models include: the Universal Soil Loss Equation (USLE) (Wischmeier and Smith 1978), RUSLE (Renard et al., 1994) and the Soil Loss Estimation Model for Southern Africa (SLEMSA) (Elwell, 1978)

1.7.2 Conceptual models

Conceptual models are based on spatially lumped forms of water and sediment continuity equations (Lane et al., 1988 in Nearing et al., 1994). They usually tend to include a general description of catchment processes, without including the specific details of process interactions which would require detail catchment information (Merritt et al., 2003). These models can therefore provide an indication of the qualitative and quantitative effects of land use changes, without requiring large amounts of spatially and temporally distributed data. Conceptual models play an intermediatory role between empirical and physically based models (Beck, 1987). Te main feature that distinguishes the conceptual models from the empirical models is that the conceptual model, whilst they tend to be aggregated, they still reflect the hypothesis about the processes governing the system behaviors (Merritt et al., 2003). The Agricultural Non-point Source Model (AGNPS) (Young et al., 1989), Agricultural Catchment Research Unit (ACRU) (Schulze, 1995), Hydrologic Simulation Program, Fortran (HSPF) (Walton and Hunter, 1996), and Simulator for Water Resources in Rural Basins (SWRRB) (Arnold et al., 1990) are among the conceptual models (Merritt et al., 2003) used in erosion and /or water quality studies.

1.7.3 Physically based models

Physically based models are based on solving fundamental physical equations describing stream flow and sediment and associated nutrient generations in a catchment (Merritt et al., 2003). They are developed to predict the spatial distribution of runoff and sediment over the land surface during the individual storms in addition to total runoff and soil loss (Morgan, 1995). Physically based models are also termed process-based models (Morgan, 1995) as they still rely on empirical equations to describe erosion processes. Most physically based models use a particular differential equation known as the continuity equation, which is a statement of the conservation of matter as it moves through space over time. The common physically based models used in water quality and erosion studies include: The Areal Non-Point Source Watershed environment Response Simulation (ANSWERS) (Beasley et al., 1980), Chemical Runoff and Erosion from Agricultural Management systems (CREAMS) (Knisel 1980), Griffith University Erosion System Template (GUEST) (Misra and Rose, 1996), European Soil Erosion Model (EUROSEM) (Morgan, 1998), Productivity, Erosion and Runoff, Functions to Evaluate Conservation Techniques (PERFECT) (Littleboy et al., 1992), and Water Erosion Prediction Project (WEPP) (Laflen et al., 1991).

1.7.4 Selection of models for use in the present study

A good model should satisfy the requirements of reliability, universal applicability, ease of use with a minimum data, comprehensiveness in terms of the factors and erosion processes included and the ability to take account of changes in land use and conservation practice (Morgan, 1995). It is generally considered that no single model is ‘the best’ for all applications. The most appropriate model for a particular study will depend on the intended use and characteristics of the catchments being considered. Merritt et al. (2003) described other factors that affect the choice of a model for application that include: data requirement including the spatial and temporal variation of model inputs and outputs; the accuracy and validity of the model including its underlying assumptions, the components of the model reflecting its capabilities; the objectives of the model use(s) including the ease of use of the model, the scales at which the model outputs are required and hardware requirements.

Models might also be acceptable if they meet their objectives and design requirements (Morgan, 1995).

The main criteria that were considered for selection of the soil loss models used in most studies include: less input requirement, computational simplicity, wide applicability and relative validity in the study areas. The conceptual and physically based models require high input data which are not usually available and are more sophisticated than the empirical models (Merritt et al.,. 2003). There is a lack of simplified and distributed physically based models that can be applied under conditions where limited data is available. Model applications under such situations have mainly tended to be of an empirical nature. To this effect, the empirical models, particularly the USLE and SLEMSA were considered for use in this study due mainly to their simplicity and less input requirement while reasonably meeting the objectives of the study. Although RUSLE is the latest, most advanced, computer based version of USLE, its use for this study was limited by the insufficient data availability for the study sites.

The Universal Soil Loss Equation (USLE) was included in the study due to its adaptation and applications in some parts of Ethiopia (Hurni, 1985; Griffiths and Richards 1989; Nyssen, 1997; Eweg et al., 1998; Reusing et al., 2000) and the fact that it is a widely applied model in the world (Nearing et al., 1994; Morgan, 1995; Merritt et al., 2003). Moreover, it is relatively simple and requires relatively few data (Wischmeier and Smith, 1978; Morgan, 1995; Merritt et al., 2003). Therefore, it can be used to provide first hand information for different planning purposes in data-poor situations like this one.

Similarly, SLEMSA was considered in this study as it was widely applied in the African continent (Igwe et al., 1999) especially the Southern Africa (Elwell and Stocking, 1982; Elwell, 1984; Granger, 1984; Abel and Stocking, 1987; Stocking, 1987; Annersten, 1988; Chakela and Stocking, 1988; Albaladejo and Stocking, 1989; Hartmann et al., 1989; Chakela et al., 1989; Elwell, 1994; Mulengera et al., 1996; Smith et al., 1997; Morgan et al., 1998; Svorin. 2003). The details of the descriptions of the input factors considered, their assumptions, procedures and sensitivity analysis of the USLE and SLEMSA models are presented in chapter 3**.**

1.8 Role of crop residue mulching on soil properties and erosion control

Mulching involves covering the soil surface with agricultural by-products (Kohnke and Bertrand, 1959) for instance, straw stubble, wood chips, plastic films (Unger and Jones, 1981) manure and natural sources like rock fragments (Box, 1981). According to Erenstein (2003), mulching (organic) can be defined as a technology whereby at least 30% of the soil surface is covered by organic material. Covering the soil with crop residue mulch increases infiltration capacity and decreases runoff and erosion losses in practically all cases (Kohnke and Bertrand, 1959). Agassi (1996) also indicated that mulching is a very efficient means to dissipate raindrop impact and control the ensuing soil surface sealing, runoff, and erosion. It can also reduce evaporation of rainwater and overhead irrigation water. Therefore it can be a vital factor in improving water use efficiency (Erenstein, 2003).

Mulching affects the physical, chemical and biological conditions of the soil; the overall conditions being good for soil and water conservation (Kohnke and Bertrand, 1959; Erenstein, 2003). The soil conservation effect of crop residue mulching is summarized in Fig 1.1 and the details of some major effects are discussed subsequently.

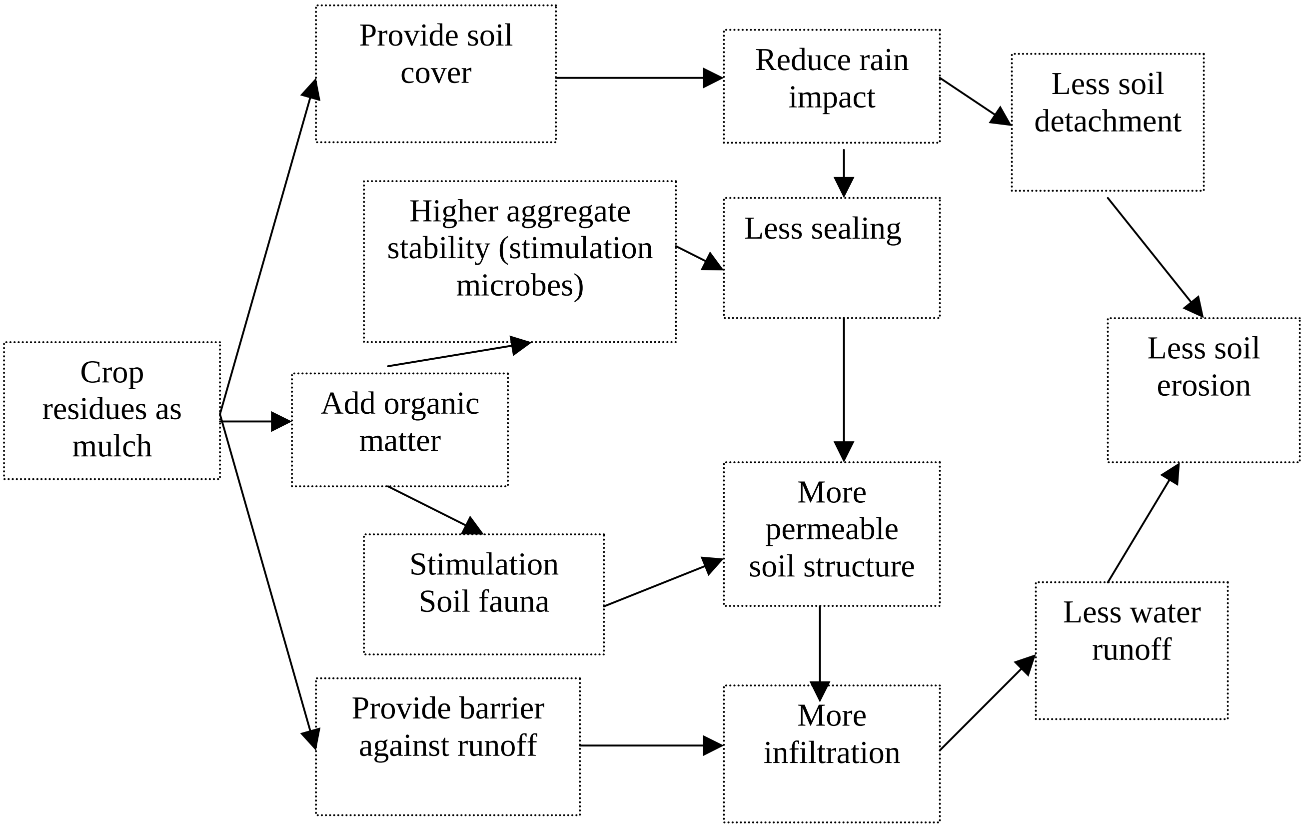


Fig. 1.1. The soil conservation effect of crop residue mulching (Erenstein, 2002)

1.8.1 Soil physical properties

Mulching affects the physical properties of soils in different ways. These include: reduction in direct impact of raindrops (Kohnke and Bertrand, 1959; Suwadjo and Abujamin, 1983), decreasing the amount and distance of splash, reducing fluctuation in soil moisture and soil temperature (Kohnke and Bertrand, 1959), reducing temperature during hot seasons (Lal, 1979; Bonsu, 1983; Suwadjo and Abujamin, 1983), increase temperatures during low temperature seasons, reduce the rate and frequency of soil freezing and depth of frost penetration, increase aggregation of soil surface resulting in improved soil structure (Suwadjo and Abujamin, 1983), and increase resistance of the soil to detachment by wind erosion.

Reports also indicate that, as compared to bare soils, mulched soils have greater porosity (Suwadjo and Abujamin, 1983); increased water holding capacity (Unger and Wiese, 1979; Unger and Jones, 1981; Edwards et al., 2000), higher infiltration rate (Bonsu, 1983), increased amount of percolation, less runoff and water erosion (Suwadjo and Abujamin, 1983), less evaporation (Unger and Jones, 1981), decreased wind velocity and erosion.

Moreover, Black and Siddoway (1979) indicated that mulching reduced soil crusting and erosion. It is also reported that mulching increases water use efficiency (Bonsu, 1983; Unger and Jones, 1981; Erenstein, 2003) and reduce soil loss (Edward et al., 2000).

1.8.2 Soil chemical and biological properties

In addition to its effect on physical properties of soils, various researchers indicated that mulching also plays a vital role in releasing plant nutrients like N, P (Buerkert et al., 2000) and K in available form (Bonsu, 1983). Mulched soils were found to encounter less loss of plant nutrients in runoff and sediments (Bonsu, 1983; Shock et al., 1997). It is also indicated that mulching a soil with crop residues result in a possible fixation of the available N and P in organic form shortly after application of straw thereby reducing its susceptibility to runoff loss (Kohnke and Bertrand, 1959). These authors also reported increased biological activities near the soil surface because of increased energy supply and more uniform moisture and temperature conditions in mulched soils. Soils with organic mulches are also reported to have stable organic matter content due to temperature regulation (Suwadjo and Abujamin, 1983). Mulching also implies C-sequestration through temporary immobilization of CO_2 (a green house gas contributing to global warming) thereby potentially converting annual cropping from a net source to a net sink of CO_2 (Kern and Johnson, 1993; Lal and Bruce, 1999; Follett, 2001; Erenstein, 2003)

1.8.3 Soil erosion control

Proper use of crop residues is one of the most effective tools to solve soil erosion problems (Larson et al., 1978; Erenstein, 2002). The reduction of runoff and erosion by surface mulches of plant residues (Schomberg and Steiner, 1999) under natural vegetation has been recognized for many years (Aarstad and Miller, 1981). According to Erenstein (2002), soil erosion tends to decline asymptotically to zero as cover increases. A complete cover of the soil surface fully protects the soil from raindrop impact (Sharma, 1996) and can conceivably eliminate soil erosion (Erenstein, 2003). In a study of corn residue management to reduce erosion in irrigation furrows, Aarstad and Miller (1978) suggested that corn residue in irrigation furrows can eliminate erosion and runoff water turbidity and increase infiltration. In another study involving the effect of different mulching rates on furrow irrigation, Aarstad and Miller (1981) observed that erosion rates, as indicated by the amount of sediments in the runoff water were decreased greatly by all residue treatments. Turbidity of runoff was markedly decreased by all residue treatment compared with that of clean furrows. They indicated that the highest residue rate (2.2 Mg ha^{-1} of residue placed uniformly along the furrows) reduced runoff water turbidities to less than those of the inflow water. Wischmeier (1973) also estimated that each 2.2 Mg ha^{-1} crop residue reduces soil loss from water erosion by 65%. In general, he reported that 3-4 Mg ha^{-1} of crop residue is needed to minimize soil erosion and reduce it to the tolerable level.

Soil surface covers dissipate raindrop impact energy, reduce the area of erodible surface causing flow energy to be dissipated on non-erodbile cover in contact with the surface, increase infiltration by reducing surface sealing and reduce the velocity of runoff flow (Box and Bruice, 1996; Sharma, 1996).

According to (Aarstad and Miller, 1981), infiltration rate increased as the amount of residue in the furrow increased. The increase in infiltration rates due to the residue results largely from reduced water velocity and increased wetted perimeter in the furrows.

In a continuous rotations of no-tillage annual winter crops (Barley, winter wheat and crimson clover) and summer crops like soybean or sorghum, Mills et al., (1988) observed that runoff and soil loss were greatly reduced where crop residues were left on the soil surface. Similar results were observed for conservation tillage of cotton in Alabama (Yoo and Touchton, 1988). Foster et al. (1985) emphasized on the physical roles of crop residues on soil surface involving dissipation of raindrop energy, retardation of runoff and consequent impedance to soil particle detachment, suspension and transport

Moreover, many other workers attribute the reduction in soil erosion due to no-tillage to increased amounts of crop residues on the soil surface which protect the surface from raindrop impact and reduce the transport capacity of surface flow (Foster et al., 1985; Meyer, 1985)

The efficiency of residue cover is affected by physical variables like rainfall, soil and topography that influence the water erosion process. Relatively low levels of residue from 1 to 3 Mg ha $^{-1}$ (20-60% cover) can greatly reduce soil losses (Rodriguez, 1997). Crop residue requirements for erosion control also depend on the type of residue, type of erosion (wind vs. water), and the condition of the residues (flat vs. standing). According to Unger (1988) requirements of crop residue are generally high for soils of loamy texture with residue flat on the soil surface.

In his studies on effect of grain straw and furrow irrigation stream size on soil erosion and infiltration, Brown (1985) observed that straw reduced erosion as water entered the furrows from gated pipes. The straw treated furrow is wider and shallower increasing the wetting perimeter than the non-straw treated furrows. Straw reduced net sediment yield by 52% and 71% during the irrigation season at low and high flow rates respectively. Runoff and soil losses were 42 and 29% higher in high flow rates respectively than in low flow rates.

In a study that evaluated the effects of combining cottage cheese whey and straw on infiltration and erosion on irrigated furrows, Brown et al. (1998) indicated that these treatments significantly reduced soil loss and increased infiltration thereby conserving soil, water and plant nutrients compared to untreated furrows at the ARS South Farm of the USDA (2.4Kms south west of Kimberly on coarse, silty, mixed, mesic, Durixerollic Calciorthid). They also indicated that straw alone significantly reduced season-long sediment outputs by 84%. The straw became partially covered and held in place by sediments creating mini-dams that slowed the water which increase the wetted perimeter causing higher infiltration.

CHAPTER 2

ERODIBILITY ASSESSMENT OF SOME SOILS OF HARERGE, EASTERN ETHIOPIA, BY USING RAINFALL SIMULATION

2.1 Introduction

The eastern part of Ethiopia including the Harerge region is characterized by a diverse climatic, topographic and soil conditions. This region is one of the most susceptible areas for various land degradation processes. Accelerated erosion, water stress, soil salinity and sodicity as well as soil fertility decline are among the main causes of soil degradation. The problem of soil surface crusting is also well recognized by the farmers in the Harerge region. Farmers usually cultivate the land once or twice to break the seals and increase infiltration (Fekadu, 2001). Surface sealing and crusting occur in most cultivated soils in many parts of the world and has major implications for agricultural production because of its effects on soil hydrological properties, erosion and crop establishment (Bajracharia and Lal, 1999). Soil surface seals and crusts reduce soil infiltration rate, increase soil strength and may increase erosion by increasing runoff (Le Bissonnais and Singer, 1993). Aarstad and Miller (1981) also indicated that rapid drop in infiltration rates of soils that are commonly observed during rainstorms are mainly due to surface sealing and crusting on the soil surface. According to Mamedov et al. (2000), surface sealing as well as naturally low infiltration rates of the soils are the main reasons for runoff initiation.

Different soil and climatic factors are responsible for soil sealing and crusting. These include soil texture, (Ben-Hur et al. 1985), clay mineralogy (Wakindiki and Ben-Hur, 2002), exchangeable sodium percentage (Levy and Van der Watt, 1988), organic matter content (Le Bissonnais and Arrouas, 1997; Singer and Le Bissonnais, 1998), citrate-bicarbonate-dithionite extractable Al and Fe content (Le Bissonnais and Singer, 1993; Singer and Le Bissonnais, 1998) and rainfall intensity. Although soil surface sealing and crusting is well recognized as one of the causes of soil degradation in the world, its extent and impact on agricultural production as well as its contribution to environmental degradation has neither been assessed nor well documented in Ethiopia in general and in the Harerge region in particular.

The objectives of this study were therefore to

(i) assess surface sealing and erodibility of soils in Harerge region of eastern Ethiopia by using a rainfall simulator;

(ii) explain the possible causes of sealing by comparing the physical and chemical properties of the soils with the measured erosion parameters and

(iii) investigate the potentially erodibile soils in Harerge region, eastern Ethiopia, so that further action can be suggested to combat the problem.

2.2 Materials and methods

2.2.1 Description of the study sites

A preliminary survey involving visual observation and characterization of the study sites and soil sampling at selected representative sites were carried out. A brief description of the study sites is given in (Table 2.1).

Table 2.1 Description of the study sites in Harerge, Eastern Ethiopia

Study site	Region	Zone	Geographical location	Altitude (m.)[a]	Topography (Slope gradient)	Crops	§Rainfall seasons	Major rocks	Remarks
AU Alluvial	Oromiya	East Harerge	N09°26' E42°02'	1980-2000	0-2% slope	Maize, sorghum, wheat, potato, beans, etc (Rotation)	March -mid May July-September	Granite Limestone	Dark reddish grey soils; Alemaya University research station.
AU Regosol					5-10% slope				Dark reddish brown to red; Alemaya University research station; 'Gende Je' area
AU Vertisol					0-2% slope				Very dark grey to black; Alemaya University research station
Adele			N09°23' E41°57'	2089-2100	5-10% slope	Chat, Sorghum, maize	March -mid May July-September	Granite	Coarse Reddish grey soil (about 50% rock fragments); Ridges on chat farms, Use farmyard manure, manual tillage with '‡ Dongora';
Babile			N09°13' E42°19'	1644-1655	5-10% slope	Chat, Groundnut, Sorghum	March - mid May July - September	Granite	Red soils; no free lime; Deep gullies common; Soil bunding and microbasins common for moisture conservation.
Hamaressa			N09°20' E42°04'	1994-2014	0-15% slope	Chat, sorghum, maize	March - mid May July-September	Granite Sandstone	Red soils; no free lime; Evidence of gully erosion; Soil bunding practiced; Use of DAP and Urea
Lange			N09°26-27' E41°47'	2025-2035	5-10% slope	Sorghum Potato Onion, Maize	March-end April July-September	Limestone Sandstone Granite	Black swelling soil; Lake Lange drying due to siltation; Bunds at irregular distances; Use of farm yard manure; use oxen for cultivation.
Hirna		West Harerge	N09°13' E41°05'	1828-1856	5-15% slope	Sorghum †Tef Onion	March – April July – end of Sept.	Basalt	Black swelling soils; no free lime; >50% rock fragments; Narrow V-shaped gullies; use of stone terraces; use of Farmyard manures and commercial fertilizers; Oxen for ploughing;
Chiro (Asebe Teferi)			N09°01-03' E40°50-51'	1922-2170	Up to 30% slope	Sorghum	March – mid May July – Mid Sept.	Basalt	Black swelling soils; no free lime; Use of stone terraces and bunds; Use Oxen for cultivation; 15% rock fragments;

Table 2.1 continued

Bedessa			N08°52-53’ E40°46’	1687-1700	2-10% slope	Maize, chick pea, Tef, chat	March- mid May July- Mid Sept.	Limestone	Black soils; show effervescence with HCl; Bunds at 50m interval; oxen for land preparation; Use farmyard manure and commercial fertilizers; Swelling and cracking of soils;
Gelemso			N08°49’ E40°32’	1786-1819	10-15% slope	Chat, maize, sorghum, Tef, sweet potato	March mid May July- mid October	Sandstones	Red soils; Ridges in chat and sweet potato farms; Use farmyard manure and commercial fertilizers
Diredawa	Diredawa	Diredawa	N09°36-37 E41°50’	1190-1195	<5% slope	Orchards, banana, papaya, vegetables	March- end May July – Sept.	Granite and Limestone	Grey loamy soil in Toni farms; Micro-basin round citrus trees; Use DAP and Urea; local ‘dongora’ and tractors for land preparation;
Amadle	Somali	Jijiga	N09°15’ E42°59’	1726-1730	<5%	Sorghum, Maize	March – end May July - September	Limestone Sandstones	Dark colored soil; free lime; Strong wind during dry months; Grass patches and few shrubs;
Dugda Hidi (Chinaksen)			N09°22’ E42°46’	1701-1715	Up to 7% slope	Sorghum, Maize	March – end May July - September	Limestone Sandstones	Red soils; free lime; Strong wind during dry months; Grass patches and few shrubs; No fertilizer use; Local people are Pastoralists
Karamara			N09°22’ E42°43’	1822-1842	Sloppy land (5-15% slope)	Chat Sorghum	March – end May July - September	Limestone Sandstones Granite	Grey soils; white crusts on the surface; free lime; Strong wind during dry months; Deep gully running down Karamara hill; Acatia shrubs common; No fertilizer use; Local people are Pastoralists

§ The study sites are characterized by bimodal rainfall pattern (see appendix 4).

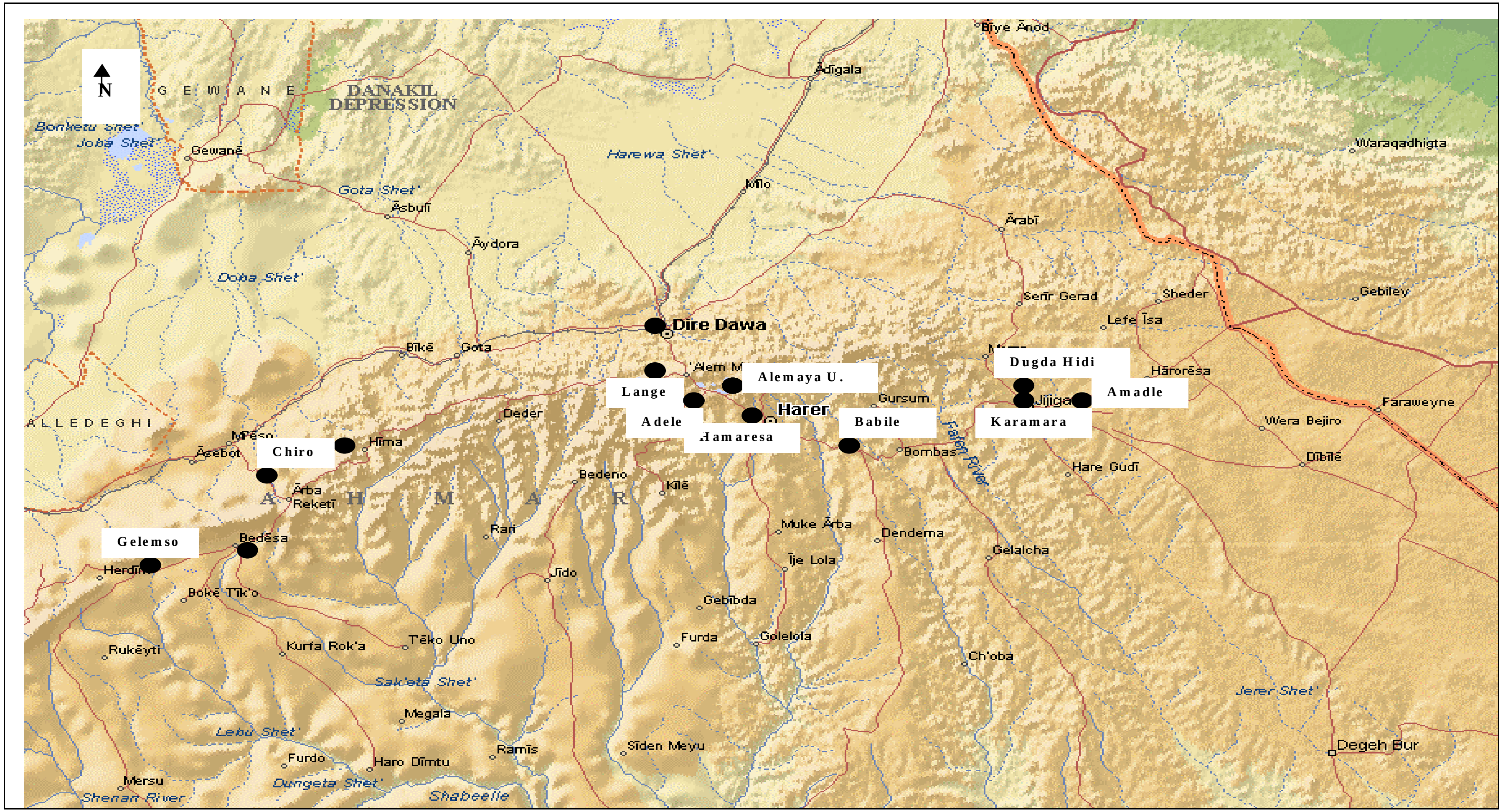
‡ ‘Dongora’ is a local manual tillage equipment

† Tef (Eragrostis tef) is a local small cereal grain crop; Chat (Catha edulis) is a common stimulant crop in the region produced for local and export markets.

[a] See appendix 3 for average altitudes of the study sites

Scale ≈1:10,000000

Fig. 2.1 Location map of Ethiopia and the study area



Scale ≈1:1000000

Fig.2.2. The study sites (black dots indicate the study sites)

2.2.2 Soil sampling and analysis of some physical and chemical properties

Composite samples that represent the soils of a given study site were collected from the top 15cm for each of the study areas. The bulk of soil samples were sub-sampled, air-dried and ground to pass through a 2mm sieve before analysis of the soil in the laboratory. The specific methods for determination of the different soil properties are indicated in Table 2.2.

Table 2.2 Methods used for determination of some of the physical and chemical properties of soils.

Soil properties	**Method of determination**
Texture	Pipette method (Day, 1965)
Aggregate stability (% water stable aggregates)	Wet sieving method (Kemper and Rosenahu, 1986)
Bulk density (BD)	Clod method (Tan, 1996)
Initial water content	Gravimetric method
Exchangeable cations (Ca^{2+}, Mg^{2+}, K^+, Na^+),	1M NH_4 OAC, pH 7 method (Tan, 1996)/ Atomic absorption spectrophotometry
pH (H_2O 1: 2.5, soil: water)	Potentiometric method (Yerima et al., 1993)
Organic carbon (O.C. %)	Walkley and Black method (Schulte, 1988)
Cation exchange capacity (CEC)	1M NH_4 OAC, pH 7 method (Tan, 1996)

2.2.3 Soil packing, rainfall simulation and data acquisition

An Erosion box (pan) 554mm long, 206mm wide, and 85mm deep (Fig 2.3) was perforated at the bottom to allow free drainage. A cotton cloth was placed on the bottom to prevent soil loss through the perforated bottom. Approximately 85mm layers of soil that were air dried, crushed to pass through 4mm sieve and mixed thoroughly were packed in the box to simulate field conditions. For soils that tend to swell upon wetting, only a 75mm layer of soil was packed in the trays to reduce errors due to overflow of the soil.

Fig. 2.3 The erosion tray and parts of the simulator system. See the position of splash, runoff and drainage collectors at the bottom of the erosion tray. The beakers on the erosion tray are meant for calibration of rainfall intensity.

A rotating disc rainfall simulator of the type described by Morin et al. (1967) was used in this experiment. Rainfall intensity was controlled by changing the aperture size of the disc, its speed and the pressure at the nozzle. After calibrating and selecting the appropriate combination of these control devices for specific rainfall intensity (60 mm/hr for this experiment), the rain was applied to the plot set at slope of 5°. The uniformity of distribution of the simulated rain on the test area was determined by measuring the volume of rain collected in beakers placed in a grid on the tray and by calculating the coefficient of uniformity using equation (2.1).

$$\mathrm{CU} = \{100(1 - \sum \frac{/ Xi - x /}{nx})\} \qquad (2.1)$$

Where, CU = Coefficient of uniformity

Xi = individual observed depth from the mean

x= Mean of observed depths

n= Number of observations

A uniformity of at least 80% were obtained and accepted. Drop diameter and size distribution was estimated using the flour pellet method (Claassens and Van der Watt, 1993). The mean diameter of raindrops was 1.9 mm; median drop velocity 6.0 ms^{-1} (estimated from calibration curve as indicated on the manual of the rainfall simulator), kinetic energy 18 $\mathrm{Jm}^{-2}\mathrm{mm}^{-1}$ and the height of the nozzle from the soil surface was 2.5m.

Runoff volume and the sediment suspended in it were measured at five minutes interval as soon as runoff started. Runoff was collected in plastic beakers which were placed under the runoff outlet of the erosion tray. The sediment yield, which is referred to as the amount of eroded sediment that leaves a specific area of land in a given time was determined after oven-drying the runoff and weighing the sediments. This term sediment yield will be used in this text to describe the amount of soil washed by runoff water from the erosion tray. Water collected by the splashboards was recorded from the beginning of the rainfall simulation every five minutes. The sediment caught by the splashboards was also collected at five minutes interval. The weight of splashed sediment was determined after oven drying.

The amount of water that infiltrated into the soil was calculated as the difference between water applied to the erosion tray and water runoff from the surface of the tray including the splash volume. Runoff and splash volume were regarded as the only water losses from the surface of the erosion tray. The following procedures and assumptions were applied to calculate the infiltration rate:

1. For every simulation run, a blank was obtained by taking the first reading of splash volume and subtracting it from other consecutive readings to compensate for the amount of water that falls directly on the splashboards and troughs and collected by splash collectors when rainfall is applied. This was determined with no soil in the trays.

2. The amount of rainfall (mm) was calculated by dividing the amount of water collected by the plot with the area of the plot.

3. It is also assumed that no water ponding occurs on the soil surface. The amount of water infiltrated is considered to be equal to the amount of water received on the erosion plot (see equation 1.1) minus runoff and net splash volume. Net splash volume is the difference between a splash volume collected at each 5 minutes interval and that collected during the first 5 minutes of the rainfall event. This procedure may overestimate infiltration rate to some extent especially during the beginning of the rainfall event.

$$Q = IAt/600 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2.2)$$

Where Q= Volume (ml) of water applied to the plots of area A per hour,
I= Intensity in mm/hr,
A= Cross-sectional area of the erosion plot (cm^2) and
t= time elapsed since the onset of rainfall (min.) for each five minute interval.

The influence of seal formation was observed by the changes in the infiltration rates of the soils.

Special considerations

The tray used in this study does not allow replacement of the water and sediments that are splashed out of the plot area. Taking this into consideration, and assuming that the water and portion of the sediments that were splashed out of the plot would have contributed to the total runoff and sediment yield respectively, an attempt was made to include these values to the runoff and sediment contained in it. Therefore, runoff in this study is considered as the sum of overland flow and splashed water. In this method, the fraction of sand and water stable aggregates in the splashed sediment were deducted from the total splash weight assuming that these are too heavy to be transported by the thin overland flow that occurs on such small erosion plots of short slope length. The equation is:

$$S.Y = W + \{S\,[1-(PWSA+Psa)/100]\} \ldots\ldots\ldots\ldots (2.3)$$

Where,

S.Y = Total sediment yield (kgm^{-2}),
W = Weight of wash off soil (sediment in runoff) (kgm^{-2}),
S = total weight of sediment in splash (kgm^{-2}),
PWSA = percent water stable aggregates and
Psa = percent sand.

However, the total sediment yield obtained using this equation did not comply with the actual field observations and soil properties (except the silt content which showed a significant positive correlation with the total sediment yield) determined in this study. On the other hand, when the sediment in runoff and splash weight were handled separately, the correlations with most of the soil properties were more relevant to the actual expectations.

Therefore, as it was difficult to accurately estimate the proportion of sediments in splash that would have contributed to sediment yield, both wash off soil and splash weight were discussed separately and sediment yield in this text refers to only the amount of sediment in overland flow. The sediments in the splash were used as indicators of the susceptibility of the soils to detachment by raindrop impact. It is however, important to note that Equation 2.3 may provide reasonable information if the proportion of fine and coarse sands in the total sand fraction are known.

2.2.4. Statistical Analysis

The means of the various erosion parameters were compared among the different study sites. Correlation analysis and regression equations were performed to test the relationships between the various erosion parameters and soil properties.

2.3 Results and discussion

In this study of the erodibility of selected soils of Harerge, eastern Ethiopia, with the aid of a rainfall simulator, the relationships between various erosion parameters, infiltration characteristics and soil properties are discussed for the different soil types. The physical and chemical properties of the different soils used in this study are presented in Table 2.3.

2.3.1 Infiltration and runoff

The total amounts of infiltrated water and runoff for the different soils in this study are presented in Table 2.4. However, for the purpose of discussing the trends in the erosion parameters with increasing cumulative rainfall over time, certain soils were grouped together based on their aggregate stability and representative soils for each group were selected (Table 2.5) and used in the discussion.

The erosion parameters measured varied among the different soils. The highest total infiltration volume which was more than 70% of the total applied rainfall, was recorded on Hamaressa soils and this is followed by Bedessa, AU Regosol, AU Vertisol and Diredawa in decreasing order of magnitude (Table2.4). On the other hand, the lowest total infiltration volume was recorded for Babile, Hirna, Gelemso and Chinaksen soils in increasing order. The maximum and minimum volumes of infiltrated water during the one-hour rainfall simulation were 71% and 49% respectively of the total water applied.

Table 2.3 Some physical and chemical properties of the soils at the study sites in eastern Harerge, Ethiopia.

Sampling site	Sand ------	Silt ----%---	Clay ---------	BD Mgm^{-3}	Initial moisture %	WSA %	pH (H_2O)	OC %	CEC cmolc kg^{-1}	Exchangeable bases (cmolc kg^{-1})				BS %	ESP	CEC Clay cmolc kg^{-1}Clay (Calculated)
										K	Na	Ca	Mg			
Adele	36.6	20.2	43.2	1.26	5.17	66.16	7.28	0.85	28.70	0.82	0.42	1.57	1.36	14.53	1.46	60
Amadle	6.5	39.5	54.0	1.10	7.19	60.03	7.91	1.68	43.48	2.67	1.37	1.45	1.26	15.52	3.15	70
AU- Alluvial	74.6	12.7	12.7	1.42	2.91	35.50	NA	0.68	9.13	1.27	0.65	1.04	0.90	42.28	7.12	54
AU-Regosol	53.1	19.5	27.4	1.31	5.44	66.18	6.55	1.62	26.96	0.92	1.11	20.05	4.83	99.81	4.12	78
AU-Vertisol	9.6	32.6	57.8	0.99	10.43	67.28	7.64	1.25	54.78	0.99	1.34	60.60	6.33	126.43	2.45	87
Babile	76.7	14.3	9.0	1.57	1.52	33.71	6.47	0.49	3.61	0.97	0.50	1.01	0.88	93.07	13.85	21
Bedessa	5.4	28.5	66.1	1.07	8.76	71.01	7.18	1.49	55.22	0.84	0.43	1.23	1.07	6.47	0.78	76
Chinaksen	10.9	42.0	47.1	1.12	4.03	60.21	7.97	1.46	34.78	3.27	1.67	1.27	1.10	21.02	4.80	63
Chiro	NA	NA	NA	1.11	8.58	79.01	6.47	NA	NA	NA	NA	NA	NA	NA	NA	NA
DireDawa	34.8	40.5	24.7	1.48	0.84	48.94	8.78	0.51	8.70	0.87	0.44	1.05	0.91	37.59	5.06	28
Gelemso	48.9	11.3	39.8	1.35	2.92	42.19	6.60	0.69	14.35	0.69	1.03	8.19	2.25	84.74	7.18	30
Hamaresa	23.3	23.0	53.7	1.22	4.75	62.78	6.53	0.98	24.35	2.05	1.05	1.24	1.07	22.22	4.31	39
Hirna	7.8	37.0	55.2	1.09	9.54	71.23	6.56	1.61	52.61	1.25	0.64	1.27	1.10	8.10	1.22	85
Karamara	49.3	20.4	30.3	1.30	5.83	59.23	8.09	1.00	32.17	1.32	1.21	45.95	4.08	163.38	3.76	95
Lange	47.4	25.5	27.1	1.30	7.77	70.41	7.63	1.18	28.26	1.12	0.57	1.28	1.11	14.44	2.02	89

BD= Bulk density; OC= Organic Carbon; CEC= Cation exchange capacity; BS= Base saturation; ESP=Exchangeable sodium percentage; WSA = Water stable aggregates; NA = Not Available.

High runoff volume, ranging from 24.1 to 30.4mm, was recorded on Babile, Hirna, Gelemso, Chinaksen and Lange soils (Table2.4). The highest runoff volume collected during the one-hour rainfall simulation corresponds to 50.7% of the total rainfall applied. On the other hand, relatively low total runoff volumes (17.42, 18.75 and 19.06mm) were collected on Hamaressa, Bedessa and AU vertisol respectively. In terms of the total amount of rainfall applied, total runoff was less than 30% for Hamaressa soils. Other soils including Adele, Amadle, Chiro, Karamara, AU Alluvial and Dire Dawa were intermediate in their runoff volume ranging from 23.59 to 21.26mm. However, the relationship between the cause and effect is not clear. For instance, the Hirna and Lange soils, which have more than 70% water stable aggregates (Table 2.3) are not the lowest in their runoff. Therefore, it seems that no single factor is totally responsible for a given change in surface sealing and runoff but the interaction of these factors is important.

Table 2.4 Runoff and infiltrated water for the one-hour rainfall simulation runs. [Values are means of three replications].

Soil name	† Runoff		Infiltration	
	mm	Percent of rainfall	mm	Percent of rainfall
Adele	23.59	39.31	36.41	60.69
Amadle	23.40	38.99	36.60	61.01
Au Alluvial	21.70	36.16	38.30	63.84
Au Regossiol	19.06	31.77	40.94	68.23
Au Vertisol	20.95	34.91	39.05	65.09
Babile	30.39	50.65	29.61	49.35
Bedessa	18.75	31.25	41.25	68.75
Chinakssen	24.78	41.30	35.22	58.70
Chiro	23.04	38.40	36.96	61.60
Diredawa	21.26	35.44	38.74	64.56
Gelemso	25.93	43.21	34.07	56.79
Hamaressa	17.42	29.04	42.58	70.96
Hirna	27.04	45.07	32.96	54.93
Karamara	22.99	38.31	37.01	61.69
Lange	24.10	40.17	35.90	59.83

† Runoff = Sum of overland flow and splash water

Table 2.5 Soil groupings and selection of representative soils for trend analysis.

Group	Representatives	Description
Bedessa Chiro Hirna	Bedessa Hirna	Aggregate stability >70%
Amadle AU Vertisol Karamara Lange	AU Vertisol	Black soils with intermediate aggregate stability (50-70%)
AU Alluvial Babile Diredawa Gelemso	Babile Gelemso	Aggregate stability <50%
Adele AU Reogosol Chinakssen Hamaressa	AU Regosol Hamaressa	Reddish soils with intermediate aggregate stability (50-70%)

The trends of infiltration rates for the 15 soils used in this study are represented in Fig. 2.4. The highest infiltration rate throughout the simulation run was observed on soils of Hamaresa. With the exception of AU Vertisol, which has nearly attained a steady state infiltration rate at the end of the run (Fig. 2.4), infiltration rate continued to decrease, although slower but not constant towards the end of the one-hour laboratory rainfall simulation.

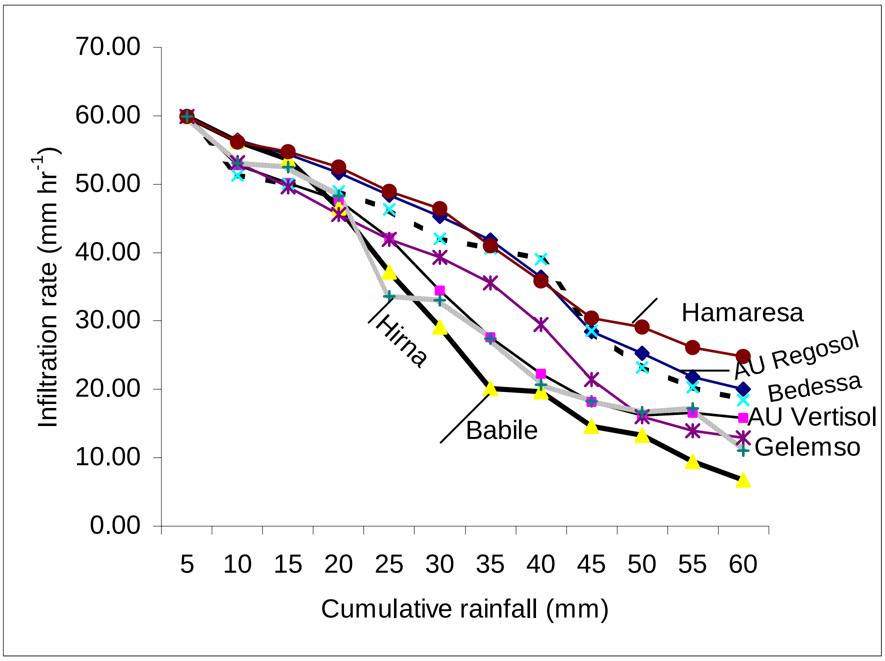


Fig 2.4 Infiltration rates (mm hr^{-1}) of selected soils over a one-hour rainfall simulation

Unlike the case for Hamaressa and AU regosol where the change in infiltration rate between the successive data points was very small, a sharp decrease in infiltration rate was observed on some soils like Babile, Hirna and Gelemso during the first 30 minutes of the run and continued decreasing with a decreasing rate thereafter. This sharp decrease in the rate of infiltration could be ascribed to surface sealing. On the contrary, the gradual decrease in infiltration rate on some soils such as Hamaressa can be attributed to the relatively higher aggregate stability.

As described earlier, the total runoff in this study was taken as the sum of overland flow and splashed water assuming that the water that has been splashed out of the plot, would have contributed to the runoff. Because of the added water splash, however, the graphs of runoff rates (Fig. 2.5) do not show the exact runoff starting time for the different soils.

Chen et al. (1980) proposed a model that divided seal formation into three stages. Stage I is from initiation of rainfall to initiation of runoff; Stage II is from initiation of runoff to steady state runoff and; Stage III is the steady state runoff. As shown in Fig. 2.4, most of the soils in this study were at stage II during the end of the one hour rainfall simulation run. The time taken from initiation of rainfall to initiation of runoff that is, stage I according to Chen et al., 1980, was different for the different soils in this study (Table 2.6). The mean earliest and latest runoff initiation times were 16.32 and 26.31 minutes which were recorded on AU Alluvial and Bedessa soils respectively. In all cases however, runoff initiation time was much more delayed than is expected under normal conditions at the rainfall intensity used in this experiment. The general delay in runoff initiation time may be ascribed to the discontinuity of rainfall for about one minute at each 5 minutes interval to collect splash and runoff. This gave some time for the water to soak into the soil increasing infiltration rate and decreasing the degree of water accumulation that would have otherwise induced early concentrated flow. In general, runoff started earlier (between 16 and 18 minutes) on AU alluvial, Amadle, Babile, Karamara and Gelemso soils. However, it started late (after 25minutes of rainfall initiation) on Bedessa, Chiro, AU Regosol, AU Vertisol and Hamaressa soils. Most of the information collected in this study support that soils on which runoff started earlier are relatively more prone to sealing than those on which runoff initiation time was delayed (compare Tables 2.4 and 2.6).

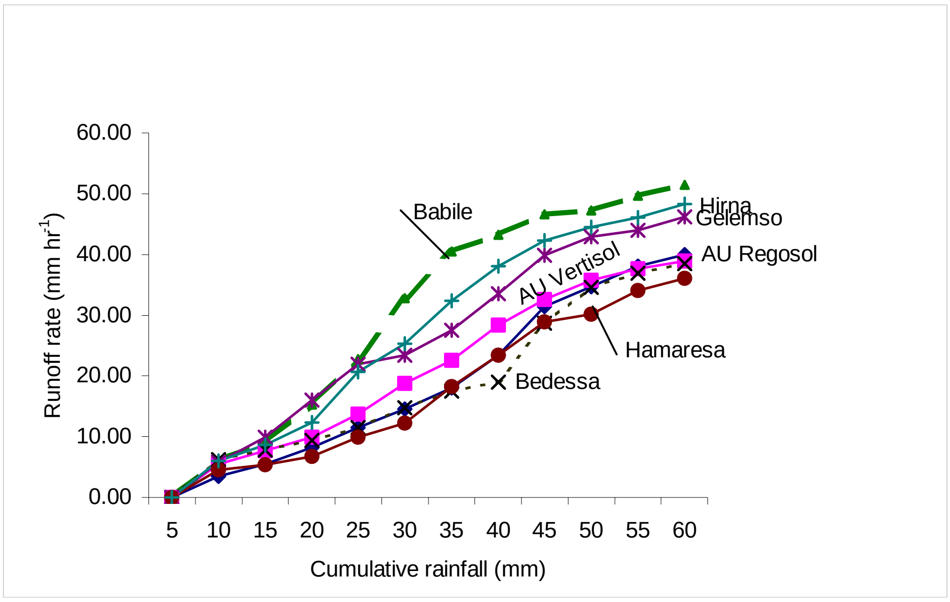


Fig.2.5 Runoff rates for selected soils during a one-hour simulated rainfall.

For the majority of the soils, runoff increased immediately after its initiation until some peak point after which the rate of increase decreased with further rainfall application. The earliest rapid increase in runoff was observed on Babile soils at about 25 minutes of the run (Fig. 2.5). The runoff rate for AU Regosol, Bedessa, and Hamaressa soils was very low until it received 30mm of rainfall after which it showed a rapid increase until it slowed down after 50 minutes. This can be attributed to the slower rate of sealing in these soils.

Differences in runoff rates among the soils are attributed to differences in the rate of seal formation (Singer and Le Bissonnais, 1998). This experiment suggests that the Babile, Hirna, Gelemso, Chinaksen and Lange soils formed seals earlier than other soils and this resulted in low infiltration rate and high runoff. A close observation of the soil properties reveals that the low final infiltration rate and high runoff in these soils is mainly associated with their exchangeable sodium percentage (ESP). Among the soils where high runoff was observed, Babile and Gelemso have the highest ESP and low aggregate stability (Table 2.3). Therefore, runoff was positively correlated with ESP (r = 0.50) and negatively correlated with final infiltration rate (r = -0.72).

The reason for the high runoff with Hirna and Lange soils which have reasonably high aggregate stability (71.23% and 70.41% respectively) and low ESP (1.22 and 2.02 respectively) is not clear.

Table 2.6 Mean time taken from initiation of rainfall to initiation of runoff and drainage in a laboratory rainfall simulation study at 60mmhr^{-1} rainfall intensity.

	Mean time to runoff initiation (Min.sec)	Mean time to drainage initiation (Min.sec)
Adele	24.45	43.52
Amadle	16.47	59.56
AU Aluvial	16.32	38.15
AU Regosol	25.03	31.17
AU Vertisol	25.01	33.00
Babile	17.08	30.04
Bedessa	26.31	32.32
Chinaksen	19.19	45.04
Chiro	25.31	36.34
Diredawa	24.10	34.11
Gelemso	18.04	41.11
Hamaresa	26.02	39.05
Hirna	20.28	34.01
Karamara	17.58	60.00
Lange	21.34	38.2

It is however, important to note that more significant correlation was obtained between the soil properties and overland flow than when total runoff (splash volume plus overland flow) is considered. Overland flow was significantly correlated with aggregate stability (r = -0.81), organic carbon (r = -0.63), ESP (r = 0.80), clay content (r = -0.61) and initial moisture content (r = -0.66) all of which are interrelated. This can be ascribed to the interactive effect of these soil properties on aggregate stability thereby affecting surface sealing which has more direct effect on overland flow than splash water.

2.3.2 Splash detachment and sediment yield

The final rates of splash and sediment yield as well as the total masses for the soils considered in this study are presented in Table 2.7. The final rates of soil splash and sediment yield ranged from 0.37 and 0.08 kg $m^{-2}hr^{-1}$ to 1.23 and 0.32 kg $m^{-2}hr^{-1}$ respectively, but these figures must be considered only as relative values as they are dependent on experimental techniques employed. The total splash and sediment yield followed more or less similar trend with runoff. The highest splash erosion was recorded on Babile (1.143 kg m^{-2}) which was followed by Gelemso (0.965 kg m-2) and Diredawa (0.951 kg m^{-2}). Sediment yield was also relatively higher on Gelemso (0.114 kg m^{-2}), Babile (0.10 kg m^{-2}) and Diredawa (0.09 kg m^{-2}) soils than on others. Hamaressa, Lange, AU regosol, Adele and Amadle had relatively lower (less than 0.060 kg m^{-2}) sediment yield as compared to other soils studied in this experiment.

Table 2.7 Mean final splash and sediment yield rates and total splash and sediment yield masses for replicated one-hour rainfall simulation runs.

Soil name	Splash erosion		Sediment yield	
	Final rate	Total mass	Final rate	Total mass
	Kg $m^{-2}hr^{-1}$	Kg m^{-2}	Kg $m^{-2}hr^{-1}$	Kg m^{-2}
Adele	0.53	0.74	0.09	0.06
Amadle	0.93	0.51	0.09	0.06
Au Alluvial	0.89	0.59	0.24	0.08
Au Regossiol	1.08	0.87	0.15	0.06
Au Vertisol	0.73	0.64	0.17	0.05
Babile	1.13	1.14	0.27	0.10
Bedessa	0.92	0.65	0.24	0.06
Chinakssen	0.81	0.67	0.17	0.07
Chiro	0.98	0.73	0.13	0.07
Diredawa	0.99	0.95	0.15	0.09
Gelemso	1.23	0.97	0.32	0.11
Hamaressa	1.03	0.82	0.09	0.05
Hirna	0.71	0.61	0.16	0.06
Karamara	0.37	0.59	0.13	0.07
Lange	0.67	0.68	0.08	0.06

Sediment yield rates for some of the 15 soils were presented in Fig. 2.6. On Babile and Gelemso soils, a sharp increase in sediment yield rates was observed both during the early initiation of runoff and late around the end of the one hour simulation run with a more or less higher rate than other soils. As explained earlier, the high detachment rate indicated by large flow detachment and splash detachment on these soils is due to their relatively low aggregate stability and infiltration rate which is mainly resulted from their high ESP and low OC contents (Table2.3). Hence, the soil particles from the broken aggregate are easily detached and transported by the splashing and running water.

For soils like Hamaressa, sediment yield rate has attained its steady state after 30 minutes and was the lowest during the final stages of the simulation run.

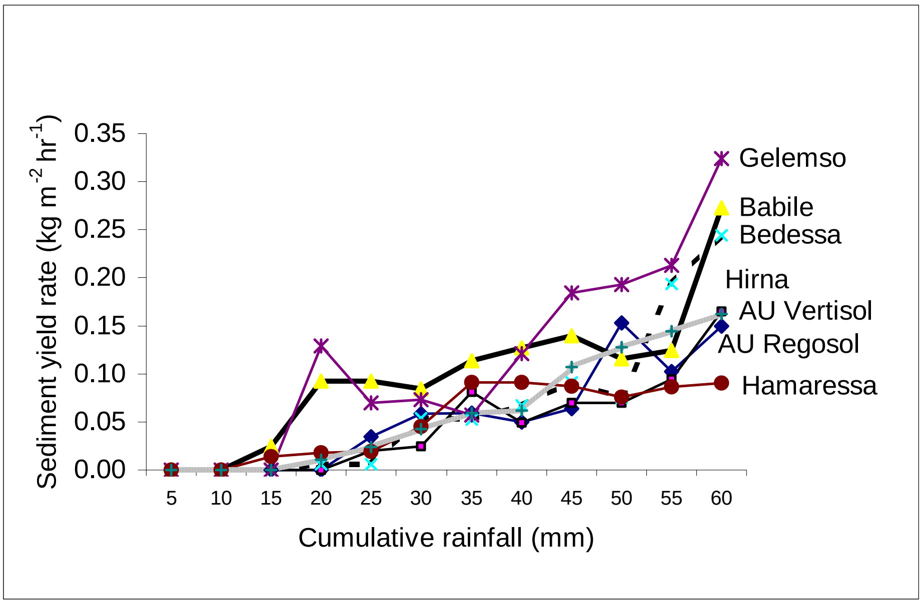


Fig.2.6 Sediment yield rate vs. cumulative rainfall during a one-hour rainfall simulation on selected soils.

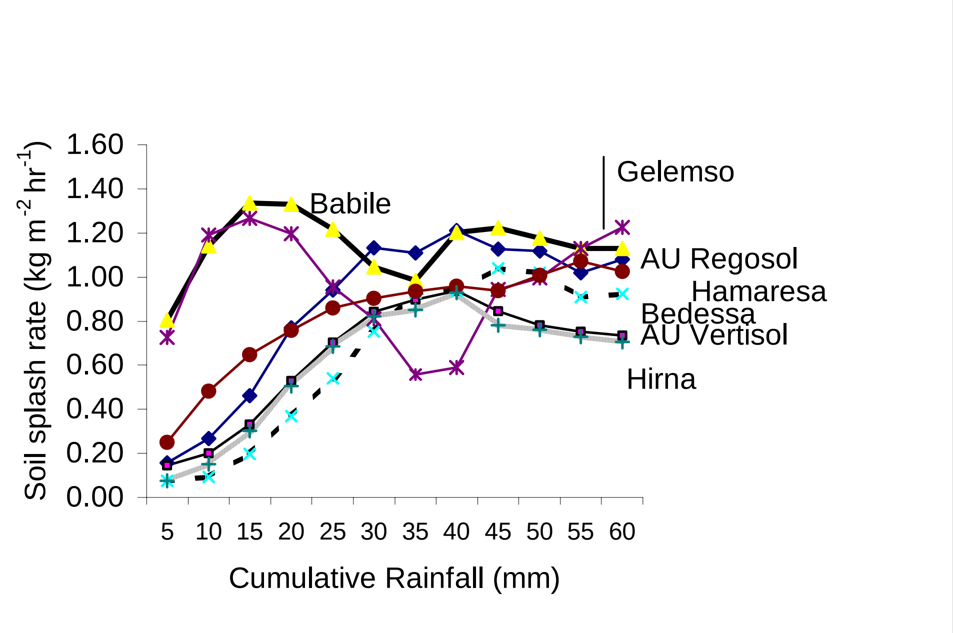


Fig. 2.7 Soil splash rate (kg m^{-2} hr^{-1}) vs. cumulative rainfall during a one-hour rainfall simulation on selected soils

The trend of soil splash rate versus cumulative rainfalls for the seven representative soils is presented in Fig 2.8. Babile and Gelemso attained their highest soil splash rates during the first 15 minutes of the rainfall event after which the rate decreased sharply especially for Gelemso (until it becomes the lowest of all) and started to raise again towards the end of the one-hour simulation. The high soil splash erosion rate during the early stages of the run on Gelemso and Babile soils is due to their weak aggregate stability and their susceptibility to detachment by raindrop impact. However, the reduction in their rate of soil splash at the middle of the simulation run (Fig.2.7) can be associated with removal of detached soil particles during the earlier runs as well as increase in shear strength (Bradford et al., 1987) of the soil due to sealing. But with a continued application of rainfall, the rate of splash started to rise mainly because of the removal of the surface seals by runoff and exposure of the underlying unsealed soil to rainfall impact.

For other soils including Hirna, AU vertisol and Bedessa, the rate of soil splash increased gradually up to about 40 minutes of the simulation period and declined thereafter. This can be explained by a gradual breakdown of the relatively strong soil aggregate and their relatively low tendency to sealing at early rainfall periods.

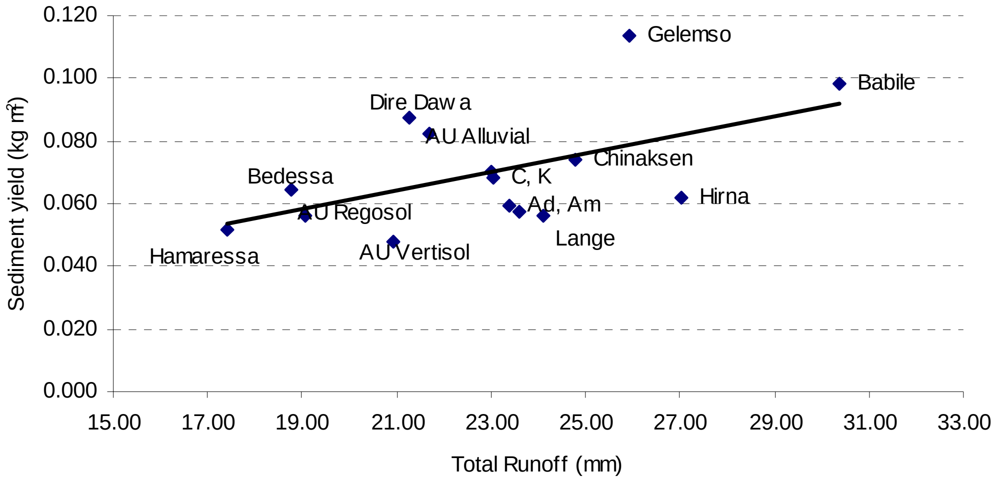
2.3.3 Relationships between runoff, splash detachment and sediment yield

Though not as high as expected, there is a significant linear relationship between total sediment yield and runoff ($r = 0.54$) (see Fig. 2.8), and total sediment yield and splash weight ($r = 0.61$). Working on seven soils of the Mediterranean climate, Singer and Le Bissonnais (1998), also reported a similar highly significant linear relationships between mass of soil eroded and total runoff ($r^2 = 0.629$). Such linear relationships between runoff and soil loss has also been reported in other studies (eg. Feleke, 1987; Mullugeta, 1988; Bobe and Gachene, 1999; Sonneveled et al., 1999)

Seal formation affects soil erosion in different ways. Surface sealing reduces infiltration rate and increases runoff (Bradford et al., 1987) thereby increasing detachment and transport of soil particles by concentrated flow. On the other hand, some reports indicate that crusting increases the resistance of the soil to detachment resulting in low sediment loss (Bradford et al., 1986; Sharma, 1996; Bajracharia and Lal, 1999). The fact that high splash weight was collected on soils with high runoff in this study is not in line with the above explanation. This could be attributed to the soil properties which are too unstable to form strong seals that can resist the impact of raindrops despite reduced infiltration rate due to clogging up of pore spaces by the dispersed soil particles. It could also be associated with the particle and aggregate sizes of the soils.

On the other hand, Hirna and Amadle soils have reasonably high runoff (27.04 and 23.40 mm respectively) but have a relatively low splash weight (0.608 kg m^{-2} and 0.514 kg m^{-2} respectively). This could be explained by the second effect of sealing where it increases the resistance of the soils to detachment due to the coherence of soil particles during the sealing process. It could also be associated with formation of temporary water ponding on the plots that may increase the gap between the impacting raindrops and the soil surface (Palmer, 1963 quoted by Bradford and Huang, 1996; Sharma, 1996) resulting in low sediment availability in the splashing water.

The total soil loss (sum of splash and sediment yield) also followed the same trend with runoff especially for the most vulnerable soils. Babile and Gelemso are the most erodible.



[Ad= Adele; Am= Amadle; C = Chiro; K= Karamara]

Fig. 2.8 Total sediment yield (kg m^{-2}) vs. total runoff for a one hour rainfall simulation on the studied soils.

In general, the absolute values (0.5 to 1.1 t ha^{-1}) of sediment yield collected in this laboratory rainfall simulation experiment for the different site are very low. This could be mainly due to the short slope length of the small erosion plots which are responsible for the low flow velocity of runoff and low shearing force resulting in less detachment and transport of soil. Most of the soil detachment in this laboratory rainfall simulation study is associated with the impact of raindrops. This is indicated by much higher splash weight than sediment yield for each soil considered. Therefore, the sediment yield and splash detachment values should only be considered as relative figures. Under normal field conditions, overland flow rates play a significant role in detaching and transporting sediments due to the high velocity of a concentrated flow in channels and rills.

2.3.4 Relationships between soil properties and erosion parameters

Regression equations and correlation coefficients between the total runoff, sediment yield and splash weight versus some soil properties are presented in Table 2.8. Total runoff is positively correlated with ESP (r = 0.50) negatively correlated with aggregate stability (r = -0.40) though none of them are significant.

However, the correlation coefficients indicated in these study should be interpreted with much care. When the effect of one factor or soil property on a given erosion parameter is discussed, attention should also be given to the interaction effects of the other factors. A positive correlation between a given soil property and erosion parameter doesn’t always imply a cause and effect relationship. For instance, a significant positive correlation was observed between bulk density and runoff volume (r = 0.70). But this alone won’t lead us to a general conclusion that soils with high bulk density will have high runoff. As a matter of coincidence, those soils with relatively high sand content like Babile in this study, are characterized by high ESP and low aggregate stability. Otherwise, in most cases, soils with high sand content and consequently high bulk density are expected to have high infiltration rate and low runoff. Besides, as this study is limited by less number of data points due to time and financial constraints, the correlation coefficients obtained between the various soil properties and erosion parameters should be interpreted with much care.

Table 2.8 Regression equations and correlation coefficients between selected soil properties and erosion parameters of some soils in eastern Ethiopia

Erosion parameter (Y)	Soil Property (X)	Regression equations	Correlation coefficient (r)
Sediment yield (kg m^{-2})	Clay (%)	Y= 0.0885 - 0.0006X	-0.68*; n=13
	OC (%)	Y= 0.1026 – 0.0294X	-0.65*; n=14
	ESP	Y= 0.0529 + 0.0041X	0.72**; n=14
	WSA (%)	Y=0.1322 - 0.001X	-0.77**; n=14
Splash weight (kg m^{-2})	Clay (%)	Y= 1.0601 – 0.0074X	-0.0.67*; n=13
	OC (%)	Y = 1.0344 – 0.2622X	-0.62*; n=14
	ESP	Y=0.5804 + 0.0375X	0.71**; n=14
	WSA (%)	Y=0.9695 – 0.0408X	-0.78**; n=13
Runoff (mm)	WSA (%)	Y = 29.289 – 0.0408X	0.4^{ns}; n=14
	ESP	Y = 20.675 + 0.5208X	0.5^{ns}; n=14

*= Significant at (P=0.05); **= Significant at (P=0.01); ns = Not significant at (p=0.05); n = number of observations

Total sediment yield is positively correlated with ESP (r = 0.72) but negatively correlated with %Clay (r = -0.68), percent organic carbon (r = -0.65), initial moisture content (r = -0.73) and aggregate stability (r = -0.77) all correlation being significant at 5 % probability level. The positive linear relationship obtained between total sediment yield and sand content and bulk density in this experiment is also mainly associated with the high ESP of the coarse textured soils. The result would have been different if the soils were uniform in their ESP but vary only in texture; because various studies (including Trott and Singer, 1983; Obi et al., 1989; Merzoak and Blake, 1991) reported a negative relationship between sand content and erosion rate.

The negative correlation between sediment yield and other soil properties like clay content, organic carbon content, CEC, initial moisture content and aggregate stability is mainly attributed to the aggregating and stabilizing effect of clay and organic matter on soil particles. All these soil properties are interrelated and the effects are expressed through their effect on aggregate stability and in turn on the erosion parameters. The aggregate stability of the soils (aggregate sizes 0.5 – 2mm) at the study sites is presented in Fig. 2.9 and the relationships between aggregate stability and major erosion parameters is presented in Fig. 2.10. High CEC, initial moisture content and high percentage of water stable aggregates are all functions of high clay and organic matter contents.

Splash erosion is positively and significantly correlated with % sand (r=0.72), bulk density (r = 0.82), and ESP (r = 0.71), but negatively correlated with %clay (r = -0.67), %OC (r = -0.62), CEC (r = -0.88), initial moisture content (r = -0.67) and aggregate stability (r = -0.78).

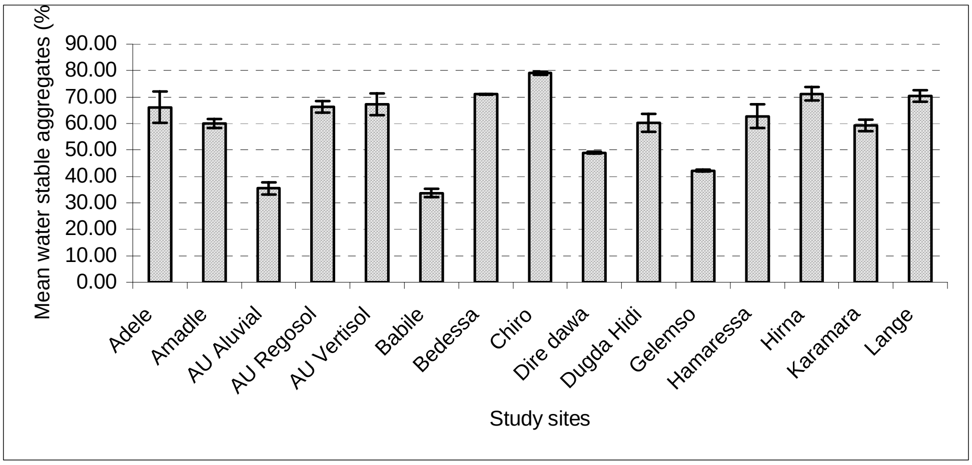


Fig. 2.9 Aggregate stability values for the soils of the study sites. [Y-error bars indicate standard deviations]

The positive correlation among aggregate stability, clay content, organic matter content and CEC and the negative correlation between these soil properties and erosion parameters indicate that these soil properties are the most influential in reducing runoff and soil loss. Similar positive linear relationship between aggregate stability and other soil properties such as clay content and organic matter content has also been reported in several studies (Kemper and Kotch, 1966; Goldenberg et al., 1988; Shainberg et al, 1997).

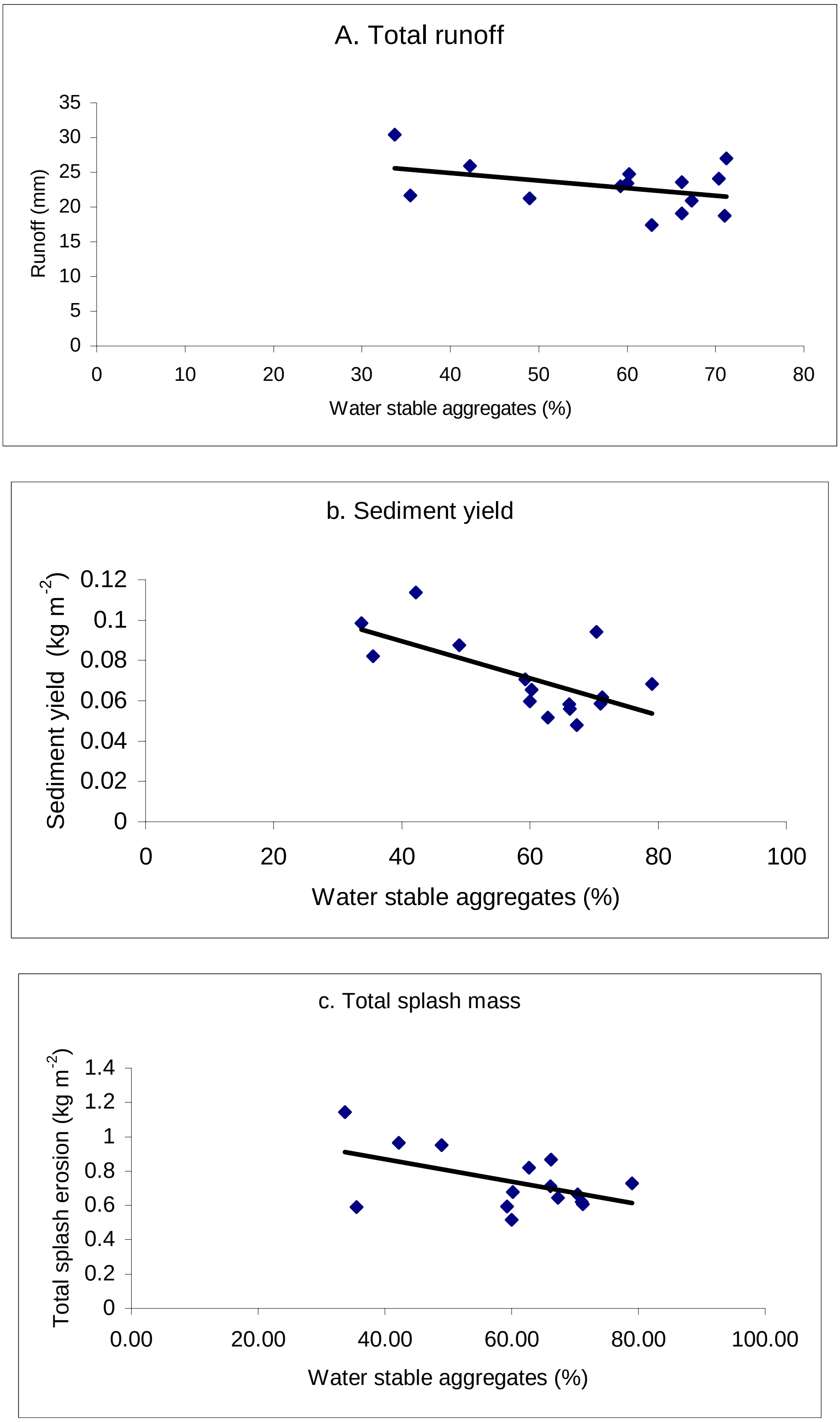


Fig. 2.10 Relationships between percent water stable aggregates and total (a) runoff, (b) sediment yield, and (c) splash weight

Gollany et al. (1991) also found that aggregate stability increases with clay content. Similarly, Le Bissonnais, 1988 (quoted by Le Bissonnais, 1996) also reported an increase in aggregate stability (%>0.2mm) with increasing CEC and clay content. However, with a wider range of soils, Le Bissonnais and Singer (1993) as well as Pierson and Mulla (1990) didn't find significant correlations between clay content and aggregate stability. This may be associated with variations in the types of the clay.

On the other hand, the fact that soil properties such as percent sand, bulk density and ESP, that are negatively correlated with aggregate stability, have all positive linear relationships with runoff, sediment yield, and splash detacment, is mainly attributed to the overwhelming effect of high ESP on reducing aggregate stability and increasing runoff and soil erosion due to surface sealing. Several studies (Agassi et al., 1981; Singer et al., 1982; Shainberg and Latey, 1984) also reported that increase in ESP caused more dispersion, crust formation and erosion though the effect varied among different soils (Le Bissonnais, 1996). Some soils are affected at very low ESP, others are affected only at high ESP and some are not affected at all. Levy and Van der Watt (1988) found that dispersion of a Kaolinitic soil was not significantly affected in the ESP range of 1% to 9% while two other soils (i) with mixed kaolinitic, illite and monmorilonite and (ii) with illite and interstratified minerals were significantly affected at ESP of 4.3%. The ESP of our soils in this study is in the range of 0.78 for Bedessa to 13.85 for Babile (Table 2.3) and an apparent negative linear relationship between ESP and aggregate stability is shown (Fig. 2.11).

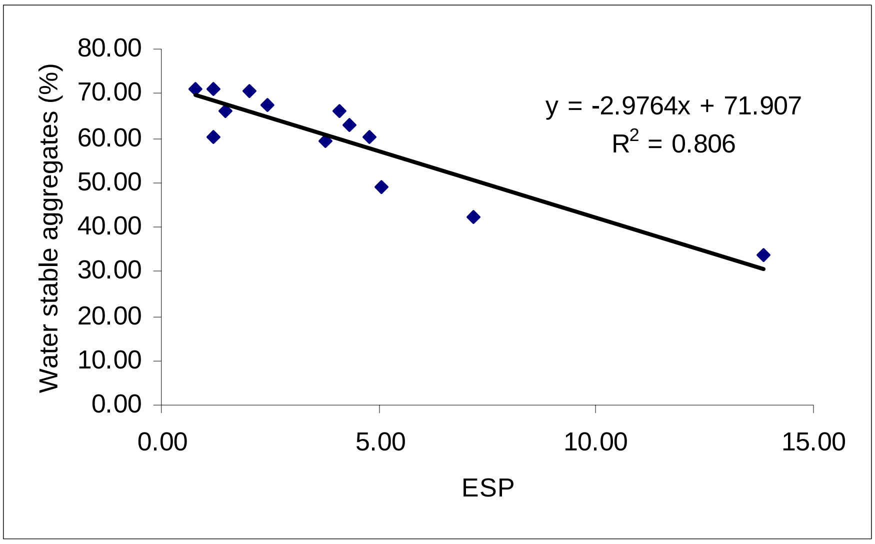


Fig. 2.11 The relationship between aggregates stability and ESP of the soils in the study areas.

2.4 Conclusion

Soil erodibility assessment of selected Harerghe soils under laboratory rainfall simulation indicate that different soils have different tendencies to seal formation, runoff and soil loss. Soil erodiblity in this study refers to the measure of the combined effect of sediment and splash loss after one hour of rainfall simulation. Soils of Babile, Gelemso, and Diredawa are found to be more susceptible to surface sealing and are more prone to splash detachment and sediment yield. This was mainly attributed to their relatively high ESP and subsequent low aggregate stability and low infiltration rate which led to high runoff and soil loss. The soils which were found to be relatively resistant to erosion such as Hamaressa, Bedessa, Au Regosol and AU vertisol were characterized by high aggregate stability and most of them have high % clay, % organic matter and CEC but low ESP.

In general, although there is some indication that the majority of the soils with low organic matter content, clay, CEC, and water stable aggregates were more erodible than those having relatively high content of these soil properties, no single soil property was found to affect soil erodibility independently. The interaction effect of the soil properties on erosion parameters may complicate the relationship. Besides, some other important soil properties (like clay mineralogy, CBD extractable Fe and Al) which are not determined in this study but are reported to have a significant effect in soil aggregate stability might also had a hidden effect on the erosion parameters of these soils. Therefore, the reason for high or low erodibility of a given soil under a specific slope and rainfall characteristics is a function of the interaction of its physical and chemical properties and hence, is different for different soils.

CHAPTER 3

PREDICTION OF SOIL LOSS USING SOIL EROSION MODELS

3.1 Introduction

Ethiopia is one of the most ecologically sensitive regions of the world for accelerated erosion (Lal and Pierce, 1991). The Harerge region of eastern Ethiopia, especially the highlands (with altitudes greater than 1500m) are among the highly affected areas by land degradation due to erosion. This is why the Soil Conservation Research Project (SCRP) selected one of its representative sites at Hunde Lafto (West Harerge) and established soil erosion experimental plots to evaluate the effect of various soil conservation measures. Despite many efforts made to quantify the extent of soil loss in the country, the available information at this stage is inadequate as it was mainly based on results obtained from selected agro-climatic regions. Therefore, more detailed and extensive work is required to assess the spatial variability and extent of soil erosion within a given region.

This study was initiated to this effect, to estimate soil loss in some areas of Harerge, eastern Ethiopia using two empirical soil loss models namely Soil Loss Estimator for Southern Africa (SLEMSA) and the Universal Soil Loss Equation (USLE). These two models were selected mainly due to the limited amount of information they require and the relative simplicity of collecting the required input data to run the models because of the limited data available for the study areas.

One of the purposes of predicting soil erosion hazards and factors responsible for the same is to get information for planning of appropriate soil management systems based on the severity of erosion in specific areas. Sustainable soil management systems should be developed to reduce further degradation and restore the productivity of the eroded land. The aims of this study were therefore,

1. To estimate extent of soil loss at different areas in the Harerge region using SLEMSA and USLE models so that planning of management techniques can be suggested in order to reduce further degradation,

2. To analyze the sensitivity of the above models to their input variables and evaluate their applicability to these areas for further study and

3. To estimate the tolerable soil loss as well as soil life for the study sites under the current management situations.

3.2 Soil loss estimation using SLEMSA

3.2.1 Introduction

Soil Loss Estimation Model for Southern Africa (SLEMSA) was initially developed for Zimbabwean conditions by Elwell (1978) to predict long term average annual soil losses by sheet and rill erosion from small scale farming areas for specific combination of physical and management conditions (Schulze, 1979). Since then, it has been widely used to predict soil loss in African environments (Elwell and Stocking, 1982). Among others, it was used for assessing areas of high silt discharge into Richards Bay in South Africa (Schulze, 1979), for assessing rates of soil erosion in Botswana (Abel and Stocking, 1987), to develop erosion hazard map for the SADC (Southern African Development Community) region (Stocking et al., 1988), for erosion hazard assessment in Malawi (Paris, 1990), to predict soil losses from small scale farming areas in Zimbabwe (Grohs and Elwell, 1993) and to predict soil loss in the Lesotho Highlands Water Project (Smith et al., 1997).

The SLEMSA model is neither meant for estimation of sediment yields to rivers or dams nor soil deposition in depressions. It is essentially a model for soil removal (Schulze, 1979). However, it can be regarded as a useful model in differentiating areas of high and low erosion potential (Schulze, 1979).

In this study, it has been envisaged that SLEMSA could be used to the conditions of eastern Ethiopia since the equation employed represents the major factors affecting erosion (Foster and Meyer, 1977 as quoted by Smith, 1999) and it only requires determination of appropriate values for the different factors.

3.2.2 Materials and methods

The study sites are the same as those indicated in chapter 2. However, some of the sites do not have weather stations and lack rainfall data. For such sites, the rainfall data of the nearest study site with a complete data set was used to comply with the input requirements of the models.

The major erosion control variables that have been identified and expressed numerically (Elwell, 1977 cited by Schulze, 1979) in the SLEMSA model include: rainfall kinetic energy (E), percent effective vegetal cover (i), soil erodibility index (F), percent slope steepness (S) and slope length (L). These variables were combined into three factors namely, a factor that describes soil loss from bare plot (K), a canopy cover factor (C), and a topographic factor (X).

The above three factors were combined into the general SLEMSA model as follows:

$$Z = K\ X\ C \qquad (3.1)$$

(Department of Agricultural Technical Services, 1976; Schulze, 1979; Morgan, 1995)
Where

Z = Predicted mean annual soil loss (t $ha^{-1}yr^{-1}$),

K = Mean annual soil loss (t $ha^{-1}yr^{-1}$) from a standard field plot of 30m long, 10m wide, 2.5° slope for a soil of known erodibility F under a weed free bare fallow,

X = Dimensionless combined slope length and steepness factor which is the ratio of soil loss from a plot of length L and slope percent S, to that lost from the standard plot and

C = dimensionless crop management factor which is the ratio of soil loss from a cropped plot to that lost from the bare fallow

3.2.2.1 Estimation of K for SLEMSA

Field observation of the research sites and laboratory soil analysis were the main sources of input data used. The soil erodibility index F (see equations 3.4 to 3.6) was estimated based on the soil textural classes and other relevant soil surface and subsurface conditions that directly or indirectly affect the soil's inherent sensitivity to erosion including percent clay content in the B horizon, ridging, self mulching, drainage, surface crusting, previous erosion damage, tillage techniques, moisture retention capacity, and dominance of sands and silts (Appendices 1.4A and 1.4B).

Weather data were obtained from the weather bureau of the region where the respective research site is located. Due to the absence of weather stations at some of the sites considered in this study, the data of the nearest weather station was used. Accordingly, weather data of Alemaya University was used for AU Regosol, AU vertisol, AU Alluvial (all of which are located in Alemaya University campus), Adele and Hamaressa. Similarly, weather data of Chiro (Asebe Teferi) was used for Hirna. For the three sites in the Somali region namely, Amadle, Dugda Hidi (Chinaksen) and Karamara, data from a single weather station (i.e. Jijiga) was used. Hence, most of variabilities in the estimated soil losses between the research sites that shared the same rainfall data will be mainly associated with factors other than rainfall erosivity.

Estimation of rainfall kinetic energy (E) is based on the annual rainfall data. The kinetic energy has been expressed in terms of rainfall intensity equation developed by Elwell and Stocking (1973) as quoted by Department of Agricultural and Technical Services (1976) as follows:

$$E = (29.82 - 127.51/I) \qquad (3.2)$$

Where,

E= Rainfall kinetic energy in $Jm^{-2}mm^{-1}$ and

I= Rainfall Intensity in mm hr^{-1}

According to the Department of Agricultural Technical Services (1976), charts from autographic rain gauges should be analysed to obtain storm, daily, monthly or annual values for E. However, owing to the lack of such detailed and consistent information for the research sites under consideration, the tabulated provisional values of rainfall energy (E) (Elwell and Stocking, 1973 as quoted in Department Agricultural Technical Services, 1976) (Appendix 1.1) based on mean annual rainfalls were used for this study. Hence, the estimated rainfall energy for the study sites based on the range of their annual rainfall is presented in Appendix 1.2.

The value of the K factor was determined by relating mean annual soil loss to mean annual rainfall energy (E) using the exponential relationships (Morgan, 1995):

$$\ln K = b \ln E + a \qquad (3.3)$$

Where E is in $Jm^{-2}mm^{-1}$ and the value of a and b are functions of the soil erodibility factor (F):

$$a = 2.884 - 8.2109F \qquad (3.4)$$

$$b = 0.4681 + 0.7663F \qquad (3.5)$$

By substituting equations 3.4 and 3.5 into equation 3.3, we get

$$K = \exp\left[(0.4681 + 0.7663F)\ln E + 2.884 - 8.1209F\right] \qquad (3.6)$$

The estimated K values based on the above sub models are presented in Table 3.1.

3.2.2.2 Assumptions and procedures used to estimate the C values for SLEMSA

The cover information for the sites was obtained through visual observation of the sites and by estimations based on the mean monthly and annual rainfall data. The types of vegetation and/ or dominant crops grown in each site were identified and the percent surface cover during a certain season of the year was estimated based on the growing season of each crop and the temporal rainfall distribution. Therefore, a year is divided into four seasons representing three months each. For most of the sites in this study, October – December are considered to be dry seasons. The same is true for January - March except for few ‘Belg’(the first rainfall season of the year) rainfall events that start in March. Even if the ‘Belg’ rainfall starts in March at the majority of the research sites, surface cover on agricultural lands during this period is very poor due to the maximum disturbance of the land by cultivation and subsequent bare soil surfaces that are prone to erosion. Hence, a relatively small percent cover value is assigned to crops during this season.

October– December are usually seasons for ripening and harvesting for many agricultural grain crops. Though harvesting reduces the percent cover (especially when the residue is removed from the land) a relatively better estimate of cover was assigned to crops during this season as compared to that of January- March. April to June is a season mainly for planting, seedling emergence and vegetative growth for most crops grown in the regions as a whole including sorghum and maize. The percent cover of the land by crops like maize and sorghum during these seasons will receive a better value than for both October-December and January –March. During July –September all crops will be in a vegetative stage and provide the maximum surface cover. Therefore maximum surface cover values for different crops were allocated for the sites during this season.

The crop management factor C, calculated from the value of soil loss from standard bare soil condition and that of a cropped field (Morgan, 1995) depends on the percentage of the rainfall energy intercepted by the crop (i). Some of the procedures followed to calculate C value for SLEMSA include (Appendix 1.5):

i. Dominant crops and vegetation for each site were identified and percent cover was estimated for each crop separately based on the expected growth stage and stand of a particular crop at a specific season.

ii. The average value of the product of the percent cover and fraction of rainfall during that season (ratio of the seasonal total rainfall to annual rainfall) for each crop was used to calculate the seasonal percent rainfall energy interception, i value.

iii. The sum of i values for the four seasons were taken as the annual rainfall interception for a given locality.

iv. For crops and natural grasslands with $i<50$ percent, the crop management factor C was calculated using equation 3.7.

$$C = e^{(-0.06i)} \qquad (3.7)$$

and for dense pastures and mulches when $i \geq 50$ percent, it is

$$C = (2.3 - 0.01i)/30 \qquad (3.8)$$

3.2.2.3 Procedures used to estimate the topographic factor X for SLEMSA

Due to the absence of data on the relationship between slope characteristics and soil loss for the areas for which SLEMSA was developed (Elwell, 1977 as quoted by Schulze, 1979) the slope factor X of the USLE (Wischmeier and Smith, 1965) was adapted to be more representative of the conditions of the experiments during the development of the model. Hence, the topographic factor is given by

$$X = \sqrt{L}(0.76 + 0.53S + 0.076S^2)/25.65 \qquad (3.9)$$

Where

X=	the ratio of soil loss from a plot of length L and slope percent S, to that lost from the standard plot
L=	slope length in m
S=	Slope gradient in percent.

The topographic features of the studied areas vary widely ranging from nearly level at AU Vertisol, AU Alluvial and Diredawa Toni Farm to hilly terrain in Asebe Tefri (Chiro) (Appendix 1.3). It is well known that a single value of slope gradient will not represent the topography of the whole area. For the purpose of using the model, however, a representative average slope for each site was considered. Therefore, it should be stressed that the value of S indicated for each site is a gross oversimplification of the topography of the area. No cognisance has been taken of slope convexity (which would yield greater soil loss) or concavity (yielding smaller soil losses) (Schulze, 1979). For computational purposes, all slope gradients greater than 25% were assigned the value 25% because SLEMSA has not been designed for higher slope gradients (Schulze, 1979).

According to Wischmeier and Smith (1965), effective slope length is defined as the distance from the point of origin of overland flow to the point where either the slope decreases enough that deposition begins; or runoff water enters a well-defined channel. The slope gradient and length for the study sites are presented in Appendix 1.3. The topographic factor, X was estimated for each study site using equation 3.9 and presented in Table 3.1 and Appendix 1.3.

3.2.3 Results and discussion

The values for the factors involved in the SLEMSA model and the predicted soil loss for the study sites using this model is presented in Table 3.1. Details of calculations and guidelines for estimating the input factors of SLEMSA are given in Appendix 1.1 – 1.5.

Table 3.1 Estimated input variables of SLEMSA model and calculated soil loss (t $ha^{-1}yr^{-1}$) for some sites in eastern Ethiopia

Site	F	a	b	E	K	X	C	Z (t $ha^{-1}yr^{-1}$)
Adele	5.50	-42.28	4.68	17600.00	54.38	7.53	0.058	23.81
Amadle	3.50	-25.85	3.15	12200.00	60.41	1.85	0.053	5.93
AU Aluvial	5.00	-38.17	4.30	17600.00	74.51	0.92	0.069	4.74
AU Regosol	5.00	-38.17	4.30	17600.00	74.51	5.33	0.062	24.72
AU Vertisol	5.00	-38.17	4.30	17600.00	74.51	0.75	0.055	3.09
Babile	3.50	-25.85	3.15	14000.00	93.20	7.04	0.107	70.23
Bedessa	6.00	-46.38	5.07	21000.00	97.11	2.98	0.060	17.36
Chiro	6.00	-46.38	5.07	17600.00	39.69	10.72	0.060	25.54
Dire Dawa	6.00	-46.38	5.07	14000.00	12.45	1.43	0.060	1.07
Dugda Hidi	3.50	-25.85	3.15	12200.00	60.41	2.77	0.058	9.69
Gelemso	5.00	-38.17	4.30	23000.00	235.44	7.12	0.059	98.84
Hamaresa	6.00	-46.38	5.07	17600.00	39.69	10.72	0.101	42.99
Hirna	6.50	-50.49	5.45	17600.00	28.97	6.36	0.062	11.43
Karamara	3.00	-21.75	2.77	12200.00	95.25	7.04	0.093	62.39
Lange	5.50	-42.28	4.68	19000.00	77.82	5.83	0.066	29.96

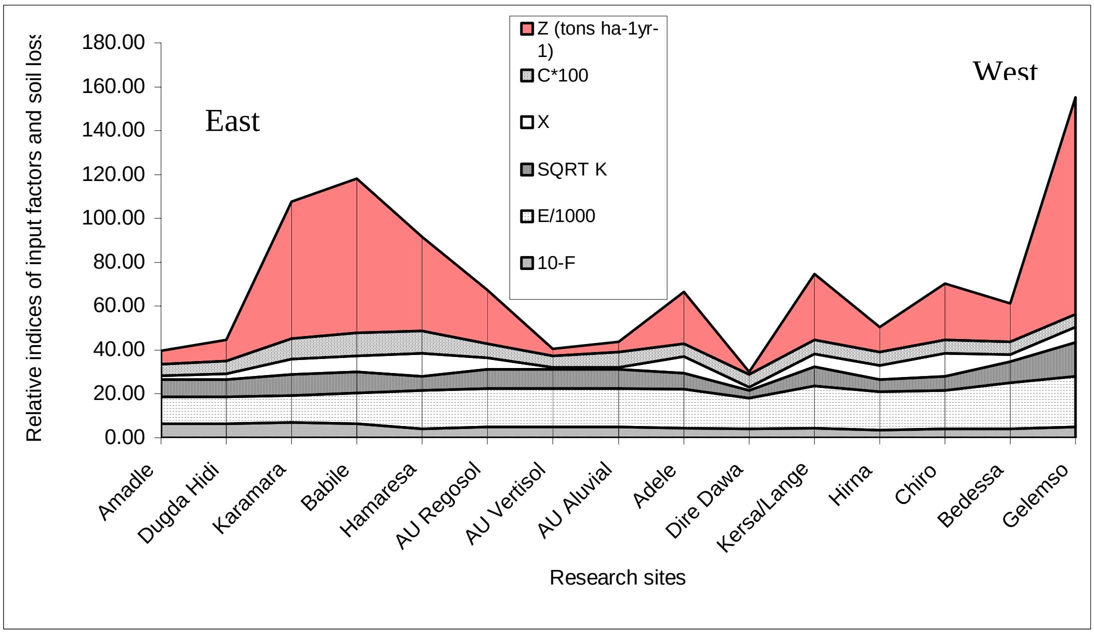
3.2.3.1 Estimated soil losses using SLEMSA

The estimated soil losses for the study sites in eastern Ethiopia ranged from 1.07 t ha^{-1} yr^{-1} for Diredawa to 98.84 t ha^{-1} yr^{-1} for Gelemso (Table 3.1). The estimated soil losses were higher at Gelemso, Babile, Karamara, and Hamaressa all of which were above 40t ha^{-1} yr^{-1}. These high soil loss values for these areas are attributed to the combined effects of the various factors affecting erosion at each site.

In some areas, a single factor may have an overwhelming effect than others leading to large differences in the estimated soil loss among the research sites. For instance, the highest soil loss estimated at Gelemso is mainly due to its highest K value (Table 3.1) which is a function of rainfall erosiviy and soil erodibility factors. This is again mainly associated with its higher mean annual rainfall (1146mm) averaged over nine years. For other sites like Karamara, Babile and Hamaressa, where relatively higher soil loss estimates were also recorded, no single factor seemed more important than any other factors in affecting the estimated soil loss values. At Babile and Karamara, all values of the three factors are relatively higher resulting in higher soil losses. The higher estimated soil loss at Hamaressa was largely due to the higher values of the topographic, X factor and crop cover, C factors than the K factor. In general, although one or two factors may be responsible for the high or low soil loss in a given area, the combined effect of the values of all three factors is most important.

Lowest estimated soil loss values were obtained for Diredawa, AU vertisol and AU Alluvial. These sites have more or less similar values for the crop cover factor with other sites where relatively high soil losses were estimated. However, their values of the K and X factors are very low. Actually these areas are relatively level lands and the topographic factors are relatively low resulting in low soil loss values.

To facilitate a comparison between the contributions of the different erosion factors on the estimated soil loss, the values for various erosion factors are transformed so as to fit into a graph that is presented in Fig 3.1. It was indicated that the estimated soil loss was relatively higher where all erosion parameters are proportionally high. The higher slope factor at Hamaressa and Chiro had a more pronounced effect on increasing estimated soil loss but the low slope factors at AU Vertisol, AU Alluvial and Diredawa had contributed a lot to reduction in estimated soil loss. According to Fig. 3.1, the effect of crop cover factor was more or less constant at most of the sites and was not the main contributor to the variation of soil loss values among the study sites. However, since the effect of any single factor on the predicted soil loss is dependent on the values of the other factors, separate evaluation of each factor is not reasonable.



*Z=Estimated soil loss (t ha^{-1}yr^{-1}); C*100= Crop cover index times 100; X= Topographic factor; SQRT K = Square root of K values; E/1000= Erosivity index divided by 1000; 10 – F= 10 minus erodibility factor F. [The study sites are arranged according to their east-west geographical locations]*

Fig. 3.1 Relationships among the indices of erosion factors and soil loss as estimated by using SLEMSA at the study sites.

3.2.3.2 Sensitivity of soil loss estimated by SLEMSA to changes in input variables

The sensitivity of the soil loss estimated by SLEMSA to changes in some of its input variables was tested by increasing or decreasing some of the factors by 20%. All other factors were fixed while the effect of one factor was tested. In this study, the response of estimated soil loss to changes in soil erodibility factor (F), slope gradient (S) and length (L), rainfall kinetic energy index (E) and percentage rainfall energy intercepted by cover (i) was evaluated. The estimated soil loss due to changes in one of its input variables while keeping the others constant, and the percentage change as compared to the original estimated soil loss is presented in Table 3.2.

Table 3.2 Response of soil loss estimated by SLEMSA to changes in some input variables.

Study site	Soil loss base value	Soil loss with 20% increase in F		Soil loss with 20% decrease in E		Soil loss with 20% decrease in S%		Soil loss with 20% decrease in slope length		Soil loss with 20% increase in i	
	t ha^{-1} yr^{-1}	Amount t ha^{-1}yr^{-1}	% decrease	Amount t ha^{-1}yr^{-1}	% decrease	Amount t ha^{-1}yr^{-1}	% decrease	Amount t ha^{-1}yr^{-1})	% decrease	Amount t ha^{-1}yr^{-1}	% decrease
Adele	23.81	11.91	49.98	8.37	64.83	17.19	27.79	21.30	10.56	22.29	6.37
Amadle	5.93	3.13	47.14	2.94	50.49	4.57	22.86	5.30	10.56	6.39	-7.70
AU Aluvial	4.74	2.53	46.73	1.82	61.69	4.28	9.76	4.24	10.56	4.04	14.76
AU Regosol	24.72	13.17	46.73	9.47	61.69	17.85	27.79	22.11	10.56	23.07	6.66
AU Vertisol	3.09	1.64	46.73	1.18	61.69	2.79	9.76	2.76	10.56	3.22	-4.21
Babile	70.23	39.97	43.09	34.77	50.49	49.97	28.85	62.82	10.56	44.67	36.40
Bedessa	17.36	9.59	44.75	5.60	67.71	12.78	26.35	15.52	10.56	16.38	5.60
Chiro	25.54	11.99	53.04	8.25	67.71	17.34	32.11	22.84	10.56	24.67	3.41
Dire Dawa	1.07	0.41	61.95	0.35	67.71	0.91	15.13	0.96	10.56	1.01	6.19
Dugda Hidi	9.69	5.12	47.14	4.80	50.49	7.65	21.04	8.67	10.56	9.04	6.73
Gelemso	98.84	64.63	34.61	37.87	61.69	69.17	30.01	88.40	10.56	92.01	6.91
Hamaresa	42.99	20.19	53.04	13.88	67.71	29.19	32.11	38.45	10.56	27.06	37.06
Hirna	11.43	5.04	55.90	3.39	70.36	8.00	30.01	10.22	10.56	10.73	6.16
Karamara	62.39	36.12	42.10	33.65	46.07	44.39	28.85	55.80	10.56	38.62	38.09
Lange	29.96	15.99	46.65	10.54	64.83	21.64	27.79	26.80	10.56	26.56	11.35

†The cover factor for SLEMSA is computed using two different equations when i is less than 50 (eqn. 3.7) and when i is greater than or equals to 50 (Eqn.3.8). When the percent rainfall interception, i increase from below 50 to above 50, it results in a higher C value which yields a slightly higher soil loss contrary to the expectations.

Soil loss responded highly to change in soil erodibility factor F at all study sites. A 20% increase in the value of soil erodibility factor F halved the estimated soil loss at Adele, Chiro, Diredawa, Hamaressa and Hirna. The minimum response to change in soil erodibility factor was 34.61% which was recorded at Gelemso.

The change in soil loss due to 20% decrease in rainfall kinetic energy index (E) is directly proportional to the values of the soil erodibility factor (F) of the respective study sites. Those sites with a relatively high F value (i.e. low erodibility hazard) showed a strong response to change in E. On Hirna soils, that has the highest estimated F value, the estimated soil loss decreased by 70.36% with 20% decrease in the E value. Moreover, the estimated soil losses at 14 of the 15 study sites decreased by more than 50% due to the 20% decrease in E. The least response to 20% decrease in rainfall energy (E) was 46.07% decrease in soil loss at Karamara. This can be associated with the smaller F value for Karamara soils (see appendix 1.4).

A 20% decrease in slope gradient also reduced estimated soil loss by 9.76 - 32.11%. However, the model is generally less sensitive to slope gradient as compared to other factors. Areas having higher slope gradients showed greater responses to decrease in the gradient than those with lower slope gradients. Accordingly, for Chiro and Hamaressa that have slope gradients of greater than 25%, the estimated soil loss was reduced by 32% for a 20% reduction in slope gradient.

The percent decrease in soil loss for the 20% decrease in slope length was constantly 10.56% for all sites. It seems that SLEMSA is the least sensitive to decrease in slope length as compared to that for the other input variables except for cases where the sensitivity of the percent rainfall energy interception factor, (i) is very low especially when it is larger in magnitude representing poor cover.

The sensitivity of estimated soil loss to percent crop cover (rainfall interception factor, i) varied for the different study sites. Soils with initially poor cover (i.e higher C value) showed higher sensitivity to a 20% increase in percent cover. Soil loss decreased by more than 35% at Babile, Hamaressa and Karamara due to 20% increase in percent cover.

The sensitivity of the model is very low when the percent cover that was initially less than 50% is increased to above 50%. When i is less than 50%, an exponential equation is used to calculate the C factor but when i is greater or equals to 50%, a less sensitive linear equation is used (Fig.3.2).

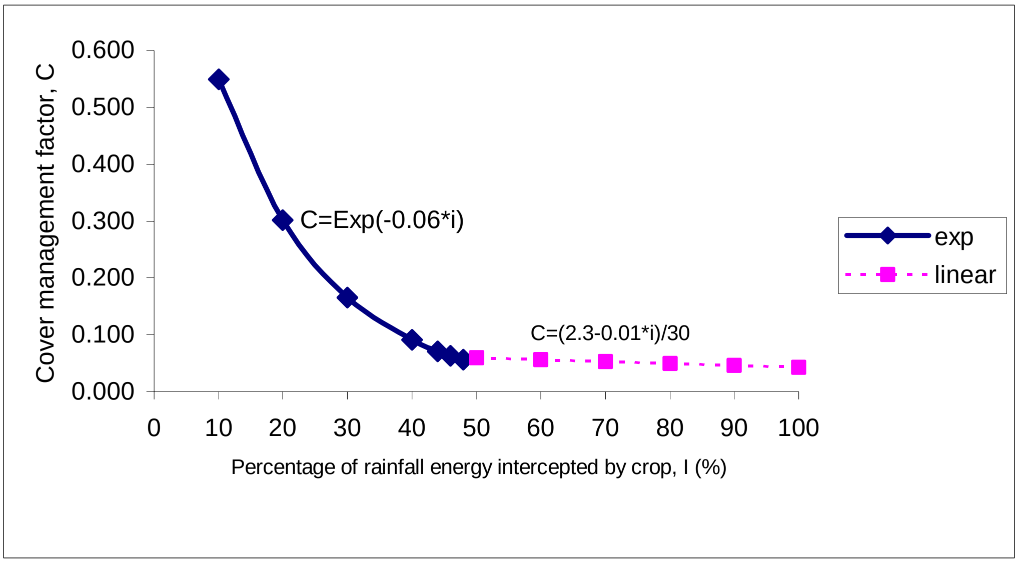


Fig.3.2 The relationship between percent rainfall energy interception (i) and the C factor for SLEMSA (Adapted from Department of Agricultural and Technical Services, 1976).

Consequently, a very small response, which was even negative at some sites, was observed for a 20% increase in i at most of the study sites. This may suggest that more research is required to modify the cover management factor and to get a reasonable output from the model.

In the case of Gelemso, it seems that soil crusting is the major factor once it had formed and increase in canopy cover as such will not improve soil protection. However, under natural conditions with more canopy cover, the soil will be better protected due to organic matter addition on the soil surface.

In general, though the response of soil loss to change in any one factor varied among the sites, the change was most sensitive to decrease in E (which is one of the major reasons for soil crusting) as compared to the other factors. For most of the study sites, the effect of the four factors can be rated as: E > F > S > i in accordance with their relative importance towards affecting the magnitude of the estimated soil loss with an equal change in these factors. Schulze (1979), working in the key area of the Drakensberg (South Africa), also indicated that SLEMSA is highly sensitive to its input variable especially to rainfall erosivity and soil erodibility. Therefore, due to the high sensitivity of the model to erosivity and erodibility factors, the input variables should be measured or estimated as accurately as possible to get more reliable soil loss estimates for the sites before making decision on conservation planning. Moreover, all assumptions considered under each factor for soil loss estimation in these study should be taken into consideration during interpretation and comparison of soil loss values at various sites.

3.3 Soil loss estimation using USLE

3.3.1 Introduction

The Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965, 1978) is the most widely known and used empirical soil loss model all over the world. Later in the 1980's, the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) modified the model to the Revised Universal Soil Loss Equation (RUSLE), which was an improved version of USLE for northeastern areas of the USA incorporating new approaches, new data from different locations, and corrections of the USLE limitations (Yoder and Lown, 1995; Smith, 1999). RUSLE is computer based, replaces the tables, figures, and tedious USLE calculations with simplified keyboard entry (Yoder and Lown, 1995) while maintaining the basic structure of USLE. Unfortunately, due to inadequate availability of input data for the study sites to comply with the input requirements of RUSLE, only USLE was used to estimate soil loss for the sites. The USLE computes sheet and rill erosion using values representing the four major factors affecting erosion, namely climate erosivity R, soil erodibility K, topography LS and land use and management CP (Kenneth et al., 1991). Like the SLEMSA, the USLE doesn't estimate deposition, sediment yield at a down stream location and ephemeral gully erosion and does not represent fundamental erosion processes and interactions (Kenneth et al., 1991). It is however, found to adequately represent the first order effects of the factors that affect sheet and rill erosion. The USLE involves:

$$A = R \times K \times LS \times C \times P \qquad (3.10)$$

Where A is the computed long term average annual soil loss per unit area, R is the rainfall factor, K is the soil erodibility factor, LS is the topographic factor, C is a cover management factor, and P is the support practice factor. The USLE has been used widely all over the world either in the same or modified forms (Tiwari et al., 2000). Hurni (1985) also used this model to assess soil erosion in Ethiopia. He even modified some factors of the USLE for the Ethiopian conditions. Three of the most significant modifications include R (rainfall erosivity index), C (land cover) and P (management factors) factors. This was a valuable input to the erosion and soil conservation research in Ethiopia since the 1980’s. However, the available information in this regard is still a gross oversimplification of the realities in different localities. There is a need to conduct a detailed and extensive assessment of erosion hazard taking the various site-specific erosion factors into consideration.

The objective of this experiment was to assess the erosion hazard in selected areas of Harerghe using the USLE as was originally described by Wischmeier and Smith (1978) as well as taking some of the recommendations of Hurni (1985) for Ethiopian conditions into considerations. The results of this study was compared with that estimated using SLEMSA to have a general comparative overview of the erosion hazard indices in the study areas. Sensitivity analysis of the input variables were also conducted to see how a change in a given factor affects the magnitude of estimated soil loss. The soil loss values estimated by these models will help the extension agents and policy makers to recognize the relative severity of erosion in a given locality and will help to prioritise and suggest appropriate soil management strategies in accordance with the level of hazard.

3.3.2 Materials and methods

3.3.2.1 Procedures used to estimate the factors in USLE

3.3.2.1.1 The rainfall erosivity factor, R

The mean annual rainfall used for the different sites in this model is the same as that used for SLEMSA (Section 3.2.2.1). According to Wischmeier and Smith, (1978), erosivity is calculated from the kinetic energy of rainfall (which in turn is estimated from the mean annual rainfall and 30minute rainfall intensity value (Morgan, 1995).

$$R = EI_{30}/1000 \qquad (3.11)$$

Where,

R= rainfall erosivity factor in metric units

E = Rainfall kinetic energy, Jm^{-2}

I_{30} = 30 minute rainfall intensity, $mmhr^{-1}$ (Morgan, 1995).

However, rainfall kinetic energy and intensity data are not available in most cases. Therefore, the erosivity factor R that was adapted by Hurni (1985) for Ethiopian conditions based on the easily available mean annual rainfall P was used in this study. It is given by a regression equation:

$$R = -8.12 + 0.562*P \qquad (3.12)$$

Where, P is the mean annual rainfall, mm

The mean annual rainfall (P) and the calculated erosivity factors (R) for the study sites are presented in Appendix 2.1.

3.3.2.1.2 Soil erodibility factor, K for the USLE model

Soil texture, organic matter content, soil structure and permeability were the main soil properties used to estimate the soil erodibility factor K. These soil properties were used to compile a nomograph from which the K value could be read (Wischmeier et al., 1971). For the cases where the silt fraction doesn’t exceed 70%, equation 3.13 (after Wischmeier and Smith, 1978) could also be used to estimate the K values for USLE. For the soils of this study, since the K values obtained from the two methods were almost similar (see appendix 2.4), equation 3.13 was used.

$$K = 0.01317\left[0.00021(12 - OM\%)M^{1.14} + 3.25(Ss - 2) + 2.5(Ps - 3)\right] \qquad (3.13)$$

Where,

OM% = per cent organic matter

Ss = Structure code (Appendix 2.3),

Ps = Permeability Code (Appendix 2.2),

M = product of the primary particle size fractions, i.e. [SS%*(SS%+Sa%)],

SS% = percent silt plus very fine sand (0.002-0.1mm size fraction) and

Sa = Per cent sand (0.1-2mm size fraction).

3.3.2.1.3 Topographic factor (LS)

This factor is estimated from the slope length and slope gradient of a given area. To obtain a realistic value for slope length is difficult because it involves considerable judgement. It could therefore be expected that this value will vary for different users. In this study, a roughly representative slope length for the study sites under consideration was recorded during the field survey and this value was used to calculate the topographic factor (LS) in conjunction with the slope gradients as indicated in equation 3.14. The estimated slope lengths and gradients as well as the calculated values of the LS factors are presented in Appendix 2.8.

$$LS = (l/22.13)^n\,(0.065 + 0.045S + 0.0065S^2) \qquad (3.14)$$

Where

l =slope length m

n= an exponent related to slope gradients ($n=0.5$ if $S \geq 5\%$; $n=0.4$ if $3\% \leq S < 5\%$; $n=0.3$ if $1\% \leq S < 3\%$, $n=0.2$ if $S < 1\%$) (Torri, 1996)

S= Slope gradient %

3.3.2.1.4 Cover and management factor (C)

The same assumptions pertaining to the percent cover of crops during the various seasons of a year that have been used for SLEMSA (section 3.2.2.2) were applied here. The cover and management factor C is dependent upon the percentage of the rainfall energy intercepted by the crop (Morgan, 1995). Therefore, a weighted C factor is calculated per season by considering the major crops growing in a particular area and the temporal rainfall distribution during the four seasons of the year (Appendix 2.6) and the sum of these values for the four seasons is considered as the mean annual C value for a particular site. The individual C-values of each period were weighed according to the percentage of the mean annual rainfall in that period and summed to obtain the annual C-value. The basic C values for various crops and the calculation procedures of these values for the study sites is presented in Appendices 2.5.1 - 2.5.3.

3.3.2.1.5 Support practice factor, P

P is defined as the ratio of soil loss with specific support practice to the corresponding loss with up and down slope tillage. The support practice affects erosion primarily by modifying the flow pattern, grade and direction of surface runoff and by reducing runoff amount and rate (Lorenz and Schulze, 1995). Cultivated land that is tilled directly up and down slope will have a P-factor of unity. Tillage and planting on the contour reduce erosion depending on the slope of the land. Estimated P values for various support practices is given in Appendix 2.7 (after Wischmeier and Smith (1978); Roose, (1977); Chan, 1981 quoted by Morgan, 1995)). Based on these, the P values of the study sites have been estimated and are presented in Table 3.3 and Appendix 2.8.

3.3.3 Results and discussion

3.3.3.1 Estimated soil loss at the study sites using USLE

The estimated values of the various soil loss factors and the amount of soil loss in tons per hectare per year are presented in Table 3.3.

The estimated soil loss among the study sites varied from 1.74t ha^{-1}yr^{-1} at AU Alluvial to nearly 135 t ha^{-1}yr^{-1} at Gelemso. High soil loss was also estimated for Karamara, Adele, Hamaressa, and Babile all of which are above 50 t ha^{-1}yr^{-1}. Some sites including AU alluvial, AU vertisol, and Diredawa have estimated soil losses of less than 10 t ha^{-1}yr^{-1}. These sites are characterised by low slope gradients resulting in low value of LS (topographic factors) factors and consequently low soil loss. In general, however, 80% of the studied sites have estimated soil losses of more than 10 t ha^{-1}yr^{-1} which is beyond the tolerable limits given by Smith et al. (1997) for most soils.

The results indicate that all soil erosion factors are important in determining the amount of soil loss. Gelemso, where the highest estimated soil loss was recorded, is characterised by the highest rainfall erosivity factor as well as high values of other factors.

Table 3.3 Estimated values of erosion factors and soil loss estimated by using USLE for some soils of Harerge, eastern Ethiopia.

Research site	P	C	K	**LS**	†R	Soil loss t $ha^{-1}yr^{-1}$
Adele	0.50	0.58	0.20	3.50	459.00	92.69
Amadle	0.50	0.44	0.22	0.86	309.00	12.85
AU Alluvial	0.60	0.38	0.06	0.30	459.00	1.74
AU Regosol	0.60	0.40	0.18	2.48	459.00	47.26
AU Vertisol	0.60	0.46	0.20	0.23	459.00	5.79
Babile	0.60	0.47	0.16	3.28	378.00	57.47
Bedessa	0.30	0.41	0.12	1.38	589.00	12.35
Chiro	0.14	0.51	0.22	4.99	460.00	36.36
Dire Dawa	0.50	0.17	0.29	0.46	358.00	4.12
Dugda Hidi	0.50	0.31	0.27	0.99	309.00	12.98
Gelemso	0.60	0.53	0.20	3.31	637.00	135.04
Hamaresa	0.40	0.51	0.18	4.99	459.00	83.79
Hirna	0.14	0.43	0.22	2.96	460.00	17.94
Karamara	0.70	0.57	0.23	3.28	309.00	93.22
Lange	0.30	0.51	0.22	2.71	501.00	46.67

†R is calculated based on the adaptation of Hurni (1985) for Ethiopia (See appendix 2.9)

At Karamara, though the rainfall erosivity factor is relatively smaller than other sites, higher soil loss was estimated due to higher values of the P, C, K and LS factors. Similarly, the higher soil loss estimated for Adele and Hamaressa can be attributed among others to higher C and LS factors respectively. The estimated soil losses for the study sites are within the range of soil loss estimated for the Ethiopian highlands by the Soil Conservation Research Project (SCRP) which ranges from 0 to 300 t ha^{-1} yr^{-1} (Hurni, 1985; Nyssen et al., 2003).

3.3.3.2 Sensitivity analysis of USLE to its input variables

Changes in estimated soil losses at the study sites in response to 20% change in the input variables of USLE were estimated by altering one variable at a time. The variables were changed in such a way that the change in soil loss is less than the base value. This can be used as an indicator of the amount of soil loss reduction by an improvement in a certain management practice. Accordingly, the observed percentage surface cover was increased by 20% whereas other factors including slope gradient, slope length, mean annual rainfall and soil conservation practice factor were all reduced by 20% to evaluate the change in estimated soil loss. The soil erodibility factor (K) was not considered in this sensitivity analysis mainly because of the complication resulting from several factors affecting it.

The estimated soil losses after 20% change in the input variables and the percentage changes from the initial values are presented in Table 3.4.

The results indicate that the USLE is least sensitive to changes in slope length at all study sites as compared to other factors evaluated. Moreover, the effect of slope length was modified by slope gradient. A 20% decrease in slope length resulted in a maximum of 10.56% decrease in soil loss for all sites having slope gradients greater than 5%. The highest reduction in soil loss in response to 20% change in the input variables was due to slope gradient and percent cover. For the majority of the sites, reducing the slope gradient by 20% reduced soil loss by more than 25%. The sensitivity to slope gradient is more pronounced at higher slope gradients.

Table 3.4 Changes in soil loss with changes in input variables of USLE for soils of Harerge, eastern Ethiopia.

Study sites	†SL Base value	SL due to 20% increase in % cover		SL due to 20% decrease in P factor		SL due to 20% decrease in annual rainfall		SL due to 20% decrease in slope length		SL due to 20% decrease in slope gradient	
	$t\ ha^{-1}yr^{-1}$	Amount $t\ ha^{-1}yr^{-1}$	% Decrease	Amount $t\ ha^{-1}yr^{-1}$	% decrease	Amount $t\ ha^{-1}yr^{-1}$	% decrease	Amount $t\ ha^{-1}yr^{-1}$	% decrease	Amount $t\ ha^{-1}yr^{-1}$	% decrease
Adele	92.69	79.32	14.42	74.15	20.00	73.71	20.48	82.91	10.56	66.91	27.81
Amadle	12.85	9.62	25.15	10.28	20.00	10.23	20.39	11.50	10.56	8.72	32.17
AU Alluvial	1.47	0.99	32.63	1.17	20.00	1.17	20.48	1.41	4.00	0.69	53.20
AU Regosol	47.26	32.78	30.63	37.81	20.00	37.58	20.48	42.27	10.56	34.12	27.81
AU Vertisol	5.79	4.44	23.29	4.63	20.00	4.60	20.48	5.41	6.48	4.19	27.57
Babile	57.47	44.71	22.19	45.97	20.00	45.76	20.37	51.40	10.56	40.87	28.87
Bedessa	12.35	8.85	28.31	9.88	20.00	9.83	20.37	11.05	10.56	9.09	26.37
Chiro	36.36	29.49	18.91	29.09	20.00	28.93	20.43	32.52	10.56	24.68	32.13
Dire Dawa	3.57	0.16	95.61	2.86	20.00	2.84	20.39	3.30	7.5	3.00	16.00
Dugda Hidi	12.98	7.31	43.69	10.38	20.00	10.33	20.39	11.87	8.54	10.25	21.04
Gelemso	135.04	110.89	17.88	108.03	20.00	107.69	20.25	120.78	10.56	94.48	30.03
Hamaresa	83.79	67.69	19.22	67.03	20.00	66.63	20.48	74.94	10.56	56.87	32.13
Hirna	17.94	13.26	26.08	14.35	20.00	14.27	20.43	16.04	10.56	12.55	30.03
Karamara	93.22	79.27	14.97	74.58	20.00	74.22	20.39	83.38	10.56	66.31	28.87
Lange	46.67	37.84	18.91	37.33	20.00	37.17	20.36	41.74	10.56	33.69	27.81

†SL = Soil loss

For the study sites having slope gradients of less than 5%, the change in soil loss was higher in response to change in other input variables than to slope gradient. For instance, the change in estimated soil loss at AU Alluvial, AU Vertisol and Diredawa, all of which have slope gradients of less than 5%, showed more response to the soil conservation practise factor, annual rainfall and percent surface cover as compared to that of slope gradient.

The percentage reduction in soil loss in response to decrease in the soil conservation practice factor and mean annual rainfall was constant at all research sites due to the linear relationship between soil loss and these factors. A 20% decrease in these factors resulted in 20% decrease in soil loss for all study sites.

The effect of the changes in surface cover factor varied for different sites. A 20 percent increase in percentage surface cover reduced soil loss by a factor ranging from 14.42 % at Adele to 95.6 % at Diredawa. It was higher for areas with relatively higher initial percent cover (i.e. smaller C values). For Diredawa, Dugda Hidi, AU Alluvial, AU Regosol and Bedessa, increasing the percent cover by 20 % brought about the largest reduction in soil loss than other input variables.

In general, USLE is more sensitive to changes in slope gradients and surface cover and less so to that of slope length. The implication is that, a small deviation in estimating or measuring slope gradient and cover may lead to large errors in estimating the actual soil loss for a given area. Areas that have relatively small percent cover (C values greater than 0.50) such as Adele, Chiro, Gelemso, Hamaressa, Karamara and Lange showed less sensitivity to the 20% increase in percent cover. For these sites, soil loss was more sensitive to slope gradient, conservation practice factor and mean annual rainfall than the C factor.

The amount of error encountered in estimating soil loss due to inaccurate measurement or estimation of the input variables like conservation practice factor P and rainfall erosivity factor R is proportional to the degree of inaccuracy. That is, a 20% change in these variables results in a 20 % change in soil loss. Although the effect of slope length on soil loss is well recognized, the estimated soil loss is least affected by a change in slope length than other erosion factors.

3.4 Comparison of soil loss estimated by SLEMSA and USLE

A summary of soil loss values estimated by SLEMSA and USLE is presented in Fig. 3.3. Significant correlation (r = 0.87) was obtained between the soil loss values estimated by the SLEMSA and USLE. However, for some of the study sites, large variation was obtained between the pairs of soil loss values estimated by the two methods. Fig.3.3 indicates that soil loss estimated by SLEMSA is greater than that estimated by USLE for AU alluvial, Babile and Bedessa. For the rest of the study sites, however, the estimated values were higher using USLE than SLEMSA. The soil loss estimated by USLE as compared to SLEMSA is more than three fold for Adele and Diredawa and about twice for Amadle, AU Regosol and Hamaressa. The large differences between some of the values of soil losses estimated by the two methods can be attributed to the differences in the sensitivity of the two models to their input factors. At Adele, for instance, the F value (soil erodibility index) for SLEMSA is high indicating low erodibility (Table 3.1) and the C and LS factors of USLE for the same site are relatively high (Table 3.3). Hence, as the SLEMSA is highly sensitive to the soil erodibility factor and the USLE to the cover and topographic factors, the higher C and LS factors of USLE and the low erodibility indicator (high F value) for SLEMSA resulted in higher soil loss value for USLE than the SLEMSA model. Similarly, when the value of the factor(s) to which one of the models is highly sensitive is too high, the resulting estimated soil loss for that model will be higher and vice versa as compared to the soil loss estimated by the other model. However, as the reasons for the differences in the soil losses estimated by the two methods mainly result from combinations the effects of all factors involved in both models, no single factor is usually considered accountable for the variations.

Although the differences between the estimated soil losses using the SLEMSA and USLE is large for some sites, the majority of the study sites have nearly comparable soil loss values which are highly correlated.

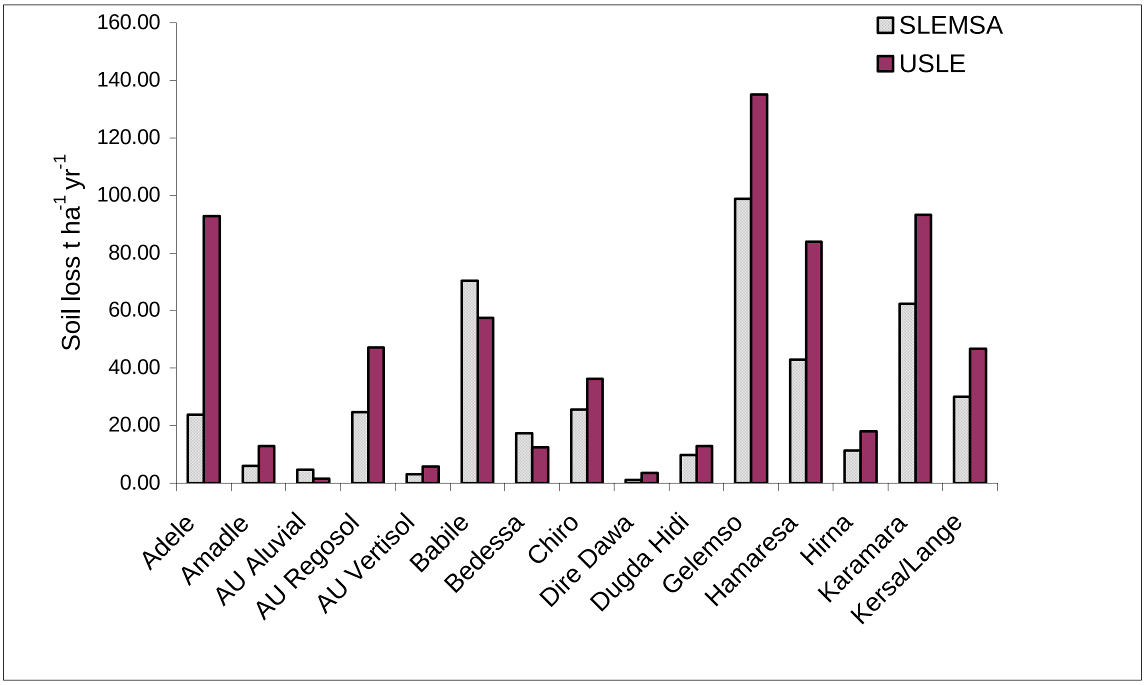


Fig. 3.3 Soil loss (t ha^{-1} yr^{-1}) estimated by SLEMSA and USLE at selected sites in Hareerghe, eastern Ethiopia.

Therefore, depending on the relative ease of determination of the input variables and the level of accuracy required, either of the two methods can be used to assess the degree of severity of soil erosion under the prevailing conditions of Hareerghe, east Ethiopia.

3.5 Qualitative comparison of soil erodibility indices determined in the laboratory trials and soil loss estimated using the SLEMSA and USLE models

In an attempt to validate the soil loss estimated by the USLE and SLEMSA models at different sites their values were compared to that obtained in the laboratory rainfall simulation trials. Although it could not be acceptable to compare exact figures it can be expected that tendencies should be comparable.

The 15 soils considered in this study were compared based on the amount of sediment transported by runoff from the small erosion trays in the laboratory. These values were used to rank the erodibility hazard as low, medium or high. This comparison was based only on the values of the sediment yield of the soils considered in the study and is not related to any other standard references. To simplify the comparison, the values were expressed as a percentage of the maximum value recorded for the soils in the study. Hence, those sites having percentage values of greater than 60% were considered as highly erodibile and are marked as H; 50 –60% Medium (M) and less than 50% were considered low (L).

Similarly, the erosion hazard of the research sites, where soil samples were collected for the lab trials, were also ranked based on the soil loss values estimated using the SLEMSA and USLE models. Here again, the estimated soil loss values for the different study sites were expressed as percentages of the maximum values obtained for each model. The erosion hazard was then ranked as high (when the percentage values were >20%), medium (10-20%) and low (<10%) for both cases.

The reason why different ranges of figures are used for the laboratory and model values is due to the fact that the laboratory values are relatively less dispersed indicating a minimum figure (when expressed as percentage of the maximum value) of 42% which is greater than most of the figures estimated by the soil loss models.

It should however be noted that the soil loss determined in the laboratory small trays doesn't normally represent the actual field conditions. Comparing such soil loss values with the estimated values without careful considerations to the limitations may therefore lead to wrong conclusions. In the rainfall simulation studies, the effects of many erosion factors are simplified just to obtain a relative estimate of the soil's susceptibility to erosion. Therefore, the values obtained in the laboratory should only be considered as relative indices to compare treatment effects. Examples of the limitations in the laboratory rainfall simulation experiments in this study include:

1. Difficulty to simulate the actual field topography: The erosion tray was very small and the various irregularities in the field landscape were not considered. Despite the differences in the actual topography of the study sites from where the soils were collected, all soils were subjected to 5° slope gradient for the laboratory rainfall simulation study.

2. Difficulty to simulate natural rainfall characteristics: The various study sites (from where the soils were collected) have different rainfall characteristics. However, it was difficult to simulate such variations in the laboratory. Therefore, all soils were tested at 60mm hr^{-1} of rainfall intensity that was applied for one hour.
3. No cover and management practice was taken into consideration for the laboratory studies. The simulated rainfall was applied on a bare soil surface.

On the other hand, soil loss estimation using erosion models takes almost all of these factors into consideration. Therefore, quantitative comparison of soil loss values obtained in the laboratory with those estimated using erosion models is impractical. However, to evaluate the effect of the inherent soil erodibility on the actual soil loss and assuming that all the other field specific factors are similar for the various study sites, some qualitative comparison has been made among the soils of the various study sites and are presented in Table 3.5.

Table 3.5 Comparison of soil loss values from laboratory trials and that estimated using the USLE and SLEMSA models as well as visual field observations.

Study sites	Relative erosion hazard						
	Estimated				Measured		Field observation
	SLEMSA		USLE		Lab Erodibility		Visual rating
	Value	Rating	Value	Rating	Value	Rating	
Adele	24	H	69	H	51	M	H
Amadle	6	L	10	L	52	M	L
AU Aluvial	5	L	1	L	72	H	L
AU Regosol	25	H	35	H	49	L	H
AU Vertisol	3	L	4	L	42	L	L
Babile	71	H	43	H	87	H	H
Bedessa	18	M	9	L	57	M	L
Chiro	26	H	27	H	65	H	H
Dire Dawa	1	L	3	L	60	M	L
Dugda Hidi	10	L	10	L	77	H	L
Gelemso	100	H	100	H	100	H	H
Hamaresa	44	H	62	H	45	L	H
Hirna	12	M	13	M	54	M	M
Karamara	63	H	69	H	62	H	H
Lange	30	H	35	H	49	L	H

H= High; L= Low; M= Medium

NB: The values in the table are expressed as percentages of the maximum value in each column.

As indicated in Table 3.5, qualitative assessment of the soil loss values obtained by using the SLEMSA and USLE models reveal that the values obtained by using both models agree well with the actual field observations for almost all of study sites though the actual quantitative values may differ. On the other hand, only 60% of the laboratory soil erosdibility values are in direct agreement with the estimated and observed soil erosion values. The reasons for the discrepancy may be different for the different sites. The laboratory soil erodibility for AU regosol, Hamaresa and Lange soils were low as opposed to the high erosion hazard at the sites as estimated using both models and based on field observations. In the cases where the laboratory trials indicate low erodibility (stable soils) in contrast to the higher field values, it can be concluded that the management of the field is poor. Other probabilities are inadequate simulation of the actual field topography of the sites in the laboratory that are normally more accountable for high erosion in the field. In the field, these soils occur on slopes of greater than 15% with undulating landform but all were set to slope gradients of 5° in the lab.

Some discrepancies between the estimated and measured soil loss values were also observed on some soils where the laboratory soil erodibility ranged from Medium to High (Amadle, AU Alluvial, Diredawa and Dugda Hidi) as opposed to the low estimated soil loss values. This could mean good field management or topography is again the main factor for these discrepancies. Almost all of these soils occur on a very low slope gradients (<5% slope gradient) with relatively flat landforms. Besides, most of these sites have low rainfall erosivity. Therefore, although these soils are potentially erodible as evidenced from the laboratory results, the level field topography and low natural rainfall erosivity of these sites are mainly responsible for the low soil erosion hazards.

In general, laboratory rainfall simulation studies are limited by various assumptions. Hence, these values cannot be reliably used for validation of various models. Meaningful validation of the erosion models for the study sites should be based on field based measurements of soil loss from runoff plots under natural rainfall conditions. It is however, worth mentioning that laboratory soil erodibility values provide some indications of the soils' inherent susceptibility to erosion and are valuable particularly when comparison of various treatment effects on soil erosion at a limited cost and controlled conditions are envisaged.

3.6 Estimation of tolerable soil loss and soil life for the study sites

Tolerable soil loss is defined as the maximum acceptable rate of soil erosion (Morgan, 1995). The only tolerable rate of soil loss equals the rate of soil formation. However, although the rates of soil loss can be measured, the rates of soil formation are so slow that they cannot be easily determined. The rate of soil formation throughout the world is estimated to range from 0.01 to 7.7mm y^{-1} (Buol et al., 1973) and the average is about 0.1mm y^{-1} (Zachar, 1982). In Africa, Dunne et al. (1978) estimated rates of soil formation in Kenya to range from 0.01 to 0.02 mm y^{-1} in the humid areas but fall bellow 0.01mm y^{-1} in the semi-arid areas. In Ethiopia, Hurni (1983 as quoted by Nyssen, 2003), categorized average soil formation rates based on the agro-climatic zones which are delimited based on altitude (m) and annual rainfall (mm). Accordingly, the soil formation rates ranged from 1 t ha^{-1} yr^{-1} for Berha “desert” (altitude <500m) to16 t ha^{-1} $year^{-1}$ for ‘Wet Woina Dega’ (altitude: 1500-2300m; annual rainfall >1400 mm) agro-climatic zones. (Appendix 5.0). The research sites in this study fall within three agroclimatic zones namely Dry Kolla, Dry Weyna Dega and Moist Weyna Dega and have soil formation rates of 3, 6 and 12 t ha^{-1} yr^{-1}.

Due to a wide variability of conditions affecting the rate of soil formation in a given locality, current values for soil loss tolerance are highly uncertain. Morgan (1995) also indicated that a better guideline to estimate tolerable soil loss is assessment of the rate of natural soil loss in the area. Assuming that the environment is stable under natural conditions, the rate of permissible soil loss will be close to the rate of new soil formation by weathering leading to tolerance values of 1 to 2 t ha^{-1} yr^{-1}. Soils with shallow root zone or other restricting characteristics are generally assigned lower tolerances (Kirkby and Morgan, 1980 quoted by Smith et al., 1997) which can be as low as 4.4 t $ha^{-1}yr^{-1}$ (El-Swaify et al., 1983 cited by Smith et al., 1997). Deep, medium textured, moderately permeable soils with subsoil characteristics favourable for plant growth are assigned tolerances of up to 11 t $ha^{-1}yr^{-1}$ (Smith et al., 1997). Soil loss tolerances of 3 to 10 t ha^{-1} yr^{-1} can therefore be considered for practical purposes.

In this experiment, the soil loss tolerance values were estimated by using the methods suggested by the Department of Agricultural Technical Services (1976) for SLEMSA model. Accordingly, the tolerable soil losses for the study sites that were estimated based on the bulk density (Table 2.3) of the soils ranged from 2 to 5 t $ha^{-1}yr^{-1}$ (Table 4.5). Based on this estimation, the soil loss estimated for all sites by SLEMSA and USLE are beyond the tolerable limit except for AU alluvial and Diredawa (compare Tables 3.1, 3.3 and 3.6). This indicates that the majority of the soils in Harerge under the current management situation are prone to severe degradation by water erosion if appropriate land management practices are not implemented to control the situation.

Estimates of the life expectancy of a soil under a given farming system, provide a basis for formulating land use practices, and where a limited soil life is envisaged, it will indicate the time available to devise means to reduce soil losses (Department of Agricultural Technical Services, 1976). It can also be used as a powerful argument in convincing farmers to adopt improved conservation practices.

To have a rough overview of the long-term erosion hazard in the study areas, the expected soil life for the top 0.15m of the productive soil surface has been estimated by using equation 3.15 and presented in Table 3.6.

$$Lf = \frac{D * M}{SL - Sf} \qquad (3.15)$$

Where, Lf = soil life (years),

D = soil depth in meters,

M = mass of soil in tones per hectare – meter ,

SL = Estimated rate of soil loss in t $ha^{-1}yr^{-1}$ and

Sf = Estimated rate of soil formation in t $ha^{-1}yr^{-1}$ (This value is considered to be insignificant and has not been considered in the calculation).

Table 3.6 indicates that, at the prevailing rate of soil erosion at most of the study sites in Harerge, the fertile top 15 cm of the soil surface will be lost and its productivity be severely affected within a period of 17 years at Gelemso and less than 40 years at Adele, Babile, Karamara and Hamaressa. In general, more than 50% of the study areas are likely to lose the top 15cm of the productive soil within a period of less than 100 years.

Table 3.6 Estimated tolerable soil loss and soil life for some sites in Harerge, eastern Ethiopia**.**

Study sites	†Estimated Soil loss t $ha^{-1}yr^{-1}$	Mass of soil t ha^{-1}-m	‡Tolerable Soil loss t $ha^{-1}yr^{-1}$	Soil mass t ha^{-1}-15 cm	No. of years to lose the top 15cm soil
Adele	58.25	12600	3	1890	32
Amadle	9.39	11000	2	1650	176
AU Aluvial	3.24	14200	4	2130	657
AU Regosol	35.99	13100	3	1965	55
AU Vertisol	4.44	9900	2	1485	335
Babile	63.85	15700	5	2355	37
Bedessa	14.85	10900	2	1635	110
Chiro	30.95	11000	2	1650	53
Dire Dawa	2.60	14800	4	2220	855
Dugda Hidi	11.34	11200	2	1680	148
Gelemso	116.94	13600	3	2040	17
Hamaresa	63.39	12200	3	1830	29
Hirna	14.68	10900	2	1635	111
Karamara	77.80	13000	3	1950	25
Lange	38.31	13000	3	1950	51

†Estimated soil loss is the average of soil loss values estimated by SLEMSA and USLE models.

‡Tolerable soil loss is estimated based on the recommendation of Department of Agricultural Technical Services (1976) for light, medium and heavy textured soils.

It should be noted however that, none of these models were meant for estimation of soil loss from steep slopes and rugged topographies like the ones dominating most of the Ethiopian highlands including Hareghe. Therefore, the actual soil loss under most of the Ethiopian conditions, where erosion is largely exacerbated by the high velocity and volume of surface flow, could more likely be greater than the estimated values resulting in much shorter soil life than the ones indicated in Table 3.6. Hence, the soil life indicated here should only be considered as rough relative estimates as the actual time required for erosion of a given depth of soil is a function of many other factors that are not taken care of in either of these models and require a detailed process based analysis (Nearing et al., 1994; Morgan, 1995).

3.7 Conclusion

The amount of estimated soil loss from rill and interill areas obtained by using SLEMSA and USLE for the study sites in Harerge, eastern Ethiopia varied among the sites. The soil loss values estimated by these methods were however, highly correlated. In both cases, the estimated soil loss was higher for Gelemso, Babile, Hamaressa and Karamara but lower for AU alluvial, AU Vertisol and Diredawa. These variations in soil loss among the study sites were functions of the interactions of the various factors affecting erosion.

Sensitivity analysis of the models to their input variables revealed that SLEMSA was highly sensitive to changes in rainfall kinetic energy (E) and soil erodibilty (F) and was less sensitive to slope length and vegetal cover. On the other hand, for the majority of the study sites, USLE was highly sensitive to slope gradient and cover but less sensitive to slope length. Considering the magnitude of percent reduction in soil loss with 20% change in the input factors, the rainfall kinetic energy factor (E) and Soil erodibility index (F) of SLEMSA brought about the largest reductions. In this respect, SLEMSA can be considered highly sensitive to changes in most of its input variables than USLE. But most of these changes are little affected by management practices.

Among the factors involved in estimating soil loss in both models the rainfall erosivity factor is not usually directly affected by different management practices. However, soil erodibility, topographic, cover and conservation practice factors can be modified through various soil and land management practices. Therefore, the fact that the USLE is more sensitive to changes in slope gradient and cover (which can be modified through improved management practices) than the SLEMSA may suggest the suitability of using the USLE especially where comparison of the effects of cover management and conservation practices on soil loss deems important.

To obtain a reasonably accurate soil loss index for a given site using either of these models, the most sensitive inputs variables should be estimated or measured as accurately as possible because slight error in measuring these input variables results in a tremendous deviation of the estimated soil loss from the actual one.

CHAPTER 4

EFFECT OF SOIL TEXTURE, SLOPE GRADIENT AND RAINFALL INTENSITY ON RUNOFF AND EROSION

4.1 Introduction

Soil erosion by water occurs due to complex interactions of sub processes between detachment and transport of soil materials. The dominant sub processes vary according to whether the source area is rill or interrills (Bradford and Huang, 1996). In both cases however, although the mechanism may differ, the main reasons for soil erosion include soil characteristics, rainfall characteristics, topography, soil surface and cover situation as well as the land use and management history. Among the topographic features, slope affects soil erosion through its morphological characteristics and aspect (Torri, 1996). One of these morphological characteristics, namely slope gradient was introduced in quantitative relationships estimating soil loss (Zingg, 1940; Wischeimer and Smith, 1978). The effect of slope on erosion has been studied extensively, with conclusions that overall erosion rates increase with increasing slope steepness (Zingg, 1940; Van Liew and Saxton, 1983; Grosh and Jarrett, 1994). Poesen (1987) also indicated that runoff and erosion usually increase with increase in slope gradient but in unstable soils that tend to seal, the effect of slope on infiltration rate and runoff can be complementary. With increase in slope angle there may be a tendency of seal erosion and subsequent increase in infiltration rate and decrease in runoff despite the fact that velocity of runoff increases with increase in slope gradient. According to Poesen (1984), as slope steepness increases, the number of drop impacts per unit surface area and the drop impacts energy both decrease thereby decreasing splash detachment. On the other hand, as slope steep-ness increases, degree of surface sealing decreases and rate of soil resistance or strength decreases thereby increasing splash detachment (Poesen, 1984). Bradford and Huang (1996), also indicated that the effect of slope length and slope steepness on particle detachment by overland flow is negligible for interrill areas although on very steep and long slopes interrill erosion may occur for very short distances (centimetres). The discussion in this chapter primarily focuses on interrill erosion processes and some of the factors that affect it.

Several authors indicated the importance of soil texture in determining aggregate stability, infiltration rate, runoff and erosion (Trott and Singer, 1983; Obi et al., 1989; Gollany, etal 1991; Le Bissonnais and Singer, 1993). According to Bradford and Huang (1992), soil texture seems to be one of the most important soil variables influencing soil surface sealing and splash detachment. Although crusts can form on soils of any texture, soils with high silt contents are more conducive to surface sealing (Tackett and Pearson, 1965). Le Bissonnais (1996) also indicated that soil erodibility increases when silt and fine sand fraction increases and clay decreases. Bradford and Huang (1992) obtained a negative correlation between silt and infiltration rate under simulated rainfall. The same result was reported earlier by Bradford et al. (1987) with different kinds of soils. Obi et al., (1989) working with various sandy soils in Nigeria found a negative correlation between sand content and runoff and erosion. Similar significant negative correlation between coarse sand and erosion rate was reported by Trott and Singer (1983).

It is well established that the amount of soil that is detached by a particular rain event is related to the intensity at which this rain falls. Smaller drops that dominate low intensity rainfall are less efficient in detaching soil (Sharma and Gupta, 1989; Salles and Poesen, 2000) but at high intensity rainfall, saturation and ponding (at least at low depths) may increase the efficiency of detachment (Torri et al., 1987). Different relationships between rainfall intensity and kinetic energy have been described. Some researchers reported a direct relationship (van Dijk et al., 2002). Logarismic (Wischmeier and Smith, 1978), and exponential (Kinnel, 1980) equations were also developed to describe the relationship between rainfall intensity and kinetic energy.

Surface sealing is one of the reasons why infiltration rates decrease with time (Mannering, 1967). This decrease is a major cause of increased surface runoff and erosion (Moldenhauer and Long, 1964). Mamedov et al. (2000) also indicated that surface sealing as well as natural low infiltration rate are the main reasons for runoff initiation. Although reports are available on the magnitude and extent of damage of soil erosion, little has been done to quantify the interactive effects of soil texture, slope and rainfall intensity on surface sealing, infiltration, runoff, and soil loss.

The aims of this experiment were therefore to

- study the effect of soil texture on seal formation and subsequent impact on infiltration, runoff and erosion,
- compare the effect of two rainfall intensities on different erosion parameters,
- determine the effect of slope gradient on seal formation, infiltration, soil erodibilty, runoff and erosion and
- and examine the interaction effects of soil texture, rainfall intensity and slope gradient on various erosion parameters.

4.2 Materials and methods

Soil texture was determined by pipette method (Day, 1965) and the textural classes of the major soils of Harerge, eastern Ethiopia, are presented on the textural triangle (Fig.4.1). To study the influence of soil texture on soil erosion parameters, three soil types whose particles sizes are dominated by any of the three soil separates sand, silt or clay were selected from these soils. The clay contents of Bedessa and AU vertisol are both high enough to represent the clay dominated soils for this experiment but AU vertisol was selected due to its relative accessibility in terms of distance from the laboratory. For silt-dominated soils, the Diredawa soil was selected. Accordingly, both Babile and AU Alluvial are comparable in terms of their high sand content but AU alluvial was selected due to its relative accessibility. Once the soils were selected, representative top (0-15cm) soil samples were collected for the rainfall simulation experiment. Some physical and chemical properties of the soils used in this study are presented in Table 2.3 of chapter 2.

An Erosion box (pan) that is 554 mm long, 206 mm wide, and 85 mm deep was perforated at the bottom to allow free drainage and pieces of cotton cloth was placed on it to prevent soil loss through the perforated bottom. Approximately 85mm thick layers of disturbed soil samples that were air dried, crushed to pass through 4 mm sieve were mixed thoroughly and packed in the box based on the bulk densities of the soils under consideration. Soils that tend to swell upon wetting were packed in such a way that some 10mm of the tray depth was left unfilled on top to reduce errors due to overflow of the soil out of the tray by swelling.

A rotating disc rainfall simulator of the type described by Morin et al. (1967) was used in this experiment to apply rainfall at intensity of 30 or 60mm hr^{-1}. Rainfall intensity was controlled by changing the aperture size of the disc, its speed and the pressure at the nozzle. After calibrating and selecting the appropriate combination of these control devices for specific rainfall intensity, the rain was applied to the air-dry soils packed in the erosion tray that were set at slope gradients of either 5, 10 or 15° each with three replications. The characteristics of the simulated rainfall are presented in chapter 2.

Overland flow and the sediment suspended in it were measured at five minutes interval as soon as runoff started. These were collected in plastic beakers that were placed under the runoff outlet of the erosion tray. The sediment yield, which is referred to as the amount of eroded sediment that leaves a specific area of land in a given time, was determined after oven-drying the runoff and weighing the sediments. These values didnnot include splashed sediments. Splash volume was collected from the beginning of the rainfall simulation at five minutes interval. Sediments caught by the splashboards surrounding the erosion plot were washed into splash collectors at every five minutes. The weight of splashed soil was determined after oven drying.

The effects of texture, slope gradients and rainfall intensity on the erosion parameters including total runoff, sediment and splash yields after the one-hour rainfall event and their trends during each rainfall event are discussed.

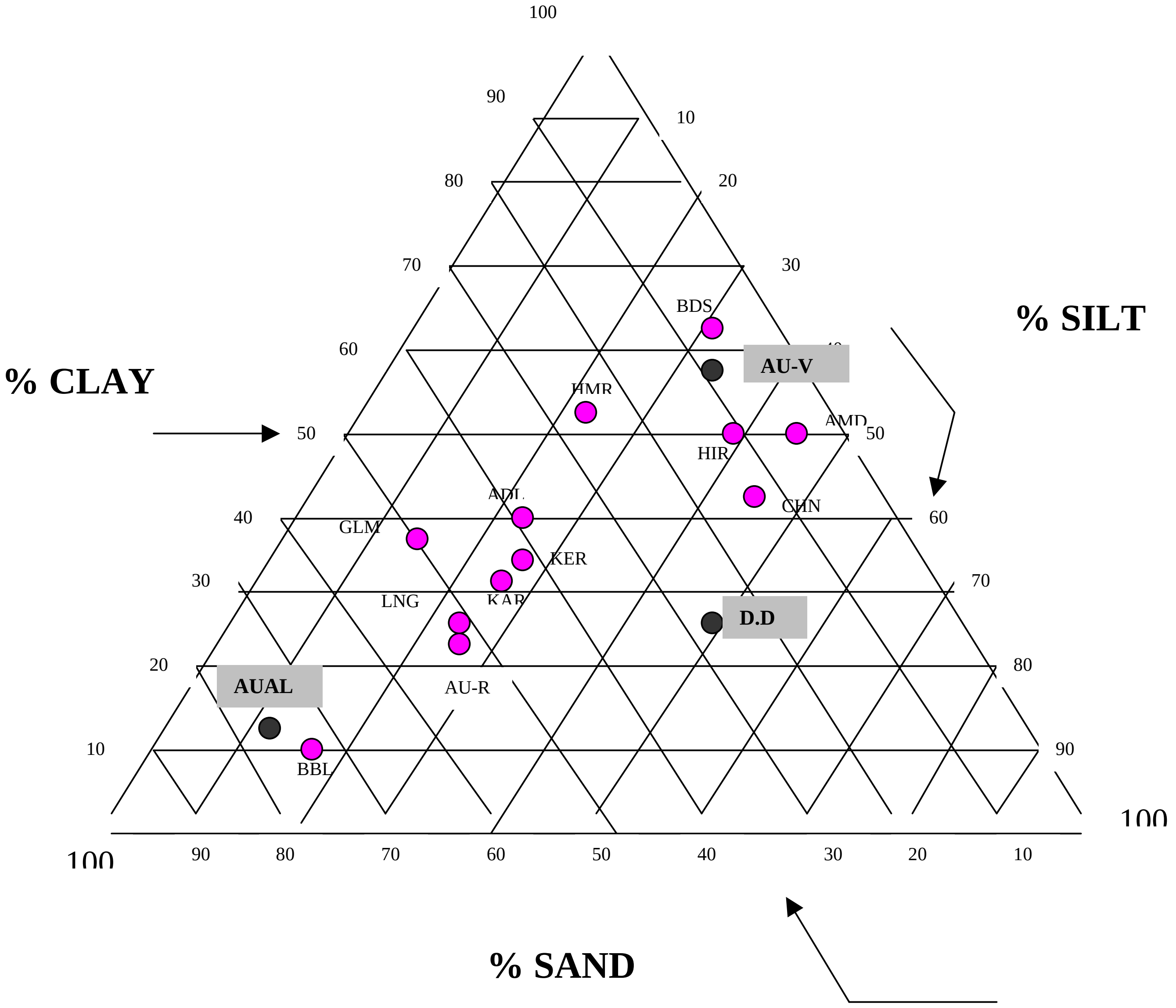


Fig. 4.1 Textures of selected soils from Harerge, eastern Ethiopia.

BD=Bedessa, HMR= Hamaressa, AU-V= Vertisols of Alemaya University campus, AMD=Amadle, HIR= Hirna, CHN= Chinaksen, ADL= Adele, KE=Kersa, GLM=Gelemso, KAR= Karamara, LNG=Lange, AU-R= regosols of Alemaya University, AU-AL=Alluvial sand of Alemaya University, BBL= Babile, DD=Diredawa

The amount of water that infiltrated into the soil was calculated as the difference between water applied to the erosion tray and that lost from the surface of the tray.

Splash volume was taken as water lost from the erosion tray because in this experiment, no replacement of the splashed material was allowed. Hence, overland flow and splash volume were regarded as the only water losses from the surface of the erosion tray. The following procedures and assumptions were applied to calculate the infiltration rate:

- For every simulation run, the first reading of splash volume was subtracted from other consecutive readings to adjust for the amount of water that falls directly on the splashboards and troughs and collected by splash collectors when rainfall is applied on an empty (without soil) plot.

- The amount of rainfall is calculated by dividing the amount of water collected by the plot to the area of the plot.

- It is also assumed that no water ponding occurs on the soil surface. The amount of water infiltrated is considered to be equal to the amount of water received on the erosion plot (see equation 4.1) minus runoff and net splash volume. Net splash volume is the difference between a splash volume collected at each 5 minutes interval and that collected during the first 5 minutes of the rainfall event. This procedure may overestimate infiltration rate to some extent especially during the beginning of the rainfall event.

$$Q = IAt/600 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(4.1)$$

Where, Q= Volume (ml) of water applied to the plots of area A per hour,

I= Intensity in mm hr^{-1},

A= Cross-sectional area of the erosion plot (cm^2) and

t= time elapsed since the onset of rainfall (min.)

The influence of seal formation was observed by the change in the infiltration characteristics of the soils.

Special considerations

The tray used in this study doesn't allow replacement of the water and sediments that are splashed out of the plot area. Taking this into consideration, and assuming that the water and portion of the sediments that were splashed out of the plot would have contributed to the total runoff and sediment yield respectively, an attempt was made to include these values to the runoff and sediment contained in it. Therefore, runoff in this study is considered as the sum of overland flow and splashed water. In this procedure, the fraction of sand and water stable aggregates in the splashed sediment were deducted from the total splash weight assuming that these are too heavy to be transported by the thin overland flow that occurs on such small erosion plots of short slope length. The equation is:

$$S.Y = W+\{S\ [1-(PWSA+Psa)/100]\} \ldots\ldots\ldots\ldots \quad (4.2)$$

Where,

S.Y = Total sediment yield (kg m^{-2})
W = Weight of wash off soil (sediment in runoff) (kg m^{-2})
S = total weight of sediment in splash (kg m^{-2})
PWSA = percent water stable aggregates
Psa = percent sand

However, the total sediment yield obtained using this equation didn't comply with the actual field observations and soil properties. On the other hand, when the sediment in runoff and splash weight were handled separately, the correlations with most of the soil properties were more relevant to the actual expectations.

Therefore, as it was difficult to accurately estimate the proportion of sediments in splash that would have contributed to sediment yield, both wash off soil and splash weight were discussed separately and sediment yield in this text refers to only the amount of sediment in overland flow. The sediments in the splash were used as indicators of the susceptibility of the soils to detachment by raindrop impact. It is however, important to note that equation 4.2 may provide a reasonable information if the proportion of fine and coarse sands in the total sand fraction are known.

Statistical analysis

The experimental layout was a completely randomized block less design (CRD). Treatments consist of three different textured soils (clay, silt, or sand dominated), three slope gradients (5, 10 and 15 degrees) and two rainfall intensities (30 and 60mm/hr). Statistical analyses were done using a SAS computer software (TCP 3270 version 2.5). Correlation analysis was also done between the dependent and independent variables. The level of probability used in this text was p = 0.05 unless specified.

4.3 Results and discussion

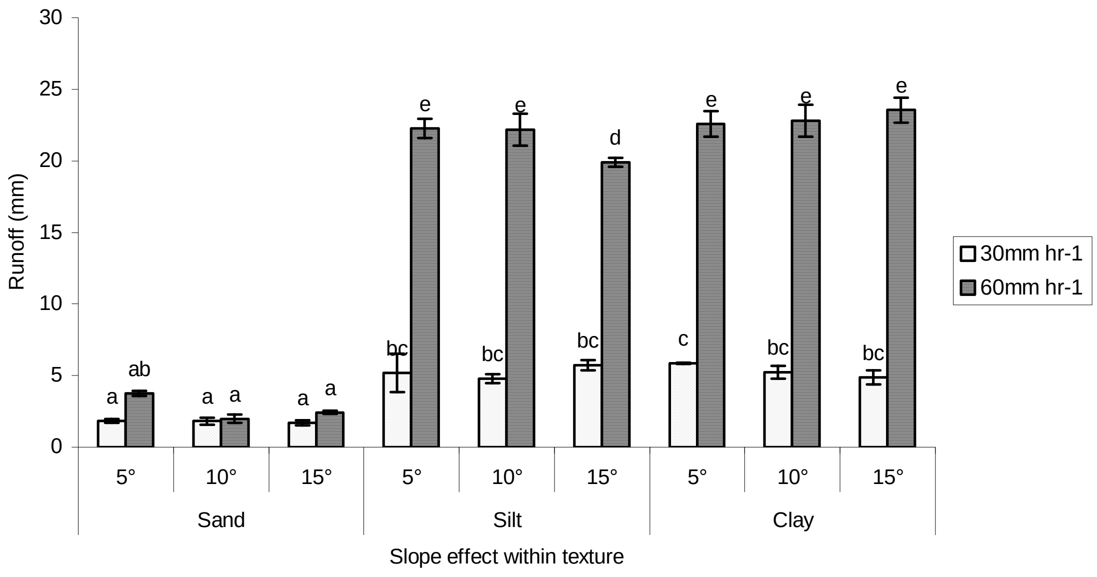
4.3.1 Analysis of total erosion parameters as affected by soil texture, slope gradient and rainfall intensity

4.3.1.1 Runoff

Analysis of variance of the effects of soil texture, slope gradient and rainfall intensity on the total runoff collected during the one-hour simulated rainfall revealed a highly significant ($P<0.0001$) interaction.

On the sandy alluvial soils from the Alemaya university campus, little runoff was collected that was also not significantly different between the three slope gradients at both 30 and 60mmhr^{-1} rainfall intensity (Fig. 4.2). Runoff occurs when rainfall intensity exceeds infiltration rate. As expected, the high infiltration capacity of sandy soils resulted in a relatively low runoff as compared to the other similarly treated soils.

According to Nearing et al. (1991), slope has the most direct effect on the erosivity of overland flow by determining its stream power and runoff increases with increase in slope gradient. However, soil surface conditions and storm characteristics also modify its effect on runoff and soil loss. The consequence of this is the absence of a unique relationship between runoff and slope characteristics unless long-term trends are of interest (Torri, 1996). The results in this experiment indicate that the little runoff collected from sandy soils was not significantly affected by the applied slope gradients. The limited effect of slope gradient on runoff (total volume) could also be due to the fact that 'infiltration' is a 'soil physical property' said to be independent of slope gradient. However, the runoff velocity is slope dependent.



Means indicated by the same letter are not significantly different (P=0.05)
Y-error bars indicate standard deviations

Fig. 4.2 Mean runoff (mm) at different slope gradients and rainfall intensities for the three soil textural classes.

On the Diredawa silty soils, a higher (P<0.001) runoff volume was collected at 60mm/hr rainfall intensity as compared to that for 30 mm hr^{-1} under all slope gradients (Fig. 4.2). At 30 mm hr^{-1} intensity, no significant differences in runoff among the slope gradients were observed. However, at a rainfall intensity of 60mm/hr, the runoff at 5 and 10° slope gradients were significantly higher than that of 15° slope (P=0.02 and P<0.03 respectively). The relatively low runoff observed at 15^{0} slope could be ascribed to a decrease in the degree of surface sealing with increase in slope steepness (Poesen, 1984; Bradford and Huang, 1996) and a subsequent increase in infiltration.

On the clay-dominated swelling soils collected from Alemaya university vertisol, runoff was not significantly different along the slope gradients at both 30 and 60 mm/hr intensity (Fig 4.2).

The effect of soil texture and rainfall intensity on runoff seems to be more pronounced than that of slope gradient. The limited effect of slope gradient on runoff in this laboratory rainfall simulation study could be among others related to the very short slope length of the erosion plots unlike the actual field conditions because the slope length is too short for the sheet flow to develop into channels (rills) and form high flow depth. Hairsine and Rose (1991) proposed that when the flow depth is less than or equal to a breakthrough depth and flow driven processes are inactive, erosion is independent of slope.

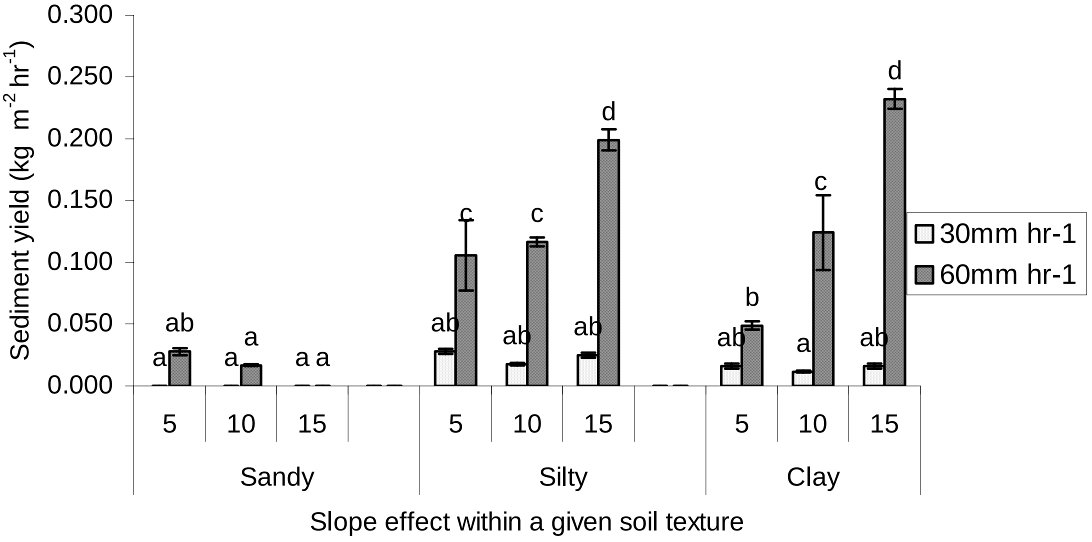
In general, runoff followed a decreasing order of magnitude as follows: Clay-60mm/hr, Silt-60 mm hr^{-1}, Clay-30 mm hr^{-1}, Silt 30 mm hr^{-1}, Sand 60 mm hr^{-1}and sand-30 mm hr^{-1} regardless of the slope gradient.

At least a 250% increase in runoff volume has been observed when rainfall intensity is increased from 30 mm hr^{-1} to 60 mm hr^{-1} for the silt and clay dominated soils. This clearly indicates that the effect of rainfall intensity on runoff is more prominent than the other two variables considered in this study.

4.3.1.2 Sediment yield

A significant interaction among soil texture, slope gradient and rainfall intensity on sediment yield was observed. Therefore, the effect of any one factor on sediment yield cannot be discussed with out taking the other two factors into consideration.

At rainfall intensity of 30 mm hr^{-1}, no sediment yield was recorded on sandy soil under all slope gradients (Fig. 4.3) because of the high infiltration rate and no runoff that would have otherwise carried the sediments down the slope. However, at 60 mm hr^{-1} intensity, some sediment yield has been recorded at low slope gradients though none are statistically significant. Although the sand particles are relatively loosely aggregated, they are too heavy to be transported down the slope unless sufficient velocity of water is applied which is however not attained due to high infiltration rate. Surface sealing and low infiltration rate are the main reasons for runoff initiation and for sediment transport (Mamedov et al., 2000). The data on sediment yield among the slope gradients followed a similar trend with that of runoff on sandy soils. Hence, low runoff and sediment yield could also be an indication of no seal formation on the sandy soils.



Means indicated by the same letter are not significantly different (P=0.05)
Y error bars indicate standard deviations

Fig.4.3 Change in sediment yield as influenced by rainfall intensity, slope gradient and texture

Silt dominated soils were found to be more susceptible to particle detachment as sediment yield at both rainfall intensities compared to sandy soils. This could be due to the relative transportability of fine and none aggregated silt particles (Le Bissonnais, 1996) as compared to the larger sand particles. Moreover, silt dominated soils also have lower infiltration rates than sandy soils which will enhance runoff and sediment yield. This high erodibility of the silt-dominated soils is line with many other studies (Romkens et al., 1977; Bradford et al., 1987; Bradford and Huang, 1992) that reported a negative correlation between silt content and infiltration rate. Ben-Hur et al. (1985) also indicated that medium textured soils (silty and loamy sand) are often the most susceptible to crusting and erosion. It has also been stressed however that interaction between texture and other parameters like clay mineralogy and organic matter content could modify this relationship.

The effect of slope gradients is not significant at the 30 mm hr^{-1} intensity for the silt soils. Sediment yield was significantly higher at 60 mm hr^{-1} than for 30 mm hr^{-1} for all slopes. This is mainly due to the fact that infiltration rate is greatly exceeded at this high intensity rainfall. At the 60 mm hr^{-1}intensity, a significantly higher sediment yield was recorded on 15^{o} ($P<0.0001$) slope while the difference was not significant on slopes of 5° and 10°. The absence of significant difference between sediment yield recorded on 5 and 10° slope gradients on silt dominated soils as compared to an increasing trend observed in clay soils (Fig. 4.3) can be attributed to the more susceptibility of the loosely aggregated silt dominated soils to detachment and transport by low velocity overland flow induced by lower slope gradients as compared to the well aggregated clay soils that could be too heavy to be transported by such low velocity flows.

The sediment yield on clay soils followed almost similar trends (Fig 4.3). At 30 mm hr^{-1}, it was not significantly different among the slope gradients. Application of rainfall at 60 mm hr^{-1} resulted in a higher ($P<0.0001$) sediment yield with increasing slope gradient. These results are in agreement with the work of Warrington et al. (1989) who reported a rapid increase in soil loss with increasing slope gradient which ranged between 5 and 25% on smectitic soils. Working with rainfall simulation in South Africa, Stern (1990) also reported higher particle concentration in runoff on the 30% slope gradient as compared to the 5% on Msinga kaolinitic clay loams and Jozini illitic sandy loam soils.

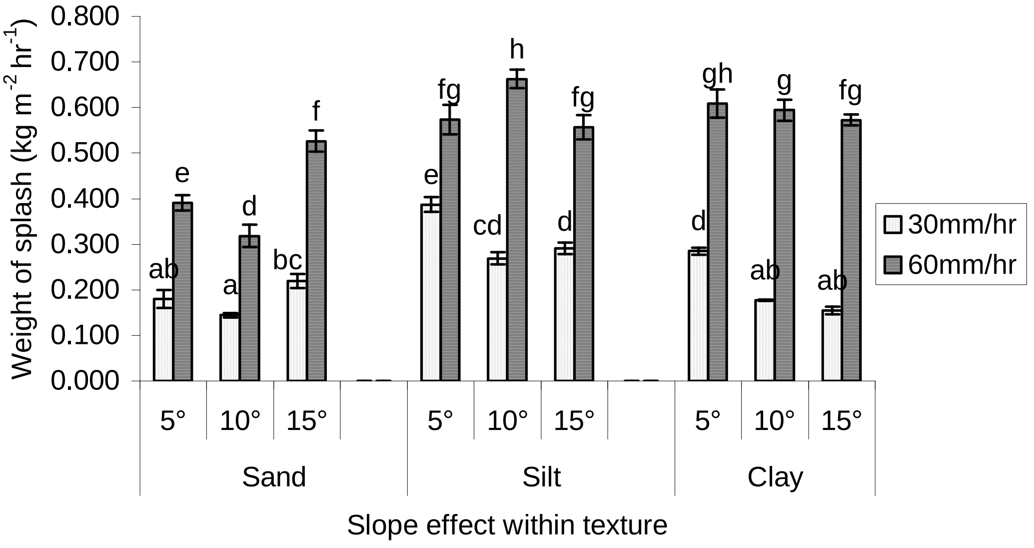
In general, rainfall at an intensity of 30 mm hr^{-1} did not produce a significant difference in sediment yield for all the textural classes used at 5° slope (Fig 4.3). But at 60 mm hr^{-1} intensity on the same slope, significantly higher sediment yield was recorded on silty and clay dominated soils. The sediment yield for clay soils at the 60 mm hr^{-1} intensity did not differ significantly from that for silt soils at similar intensity especially at 10° (P = 0.656) and 15°(P=0.0566) slopes. While indicating the importance of aggregate breakdown in the process of crusting, Le Bissonnais (1996) indicated the equal importance of the characteristics of the detached particles such as their sizes and aggregate stability.

4.3.1.3 Splash erosion

Splash erosion occurs due to raindrop impact that initiates soil detachment. The impact droplets are transferred outward from the center of the impact while encapsulating solids and carrying them to the landing point (Sharma, 1996). Unlike the field conditions where the net splash transport is minimum, the design of the erosion tray in this laboratory experiment doesn't allow replacement of the splashed materials that are transported out of the plot area. The amounts of sediments detached and transported by the raindrop impact are considered as indices that indicate the relative degree of susceptibility of the soils to detachment under various treatments. Hence, the splash values in this experiment should not be extrapolated to larger areas but can be used to compare treatment effects.

As presented in Fig 4.4, soil texture, slope gradient and rainfall intensity showed a highly significant interaction effect on splash erosion ($P<0.001$). For all the different textured soils and slope gradients, at the high intensity rainfall (60 mm hr^{-1}), treatments produced more sediments due to splash compared to the low (30 mm hr^{-1}) intensity. It has been reported (Agassi et al., 1994) that, the amount of soil splash increases as both rainfall intensity and rainfall energy increases though the rate of increase will depend on factors such as antecedent soil water content, mechanism of aggregate breakdown, and soil properties such as clay mineralogy, texture, organic matter and exchangeable sodium content.

Among the different slopes on sandy soils, only small differences occurred that was seldom significant. At 30 mm hr^{-1} rainfall, significant difference (P=0.0221) was observed only between 10 and 15^o slope the latter being higher. At 60 mm hr^{-1} rainfall, all slopes showed significant differences, but the relationship was not linear with increasing slope gradients. Poesen (1985) and Morgan (1978) also found no significant relationships between detachment and slope. On the other hand, several studies (such as Quansah, 1981; Mosley 1973, Grosh and Jarrett, 1994) reported greater splash detachment with increase in slope gradient.



Means indicated by the same letter are not significantly different (P=0.05)
Y error bars indicate standard deviations

Fig. 4.4 Mean splash weight (kg m^{-2} hr^{-1}) as affected by slope gradient and rainfall intensity within soil textural classes.

In the case of silty soils, the relatively low splash erosion on 5° slope as compared to the one on 10° slope gradient at 60 mm hr^{-1} intensity could be explained by two possible reasons. For one thing, the degree of surface sealing is high at low slope gradient resulting in relative increase in the resistance of the soil particles against the impact of raindrop. Seal development increases the shear strength of the soil surface (Bradford et al., 1987; Mamedov et al., 2000) and thus reduces soil detachment (Moore and Singer, 1990). The other possible reason could be attributed to possibility of high surface water depth at low slope gradients mainly due to slow velocity of overland flow, which might have resulted in a subsequent decrease in splash as compared to the one the high slope gradient. Moses and Green (1983) also indicated that airborne detachment appears to be most intense at zero water depth and is greatly reduced at higher water depths depending on drop size. The relatively low splash erosion from silt soils on 15° slope as compared to the one on 10° slope seems to be contrary to the general expectation of the relationship between slope gradient and splash erosion. Nevertheless, this low splash erosion on steep slopes could also be due to the relative decrease in the amount of drops impacting the soil surface with increase in slope gradient. But this relationship was not consistent among the different soil types and needs further investigation.

On the soils with high clay content, slight decrease in splash weight was observed with increasing slope gradient at both 30 and 60 mm hr^{-1} intensity although the difference is not significant for the latter. The relatively higher splash erosion on 5° slope gradient as compared to the higher slope gradients could be due to the difference in the number of drop impacts received on the soil surface at various slope gradients. In a rainfall simulation study at intensity of 65 mm hr^{-1}, Bradford and Huang (1996) found that for clay loam and clay soils, splash values on 20 % slope were less than on 9%. They also reported a significant interaction between soil properties (aggregate stability, soil strength, and surface sealing) and slope steepness.

In general, for all slope gradients and rainfall intensities, higher splash was observed on silty soils though it was seldom significantly different from clay soils at 60mm hr^{-1} intensity. Splash was significantly lower on sandy soils.

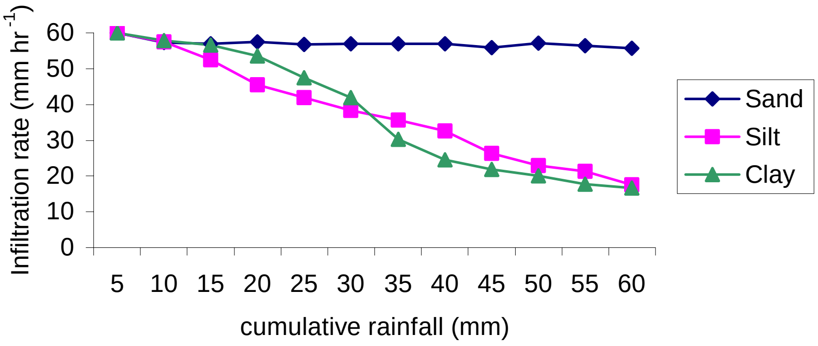
4.3.2 Trends of erosion parameters during rainfall event

For the trend analysis with time, runoff, infiltration rate, sediment yield and splash erosion data that were determined at every five minutes since their initiation was used. Since the overall trend for most of the erosion parameters was similar at 30 mm hr^{-1} and 60 mm hr^{-1} of rainfall intensity, only those for 60 mm hr^{-1} will be discussed in this text.

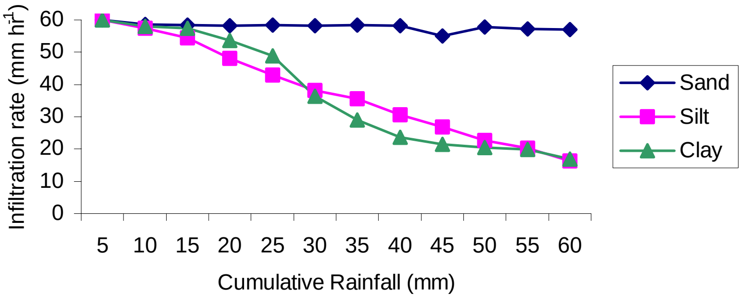
4.3.2.1 Infiltration rate

The infiltration rate of the three soils followed a clearly different pattern (Fig. 4.5). In sandy soils, steady state infiltration rate was attained during the early minutes of the rainfall event with a higher infiltration rate maintained throughout the rainfall event under all slope gradients. The higher infiltration rate observed in this sandy soils could be an indication of no seal formation and presence of large number or macropores. Variations in slope gradient did not result in a significant difference in infiltration rate for the sandy soils.

a.) 5° slope



b.) 10° slope



c.) 15° slope

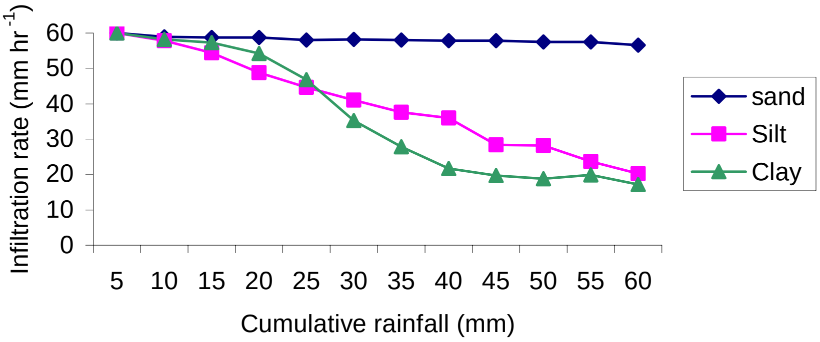


Fig. 4.5 Infiltration (mm hr^{-1}) curves of three soil textures under three slope gradients at 60 mm hr^{-1} rainfall intensity

In the case of silty soils, steady state infiltration was not attained during the whole rainfall event. A continuous decrease in infiltration rate was observed over the 60 minutes time. This reduction in infiltration rate could be attributed to continuous breakdown of soil aggregates that gradually clog pore spaces and increase the rate of seal formation.

For the first half hours of the rainfall event in clay-dominated soils, the infiltration rate was greater than those of silt dominated soils. This could be due to the high soil aggregation and aggregate stability in clay-dominated soils. However, the infiltration rates decreased to lower values than that of the silt soils then after. This could be ascribed to the swelling properties of the clay soils. Few minutes before the end of the one-hour rainfall simulation period, the infiltration rate in clay soil reached its steady state indicating the final stage of swelling. At this steady state infiltration rate, runoff seems to have approached its peak (Fig.4.6).

4.3.2.2 Runoff

Little runoff was observed on alluvial sands if at all (Fig.4.6A). It rarely exceeded 4mm at each five-minute interval of rainfall. This is mainly due to the coarse textured soil that encourages more infiltration and drainage than runoff. Even the little amount recorded is due to the added splash water to the total runoff. The other possible reason could be due to the entry of fore ward splashes into the runoff outlet rather than overland flow. The fact that relatively higher runoff was recorded at 5° slope as compared to the higher slope gradients could also be due to similar anomaly.

For Diredawa silt soils (Fig. 4.6B), runoff increased linearly from the time it commenced till the end of the simulation period under all slope gradients. This could be due to the gradual surface sealing and subsequent reduction in infiltration that will end up in increased runoff with time until all the pores get clogged and runoff becomes constant. The fact that higher runoff rates have been observed on 5° and 10° slopes than that on the 15° slope seems to contradict the general common understanding that runoff increases with slope gradient. It can however, be attributed

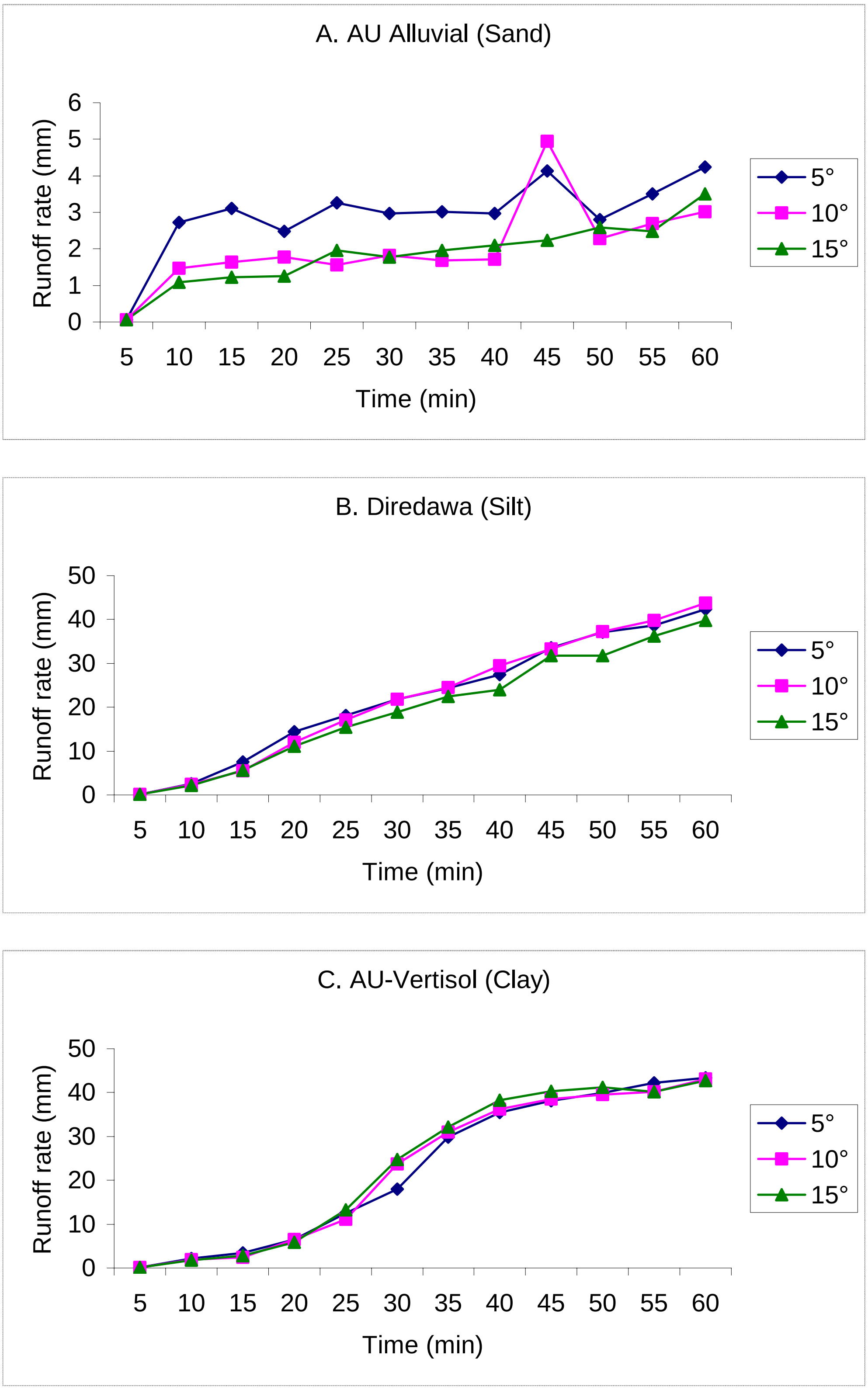


Fig. 4.6 Runoff (mm) trends at various slope gradients for the sand, silt and clay dominated soils

to decrease in the rate of surface sealing at high slope gradients thereby increasing the infiltration rate and leading to low runoff.

On the clay-dominated soils, runoff increased slowly for the first 15 minutes with sharp increase between 25 and 30 minutes since its commencement and then increased slowly again that almost became constant after about 50 minutes of the rainfall period (Fig 4.6C). The rate of runoff during the rainfall event on this clay-dominated soil was high at high slope gradients. Runoff is usually initiated due to surface sealing and/or natural low infiltration rate of soils. The clay-dominated soils have naturally low infiltration rates due to the abundance of fine particles and subsequent micro-pores as well as their tendency to swell. At low slope gradients, the water gets sufficient time to soak into the soil resulting in higher infiltration rate and reduced runoff.

4.3.2.3 Sediment yield

For sand dominated soils, sediment yield followed a similar trend to that of runoff and will therefore receive a similar explanation. The general trends of both runoff and sediment yield on sandy soils were irregular among the slope gradients. Besides, the amounts of runoff and sediment yield at any one point during the simulation was very small.

For the silt-dominated soils of Diredawa, sediment yield was almost constant from the time of runoff commencement up to about 50 minutes and showed a rapid increase thereafter (Fig. 4. 7B). The rate of increase is higher at higher slope gradients. This increase in the rate of sediment yield at the latter stage of rainfall could be attributed to the increase in runoff concentration as thicker layer of water flows at faster speeds that may even wash the seals formed during the early stages of rainfall.

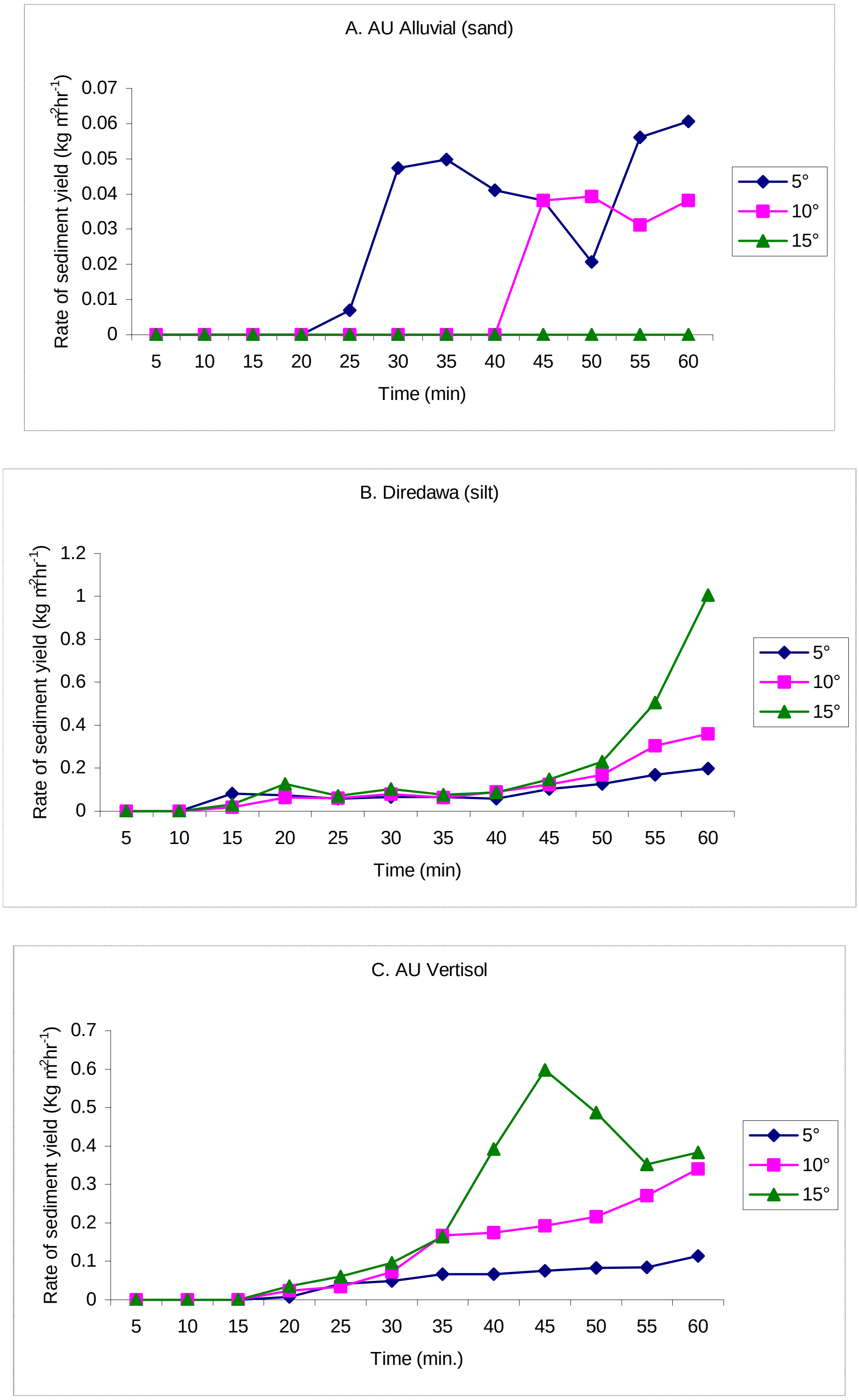


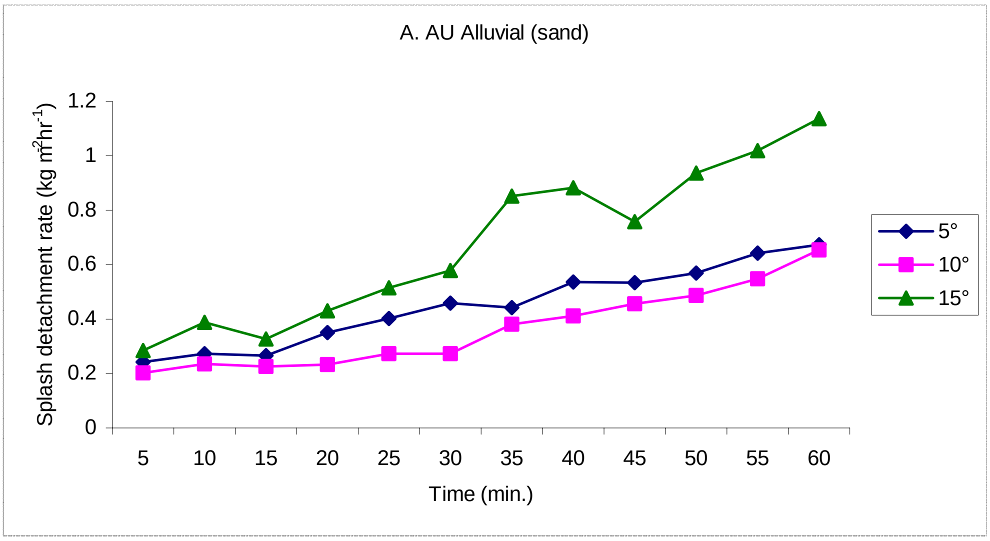
Fig. 4.7 Trends of sediment yield (kg m^{-2} hr^{-1}) at various slope gradients for the sand, silt and clay dominated soils at rainfall intensity of 60mm hr^{-1}.

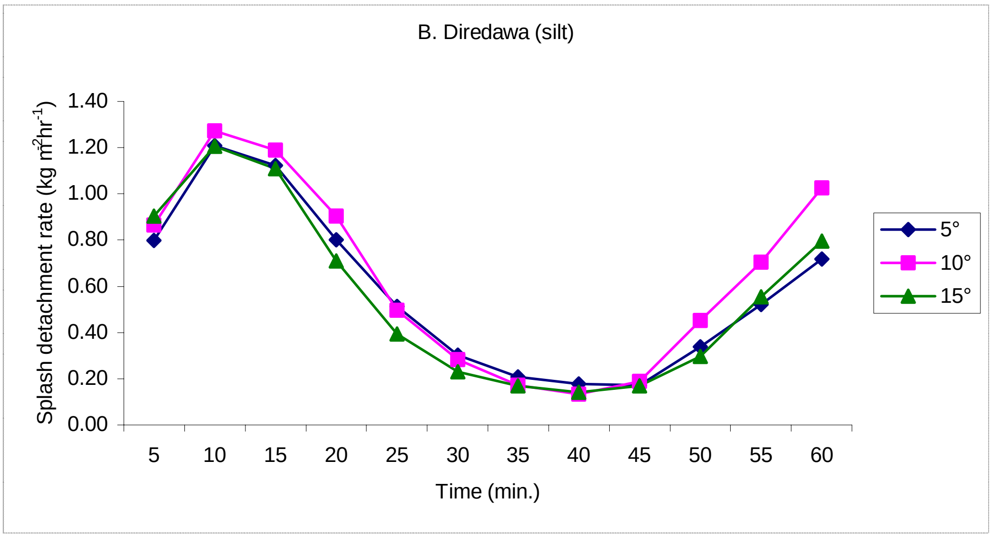
For clay dominated soils of Alemaya university vertisols, sediment yield increased with increase in time of rainfall application for all slope gradients from about 15 minutes onwards. The rate of increase was high at the higher slope gradients. The trend of sediment yield at the slope gradient of 15° on the clay soils is in agreement with the one presented by Stern (1990) for his control plots on Msinga clay loams at 30% slope gradient. The rapid increase in sediment concentration is associated with increase in runoff (Fig. 4.7C) and availability of loose particles on the soil surface. With depletion of the loose particles and development of compacted seals (after 50 minutes), the concentration of sediment in runoff subsequently decreased.

4.3.2.4 Splash detachment rate

The soil material which has been splashed from the erosion plot and captured by the splashboards that are fixed to the periphery of the plot has been washed to splash collectors at 5 minutes interval and was recorded as splash weight after oven drying. The values reported here are averages of three replicates.

For alluvial sand, splash weight increased almost linearly with increase in time for all slope gradients under consideration (Fig. 4.8A). It was slightly larger in magnitude at 15° slope as compared to the 5° and 10° slopes throughout the one-hour simulation time. The splash weight recorded at 10° slope was however lower than the one at 5° slope all the way during the simulation period. Though the difference may not be significant, such result is usually unexpected because more downward splash is normally expected at higher than lower slope gradients. But it could still be related to the variation in the total number of drop impacts per unit area of the plots at various slope gradients. During the early dry run, splash from sandy soils was very small and increased with increasing wetness of the soil. This could be attributed to the absorption of most of the incoming water by the dry and relatively rough soil surface and subsequent reduction in the splash energy. But as the soil gets wetter and the surface becomes smooth, splash energy increases and more water bounces from the soil surface carrying loose sediments.





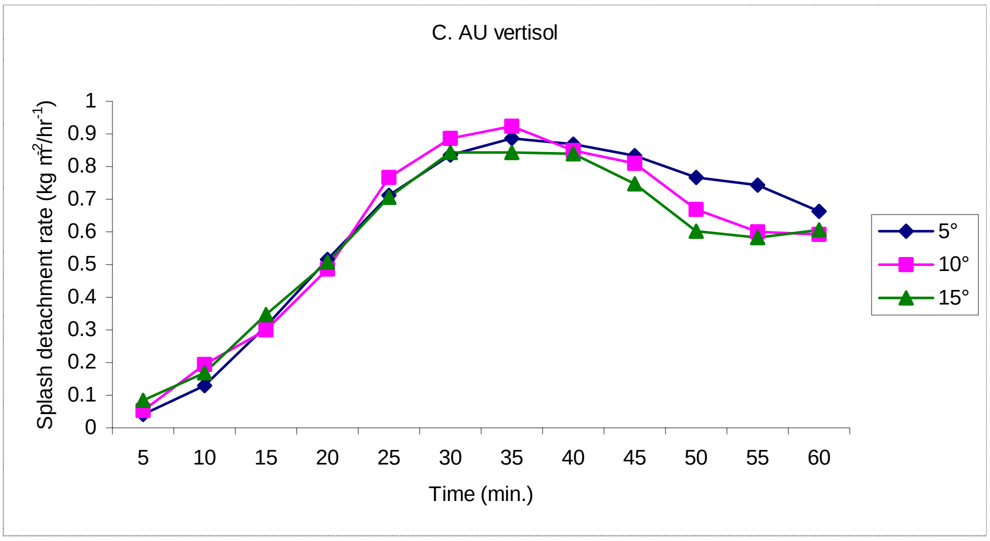


Fig. 4.8 Trends of splash detachment rates (kg m^{-2} hr^{-1}) at various slope gradients for the sand, silt and clay dominated soils.

For Diredawa silt soils, splash weight followed nearly a parabolic trend with time for all slope gradients. Splash weight was generally higher at 10° slope than the other two slope gradients. However, the difference doesn't seem significant. For all slope gradients, high splash weight was recorded for the first 15 minutes of rainfall and late after 45 minutes. The higher splash during the initial dry run could be due to the abundance of loose light weighted silt materials on the surface that can easily be carried by the bouncing water. However, as the soil gets wetter with time, aggregates breakdown and surface sealing occurs due to close up of soil pores by the fine particles from the broken aggregates. The coherence of these particles from the broken aggregates strongly resists the shearing force of the splashing raindrops resulting in less splash erosion. With further wetting of the soil (cumulative rainfall >50mm), the seal will disintegrate and more particles may become suspended thereby being carried by the splashing water. This indicates that silt dominated soils are prone to detachment by the impact of raindrops at the beginning of rainfall on dry surfaces and after heavy rainfall that lasts for long time (Fig.4.8B).

Splash erosion on vertisols (clay dominated soils) increased rapidly for the first 30 minutes and started declining thereafter (Fig. 4.8C). The trend of splash weight was similar for all slope gradients with no significant difference among them. The linear increase in splash weight at the early stages of rainfall could be attributed to the availability of unaggregated fine materials and partial breakdown of relatively unstable aggregates as the soil gets wetter. With further increase in cumulative rainfall (>35mm), the more stable aggregates are left behind on the surface that will disintegrate slower and produce less splash material. This has eventually lead to less splash production. Besides, when the soil is saturated and runoff starts, it results in a temporary water ponding that may increase the gap between the soil surface and the falling raindrops. Hence the splashing water bounces with little contact with the soil surface.

Comparison of the trend of the mean splash weight for the three soil textural classes reveals that silt dominated soils are more prone to splash erosion than sand and clay dominated soils at a cumulative rainfall of less than 20mm. Splash erosion increased linearly with increase in cumulative rainfall on sandy soil. A similar increase was observed for clay soils during the early stage of the run but started declining after 35minutes.

4.3.3 Correlation between some erosion parameters

Correlation analysis was performed to observe the general relationship among the various erosion parameters measured in this study. Only the total values (collected during the one hour rainfall simulation) of each erosion parameter were used for this analysis. The correlation coefficients are presented in Table 4.1.

Table 4.1 Correlation among some of the erosion parameters

	Runoff	Splash wt	Sediment yield	Water retention	Time to Runoff	Final IR
Runoff	1.00					
Splash erosion	0.80	1.00				
Sediment yield	0.83	0.70	1.00			
Water retention	0.53	0.17	0.33	1.00		
Time to Runoff	-0.74	-0.61	-0.63	-0.57	1.00	
Final Infiltration Rate	-0.51	-0.07	-0.34	-0.68	0.44	1.00

Sediment yield and splash erosion were highly and positively correlated with runoff (r= 0.83; r=0.80 respectively). Similar positive correlations were also observed on the different soils as described in chapter 3. Other studies also reported similar linear relationships between runoff and soil loss (Feleke, 1987; Singer and le Bissonnais, 1998; Sonneveled et al., 1999). This indicates that high soil erosion was associated with high runoff volume. Factors that encourage high runoff such as high rainfall intensity and medium and fine textured soils also exacerbate splash erosion. The negative correlation between the time to runoff initiation and sediment yield (r=-0.63) as well as splash weight (r=-0.61) indicate that high sediment yield and splash are collected under conditions that induce early runoff initiation. Positive correlation was also observed between sediment yield and splash erosion (r=0.70). Hence, most of the factors that affect sediment yield also tend to have a similar effect on splash erosion. Runoff and sediment yield are negatively correlated with the final infiltration rate (r=-0.51; r=-0.34 respectively) indicating that soils with high final infiltration rate are less susceptible to runoff and erosion. At this junction, it is important to note that though the amount of data used for this correlation analysis was not large enough to produce more tangible information, it would give a better view of the influence of the different factors on erosion.

4.4 Conclusion

The effect of soil texture, slope gradient and rainfall intensity on erosion parameters including runoff, sediment yield, splash erosion, and infiltration was studied under laboratory rainfall simulation. For most of the erosion parameters, the interaction effect among soil texture, slope gradient and rainfall intensity was significant. In general however, high rainfall intensity induced high runoff, sediment yield, splash and drainage. The effect of slope gradients on most of the erosion parameters was not significant as the plot size is too small to bring about a concentrated and speedy flow. The effect of soils dominated by any one of the three soil separates on the erosion parameters was largely dependent on rainfall intensity and slope gradient.

A positive correlation was found among runoff, sediment yield, and splash erosion indicating that most of the factors whose effects are studied in this experiment affect these erosion parameters similarly. For instance, final infiltration rate which is considered as an indicator of the degree of surface sealing was negatively correlated to runoff and sediment yield. This indicates the direct impact of sealing on runoff and erosion. Such information can provide a hint to the management of similar soils provided that other factors that are not considered in this study are constant. However, data obtained under laboratory rainfall simulation can’t be directly applied to field conditions, as the soil characteristics, topography, soil surface phenomena as well as climatic conditions can’t be represented exactly the way they are in the field. Laboratory studies are much simplification of the actual field situations. However, if interpreted with care, valuable information can be obtained from the laboratory rainfall simulation studies within a reasonably short time. This information can be used as a valuable input for further field scale studies and to make preliminary management decisions in the absence of a more comprehensive and representative data.

In this particular study, because of the nature of the experiment, which was entirely based on investigation of the interaction effects of slope gradient, soil texture and rainfall intensity on erosion parameters in the lab using simulated rainfall, no attempt was made to relate any of the results to the results of SLEMSA and USLE predictions.

CHAPTER 5

CHANGES IN SOIL ERODIBILITY UNDER SIMULATED RAINFALL AS INFLUENCED BY MULCHING RATES AND APPLICATION METHODS

5.1 Introduction

Agriculture in developing countries is mainly based on crop production whose main products include grain and straw. The grain is mainly used for human consumption while the crop residue is used for various purposes including for construction of huts, as a source of fuel and fodder (Lal, 1995). Because of these uses, virtually no crop residue is left on the soil surface for soil and water management purposes or is incorporated into the soil to maintain the organic matter content.

On the other hand, many reports indicate the effectiveness of crop residue as a surface cover to protect the soil surface against the impact of raindrop energy (Meyer et al., 1970; Larson et al., 1978) and to improve water infiltration and storage (Lal, 1995). Different reports also indicated that mulching is one of the most cost effective means of crop residue usage (Dickey et al., 1985; Shelton et al., 1995). Moreover, several other related studies (Aarstad and Miller, 1978; Foster et al., 1985; Meyer, 1985; Box and Bruce, 1996; Sharma, 1996; Idowu et al., 2001) indicated that raindrop impact energy is reduced by covering the soil surface with crop residues which consequently reduce surface sealing, increase infiltration and reduce surface runoff and erosion. Lal (1976) demonstrated that soil loss could significantly be reduced with increasing rates of mulch application on a tropical alfisol. Different scientists working under different climates and much different soils have reported reduction in soil loss and runoff due to surface residues, even on very steep slopes (Lal, 1982; Norton et al., 1985).

In most of the studies the effectiveness of crop residue was evaluated by applying a certain rate of the residue on the soil surface. However, under practical field conditions, the residue that is left on the soil surface is usually incorporated into the soil during cultivation to prepare the soil for the next crop thereby reducing its effectiveness as a mulch.

The objectives of this experiment were therefore to

(1) Evaluate the effectiveness of different mulching rates in controlling runoff and erosion on Alemaya regosols of Ethiopia and

(2) Compare the differences in effectiveness between surface application and incorporation of crop residues in controlling runoff, soil loss, and splash detachment under different rainfall intensities.

5.2 Materials and methods

The soil used in this experiment was a sandy clay loam regosol obtained from Alemaya University Experimental Field Station, Ethiopia. Regosols are the most dominant soils in Alemaya district. These soils are dark reddish brown to red in colour and have 53.1% sand, 19.5% silt and 27.4% clay with an organic carbon content of 1.62%. The most common soil forming rocks in the sampling areas include granite and limestone the former being more predominant.

Composite soil samples that represent the entire soils of the area were collected from the top 0.15 m. of the soil surface. Air-dried soils that passed through 4mm sieve were packed into the erosion trays having dimensions of 554 mm-long, 206 mm-wide and 85 mm deep. After packing the soil into the erosion trays, wheat residue was applied at rates of 0, 4, and 8 Mg ha^{-1} either by uniformly spreading over the soil surface or by incorporating it into the soil.

The erosion plot was inclined to 5° slope gradient and was subjected to two rainfall intensities of 30 and 60 mm hr^{-1} for 1 hour. The rain intensity treatments were applied at random to the different mulching treatments. The splashed material was collected from splashguards and troughs mounted at the borders of the plots in such a way that the splashed sediments could be trapped. The sediment was washed into the splash collectors at five minutes during the treatment. The amount of sediment carried by surface flow was also collected and both sources of sediment determined after oven drying the effluent containing the sediments. Runoff volume was also collected at five minutes interval. Unlike the case in other experiments where runoff was considered to be the sum of splash water and surface flow, only the surface flow was taken as runoff in this experiment because of some technical difficulties in the measurement of the splash volume.

Statistical analysis

The experiment consisted of a 3 x 2 x 2 factorial involving three rates and two application patterns of wheat residue and two rainfall intensities. CRD with three replications was used. The experimental data were statistically analysed by using the SAS computer software. Regression analysis was done to assess the relation between percent surface cover of the residue and splash weight. Correlation analysis was also done to assess the relation between the erosion parameters. The level of significance used was $P<0.05$ unless otherwise stated.

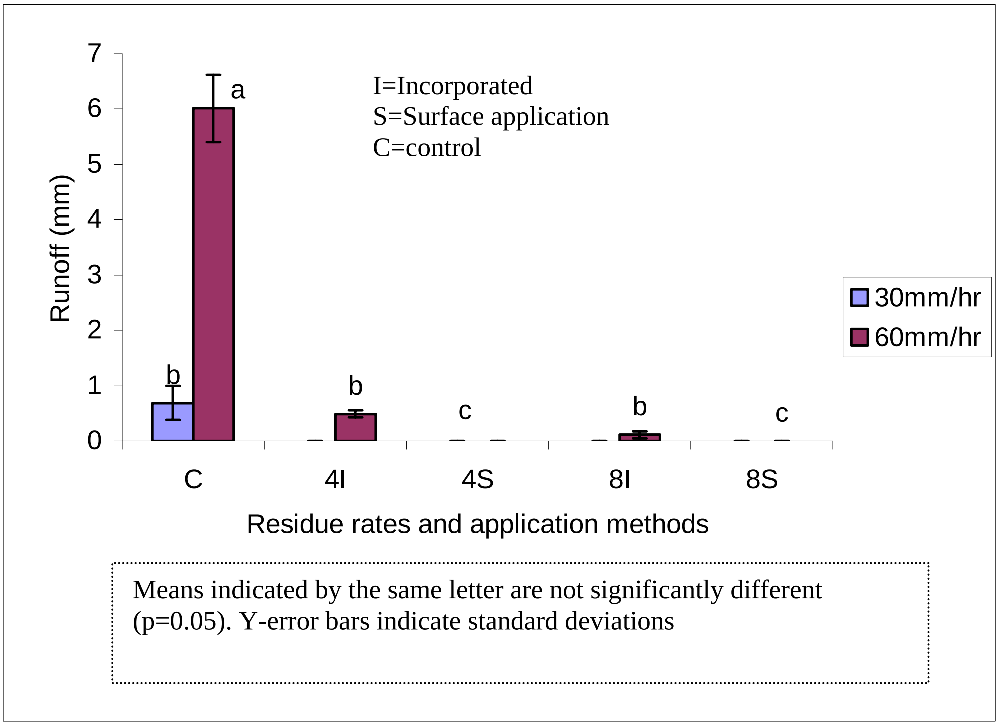
5.3 Results and discussion

5.3.1 Runoff

The mean runoff collected from the different erosion trays during the one-hour rainfall simulation is presented in Fig. 5.1. At both 30 and 60mm hr^{-1} rainfall intensities, all residue rates and application methods significantly reduced ($P= 0.0354$; and $P<0.0001$ respectively) runoff compared to the control (no residue).

The results also indicated that surface application of wheat straw at both rates (4 and 8Mg ha^{-1}) reduced runoff under both rainfall intensities. Similarly, incorporation of wheat residue into the soil at both (4 Mg ha^{-1} and 8 Mg ha^{-1}) rates reduced runoff by

92% and 98% respectively as compared to the control. Cruse et al. (2001) reported a similar reduction in the rate of overland flow with increasing residue cover. In a simulated rainfall experiment on small erosion boxes using soybean stem residue as a soil cover, they indicated that residue cover reduced the rate of overland flow by interrupting the flow path thus favouring infiltration and reducing runoff. The work reported by Lattanzi et al. (1974) also indicated that wheat straw mulching at a rate of 8 Mg ha^{-1} drastically reduced runoff from erosion pans as compared to the control plot on Russell silt loam soils that received a simulated rainfall of 64 mm hr^{-1}. Gilley et al. (1986) also supported this finding on a field plot rainfall simulation experiment at an intensity of 28 mm hr^{-1}, conducted on typic Hapludolls of South western Iowa, that addition of increasing amounts of residue up to 13.45t ha-1 reduced runoff significantly. They also indicated that runoff didn't occur on any of the treatments during the initial run.



Means indicated by the same letter are not significantly different (p=0.05). Y-error bars indicate standard deviations

Fig. 5.1 Mean runoff (mm) collected under 30 and 60 mm hr^{-1} intensity of rainfall.

On the other hand, on a field plot (22.1m long x 4m wide) experiment conducted at Charlottetown (Canada), on fine sandy loam under an average annual precipitation of 1097mm, Edwards et al. (2000) reported that runoff was not affected by barely straw mulching at a rate of 4 Mg ha^{-1}. Similar findings were reported on erosion plots of

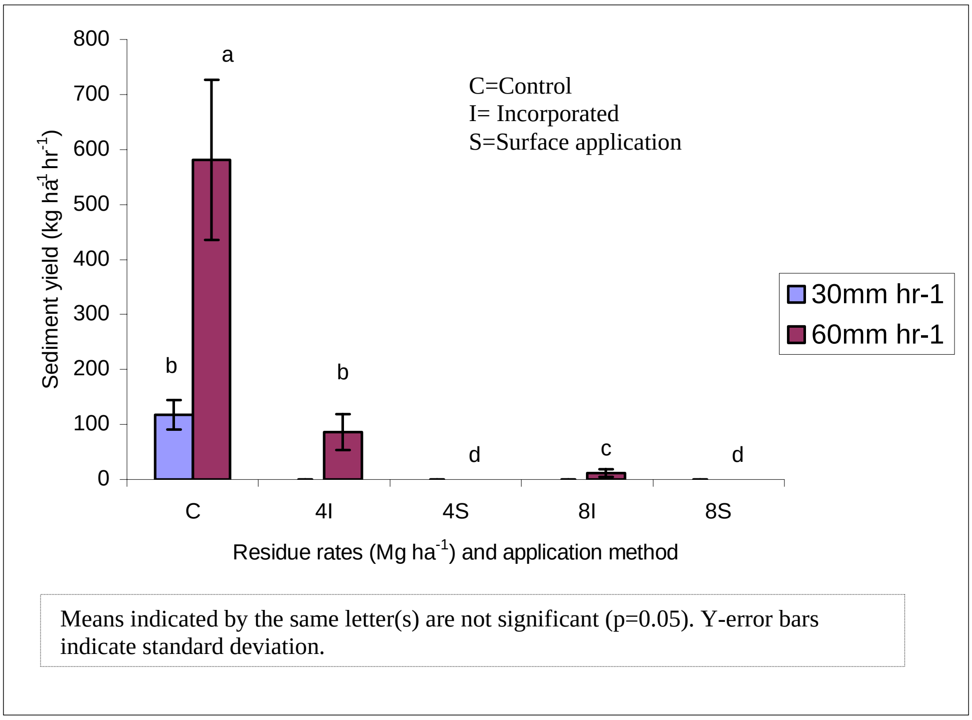
0.9m long by 0.3m wide of the same soils for surface incorporated straw rates of 2 to 8 Mg ha^{-1} (Edwards et al., 1995).

In spite of the fact that the findings reported in the literature vary much, they all indicate that there were reductions in runoff. Where little or no effects were observed, it was usually due to variations in the soil properties. It could probable be expected that in soils high in organic matter content in the cool areas of the world, less response to mulching could be expected. The results reported here however are for soils that are relatively low in organic matter content and mulching leads to significant reductions in runoff.

The small-scale laboratory results should be supplemented with field scale experiments before making decisions as extrapolation of such data that are obtained from very small erosion plots to field applications can be misleading. This is mainly because, under field conditions, various surface phenomena encourage runoff to flow at higher concentrations and high velocity that can even remove the residue itself. It should be noted that, the fact that this experiment was conducted on fresh wheat straw might have also exaggerated the results. Because, crop residues applied to the field conditions normally disappear with time through decomposition and/or removal by various factors like wind, animals, and overland flow, which will gradually reduce the effectiveness of the residue to control the various erosion parameters.

5.3.2 Sediment yield

The sediment yield followed a similar trend to that of runoff under all treatments. None of the interactions among the rainfall intensities, residue rates and application methods were significant. However, sediment yield was significantly different at 30 and 60mm hr^{-1} ($P=0.0038$) of rainfall. No sediment yield was observed on residue treated plots at rainfall intensity of 30mm hr^{-1} as there was no runoff. At this rainfall intensity, sediment yield was recorded only on the control plots.



Means indicated by the same letter(s) are not significant (p=0.05). Y-error bars indicate standard deviation.

Fig. 5.2 Mean weight of sediment yield (kg ha^{-1} yr^{-1}) collected under 30 and 60 mm hr^{-1} intensity of rainfall.

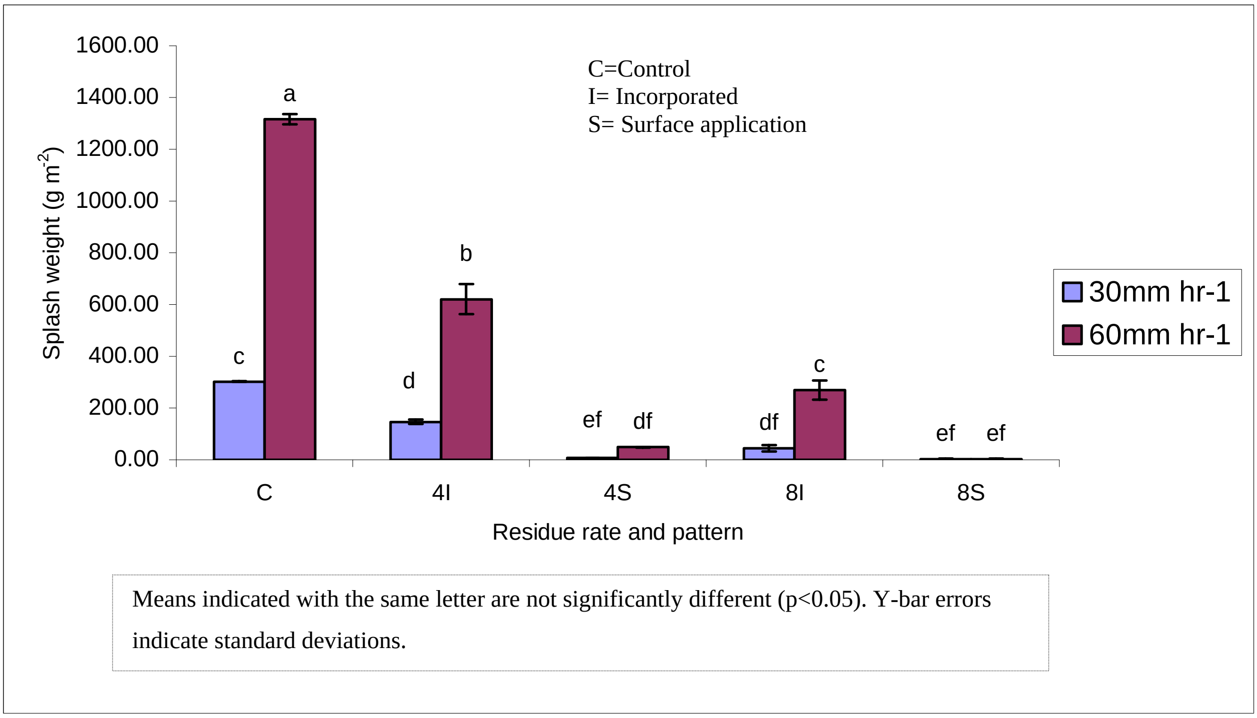
When the simulated rainfall was applied at 60mm hr^{-1}, some sediment yield was collected on residue-incorporated plots in addition to the control plot. At this rainfall intensity, residue cover has significantly reduced sediment yield as compared to the bare soil. Similar effects of crop residue mulch on sediment yield were reported by several authors (Mannering and Meyer 1962; Singer and Blackard, 1978; Singer et al., 1981; Edwards et al., 1995; Cruse et al., 2001). Among the plots to which wheat straw was applied, the highest sediment yield was recorded on the plot that received wheat straw at a rate of 4 Mg ha^{-1} incorporated into the soil.

At both simulated rainfall intensities, surface application of wheat straw at 4 Mg ha^{-1} and 8 Mg ha^{-1} prevented sediment loss. Besides, incorporation of the residues at rates of 4 and 8 Mg ha^{-1} reduced sediment yield by 85 and 98% respectively as compared to the control at a rainfall intensity of 60mm hr^{-1}. This indicates that application of wheat straw as low as 4 Mg ha^{-1} can sufficiently reduce soil loss resulting from runoff on interrill areas under the conditions specified in this experiment. In Canada, from an experiment conducted soil on cassettes filled with fine sandy loam soils under natural rainfall, no differences in soil loss was reported between plots that received barely residue rates of 4, 6, and 8 Mg ha^{-1} (Edwards et al., 1995) while at a straw rate of 2 Mg ha^{-1}, soil loss was about twice of that obtained under the above residue rates. Therefore, it was suggested that more than 4 Mg ha^{-1} (that is considered as a standard rate), residue rate is not needed to reduce soil loss while less than this amount provides significantly less than the maximum achievable erosion control. Here again, due to the differences in the climatic conditions that would bring about differences in organic matter content, the responses of the Ethiopian soils and those of the cool areas such as Canada to mulching could be different.

5.3.3 Splash detachment of soil

For erosion experiments conducted on small runoff plots (trays) in the laboratory, measurement of splash detachment is more representative to the actual field conditions than runoff and sediment yield; because in both laboratory and field conditions, slope length has little impact on the amount of splashed sediment as opposed to the case of runoff and sediment yield which are significantly affected by slope length and landform.

The mean splash weight as affected by residue rates and application methods is presented in Fig.5.3 for two rainfall intensities. The rates and patterns of wheat residue as well as rainfall intensity showed a significant interaction ($P<0.001$) effect on splash detachment. When rainfall was applied at an intensity of 30mm hr^{-1}, both surface and mixed residue application methods had significantly ($P<0.001$) reduced splash detachment as compared to the control. However, at this same rainfall intensity, splash detachment was not significantly different between surface and mixed patterns of wheat residue applied at a rate of 8 Mg ha^{-1}. Surface application of 4 Mg ha^{-1} wheat straw was significantly better ($P=0.001$) in reducing splash detachment than incorporation of the same amount of this residue into the soil. Though splash weight generally decreased with increase in the rate of crop residue application, between residue application rates of 4 and 8 Mg ha^{-1} for a given pattern of application.



Means indicated with the same letter are not significantly different (p<0.05). Y-bar errors indicate standard deviations.

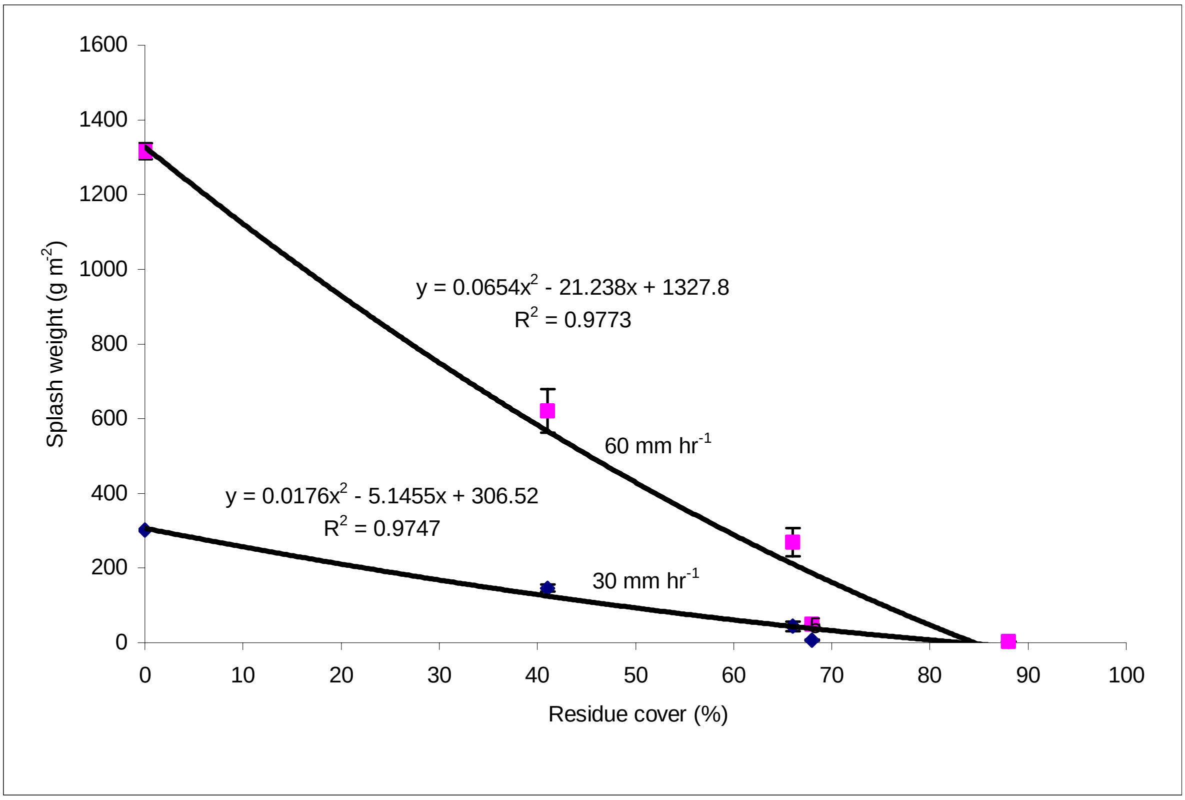
Fig. 5.3 Mean splash weight as affected by wheat residue rates and patterns at rainfall intensities of 30 and 60mm hr^{-1}.

At a rainfall intensity of 60 mm hr^{-1}, incorporation of 8 Mg ha^{-1} wheat residue significantly reduced splash weight as compared to 4 Mg ha^{-1} ($P<0.0001$). However, splash weight didn't differ significantly between surface application of 4 and 8Mg ha^{-1} residue rates because very little splash was recorded. In general splash weight decreased in the order of Control > 4I>8I>4S and 8S at both 30mm hr^{-1} and 60mm hr^{-1} rainfall intensities.

This experiment reveals that, in addition to the amount of crop residue added to the soil, much attention should be given to the method of its application. As indicated before, 4 Mg ha^{-1} wheat straw applied on the soil surface was more effective in controlling splash loss than incorporating even twice as much residue into the soil. This is because more percentage surface cover is obtained when a residue is uniformly spread on the soil surface than when it is incorporated into the soil. In 1954, Osborn (quoted by Singer and Blakard, 1978), using rainfall simulation, showed that percent of the soil surface occupied by cover was the single most effective measure of the effectiveness of cover in reducing splash erosion.

The general trend of splash detachment under various surface covers is presented in Fig.5.4 for 30mm hr^{-1} and 60mm hr^{-1} intensity of simulated rainfall. Splash weight responded more linearly to percentage surface cover than crop residue weight. At both rainfall intensities, splash weight decreased with increase in percent residue cover. Similar inverse relationships between percent residue cover and splash weight had been reported by several researchers (Lattanzi et al., 1974; Singer et al., 1981; Edwards et al., 2000; Cruse et al., 2001).

As shown on Fig 5.4, second- order polynomial curves fit the data points best for both rainfall intensities with coefficient of determination of greater than 0.97. However, the regression equations do not provide a valid estimate of splash weight when the surface cover exceeds 83% for 30mm/hr and 84 % for 60mm/hr rainfall intensity.



Y-error bars indicate standard deviations (g m^{-2})

Fig. 5.4 Splash weight as affected by percent residue cover and rainfall intensity for the 30 and 60 mm hr^{-1} intensity rain shower.

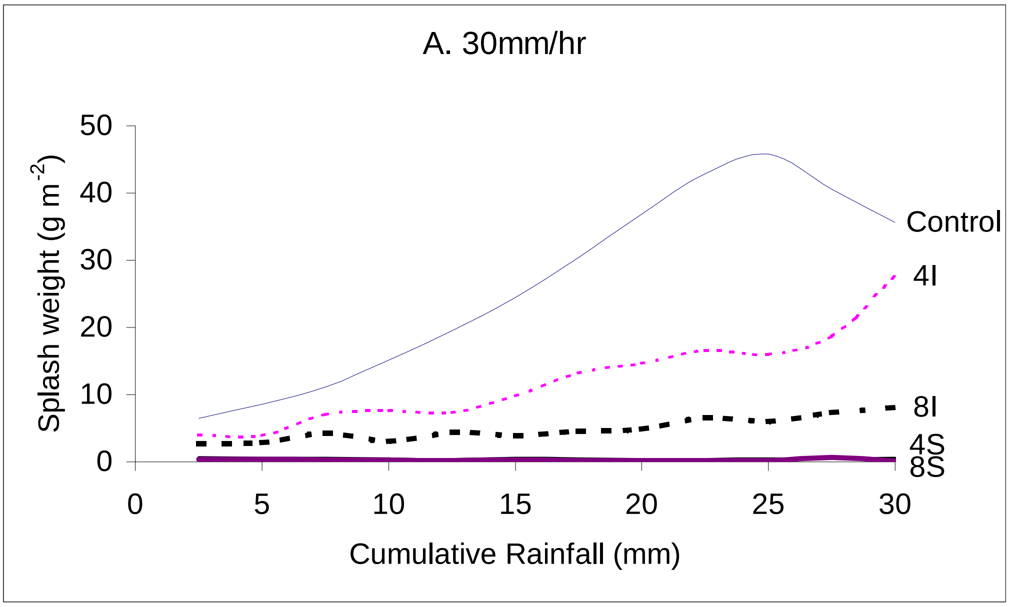
5.3.4 Trend of splash detachment with increasing cumulative rainfall

The trend of splash detachment with increasing cumulative rainfall for rainfall intensity of 30 and 60 mm hr^{-1} is presented in Fig. 5.5. For both rainfall intensities at the control plots, splash detachment increased with increasing cumulative rainfall for the first 25mm of rain and started decreasing thereafter. The rate of increase during the first 25mm of rainfall was higher for 60 mm hr^{-1}. The increase in splash detachment at the first half of the runs and decrease thereafter can be attributed to two main reasons. Firstly, at the beginning of the runs, the soil particles are dry and relatively loose and hence are more susceptible to detachment by the direct raindrop impact. As the soil gets wetter with increased rainfall, particles from the broken aggregates start to fill the pore spaces forming seals that are resistant to the splashing force of the raindrops, and hence reduced availability of the soil particles for detachment. Secondly, with increasing cumulative rainfall, the soil becomes gradually saturated and some ponding of water may occur. This temporary ponding of water on the soil surface may increase the gap between the falling drops and the soil particles and hence, reducing splash detachment.

For the residue treated plots that received rainfall at 30 mm hr^{-1} intensity, splash detachment increased almost linearly with increase in cumulative rainfall especially where the residues were incorporated. For equal rate of residue application, the rate of increase in splash weight was higher for the incorporated residues than those applied on the surface. Surface applications of 4 and 8 Mg ha^{-1} wheat residue have almost protected the soil from raindrop impact during the whole rainfall event.

At a rainfall intensity of 60 mm hr^{-1}, the trend of splash detachment with increasing cumulative rainfall formed a bell-shaped curve on the control plot. The possible reasons for the initial sharp increase in splash weight and gradual decrease latter on, as mentioned earlier are the availability of loose soil particles during the initial runs on one hand, and surface sealing, prevalence of stable aggregates as well as water ponding during the latter stages of the runs. A slight hump on the curve at 25mm rainfall of plots to which wheat residue has been incorporated at a rate of 4 Mg ha^{-1} is also an indication of some exposure of the soil particles to raindrop impact energy making it to show some characteristics of the bare soil.

At higher residue rates, the hump nearly disappears and linear increase in splash weight (if at all) with increase in cumulative rainfall occurs. This gradual increase in splash weight on mulched surfaces could be attributed to gradual redistribution of the residues due to the continued raindrop impact leaving some openings where the soil could be exposed to the direct impact of rainfall.



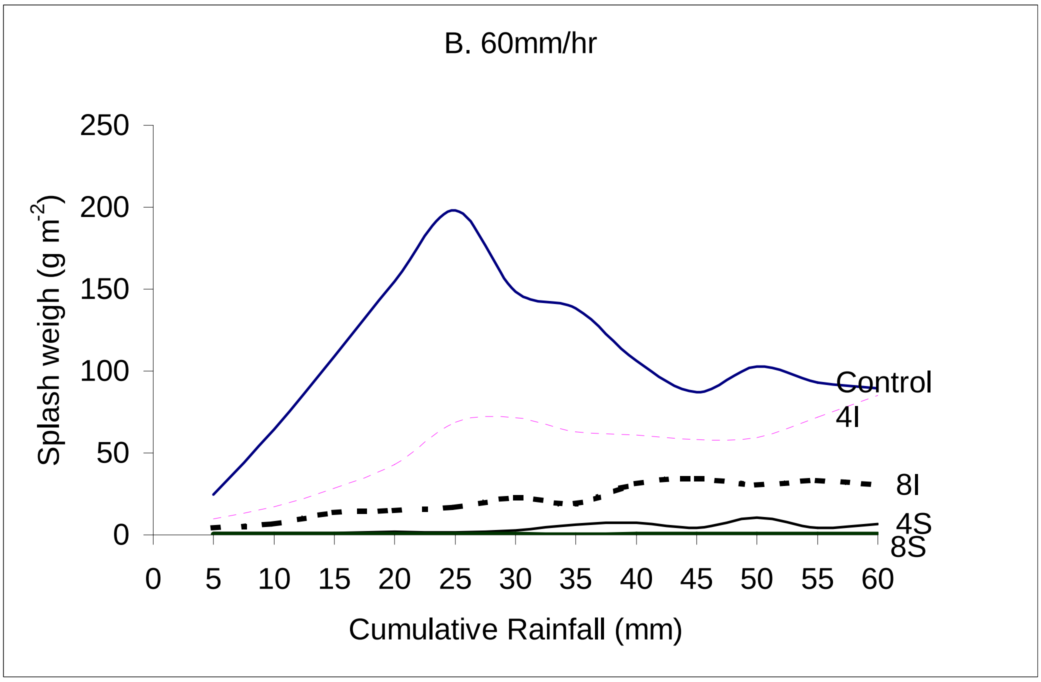


Fig. 5.5 Trends of splash detachment as influenced by rates and application methods of wheat straw under simulated rainfall intensities of (A) 30 mm hr^{-1} and (B) 60 mm hr^{-1}.

5.3.5 Relationships among the erosion parameters

Correlation analysis was performed among the erosion parameters considered in this study to assess the general trend of one erosion parameter versus others. As expected, runoff was highly correlated with sediment yield (r=0.96) and splash weight (r=0.93)

(Table 5.1). The relationship between runoff volume and sediment yield is presented in Fig 5.5. Moreover, sediment yield is also highly correlated with splash weight (r=0.87). These positive linear relationships among the erosion parameters indicate that those treatment combinations that tend to increase runoff have similar effect on sediment yield and splash detachment.

Table 5.1 Correlation coefficients (r) and P values among some erosion parameters measured in the study

	Runoff	*Sediment yield*	*Splash Weight*
Sediment yield	0.96 (P<0.0001)	1	
Splash weight	0.93 (P<0.0001)	0.87 (P<0.0001)	1
Water retention	-0.15 (P=0.3769)	-0.11 (P=0.5297)	-0.14 (P=0.4082)

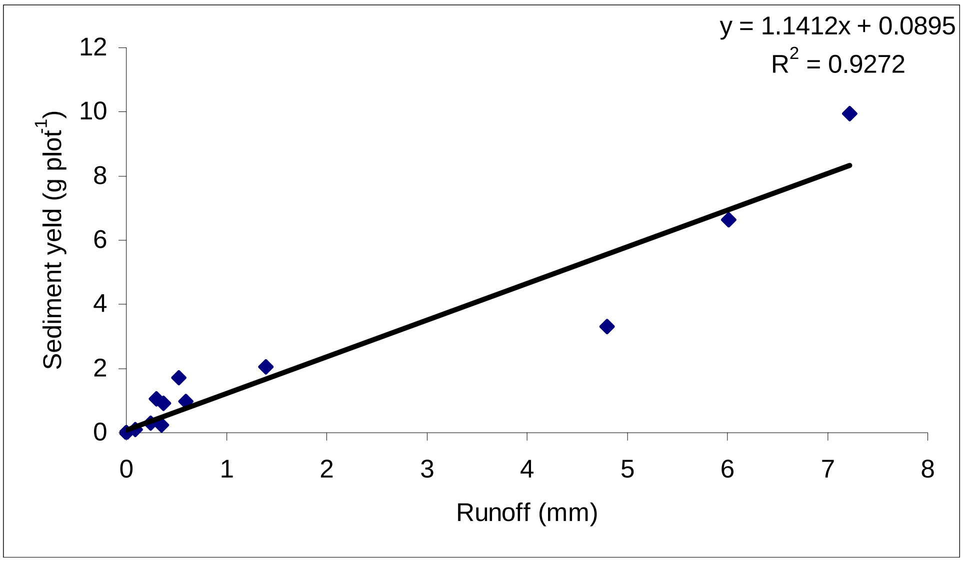


Fig. 5.6 Relationship between runoff and sediment yield under laboratory rainfall simulation.

On the other hand, the amount of water retained by the soil as well as the drainage volume were negatively correlated with runoff, sediment yield and splash detachment though none of these correlations were significant. Those treatment combinations that encouraged high water retention have also induced high drainage. Drainage and water retention showed significant correlations (r=0.63). The fact that high surface cover reduced runoff, sediment yield and splash detachment can be explained by increased infiltration rate of the soil as well as impaired raindrop impact provided by the higher mulch rates.

5.3.6 Comparison of laboratory results with model values

Laboratory based soil erosion experiments usually provide treatment effects for any given time interval within the experimental period. Extrapolation of such laboratory results either in time or space and using such information to evaluate empirical models like SLEMSA and USLE may however lead to erroneous conclusions. Furthermore, both SLEMSA and USLE are not meant for quantifying event-based erosion. Therefore, the cover effect in this small laboratory trial was not compared with the effect of canopy cover in the USLE and SLEMSA models. Such a comparison is however presented for the field trial as indicated in chapter 6.

5.4 Conclusion

Mulching reduced runoff, sediment yield, and splash erosion as compared to the bare soil at both rainfall intensities.For equal rates of wheat residue at a given rainfall intensity, surface application of the straw was more effective in reducing runoff, soil loss and splash detachment as compared to where the residue was mixed with the soil.

Besides, at 60 mm hr^{-1} rainfall intensity, runoff, soil loss and splash detachments were reduced with increased application rate of incorporated wheat residue. The same was true for splash detachment at rainfall intensity of 30 mm hr^{-1} though no runoff and sediment yield were collected at this intensity under any of the residue treated plots.

At a given rate and application method of mulching, application of rainfall at 60 mm hr^{-1} induced higher runoff, splash detachment, and sediment yield as compared to the 30 mm hr^{-1} intensity.

In general, although the general principles governing erosion loses from these small erosion pans should operate in the field, caution is however advised in extending the results of such small laboratory studies directly to predict field conditions. Therefore, it is advisable to conduct similar experiments in the field in order to correlate and calibrate the results with the data obtained in the laboratory.

CHAPTER 6

ROLE OF MULCHING ON RUNOFF AND SOIL LOSS IN FIELD PLOTS UNDER NATURAL RAINFALL

6.1 Introduction

The importance of protecting the soil surface from rainfall to preserve beneficial soil properties and thereby reduce erosion has long been recognized (Mannering and Meyer, 1962). Surface application of crop residue has proven to be very efficient in controlling soil loss and runoff from agricultural soils (Lal, 1976; Cogo et al., 1983; Roth et al., 1988). Larson et al. (1978) also indicated that proper use of crop residue is one of the most effective tools to solve soil erosion problems.

Crop residues may be used exclusively on the soil surface as a soil cover, or it may be partially mixed with the soil (Kohnke and Bertrand, 1959). As a cover, it is more effective in protecting the soil from the direct impact of the raindrops thereby reducing soil detachment, surface sealing and subsequently runoff and erosion. However, according to the literature, partial mixing of the residue with the soil surface promotes decomposition and results in improvement of soil aggregation and aggregate stability thereby making the soil more resistant to detachment. This effect may however be different under different climatic conditions. It can be assumed that under hot climatic conditions this would be less effective than under cooler conditions due to faster rate of mineralization of organic matter in the former (Grisi et al., 1998; Franzluebbers et al., 2001).

Most of the mulching studies have been conducted under laboratory rainfall simulations on small erosion pans (Lattanzi et al., 1974; Singer and Blackard, 1978; Savabi and Stott, 1994; Cruse et al., 2001; Idowu et al., 2001). The effect of mulching on infiltration, runoff and erosion may be different in magnitude under laboratory and field conditions. In the laboratory experiments, simulated rainfall is usually applied on small erosion plots and runoff occurs mainly when the infiltration capacity is sufficiently reduced and soil loss is mainly due to detachment by raindrop impact.

However, under the actual field conditions, overland flows coming from various interrill areas merge together to form channels and flow in higher concentrations and velocities depending on the gradient thereby contributing to increased runoff and subsequent soil loss. Therefore, under field conditions soil loss is not only a function of detachment by raindrop impact but also due to detachment by concentrated flow due to increased slope length.

Moreover, the percent surface cover provided by a given rate of crop residue is likely to vary when applied to laboratory erosion pans and field plots. Unlike the commonly uniform and levelled soil surfaces in the laboratory experiments, a rough soil surface that results from clods and various depressions under the cultivated field conditions, may reduce the uniformity of the residue cover leaving some spots exposed to the impact of raindrops.

Straw is conventionally spread on the soil surface or incorporated in to the soil at a rate equivalent to yield (average 4Mg ha^{-1}) (Edwards et al., 1995). Reports also indicate that increased mulching rates are expected to produce correspondingly less soil erosion (McGregor et al., 1988). On the other hand, using barely straw in a laboratory rainfall simulation study on fine sandy loam soils, Edwards et al. (1995) reported that there is no advantage in sediment control above a mulching rate of 4t/ha straw. However, the effectiveness of mulching is a function of many factors including rainfall erosivity, soil types and condition, steepness and length of slope and the type and rate of mulch applied (Foster et al., 1982; Poesen and Lavee, 1991). Hence, the need was felt to assess the effect of increased residue rates for greater erosion control and to examine the effects of surface and incorporated patterns of residue application on soil erosion control.

The aim of this experiment was therefore to assess the effectiveness of different rates and application methods of wheat residues in controlling runoff and erosion from large field runoff plots under natural rainfall.

6.2 Materials and methods

The study was conducted at the experimental field of Alemaya University, Ethiopia, during the 2002 rainfall season. The geographical location of the site is 09°26’N and 42°02’E with an altitude of 2000m. The mean annual rainfall for the last 22 years was 845mm. Dominant crops in the area include sorghum, maize, and wheat. Chat (*Catha edulis*) is also commonly grown in the area. The soil at the experimental site is a reddish brown regosol with a sandy clay loam texture underlain by granites. Some physical and chemical properties of the soils are presented in Table 6.1.

Table 6.1 Some physical and chemical properties of Alemaya Regosols

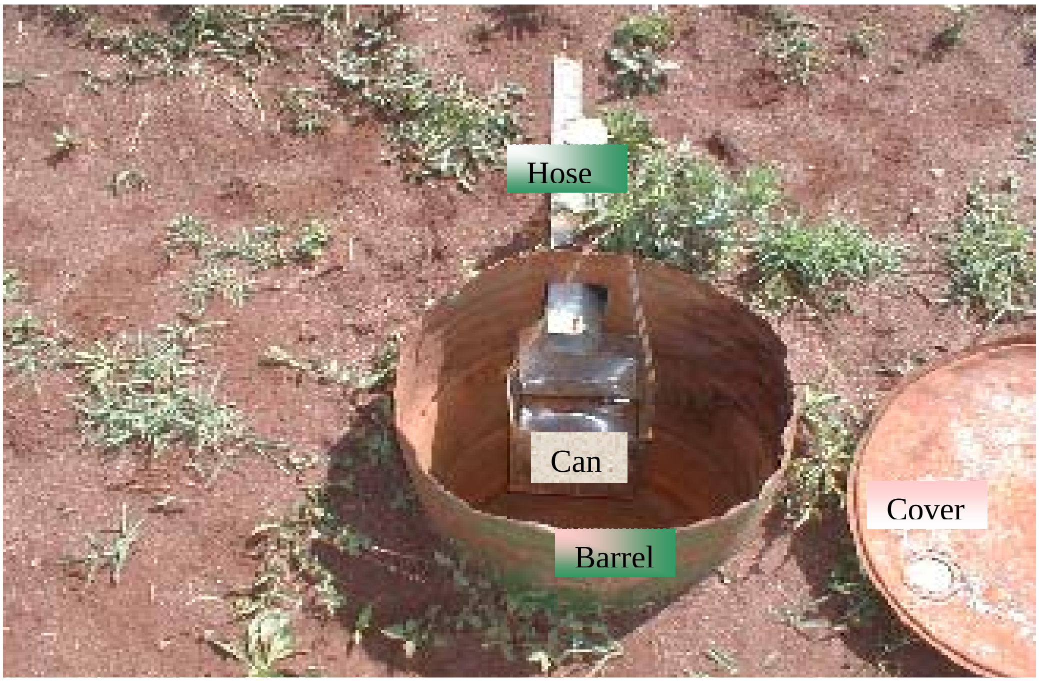
	Soil texture		OC	BD	WSA	pH	CEC		Exchangeable bases			ESP
	%		%	Mgm^{-3}	%	H_2O		………cmolc kg^{-1}…………..				
Sand	Silt	Clay						K	Na	Ca	Mg	
53.1	19.5	27.4	1.62	1.31	66.18	6.55	26.96	0.92	1.11	20.05	4.83	4.12

OC= Organic carbon; BD= Bulk Density; WSA= Water stable aggregates; ESP= Exchangeable sodium percentage

The experimental plots were constructed on cultivated lands with slope gradients of about 8 -10% before the onset of the rainfall season. Runoff plots of 10m long X 2m wide were bordered by corrugated iron sheets which were inserted into the soil to a depth of 20 cm leaving 25 cm above the soil surface to prevent lateral flows from the plots to the adjacent area. The layout of the runoff plots is shown in Fig. 6.1A.

The plots were ploughed manually to a depth of approximately 15 cm with inverted hoes locally called ‘Akafa’ before straw application. Then, the wheat straw with a soil water content of 8% was applied uniformly on the soil surface and was either left on the surface or incorporated into the soil at rates of 0, 4 and 8 Mg ha^{-1} with three replications making a total of 15 erosion plots. Percent surface cover by the straw was estimated using grid sieves of 8 mm mesh. A 10 x 10 grid mesh was counted and marked on the sieve. By randomly putting the sieve on the mulched surface, the number of openings of the sieves that were covered by the straws was counted and these were considered to represent the percent cover.

A. Experimental setup of the runoff plots



B. Runoff collectors

Fig. 6.1 Illustrations of (A) experimental layout of the runoff plots and (B) accessories for runoff collection

Table 6.2 Percent surface cover by the wheat straw applied at two rates and patterns

Residue rate (Mg ha^{-1})	Residue application methods	Mean percent cover ‡
0	-	0
4	Incorporated	41 (16.15)
8	Incorporated	66 (18.23)
4	Surface	68 (16.61)
8	Surface	88 (11.59)

‡The percent cover values presented here are means of 30 measurements each. Values in the parenthesis indicate standard deviations.

Runoff and sediment loss were collected in a barrel that was buried in the ground at a distance of about one metre from the lower end of each erosion plot. Each erosion plot was connected to a barrel through a hose of iron sheet. A cubic can having a diameter of 20 cm. was hanged in the barrel to collect runoff and sediments of small volumes (Fig. 6.1B). Run off in excess of the cans were collected in the barrel. The top of the barrel was closed securely to prevent entrance of direct rainfall and any other sediments to make sure that whatever is collected in the barrel comes only from the erosion plots.

Runoff was measured from the runoff-collection cans and barrels after each rainfall event. A rainfall in this study refers to that event which initiated runoff at least on the control plots. After thoroughly mixing the contents of the runoff collectors, a known volume of the effluent was oven dried to determine the weight of sediment. The runoff collecting cans and barrels were emptied and cleaned after each measurement to make them ready for the rainfall event.

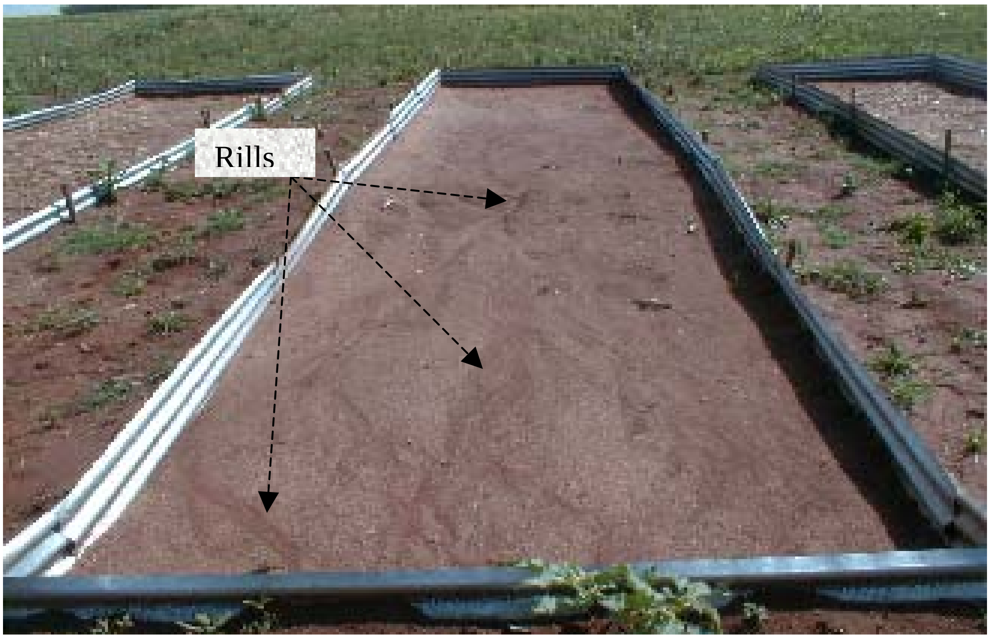
The experimental data were analyzed as randomized block design with three replications using SAS computer software. The significance level used in this text is p=0.05 unless and otherwise stated. The main limitation of this study was that the data were collected for only one season due to lack of funds and time.

6.3 Results and discussion

6.3.1 Runoff

The total runoff for the different treatments that was collected during the experimental period is presented in Fig. 6.3. The result indicated that the mean runoff collected at the control plot (without residue) was significantly higher than those from all residue treated plots ($p<0.001$). A remarkable visual evidence of higher runoff on the control plots was development of rills (Fig. 6.2A), which were not observed on the mulched plots (Fig. 6.2B).

Regression lines were constructed to show the relationship between runoff and mulching rates. The best-fit equations for the surface applied and incorporated residues are exponential with coefficients of determinations of 0.98 and 0.93 respectively. However, the regression equations shown in Fig 6.3 don't give realistic values for the surface and incorporated residue application methods at low mulching rates. Surface application of wheat residue reduced runoff significantly as compared to the same amount of residue incorporated into the soil ($p<0.01$). For a given residue application pattern, runoff was significantly lower on plots that received 8Mg ha^{-1} wheat residue than 4 Mg ha^{-1} ($p<0.01$). However, the difference between surface application of 4 Mg ha^{-1} and incorporation of 8 Mg ha^{-1} was not significant. This can be attributed to the percentage surface cover of the residue. Regardless of the amount of the residue applied, the percentage surface cover by wheat residue rates of 4Mgha^{-1} (surface) and 8 Mg ha^{-1} (incorporated) were 68 and 66 % respectively, and are comparable (Table 6.2). The percentage reductions in runoff due to surface application of 4 Mg ha^{-1} and incorporation of 8 Mg ha^{-1} were 68 and 69% respectively as compared to the control (Table 6.3). Surface application of 8 Mg ha^{-1} wheat residue reduced runoff by 95% as compared to the control plot.

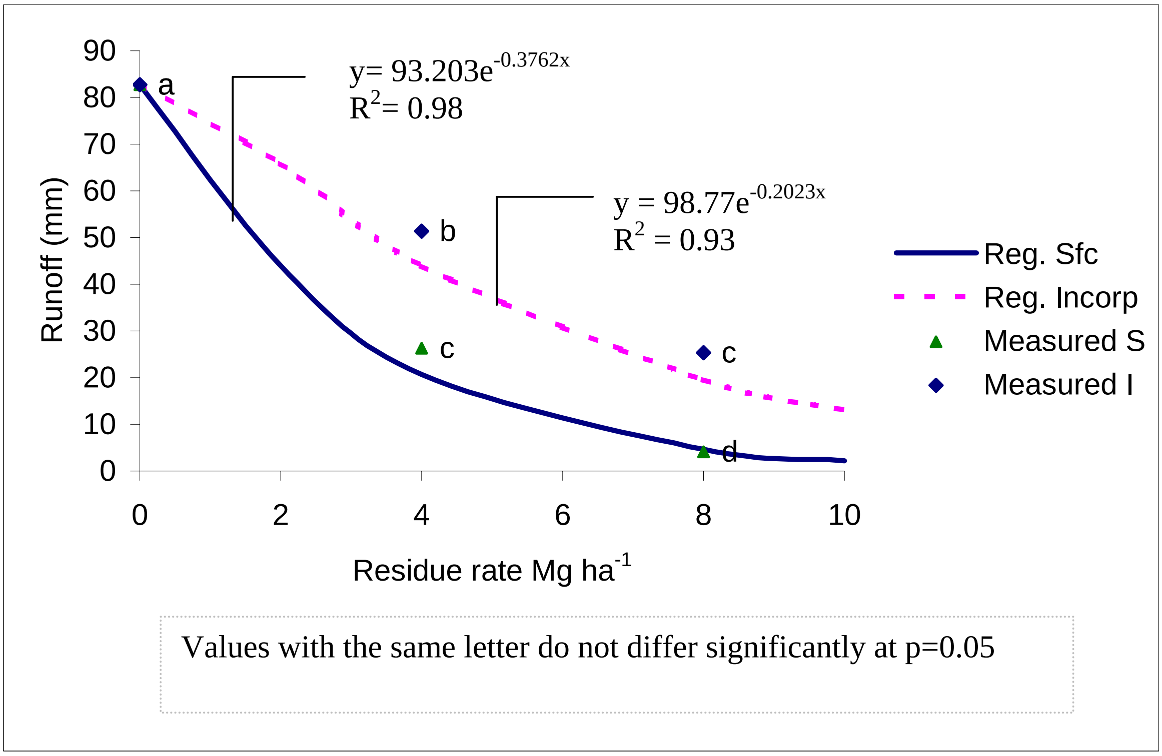


A. Control (0 Mgha^{-1}straw)

B. 8 Mgha^{-1} wheat straw applied on the surface

Fig. 6.2 Picture illustrating development of runoff pathways (rills) on the control (no straw) plot A, and absence of this on the residue treated plot, B.

The amount of rainfall collected during the experimental season of the year was 295.1mm. This refers only to the sum of rainfall that induced runoff. The total runoff during the experimental season was 28.03% of the total rainfall at the control plots (bare soils) and 17.4 to 1.4% for the mulched plots. These runoff data were highly correlated (r = 0.87) with the data obtained under laboratory rainfall simulation at 60 mm hr^{-1} intensity. The smaller correlation coefficient than what is normally expected is attributed to the absence of runoff from surface mulched plots (at both 4 and 8 Mg ha^{-1} straw) in the laboratory trials which can be associated to the short slope lengths of the laboratory erosion trays. The correlation between the lab and field results is even lower (r=0.83) when the simulated rainfall intensity is 30 mm hr^{-1} because no runoff was collected from all mulched plots in the lab at this intensity. Despite all these, the laboratory rainfall simulation results can be used as useful guides to compare the effect of various treatments on runoff and soil loss. Use of higher rainfall intensities could offer better results to clearly observe the effects of various treatments under small laboratory plots.



Values with the same letter do not differ significantly at p=0.05

Fig. 6.3 Total runoff (mm) collected during the 2002 rainfall season from the field runoff plots at Alemaya University experimental field station.

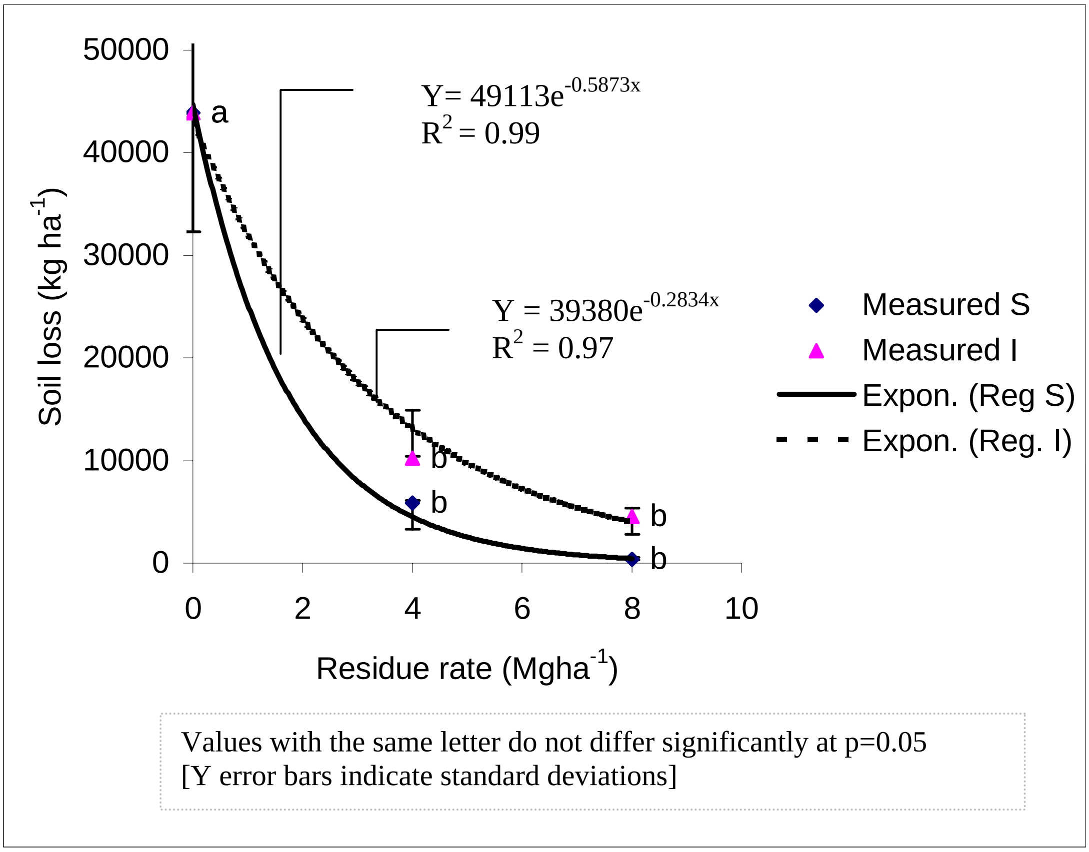
Table 6.3 Reductions (%) in runoff due to mulching as compared to the control.

Residue rate	Application method	
	Surface	Incorporated
0	0	0
4	68.2	37.9
8	95.1	69.4

6.3.2 Soil loss

The total soil loss collected from the experimental plots during the entire rainfall season is presented in Fig. 6.4. The result indicated that all crop residue rates and application methods that were considered in the study reduced soil loss significantly as compared to the control plot. The relationship between mulching treatments and soil loss was shown with exponential best-fit equations with coefficient of determinations of 0.99 and 0.97 for the surface and incorporated methods of applications respectively. However, the regression equations given in Fig. 6.4 do not provide realistic results when the residue rates are less than one Mg ha^{-1}.

Because of the financial and time constraints in this experiment, there are only few data points that are not reliable to develop dependable regression equations. Despite that, the equations may still be used to provide estimates the values of soil loss for a certain rate and method of straw application in the absence of a comprehensive data.



Values with the same letter do not differ significantly at p=0.05
[Y error bars indicate standard deviations]

Fig. 6.4 Total soil loss (kg ha^{-1}) collected during the 2002 rainfall season from the field runoff plots at Alemaya University experimental station.

The surface applied mulch at a rate of 4 and 8 Mg ha^{-1} is 42 and 92% more effective respectively in controlling soil loss than the same amount of incorporated mulch. From the residue treated plots, the highest and lowest soil loss reduction as compared to the control were 99.1% and 76.7% which were obtained by surface application of 8 Mg ha^{-1} and incorporation of 4 Mg ha^{-1} wheat residue respectively (Table 6.4). However, the difference between soil losses from the residue treated plots was not statistically significant. This indicates that under the conditions specified for the study site, mulching at a rate of 4 Mg ha^{-1} can effectively control soil loss regardless of the method of application. Therefore, application of more residue rates for erosion control may not be required unless especial cases are envisaged. This result is in agreement with that of Edwards et al. (1995) who studied the effect of barely straw under rainfall simulation at various slope gradients (5, 7 and 9%) on fine sandy loams in Canada.

Table 6.4 Reduction (%) in soil loss at residue treated plots as compared to the control.

Residue rate (Mg ha^{-1})	Methods of application	
	Surface	Incorporated
0	0	0
4	86.6	76.7
8	99.1	89.6

Comparison of the percentage effectiveness of the various rates and methods of mulching on reducing runoff and soil loss reveals that mulching is more effective in controlling soil loss than runoff. This is attributed to reduction in raindrop impact energy by mulching that reduces detachment of soil particles resulting in less sediment availability in overland flow. Moreover, the residues can gradually filter the sediments out of the running water thereby reducing the sediment concentration in the runoff in addition to reducing the runoff speed.

According to the best-fit equations shown in Fig. 6.4, surface application and incorporation of wheat straw at rates less than 1.5 and 2.2Mg ha^{-1} respectively may reduce soil loss by 50% as compared to the control. However, surface application of at least 4 Mg ha^{-1} is required to reduce soil loss to a tolerable level assuming tolerable soil loss of 3t ha^{-1} for the study site. Based on the average wheat grain yield production of 1.1t ha^{-1} and 2.8t ha^{-1} for traditional farming and improved technology packages respectively (Belay, 1997 as quoted by Sertsu, 2000), and assuming a residue: grain yield ratio of 1.5 for most cereals (Lal, 1995) the residue production rate will range from 1.65t ha^{-1} to 4.2t ha^{-1}. According to the regression equations presented in Fig 6.4, surface application of the residue obtained by conventional farming (i.e. 1.65 t ha^{-1}) may reduce soil loss at least by 50%. This result also suggests that for conditions similar to the study sites, the residues produced through application of improved technological packages will be adequate to reduce soil loss to tolerable level provided that all are left on the soil surface. However, as this information is based on only one season data, it should be confirmed by further research for lower residue rates and different agro climatic conditions.

6.3.3 Runoff and soil loss at each rainfall event

Runoff and soil loss followed similar patterns to the rainfall at the study site (Fig. 6.5). During the first part of the rainfall season, few erosive rainfalls were recorded till 18 June 2002. These rainfalls were high enough to induce erosion on most of the erosion plots. Therefore, even if the rainfall and erosion during the first part of the rainfall season look smaller than the that of the second part of the season at the experimental plots, an appreciable soil loss usually occurs during this first part of the rainfall season on cultivated farmlands due to various agricultural activities including soil cultivation and vegetation clearance during land preparation that expose the soil surface to the raindrop impact as compared to the second rainfall season where most of the crops are at good stand to provide the maximum surface cover.

No erosive rainfall occurred between 19 June and 24 July. As shown in Fig 6.5, maximum erosion was recorded from the experimental plots in August and September due to the high rainfall pattern. The effectiveness of the mulching (crop residues) in reducing runoff and soil loss was also reduced with increasing rainfall with time. Visual inspection of the experimental plots during the study period revealed that gradual redistribution of the straw within the plots and its loss with time made the soil surface more exposed to the impacts of rainfall energy. The other reason could be due to the high frequency rainfall that usually falls on already saturated surfaces that results in early initiation and higher volume of runoff, which may even carry the straws thereby reducing the effective surface cover.

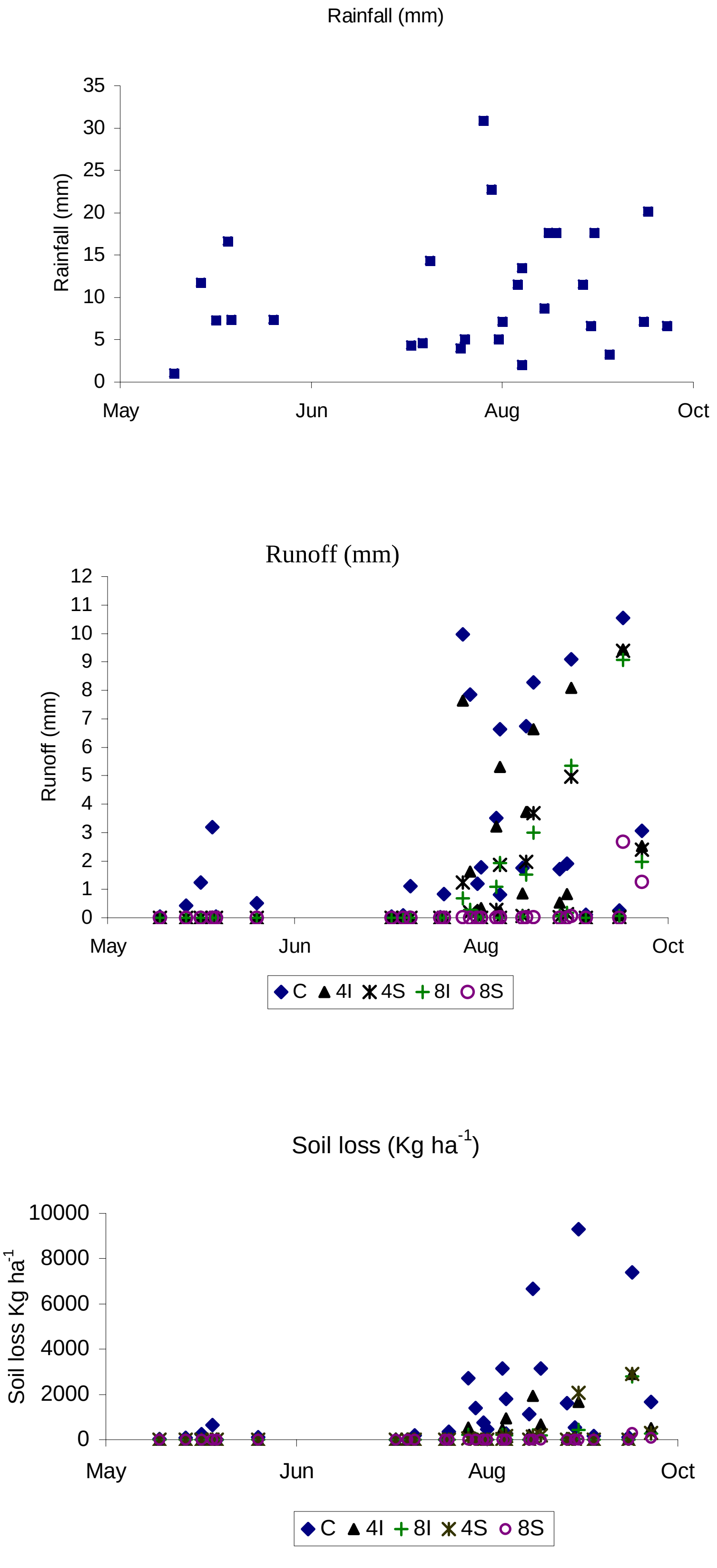
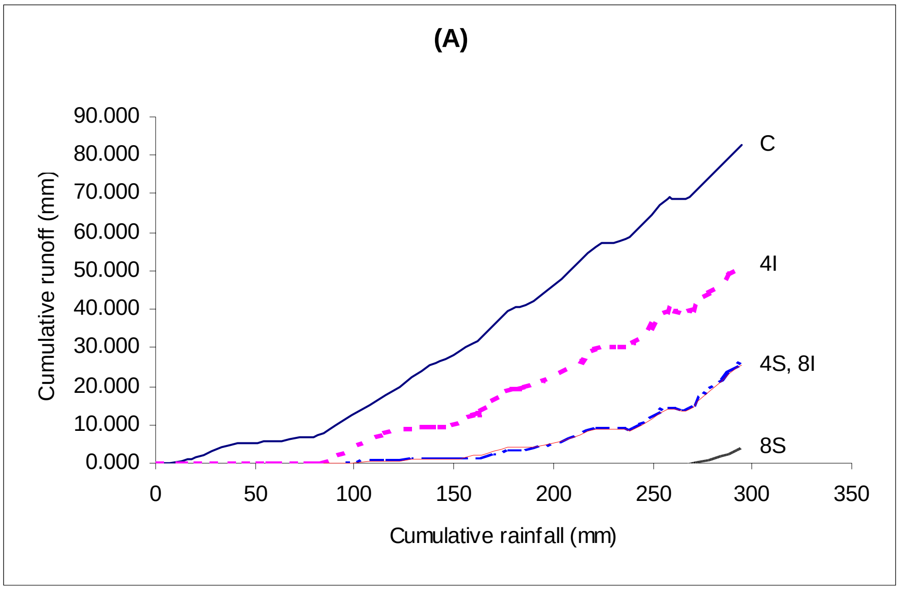


Fig. 6.5 Erosive rainfall (mm), runoff (mm) and soil loss(kg ha^{-1}) during the 2002 rainfall events at Alemaya erosion plots.

6.3.4 Trends of runoff and soil loss with cumulative rainfall

The relationship between cumulative rainfall and cumulative runoff and soil loss during the rainfall season is presented in Fig. 6.6. Runoff did not occur on residue treated plots during the first rainfall events that fell when the soil profile was dry. Successive rainfall initiated runoff later when the soil profile became wetter and due to surface sealing resulting from raindrop impacts. Higher runoff at the later stages of the rainfall season was associated with reduction in the matric potential of the soil due to the saturation of pore spaces with water and surface sealing during the first rainfall events. The fact that runoff was delayed on the residue treated plots as compared to the control (Fig.6.6A) is due to reduction in surface sealing and increased infiltration on mulched surfaces owing to reduced raindrop impact energy and increased surface roughness provided by the residue. Runoff often follows tortuous paths on the mulched plots, thus decreasing the average flow velocity (Meyer et al., 1970). Sediments are also obstructed and filtered by the crop residue reducing the overall sediment discharge.

This study indicated that surface application of a given rate of wheat residue is more effective in reducing runoff and soil loss as compared to incorporating the same amount to the soil. As shown in Fig. 6.6, Surface application of 4 Mg ha^{-1} wheat straw was as effective as incorporating twice as much wheat straw in reducing runoff. Surface application of 8 Mg ha^{-1} wheat straw effectively protected runoff and soil loss during the entire rainfall season. The fact that the rate of runoff and soil loss increased on the residue treated plots towards the end of the rainfall season could be attributed to the gradual reduction in the residue cover due to removal by overland flow and wind as well as its disintegration through time.



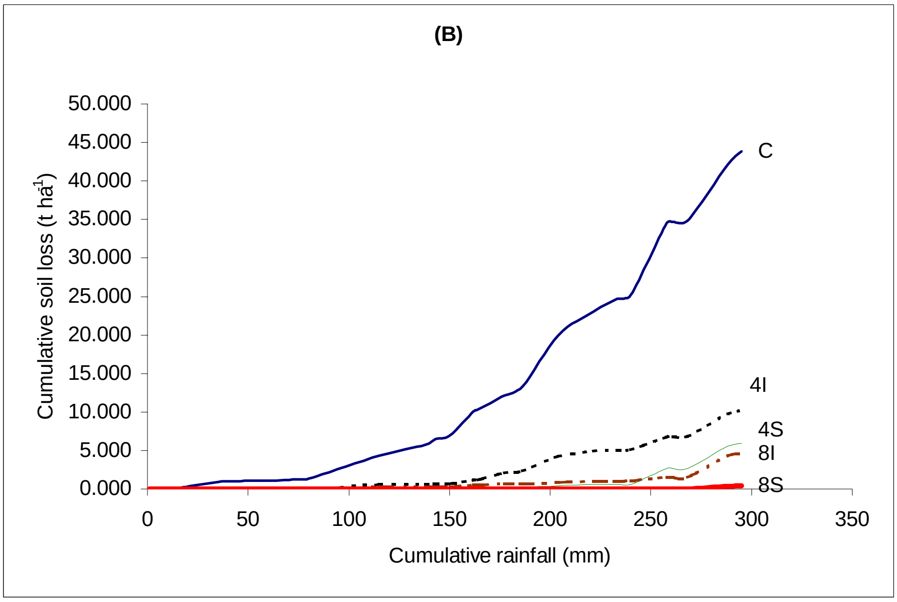


Fig. 6.6 The relationship between cumulative rainfall (mm) and cumulative runoff (mm) (A), and soil loss (kg ha^{-1}) (B) for three rates and two application methods of mulching during the 2002 rainfall season at Alemaya.]

6.4 Comparison of measured and estimated soil losses under mulching treatments

The total soil loss that was recorded from the field runoff plots during the study year was compared with the soil loss values predicted by using the SLEMSA and USLE models and are presented in Fig. 6.7.

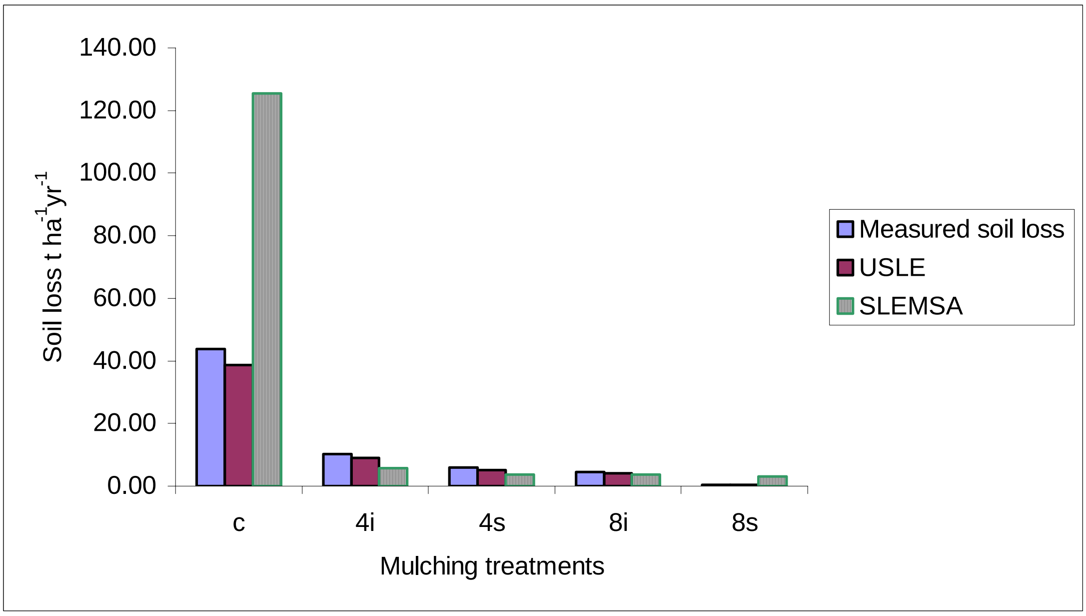


Fig. 6.7 Measured and estimated (by using the USLE and SLEMSA models) soil loss (t ha^{-1} yr^{-1}).

The results indicate that the soil loss values that were estimated by using the USLE were lower than the measured values. These values are however closer to the measured values as compared to those estimated by using SLEMSA. Moreover the USLE was more sensitive to the various percent covers provided by different mulching rates and application methods. On the other hand, SLEMSA overestimated soil loss from the bare soil as compared to the measured soil loss. It however underestimated the soil loss for the mulched plots as compared to the measured values. The differences among soil loss values for the mulched treatments as estimated by using SLEMSA were not well dispersed indicating the less-sensitivity of SLEMSA to change in cover. Although a one-year data is not sufficient to reach at some concluding remarks, the available results suggest that, the USLE is more appropriate for the conditions of this experiment to evaluate the effectiveness of percent mulch cover against soil loss as compared to the SLEMSA model.

6.5 Conclusion

Wheat straw used as mulch at rates of 4 Mg ha^{-1} and 8 Mg ha^{-1} at both application methods (surface and incorporated) significantly controlled runoff and soil loss as compared to the non-mulched plots (control) under field and natural rainfall conditions. Runoff and soil loss were reduced by at least 37 % and 76 % respectively on the residue treated plots as compared to the control. For a given application method, increased residue application rates reduced runoff significantly. Surface application of wheat residue was more effective in controlling runoff than incorporation the same amount into the soil.

Although higher rates and surface applied residue apparently reduced soil loss as compared to lower rates and incorporated ones, the difference among the residue treated plots was not statistically significant. Therefore, under limited availability of residue where it is usually used for different household purposes, 4 Mg ha^{-1} wheat straw can effectively be used to control soil loss for areas having similar topographic and climatic conditions with that of the study site. However, since this figure is still greater than the average residue production rate for most cereals in the country, further research is required to evaluate the effectiveness of lower residue rates on soil conservation.

Comparison of measured and estimated soil losses from mulched plots on Alemaya university regosol revealed that the USLE provided more realistic estimates that are closer to the measured values with greater sensitivity to changes in surface cover as compared to the SLEMSA model.

CHAPTER 7

GENERAL CONCLUSIONS AND RECOMENDATIONS

7.1 Soil erodibility

The inherent susceptibility of soils to detachment and transport by the various erosive agents is a function of soil properties including among others, texture, aggregate size and stability, organic matter content, clay mineralogy and electrolyte concentrations. The extent of each of these soil properties is different in different soils thereby influencing the degree of vulnerability of a given soil to destructive forces. These are in turn influenced by the interactive effects of the topographic, cover and rainfall factors.

Soil erodibility assessment using simulated rainfall on the three different textured soils revealed that runoff and sediment yield increased with increasing slope gradient for silt and clay dominated soils and was not significant for the sandy soils. Sandy soils were the least erodible. Despite a slight tendency of greater sediment yield on silt than clay soils at low slope gradients, the difference was not significant on higher slope gradients. This research also revealed that higher rainfall intensity (60 mm hr^{-1}) was more erosive than lower rainfall intensity (30 mm hr^{-1}) regardless of slope gradient and soil texture.

In another experiment where erodibilities of soils form 15 different locations in Harerge were evaluated using laboratory rainfall simulation, the soils showed different degrees of vulnerability to surface sealing, runoff and sediment yield which were associated with various soil properties. It was found that aggregate stability was the main determinant factor to the susceptibility of the soils to sealing, runoff and soil loss on these soils. The aggregate stability was in turn affected by organic carbon content, percent clay and ESP. Soils with relatively high ESP such as Babile (13.85) and Gelemso (7.18) were among the lowest in their aggregate stability (percent water stable aggregates 33.7 and 42.2 respectively); have highest runoff and sediment yield as compared to other soils in the study. Similarly, most of those soils with relatively low ESP, high C% and WSA such as Hamaressa, AU Vertisol and AU regosol are among the least susceptible to sealing and interrill erosion. Nevertheless, some exceptions include soils like those of Hirna where high runoff was recorded whilst having relatively high C%, low ESP and high water stable aggregates.

The soils considered in the study were placed into five categories based on the degree of their susceptibility to runoff and sediment yield. In the first category are Babile and Gelemso, which have high runoff and high sediment yield. The possible explanations for their high runoff is due to high rate of surface sealing that in turn resulted from low aggregate stability owing to high ESP, low % C and low clay content. However, the seals that are formed from the less coherent coarse particles are too weak to resist the shearing force of surface flow resulting in high sediment yield but strong enough to inhibit infiltration. Soils with high to medium runoff and low sediment yield such as Hirna, Lange, Amadle and Adele were considered in the second category. Despite the high runoff, the soils are more resistant to detachment and transport by overland flow. This could be associated with the soil properties as most of them have high clay and C % that keeps the seals coherent enough to withstand detachment.

The soils of Diredawa and AU Alluvial are composed of coarse and loose particles with low aggregate stability (%WSA =35.5 and 48.9 respectively) that resulted in medium runoff (about 35% of the applied rainfall) but high sediment yield. Despite the low aggregate stability, these soils had a better infiltration rate due to the composition of the coarse particle sizes. But these soils are susceptible to high detachment as the particles are too loose to resist the shearing force of the overland flow.

The fourth category includes Chiro, Chinaksen and Karamara soils whose composition of water stable aggregates (0.25 –2.0mm in diameter) range from 59 – 79%. The runoff and sediment yield of these soils is intermediate as compared to other soils in the study areas.

On the other hand, Hamaresa, AU regosol, Bedessa and AU vertisol have relatively low runoff and sediment yield. This can be attributed to the relatively high clay and organic carbon contents and low ESP that resulted in high aggregate stability (62 to 71% water stable aggregates) which in turn resulted in less susceptibility to sealing and high infiltration rate. Therefore, the low sediment yield in these soils could be attributed to two reasons: Firstly, the aggregates are strong enough to resist detachment and secondly, due to the high infiltration rate, the overland flow is too weak to transport the sediments.

It is important to note that the terminologies such as high, medium or low that have been used to compare the various erosion parameters in this text, were only in reference to the soils considered in the study and not to any other standard reference. Besides, extrapolating the laboratory erodibility values to a large field scale conditions may also be misleading as the sediment yield values obtained under the rainfall simulation are very much underestimated due to the short slope length. Therefore, the sediment yield values should only be considered as relative indices for qualitative assessment of the particular soils.

7.2 Soil loss modelling

The estimated soil loss obtained for the different study sites considered in this study by using SLEMSA and USLE was correlated to the laboratory soil erodibility values (sediment yield) with correlation coefficients of r=0.61 and 0.33 respectively. The low correlation between the soil loss estimated by USLE and sediment yield could be ascribed to the less sensitivity of the model to the soil erodibility factor. Both SLEMSA and USLE enabled to identify the potential erosion hazards for the study sites. Despite the differences in the procedures used in the two models, both estimated higher soil loss for Gelemso, Babile, Karamara and Hamaressa. Soil loss was lower for Diredawa, AU-vertisol and AU-Alluvial all of which occur on a relatively level topography. The high soil loss for Babile and Gelemso conforms with the relative soil erodibility values obtained under rainfall simulation suggesting that soil erodibility, among others, is the main factor contributing to high soil loss for these soils.

The difference in the estimated soil losses for the different sites was a function of the interaction of the various factors involved in calculating the soil loss. For instance, although the laboratory scale soil erodibility values were low to medium for Hamaressa and Karamara, the estimated soil loss was higher due to the field topographic situations such as high slope gradient. On the other hand, for the Diredawa and AU alluvial soils, despite the high sediment yield obtained under the laboratory study, the estimated soil loss was low due to their occurrence on relatively level topography.

The two models that were used to estimate soil loss in the study sites showed different degrees of sensitivities to their input variables. SLEMSA was highly sensitive to changes in rainfall kinetic energy (E) and soil erosdibility (F) and less sensitive to slope length and vegetal cover. The highly significant correlation between sediment yield determined in the lab and estimated soil loss by SLEMSA (r=0.61) can somehow explain this relationship. USLE was highly sensitive to slope gradient and cover but less so to slope length as compared to the other input factors.

Qualitative comparison of the soil loss values estimated by using the USLE and SLEMSA models with that obtained under laboratory rainfall simulation revealed that although some discrepancies are observed that indicate the risk of using laboratory values to validate soil loss models, these values give some indications of the soils' inherent susceptibility to erosion and are valuable especially for comparison of different treatment effects under well controlled condition at limited cost.

7.3 Soil conservation

This study indicated that under the current management situations, about 70% of the soils of Harerghe would lose the productive top 15cm of their soils in less than hundred years exposing the infertile subsoils and converting most of the agricultural lands into marginal lands. Therefore, it is imperative that appropriate management practices be designed and implemented to sustain soil productivity and reduce erosion to at least tolerable levels. It is advisable that the two approaches of soil conservation namely mechanical and biological conservation measures be designed and implemented based on the level of severity of erosion. The fact that mechanical soil conservation measures such as terraces, diversions, and bunds are costly and time consuming necessitate use of easily available farm products such as crop residue for soil and water conservation. The question is 'how much residue should be applied and how?' To answer this question, this study evaluated various rates and application patterns of wheat residue on runoff and soil loss both in the laboratory rainfall simulation and under field natural rainfall conditions. Both experiments revealed that surface application of crop residue is more effective in reducing soil loss and runoff than incorporating the same amount of the residue into the soil. Likewise, for a particular residue application pattern, runoff and soil loss decreased with increasing application rate of the mulch. However, the difference was not significant between 4 Mg ha^{-1} and 8 Mg ha^{-1} wheat straw application rates suggesting that the former can effectively control soil loss and can be used in areas where there is limitation of crop residues due to their preferential use for various other purposes provided that other conditions are similar to that of study site (AU Regosols). Yet, under the traditional low input farming, this amount of residue is usually unattainable due to low productivity. The conventional average residue production rate of 1.65t ha^{-1}, may reduce soil loss by about 50% as compared to the bare soils if it is left on the soil surface. It should however be noted that the effectiveness of mulching in controlling soils loss and runoff can vary under various slope gradients, rainfall characteristics and cover types. On steep slopes and /or higher rainfall events, the mulching material can easily be removed by concentrated overland flow. Therefore, in such cases, mulching should be supplemented with the mechanical soil conservation measures and vise versa. Research is required to evaluate the effectiveness of residue rates of less than 4 t ha^{-1}.

7.4 General remarks

One of the main factors contributing to severe soil degradation by accelerated soil erosion in Ethiopia is related to the ever-growing population pressure that led to shortage of arable lands and forced the farmers to clean and cultivate marginal areas. Moreover, the lack of adequate land use policy added to the mountainous and rugged topography as well as erratic rainfall exacerbate the problem. Therefore, the following general points need due consideration if further human induced land degradation is to be resolved.

- Create awareness among the farmers about short-term and long-term impacts of land degradation and the possible methods of reducing it which may involve family planning issues.
- Educate and support the farmer towards teaching his family so that job diversification can be possible to reduce the pressure on a given piece of land.
- Conduct farmer based research to the interest of the farmer.
- Develop, test and implement appropriate land use strategy
- Evaluate and validate indigenous and exotic soil and water management technologies based on farmer-oriented research.

Note that the above remarks are not specific outputs of this study but can provide some idea towards reducing human induced environmental degradation thereby contributing to environmental protection and its sustainability.

7.5. Research needs

Detailed process based soil loss estimation shall be made in order to get a more accurate estimate of soil loss from a particular area so that site specific management options can be executed with better confidence. Furthermore, integrated soil conservation research is required to develop a comprehensive database for modeling of the various soil erosion parameters as well as to design and implement appropriate soil conservation measures. The following broad indicators are only few of the many and diversified research needs that would be worth mentioning in relation to soil erosion and conservation:

- Conducting intensive research related to the effect of soil properties on soil erodibility under various site-specific conditions with emphasis to aggregate stability and size distribution, clay mineralogy, ionic composition, texture and organic matter.

- Assessing the relative importance of the various soil erosion parameters that are most responsible to degradation in a given area.

- Developing comprehensive database in order to develop sound erosion models which are relevant to the specific conditions of a given site. This may include accumulation of more detailed data on climate (including rainfall, temperature, evapo-transpiration, etc); soil; canopy and surface cover; topography; geology and hydrology; land management, economic and social aspects.

- Studying the effectiveness of various types and rates crop residues under different climatic, soil and topographic conditions in controlling soil erosion.

- Assessing the influence of various cropping (such as crop rotation, strip cropping) and tillage systems on erosion for various site-specific conditions.

- Evaluating the effectiveness of single and combined effects of the different mechanical and biological soil conservation measures for various soil conditions.

- Validation of the most accepted erosion models and soil conservation measures with reference to the existing situations in a given study site.

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REFERENCES

AARSTAD, J.S. and MILLER, D.E. 1978. Corn residue management to reduce erosion in irrigation furrows. *J. Soil and Water Conservation*, 33:289-291.

AARSTAD, J.S. and MILLER, D.E. 1981. Effects of small amounts of residue on furrow irrigation. *Soil Sci. Soc. Amer. J.*, 45:116-118.

ABEL, N. and STOCKING, M.A. 1987. A rapid method of assessing rates of soil erosion from rangeland: An example from Botswana. *J. Range Management*, 40: 460-466.

AGASSI, M. 1996. *Soil Erosion, Conservation and Rehabilitation*. New York: Marcel Dekker Inc.

AGASSI, M., BLOEM, D. and BEN_HUR, M. 1994. Effect of drop energy and soil and water chemistry on infiltration and erosion. *Water Resources Res*., 30 (4): 1187-1193.

AGASSI, M., SHAINBERG, I., and MORIN, J., 1981. Effect of electrolyte concentration and soil sodicity on infiltration rate and crust formation. *Soil Sci. Soc. Amer. J.*, 45:848-851.

ALBALADEJO, J., and STOCKING, M. 1989. Comparative evaluation of two models in predicting storm soil loss from erosion plots in semi-arid Spain. *Catena*, 16(3): 227-236.

ANNERSTEN, L. 1988. SADCC co-ordination in soil and water conservation. ODU Bulletin, Hydraulics Research Ltd., UK, No.9, pp.8-10.

ARNOLD, J.G., WILLIAMS, J.R., GRIGGS, R.H., and SAMMONS, N.B. 1990. SWRRB - a basin scale simulation model for soil and water resources Management. Texas .A and M Press.

BAJRACHARIA, I., and LAL, R. 1999. Land use effects on soil crusting and hydraulic responses of surface crusts on a tropical alfisol. *Hydrological Processes*, 13: 59-72.

BARTHES, B., AZONTONDE, A., BOLI, B.Z., PRAT, C., and ROOSE, E. 2001. Field scale runoff and erosion in relation to topsoil aggregate stability in three tropical regions (Benin, Cameroon, Mexico). *European J. of Soil Science*, 51: 485-495.

BEASLEY, D.B., HUGGINS, L.F., and MUNKE, E.J. 1980. ANSWERS - a model for watershed planning. *Trans Am Soc. Agric Eng.*, 23:938-944.

BECK, M.B. 1987. Water quality modelling: a review of uncertainty. *Water Resources Res.*, 23 (8): 1393-1442.

BEN-HUR, H.I., SHAINBERG, I., BAKKER, D., and KERREN, R. 1985. Effect of soil texture and CaCO3 content on water infiltration in crusted soils as related to water salinity. *Irrig.Sci.*, 6:181-194.

BLACK, A.L. and SIDDOWAY, F.H. 1979. Influence of tillage and wheat straw residue management on soil properties in the Great Plains. *J. Soil and Water Conservation*, 34 (2): 220 – 223.

BOBE, W.B. and GACHENE, C.K.K. 1999. Soil productivity evaluation under different soil conservation measures in the Harerge highlands of Ethiopia. *East Afr. Agric. and Forestry J.*, 65 (2): 95-100.

BONSU, M. 1983. Organic residues for less erosion and more grain in Ghana. In El-Swaify, W.C. Moldenhauer, and Andrew Lo (Eds.). *Soil Erosion and Conservation*. Iowa: Soil Conservation Society of America, p. 607 – 614.

BOWYER-BOWER, T.A.S. 1993. Effects of rainfall intensity and antecedent moisture on the steady- state infiltration rate in a semi arid region. *Soil use and management*, 9: 69-76.

BOX, J. E. 1981. The effects of slaty fragments on soil erosion by water, *Soil Sci. Soc. Am. J.*, 45:111-116.

BOX, J.E. and BRUCE, R. 1996. The effect of surface cover on infiltration and soil erosion. In: M. Agassi.(Ed.). *Soil erosion, Conservation and Rehabilitation*. New York: Marcel, Dekker, Inc.

BRADFORD, J.M., FERRIES, J.E., and REMLEY, P.A., 1987. Interrill soil erosion processes: relationship of splash detachment to soil properties. *Soil Sci. Soc. Am. J.* 51:1571-1575.

BRADFORD, J.M., and HAUG, C. 1992. Mechanisms of crust formation: physical components. In: M. E. SUMNER and B. A. STEWART.(eds.). *Advances in Soil Science, Soil crusting: physical and chemical processes*. Boca Roton: Lewis Publi., pp.55-72.

BRADFORD, J.M., and HUANG, C., 1996. Splash and detachment by water drops. In AGASSI, M. (Ed). *Soil Erosion, Conservation and Rehabilitation*. New York: Marcel Dekker Inc.

BRADFORD, J.M., REMLEY, P.A., FERRIES, J.E., and SANTINI, J.B., 1986. Effect of soil surface sealing on splash from a single water drop. *Soil Sci. Soc. Amer. J.*, 50:1547-1552.

BROWN, L.R., DURING, A., FLAVIN, C., FRENCH, H., JACOBSON, J., LOWE, M., POSTEL, S., RENNER, M., STARKE, L and YOUNG, L. 1990. *State of the world, 1990*. New York: World Watch Institute and W.W. Norton and company.

BROWN, M. J. 1985. The effect of grain straw and furrow irrigation stream size on soil erosion and infiltration. *J. Soil and Water Conservation*, 40 (4):389-391.

BROWN, M.J., ROBBINS, C.W. and FREEBORN, L.L. 1998. Combining cottage cheese whey and straw reduces erosion while increasing infiltration in furrow irrigation. *J. of Soil and Water Conservation*, 53 (2):152-156.

BUERKERT, A., BATIONO, A., and DOSHA K. 2000. Mechanisms of residue mulch induced cereal growth increases in West Africa. *Soil Sci. Soc. of Ame. J.*, 64:346 – 358.

BUOL, S.W., HOLE, F.D., and MCCRACKEN, R.J. 1973. Soil genesis and classification, Iowa state Univ. Press.

BURINGH, P. 1981. An assessment of losses and degradation of productive agricultural land in the world: Working group on soil policy, *FAO*, UN, Rome, Italy.

CHAKELA, Q.; MOLAPO, J.; PUTSOANE, T. G. 1989. Erosion hazard mapping of the SADCC region. Part 3. Lesotho. Report - SADCC Soil and Water Conservation and Land Utilization Programme, No.25, pp 15.

CHAKELA, Q.; STOCKING, M. 1988. An improved methodology for erosion hazard mapping. Part II: Application to Lesotho. Geografiska Annaler, A (Physical Geography),70A (3): 181-189.

CHEN, Y., TARCHITZKY, J., BROUWER, J., MORIN, J., and BANIN, A. 1980. scanning electron microscope observations on soil crusts and their formation. *Soil Sci*.130: 49-55.

CLAASSENS, A.S., and VAN DER WATT, H.V.H., 1993. An inexpensive, portable rain simulator: construction and test. *South Afr. J. Plant and Soil*, 10(1):6-11.

COGO, N.P., MOLDENHAUER, W.C., and FOSTER, G.R. 1983. Effects of crop residue, tillage induced roughness, and runoff velocity on size distribution of eroded soil aggregates. *Soil Sci. Soc. of Am. J.*, 47 (5): 1005-1008.

CRUSE, R.M., ROBERTO MIER, MIZE, C.W. 2001. Surface residue effects on erosion of thawing soils. *Soil Sci. Soc. of Am. J.* 65:178-184.

DAY, R.R., 1965. Particle fractionation and particle size analysis. p.545-567. In: Black, C.A., Evans, D.D., White, J.L., Ensminger, L.E., Clark, F.E. and Dinauer, R.C. (eds.). 1965. *Methods of soil analysis. Part I: Physical and Mineralogical Properties, including Statistics of Measurement and Sampling*, American Society of Agronomy, inc., Madison, Wisconsin, USA.

DEPARTMENT OF AGRICULTURAL TECHNICAL SERVICE. 1976. Soil Loss Estimator for Southern Africa. Development and proposed application of a model: Proceedings of a workshop held at Cedara in November, 1976. *Natal Agricultural Research Bulletin,* no.7. Natal Region, South Africa.

DICKEY, E.C., SHELTON, D.P., JASA, P.J., and PETERSON, T.R. 1985. Soil erosion in tillage systems used in soybean and corn residues. *Trans of the ASAE,* 28:1124-1129.

DUDAL, R. 1981. An evaluation of conservation needs, In:R.P.C. Morgan (ed.). *Soil conservation Problems and prospects*. Chichester: John Wiley and Sons, p. 3-12.

DUDAL, R. 1982. Land Degradation in a world perspective. *J. of Soil and Water Conservation*, 37:345–349.

DUNNE, T., DIETRICH, W.E., and BRUNENGO, M.J. 1978. Recent and past erosion rates in semi arid Kenya. *Z. f. Geomorph. Suppl*., 29: 130-140.

EBEID, M.M, LAL, R., HALL G.F., MILLER, E. 1995. Erosion effects on soil properties and soybean yield of a Miamian soil in western Ohio in a season with below normal rainfall. *Soil Technology*, 8:97:108.

EDWARDS, L., BURNEY, J., and DEHAAN, R. 1995. Researching the effects of mulching on the cool -period soil erosion control in Prince Edwards Island, *Canada. J. Soil and Water Cons*., 50(2):184-187.

EDWARDS, L.M., VOLK, A. and BURNEY, J. R. 2000. Mulching potatoes: aspects of mulch management systems on soil erosion. *Amer. J. of Potato Res.*, 77: 225–232.

ELWELL, H.A. 1978. Modelling soil losses in Southern Africa. *J. Agric. Eng. Res.* 23:117-127.

ELWELL, H. A. 1984. Sheet erosion from arable lands in Zimbabwe: prediction and control. In: Walling, D.E.; Foster, S.S.D.; Wurzel, P. (Eds.) IAHS Publication, No.144, pp.429-438.

ELWELL, H. A. 1994. Conservation tillage for sustainable crop production systems. On the feasibility of modelling annual soil loss, runoff and maize yield for the two project research sites, Domboshawa and Makoholi. Projections to other Natural Regions in Zimbabwe. Testing of and contributions to SLEMSA. pp.59.

ELWELL, H. A. and STOCKING, M. A. 1982. Developing a simple yet practical method of soil-loss estimation. *Tropical Agriculture,* 59(1): 43-48.

ERENSTEIN, O. 2002. Crop residue mulching in tropical and semi-tropical countries: An evaluation of residue availability and other technological implications (Review). *Soil and Tillage Res.,* 67: 115-133.

ERENSTEIN, O. 2003. Smallholder conservation farming in the tropics and sub-tropics: a guide to the development and dissemination of mulching with crop residues and cover crops. Agriculture, Ecosystems and Environment, 100 (1): 17-37.

EWEG, H. P. A.; VAN LAMMEREN, R.; DEURLOO, H.; WOLDU, Z. 1998. Analysing degradation and rehabilitation for sustainable land management in the highlands of Ethiopia. Land Degradation & Development,9(6):529-542.

FAHMY, H. 1998. Aswan High Dam. In: Takeuchi, K., Hamlin, M., Kundzewicz, Z., Rosbjerg, D., Simonovic, S. (eds.), Sustainable Reservoir develeopement and Management. IAHS Publication, vol. 251. Wallingford, pp.142-151.

FEKADU YOHANNES, 2001. Personal communication. Alemaya University, Department of Agricultural Engineering, P.O.Box 138, Dire Dawa, Ethiopia.

FELEKE, A. 1987. Effect of vegetative cover, tillage and planting system on runoff, soil erosion and other soil physical properties. *Agricultural mechanization in Asia, Africa and Latin America*, 18(2):23-28.

FIKRU, A. 1990. The role of land use planning in the improvement of natural resources management: In *National Conservation Strategy Conference*. Vol.3.

FOLLETT, R.F. 2001. Soil management concepts and carbon sequestration in cropland soils. *Soil Tillage Res*., 61:77-92.

FOSTER, G.R. 1990. Process based modelling for soil erosion by water on agricultural land. In: J. Boardman,, I. D.L. Foster and J.A. Dearing (Eds.). *Soil Erosion on Agricultural Land*. New York: John Wiley and Sons Ltd.

FOSTER, G.R., JOHNSON, C.B. and MOLDENHAUER, W.C. 1982. Hydraulics of failure of anchored corn stalk and wheat straw mulches for erosion control. *Transactions of the ASAE*, 25:940-946.

FOSTER, G.R., YOUNG, R.A. ROMKENS, M.J.M. and ONSTAND, C.A. 1985. Process of soil erosion by water. In R.F. Follett and B.A Stewart (Eds.). *Soil Erosion and Crop Productivity*, ASA, CSSA and SSSA Madison, pp. 137-162.

FOX, D.M. and BRYAN, R.B. 1999. The relationship of soil loss by interrill erosion to slope gradient. *Catena*, 38:211-222, www.Sciencedirect. Com

FRANZLUEBBERS, A.J., HANEY, R.L., HONEYCUTT, C.W., ARSHAD, M.A., SCHOMBERG, H.H., AND HONS, F.M.2001. Climatic influences on active fractions of soil organic matter. Soil Biology and Biotechnology, 33 (7-8):1103-1111.

FRYE, W.W., EBELHAR, S.A., MURDOCK, L.W. and BLEVINS, R.L. 1982. Soil erosion effects on properties and productivity of two Kentucky soils. *Soil Sci. Soc. Ame. J.*, 46:1051-1055.

FULLEN, M.A. and BRANDSMA, R.T. 1995. Property changes by erosion of loamy sad soils in East Shropshire, UK. *Soil Technology,* 8:1-15. www.Sciencedirect. Com

GILLEY, J.E., FINKNER, S.C., and VARVEL, G.E. 1986. Runoff and erosion as affected by sorghum and soybean residue. *Trans of ASAE,* 29(6):1605-1610).

GOLDENBERG, S., SUAREZ, D.L., and GLAUBIG, R.A., 1988. Factors affecting clay dispersion and aggregate stability of arid zone soils. *Soil Sci*., 146:317-325.

GOLLANY, H.T., SCHUMACHER, T.E., EVENSON, V.D., LINDSTROM, M.J., and LEMME, G.D., 1991. Aggregate stability of an eroded and desurfaced typic Agriustoll. *Soil Sci. Soc. Am. J.,* 55:811-816.

GRANGER, J. E. 1984. Some thoughts on soil erosion in Transkei. IMDS Discussion Papers, Institute for Management and Development Studies, University of Transkei, No.12, 25pp

GRIFFITHS, J.S.and RICHARDS, K.S. 1989. Application of low-cost database to soil erosion and conservation studies in the Awash basin, Ethiopia. *Land Degradation and Rehabilitation*, 1(4):241:262.

GRISI, B., GRACE, C., BROOKES, P.C., BENEDETTI, A. AND DELL'ABATE, M.T., 1998. Temperature effects on organic matter and microbial biomass dynamics in temperate and tropical soils. *Soil Biology & Biochemistry,* 30: 1309–1315.

GROHS, F., and ELWELL, H.A. 1993. Estimating sheet wash erosion from cropland in communal area of Zimbabwe. *Transactions of the Zimababwe Scientific association,* 67: 6-12.

GROSH, J.L. and JARRETT, A.R., 1994. Interrill erosion and runoff on very steep slopes. *Transactions of the ASAE,* 37 (4):1127-1133.

HAIRSINE, P.B., and ROSE, C.W. 1991. Rainfall detachment and deposition: Sediment transport in the absence of flow driven processes. *Soil Sci. Soc. Am. J.,* 55: 320-324.

HARTMANN, M. O.; MCPHEE, P. J.; BODE, M. L. 1989. The erodibility of some soil series in the pineapple-producing coastal area of the eastern Cape. *South African Journal of Plant and Soil*, 6(4):271-275.

HUDSON, N. 1984. *Soil Conservation. 3rd edition*. London: Batsford Academic and Educational Ltd.

HURNI, H. 1985. Erosion-Productivity-Conservation Systems in Ethiopia. *Soil Conservation Research Project (SCRP*). In Pla Sentis, I. (Ed.). Soil Conservation and Productivity. Proceedings IV International Conference on soil conservation, Maracay, Venezuela, vol. 1+2: 654-674.

HURNI, H. 1986. Guidelines for development agents on soil conservation in Ethiopia. CFSCDD, Min. of Agriculture, Addis Ababa.

IDOWU, O.J., RICKSON, R.J., and GODWIN, R.J. 2001. Erosion as affected by tillage induced roughness and surface mulch in a soil with a simulated subsurface pan. *Trans of ASAE,* 45(1):83-87.

IGWE, C. A. AKAMIGBO, F. O. R.; MBAGWU, J. S. C. 1999. Application of SLEMSA and USLE erosion models for potential erosion hazard mapping in South-eastern Nigeria. International Agrophysics, 13(1):41-48.

INTARAPAPONG, W.; HITE, D.; REINSCHMIEDT, L. 2002.Water quality impacts of conservation agricultural practices inthe Mississippi Delta. *Journal of the American Water Resources Association*, 38(2): 507-515.

KEMPER, W.D., and KOCH, E.K., 1966. Aggregate stability of soils from western United States and Canada. *Collorado Agric. Expt. Stn. Bull. no*. 1355, p.1-52. Agric. Res. Service, USDA and Collorado Agric. Expt.Stn, Fort Collins, CO.

KEMPER, W.D., and ROSENAU, R.C., 1986. Aggregate stability and size distribution. In: *Methods of Soil Analysis, Part I: .Physical and Mineralogical Methods.* Agronomy Monograph no.9 (2nd edition). American Society of Agronomy – Soil Science Society of America, 677, South Segoe Road, Madison, USA.

KENNETH G.R., GEORGE, R.F., GLENN, A.W., and JEFFREY, P.P. 1991. RUSLE: Revised Universal Soil Loss Equation. *Journal of Soil and Water Conservation, Jan.-Feb., 1991.*

KERN, J.S. and JOHNSON, M.G. 1993. Conservation tillage impacts on natural soil and atmospheric carbon levels. *Soil Sci. Soc. Am. J.*, 57:200-210.

KILEWE, A.M., 1987. Prediction of soil erosion rates and the effect of topsoil thickness on soil productivity, Ph.D. Thesis: University of Nairobi, Kenya.

KINNEL, P.L.A. 1980. Rainfall intensity-kinetic energy relationships for soil loss prediction. *Soil Sci. Soc. Am. Proc*., 45:153-155.

KNISEL, W.G.1980. CREAMS: A field scale model for Chemicals, Runoff and Erosion from Agricultural Management Systems. USDA.

KOHNKE, H. and BERTRAND, A.R., 1959. *Soil Conservation*, New York: McGraw - Hill Book Company.

KOVDA, V.A. 1983. Loss of productive land-use to salinization, *Ambio* 12: 91–93. Cited by R. Lal, 1988, Soil erosion Research Methods, *Soil and Water*

Conservation Society, 7515, Northeast Ankeny Road, Ankeny Iowa 50021-9764.

KRUGER, H.J., BERHANU, F., YOHANNES, G.M., and KEFENI, K. 1996. Creating an inventory of indigenous soil and water conservation measures in Ethiopia. In: Chris Reij, Ian Scoones and Camilla Toulmin (eds.). *Sustaining the soil: Indigenous Soil and Water conservation in Africa*. Earthscan Publication Ltd., London. pp. 170-180.

LAFLEN, J.M., LANE, L.J., FOSTER, G.R., 1991. WEPP: A new generation of erosion prediction technology. *Journal of Soil and Water Conservation*, 46:34-38.

LAL, R. 1975. Soil Erosion Problems on an Alfisol in Western Nigeria and their control. *IITA Monograph No. 1*, Nigeria.

LAL, R. 1976. Soil Erosion Problems on an Alfisol in Western Nigeria and their control. *IITA Monograph No. 1*, Nigeria.

LAL, R. 1979. Physical characteristics of soils of the Tropics: determination and management. In: R. Lal and Greenland (eds.). *Soil physical properties and crop production in the tropics*. New York: John Wiley and Sons.

LAL, R. 1982. Management of clay soils for erosion control. *Tropical agriculture*, 59 (2):133-138.

LAL, R. 1988. *Soil Erosion Research Methods*. Ankeny, Iowa: Soil and Water conservation society.

LAL, R. 1990. Soil Erosion and Land Degradation: The Global risks. In R. Lal and B.W. Stewart (eds.). *Soil Degradation*. *Advances in Agronomy*, 11: 129–172.

LAL R. 1994. Soil erosion by wind and water: Problems and Prospects. *In R. Lal (ed.) Soil Erosion Research Methods*. 2nd edition. USA:Soil and Water conservation society and St. Luice Press.

LAL, R. 1995. The role of residues management in sustainable agricultural systems. *Journal of Sustainable agriculture*, 5(4):51-78.

LAL, R, and BRUCE, J.P. 1999. The potential of world cropland soils to sequester carbon and mitigate the green house effect. *Environ. Sci. Pol*., 2:177-185.

LAL, R. and PIERCE, F. J. 1991. The vanishing resource. In: Lal, R and F.J. Pierce, (eds.) Soil management for sustainability. *Soil and Water Conservation*, IOWA: Soil and Water conservation Society, pp. 1-5.

LANE, L.J., SHIRLEY, E.D., SINGH, V.P. 1988. Modelling erosion on hillslopes. In: Anderson, M.G. (ed). *Modelling geomorphological systems*. John Wiley Publ., New York, pp. 287-308.

LARSON, W.E., HOLT, R.F and CRLSON, C.W. 1978. Residues for soil conservation. *.In Crop residue management systems*. Edited by W.S. Oswald. *Spec. publication 31 Am. Soc .Agro*., Madison: Wisc., P. 1-15

LATTANZI, A.R., MEYER, L.D., and BAUMGARDNER, M.F. 1974. Influence of mulch rate and slope steepness on interrill erosion. *Soil Sci. Soc. Am. Proc*., 38:946 -950.

LE BISSONNAIS, Y., 1996. Aggregate stability and assessment of soil crustability and erodilbility: I. Theory and Methodology. *European Journal of Soil Science* 47:425-437.

LE BISSONNAIS, Y. and ARROUAS, D., 1997. Aggregate stability and assessment of soil crustability and erodibility: II. Application to humic loamy soils with various organic matter contents. *Eur.J.Soil Sci.* 48:39-48.

LE BISSONNAIS, Y., and SINGER, M.J., 1993. Seal formation, runoff and interrill erosion from 17 California soils. *Soil Sci. Soc. Am. J*. 57: 224-229.

LEVY, G.J., and VAN DER WATT, H. 1988. Effcet of clay mineralogy and soil sodicity on soil infiltration rate. *S. Afric. J. Plant and Soil* 5: 92-96.

LIJKLEMA, L.1995. Development and eutrophication: experiences and perspectives. *Water Science and Technology*, 31(9): 11-15.

LITTLEBOY, M., SILBURN, M.D., FREEBAIRN, D.M., WOODRUFF, D.R., HAMMER, G.L., LESLIE, J.K. 1992. Impact of soil erosion on production in cropping systems. I Development and validation of a simulation model. *Australian Journal of Soil Research*, 30:757-774.

LO, K. F. A. 1990. Erosion problems and research needs of tropical soils. In: Ziemar, R.R.; O'Loughlin, C.L.; Hamilton, L.S.(eds.). IAHS Publication, No.192, pp.24-34.

LORENZ, S.A., and SCHULZE, R.E. 1995. Sediment Yield. In: Roland E. Schulze (1995). *Hydrology and Agrohydrology*. A text to accompany the *ACRU* 3.00 agro hydrological modelling system. Department of Agricultural Engineering. University of Natal, Pietermaritzburg, South Africa.

MAMEDOV, A.I., SHAINBERG, I., and LEVY, G.J., 2000. Rainfall energy effects on runoff and interrill erosion in effluent irrigated soils. *Soil Science*, 165(7):535-544.

MANNERING, J.V. 1967. The relationship of some physical properties of soils to surface sealing. Ph. D. thesis. Purdue University, IN: West Lafayette.

MANNERING, J.V., and MEYER, L.D. 1962. The effects of various rates of mulch on infiltration and erosion. *Soil Sci. Soc. Am. Proc*., 27:84-86.

MASSEY, H.F, JACKSON, M.L. and HAYS, O.Z. 1953. Fertility erosion on two Wisconsin Soils. *Agron. J*., 45: 543-547.

McCOOL, D.K. BROWN. L.C. FOSTER, G.R, MUTCHLER, G.K., and MEYER L.D. 1987. Revised slope steepness factors for the USLE. *Trans. Am. Soc. Eng.*, 30:1387-1396.

McGREGOR, K.C., BENGSTON, R.L, MUTCHLER, C.K., 1988. Effects of surface straw on interil runoff and erosion of Grenada silt loam soil. *Transactions of the ASAE*, 31:111-116.

MERRITT, W.S., LETCHER, R.A., JAKEMAN, A.J. 2003. A review of erosion and sediment transport models. *Environmental Modelling and Software*, 18:761-799.

MERZOUK, A., and BLAKE, G.R., 1991. Indices for the estimation of interrill erodibility of Moroccan soils. *Catena*, 18: 537-550.

MEYER, L.D. 1985. Interill erosion rates and sediment characteristics. In *Soil erosion and conservation*. Edited by S.A. El-Swaify, W.C. Moldenhauer and Andrew Lo, Ankeny: Soil Conservation Society of America, pp. 167-177.

MEYER, L.D., WISCHMEIER, W.H., and FOSTER, G.R. 1970. Mulch rates required for erosion control on steep slopes. *Soil Sci. Soc. Am. Proc*., 34:928-931.

MILLS, W.C., THOMASS, A.W., and LANGDALE G.W. 1988. Rainfall retention probabilities computed from different cropping-tillage systems. *Agric. Water Mgt systems*.

MISRA, R.K., ROSE, C.W. 1996. Application and sensitivity analysis of process based erosion model GUEST. *European Journal of Soil Science*, 47:593-604.

MOLDENHAUER, W.C., and LONG, D.C. 1964. Influence of rainfall energy on soil loss and infiltration rates. I. Effect over a range of texture. *Soil Sci. Soc. Am. Proc*. 28:813-817.

MOORE, D.C., and SINGER, M.J. 1990. Crust formation effects on soil erosion processes. *Soil Sci. Soc. Am. Proc*. 54:1117-1123.

MORGAN, R.P.C. 1974. Estimating regional variations in soil erosion hazard in Peninsular Malaysia, *Malay. Nat. J.* 28:94-106.

MORGAN, R.P.C., 1978. Field studies of splash erosion. *Earth surf. proc*.3:295-299.

MORGAN, R.P.C. 1986. Soil degradation and soil erosion in the loamy belt of northen Europe. In: G. Chisci and RPC Morgan (1986). Soil erosion in the European Community: Impact of changing agriculture. A.A. Balkema, Rotterdam. pp. 165-172.

MORGAN, R.P.C. 1995. *Soil Erosion and Conservation*. 2nd edition. United Kingdom: Longmann Group Limited.

MORGAN, R.P.C., QUINTON, J.N, SMITH, R.E., GOVERS, G., POESEN, J.W.A., AUERSWALD, K., CHISCI, G., TORRI, D., STYCZEN, M.E. 1998. The European Soil Erosion Model (EUROSEM): a process based approach for predicting sediment Transport from fields and small catchments. *Earth Surface Processes and Landforms*, 23:527-544.

MORGAN, R. P. C.; RICKSON, R. J.; MCINTYRE, K.; BREWER, T. R.; ALTSHUL, H. J. 1998. Soil erosion survey of the central part of the Swaziland Middleveld. *Soil Technology*, 11(3): 263-289.

MORIN, J., GOLDBERG, D., SEGINER, I. 1967. A rainfall simulator with a rotating disc. *Trans. ASAE,* 10: 74-79.

MOSES, A.J., and GREEN, P. 1983. Movement of solids in air and water by raindrop impact. Effects of drop size and water depth variations. *Aust. J.Soil Res*., 21:257-269.

MOSLEY, M.P. 1973. Rain splash and the convexity of badland divides. *Z.f.Geomorph. N.F.Suppl.Bd.,* 18:10-25.

MULENGERA, M. K.; PAYTON, R. W.; WHITE, S.; KAYOMBO, B. 1996. The challenges and options of modelling soil loss for soil conservation planning in developing countries. In: Lungu, C.(ed.). Land degradation: a challenge to agricultural production. Proceedings 5th Annual Scientific Conference, SADC-land and water management research programme, Harare, Zimbabwe, 10-14 October, 1994, pp.156-166.

MULLUGETA, T. 1988. Soil conservation experiments on cultivated land in the Maybar area, Wello region, Ethiopia. SCRP Report no.16. University of Berne. pp.127.

NASSIF, S.H. WILSON, E.M. 1975. The influence of slope and rain intensity on runoff and infiltration. *Hydrological Sciences Bulletin*, 20:539-553.

NATIONAL SOIL EROSION-SOIL PRODUCTIVITY RESEARCH PLANNING COMMITTEE. 1981. Soil erosion effects soil productivity: a research planning prospective. *J. Soil and Water conservation*, 36:82-90.

NEARING, M.A., BRADFORD, J.M., and PARKER, S.C. 1991. Soil detachment by shallow flow at low slopes. *Soil Sci. Soc. Am. J.*, 55:339-344.

NEARING, M.A. LANE, L.J., LOPES, V.L. 1994. Modelling Soil Erosion. In: Lal, R .(ed.), *Soil Erosion Research Methods*, 2nd edition, pp 127-156.

NORTON, L.D., CONGO, N.D., and MOLDEHAUER, W.C. 1985. Effectiveness of mulch in controlling soil erosion. In:S.A El-Swaify, W.C. Moldenhauer and A. Lo (eds.). *Soil erosion and conservation*, Ankeny, Iowa. :Soil conservation society of America, pp.589-606.

NYSSEN, J.1997. Soil erosion in the Tigray Highlands (ETHIOPIA). II. Soil Loss estimation. *Geo-Eco-Trop.*, 21(1):27-49.

NYSSEN, J., POESEN, J., MOEYERSONS, J., DECKERS, J, MITIKU, H., LANG, A. 2003. Human impact on the environment in the Ethiopian and Eriterean highlands-a state of the art. *Earth-Science Reviews* (*In Press*).

OBI, M. E., SALAKO, F. K., and LAL, R. 1989. Relative susceptibility of some south eastern Nigeria soils to erosion. *Catena* 16: 215-225.

OLDEMAN, L.R. 1991-92. *Global extent of soil degradation*. Bioannual report. International Soil reference and information Centre, Wageningen, The Netherlands, pp.19-36.

PARIS, S. 1990. Erosion hazard model (modified SLEMSA). Field document no 13, second version, land resource evaluation project, Malawi, 17 pp.

PETKOVIC, S.; DRAGOVIC, N.; MARKOVIC, S. 1999. Erosion and sedimentation problems in Serbia. *Hydrological Sciences Journal*, 44 (1): .63-77.

PICCOLO, A. G., PIETRAMMELARA, J. S., MBAGWU, C. 1997. Reduction in soil loss from erosion susceptible soils amended with humic substances from oxidized coal. *Soil Technology,* 10:235–245.

PIERSON, F.B., and MULLA, D.J., 1990. Aggregate stability in the Palouse region of Washington: Effect of landscape position. *Soil Sci. Soc. of Am. J.*, 54: 1407-1412.

POESEN, J. 1984. The influence of slope angle on infiltration rate and Horfonian overland flow volume. *Z. Geom. Supp. Bd*., 49:113-131.

POESEN, J. 1985. An improved splash transport model. *Z.f. Geomorph*. 29(2):193-211.

POESEN, J. 1986. Surface sealing on loose sediments. The role of texture, slope and position of stones in the top layer. P. 354-365. In F. Callebout, D Gabriels and M De boodt (eds.) *Assessment of soil surface sealing and crusting*, Belgium: Flanders Research Center for Soil Erosion and Soil Rehabilitation.

POESEN, J. 1987. The role of slope angle in surface seal formation. In V. Gardiner (Ed.) Intern. Cited by Stern, 1990.

POESEN, J.W. A and LAVEE, H. 1991. Effects of size and incorporation of synthetic mulch on runoff and sediment yield from interrills in a laboratory study with simulated rainfall. *Soil and tillage Research*, 21:209-223.

QUANSAH, C. 1981. The effect of soil type, slope and rain intensity and their interactions on splash detachment and transport. *J. Soil Sci*.32:215-224.

RENARD, K.G., FOSTER, G.R., WEESIES, G.A., and McCOOL, D.K. 1991. Predicting soil erosion by water. A guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE). *USDA* Agricultural Research Service, Tucson, AZ, USA, Report.

RENARD, K.G. LAFLEN, J.M., FOSTER, G.R., MCCOOL, D.K. 1994. The Revised Universal Soil Loss equation. In: Lal R. (ed.), *Soil Erosion Research Methods* (2nd edition), pp. 105-124.

REUSING, M.; SCHNEIDER, T.; AMMER, U 2000. Modelling soil loss rates in the Ethiopian Highlands by integration of high resolution MOMS-02/D2-stereo-data in a GIS. *International Journal of Remote Sensing*, 21(9):1885-1896.

ROBERTSON, R. A.; COLLETTI, J. P. 1994. Off-site impacts of soil erosion on recreation: the case of Lake Red Rock reservoir in central Iowa. *Journal of Soil and Water Conservation*, 49(6): 576-581.

RODRIGUEZ, O.S. 1997. Hedgerows and mulch as soil conservation measures evaluated under field simulated rainfall. *Soil Technology*, 11:79-93.

ROMKENS, M.J.M., ROSE, C.B., and NELSON, D.W. 1977. Erodibility of selected clay subsoils in relation to physical and chemical properties. *Soil Sci. Soc. Am. J.*, 41:954-960.

ROOSE, E.J. 1977. Application of the Universal Soil Loss Equation of Wischmeier and Smith in West Africa; In Greenland, D.J. and Lal, R., (eds.) *Soil conservation and management in the Humid Tropics*, Willey, 177-187.

ROOSE, E.J. 1996. Land husbandry: components and strategies. *FAO soils bulletin.* no. 70, Rome:FAO.

ROTH, C.H., MEYER, B., FREED, H.G., DERPSCH, R. 1988. Effect of mulch rates and tillage systems on infiltrability and other soil physical properties of an oxisol in Parana, Brazil. *Soil and Tillage Research*, 11(1): 81-91.

SALLES, C. and POESEN, J. 2000. Rain properties controlling soil splash detachment. *Hydrological processes* 14:272-282.

SAS. 1996. SAS User’s Guide: Statistics. Vertion 6. Statistical Analysis System Institute, Cary, NC.

SAVABI, M.R. and STOTT, D.E. 1994. Plant residue impact on rainfall interception. *Transactions of the ASAE,* 37 (4): 1093-1098.

SCHERTZ, D.L., MOLDENHAUER, W.C. SINCLAIR, H.R., FRANZEIER, D.P 1984. Field evaluation of the effect of soil erosion on crop productivity. In *Erosion and Soil Productivity*. Proceedings of the National symposium on erosion and soil productivity. Am. Soc. Agr. Eng., Michigan.

SCHOMBERG, H.H.,and STEINER, J.L. 1999. Nutrient dynamics of crop residue decomposition on a fallow no-till soil surface. *Soil Sci. Soc. Am. J.*, 63:607-613.

SCHULTE, E.E., 1988. Recommended soil organic matter tests. *North Dakota Agric.Exp.Stn.Bull*.499: 29-32.

SCHULZE, R.E. 1979. Soil Loss in the Key Area of the Drakensberg – A Regional Application of the ‘Soil Loss Estimation Model for Southern Africa’ (SLEMSA). In: Hydrology and water resources of the Drakensberg. 149-167.

Natal Town and Regional Planning Commission, Pietermaritzburg, South Africa.

SCHULZE, R.E. 1995. Hydrology and Agrohydrology. A text to accompany the *ACRU 3.00* Agrohydrological modelling system. Department of Agricultural Engineering. University of Natal. Pietermaritzburg, South Africa.

SCRP. 1985. Soil loss and runoff assessment findings, Soil Conservations Research Project (SCRP). Addis Ababa, Ethiopia.

SERTSU, S. 2000. Degraded soils of Ethiopia and their management. *Proceedings of the FAO/ISCW expert consultation on management of degraded soils in Southern and East Africa, 2nd Network Meeting*. 18-22 September 2000. Pretoria. South Africa.

SHAINBERG, I., and LETEY, J., 1984. Response of soils to sodic and saline conditions. *Hilgardia, 52:*1-57.

SHAINBERG, I. and LEVY G.J. 1996. Infiltration and seal formation processes; In Agassi, M. (ed.) *Soil erosion, Conservation and Rehabilitation.* New York: Marcel Dekker, inc., pp. 1-22.

SHAINBERG, I., LEVY, G.I., GOLDSTEIN, D., 1997. Aggregate size and seal properties. *Soil Sci*., 162:470-478.

SHARMA, P.P., 1996. Interrill erosion. In: M. Agassi *(ed.). Soil erosion, Conservation and Rehabilitation*. NewYork: Marcel Dekker, Inc., pp.125-152.

SHARMA, P.P., and GUPTA, S.C. 1989. Sand detachment by single raindrops of varying kinetic energy and momentum. *Soil Sci. Soc. of Am . J.,* 53:1005-1010.

SHARPLEY, A.N. 1985. Depth of surface soil-runoff interaction as affected by rainfall, slope, and management. *Soil Sci. Soc. of Am. J.*, 49: 1010-1015.

SHARPLEY, A.N. and SMITH, S.J. 1990. Phosphorus transport in agricultural runoff: the role of soil erosion, In: J. Boardman,, I. D.L. Foster and J.A. Dearing (Eds.). *Soil Erosion on Agricultural Land.* New York: John Wiley and Sons Ltd.

SHELTON, D.P., DICKEY, E.C., HACHMAN, S.D., STEVEN, D., and FAIRBANKS, K.D. 1995. Corn residue cover on soil surface after planting for various tillage and planting systems. *J. Soil and Water Conservation*, 50:399–404.

SHOCK, C.C., HOBSON, J.H., SEDDIGH, M., SHOCK, B.M., STIEBER, T.D., and SAUNDERS, L.D.1997. Mechanical straw mulching of irrigation furrows: Soil erosion and nutrient losses, *Agron. J.*, 89:.887–893.

SINGER, M.J., and BLACKARD, J. 1978. Effect of mulching on sediment in runoff from simulated rainfall. *Soil Sci. Soc. of Am. J.,* 42:481-486.

SINGER, M.J., JANITZKY, P., and BLACKARD, J., 1982. The influence of exchangeable sodium percentage on soil erodibility. *Soil Sci. Soc. of Am . J.*, 46:117-121.

SINGER, M.J., and LE BISSONNAIS, Y., 1998. Importance of surface sealing in erosion of some soils from the Mediterranean climate. *Geomorphology,* 24:79-85.

SINGER, M.J., MATSUDA, Y., and BLACKARD, J. 1981. Effect of mulch rate on soil loss by raindrop splash. *Soil Sci. Soc. of Am. J.*, 45: 107-110.

SMITH, H.J. 1999. Application of empirical soil loss models in Southern Africa: a review. *South Afr. J. of Plant and Soil,* 16 (3): 1-8.

SMITH, H.J. VAN ZYL A.J., CLAASSENS, A.S., SCHOEMAN, J.L., SMOTH, H.J.C., and LAKER, M.C. 1997. Soil loss modelling in the Lesotho highlands water project (LHWP) catchments areas. *Lesotho Highlands Water Project.*

Contract 617 B Erosion and sedimentation: Soil loss and sedimentation yield modelling: Stage 1, Part 1: Soil loss, March 1997.

SONNEVELD, B., KEYZER, M., ALBERSEN, P. 1999. A non-parametric analysis of qualitative and quantitative data for erosion modelling: A case study for Ethiopia. Paper presented at the conference of ISCO, Lafayette, US, 24-29 May 1999.

STERN, R. 1990. Effects of soil properties and chemical ameliorants on seal formation runoff and erosion. D.Sc.(Agric) thesis. University of Pretoria, Pretoria.

STOCKING, M . 1987. A methodology for erosion hazard mapping of the SADCC region. Report, SADCC Soil and Water Conservation and Land Utilization Programme, Southern African Development Coordination Conference, Lesotho, No.9, 32 pp.

STOCKING, M.; CHAKELA, Q.; ELWELL, H. 1988. An improved methodology for erosion hazard mapping. Part I: The Technique. *Geografiska Annaler*, A (Physical Geography), 70A (3): 169-180

SURESH, D. S.; BABU; NANDAKUMAR, V.; JOHN, B.; JAYAPRASAD, B. K.; PRAMOD, S. V. 2000.Siltation analysis in the Neyyar reservoir and forest degradation in its catchment: a study from Kerala state, India. *Environmental Geology*, 39(3/4): 390-397.

SUWADJO and ABUJAMIN, S. 1983. Crop residue mulch for conserving soils in the uplands of Indonesia. In: El-Swaify, W.C. Moldenhauer, and Andrew Lo (eds.). *Soil Erosion and Conservation*. Iowa: Soil Conservation Society of America, pp. 607–614.

SVORIN, J. 2003. A test of three soil erosion models incorporated into a geographical information system. *Hydrological Processes*, 17(5): 967-977.

TACKETT, J.L., and PEARSON, R.W. 1965. Some characteristics of soil crusts formed by simulated rainfall. *Soil Sci*., 99:407- 413.

TAN, K.H., 1996. Soil sampling, preparation and analysis. New York: Marcell Dekker, Inlc.

TIMILIN, D.J., BRYANT, R.B., SNYDER, V.A., and WAGENET, R.J. 1986. Modeling corn grain yield in relation to soil erosion using a water budget approach. *Soil Sci. Soc. Am. J.*, 50: 718-723.

TIWARI, A.K., RISSE, L.M., and NEARING, M.A. 2000. Evaluation of WEPP and its comparison with USLE and RUSLE. *Transactions of the ASAE* 43 (5): 1129-1135.

TORRI, D. 1996. Slope, aspect and surface storage. In *Soil erosion, conservation and rehabilitation*. Edtted by M. Agassi, New York: Marcel Dekker, Inc., pp. 77-106.

TORRI, D., SFALANGA, M., and DEL SETTE, M. 1987. Splash detachment: Runoff depth and soil cohesion. *Catena* 14:149-155.

TRIPATHI R.P. and SIGNH, H.P. 1993. *Soil Erosion and Conservation.* New Delhi: Willey Eastern Limited.

TROTT, K. E., and SIGER, M.J. 1983. Relative erodibility of 20 California range and forest soils. *Soil Sci. Soc. of Am* . *J*., 47:753-749.

UNEP, 1991. Status of desertification and implementation of the UN plan of action to combat desertification. UNEP. Nairobi, Kenya.

UNGER, P.W. 1988. Residue management for dryland farming. In: *Proc. Int'l Conf." Challenges in dryland agriculture: A global perspective*," Amarillo/Bushland, Texas: pp. 483-489

UNGER, P.W. 1996. Common soil and water conservation practices. In M. Agassi (ed.). *Soil erosion, Conservation and Rehabilitation*. New York: Marcel Dekker, Inc., pp. 239 – 266.

UNGER, P.W. and JONES, O.R. 1981. Effect of soil water content and a growing season straw mulch on grain sorghum. *Soil Sci. Soc. Am. J.*, 45:129–134.

UNGER, P.W. and WIESE, A..F. 1979. Managing irrigated winter wheat residues for water storage and subsequent dryland grain sorghum production, *Soil Sci. Soc. of Am. J.*, 43:582–588.

VAN DER WATT, H. and VALENTIN, C. 1992. Soil crusting: The African view. In M.E. SUMNER and B. A. STEWART (eds). *Advances in Soil Sciences. Soil crusting: physical and Chemical processes*. Boca Roton :Lewis Publi., pp. 301-338.

VAN DIJK, A.I.J.M., BRUIJNZEEL, L.A., ROSEWELL, C.A. 2002. Rainfall intensity-kinetic energy relationships: a critical literature appraisal. *Journal of Hydrology,* 261:1-23.

VAN LIEW, M.W., and SAXTON, K.E. 1983. Slope steepness and incorporated residue effects on interrill erosion. *Transactions of the ASAE,* 26(6):1738-1743.

VERSTRAETEN, G.; POESEN, J. 2002 Regional scale variability in sediment and nutrient delivery from small agricultural watersheds. *Journal of Environmental Quality*, 31(3): 870- 879.

WAKINDIKI, I.I.C., and BEN-HUR, M., 2002. Soil mineralogy and texture effects on crust micromorphology, infiltration and erosion. *Soil Sci. Soc. of Am. J.*, 66:897-905.

WALL BAKE, G. W. VAN DEN. 1987. Siltation and soil erosion survey in Zimbabwe. IAHS Publication, No.159, pp. 69-80.

WALTON, R., HUNTER, H. 1996. Modelling water quality and nutrient fluxes in the Johnstone River Catchment, North Queensland. In: *23rd Hydrology and Resource symposium*. Sydney.

WARRINGTON, D., SHAINBERG, I., AGASSI, M., and MORIN, J. 1989. Slope and phosphogypsum's effect on runoff and erosion. *Soil Sci. Soc. Am. J.*, 53:1201-1205.

WATSON, D.A. and LAFLEN, J.M. 1985. Soil strength, slope, and rain intensity effects on interrill erosion. *Trans. ASAE.*, 29:98-102.

WEST, L.T. CHIANGE S.C. and NORTON L.D. 1992. The morphology of surface crust: In Sumner, ME and Stewar , BA (eds*). Soil crusting: Physical and chemical processes*. Boca Roton: Lewis Publi., pp. 73-92.

WILLIAMS, J.R. 1975. Sediment yield predictions with universal equation using runoff energy factor. In: *Present and Perspective Technology for predicting Sediment and Yields and sources*, ARS, USDA, 40. pp. 244-252.

WILLIAMS, J.R., SHARPLEY, A.N. and TAYLOR, D. 1990. Assessing the impact of erosion on soil productivity using the EPIC Model. In: J. Boardman, I.D.L Foster and J.A. Dearing (Eds). *Soil erosion on agricultural land*. J. Willey, Chichester, pp. 461-464.

WISCHMEIER, W.H. 1973. Conservation Tillage to control water erosion. In: Conservation Tillage, Soil Cons. Soc.Am., Ankeny, Iowa, pp.133-141.

WISCHMEIER, W.H., JOHNSON, C.B., and CROSS, B.V. 1971. A soil erodibility nomograph for farm land and construction sites. *Journal of Soil and water Conservation,* 28:189-193.

WISCHMEIER, W.H., and SMITH, D.D. 1965. Erosion losses from cropland east of the Rocky Mountains. *USDA, Agric. Hand book No. 537*, Washington.

WISCHMEIER, W.H., and SMITH, D.D. 1978. Predicting Rainfall erosion losses. A guide to Conservation Planning. *USDA. Handbook No. 537*, Washington, DC.

WITHERS, P. J. A. and LORD, E. I. 2002. Agricultural nutrient inputs to rivers and groundwaters in the UK: policy, environmental management and research needs. *Science of the Total Environment*, 282/283: 9-24.

YERIMA, B.P.K., SERTSU, S., and BAISA T., 1993. *Manual for Soil Analysis. Part I. Soil Chemical Analysis.* Vol.1, Watershed Development and land use department, Ministry of natural resources development and environmental protection, UNDP/FAO. Addis Ababa, Ethiopia.

Yoder, D. and Lown, J. 1995. The future of RUSLE: Inside the new Revised Universal Soil Loss Equation. *Journal of Soil and Water Conservation,* 50 (5): 484-489.

YOO, K.H.and TOUCHTON, J.T. 1988. Surface runoff and sediment yield from varied tillage systems of cotton. *Trans. ASAE*, 31:1154-1158.

YOUNG, A. 1989. Agro*forestry for Soil Conservation*. U.K: C.A.B. International.

YOUNG, R.A., ONSTAD, C.A., BOSCH, D.D., ANDERSON, W.P. 1989. AGNPS: A Non-Point Source pollution model for evaluating agricultural watersheds. *Journal of Soil and Water Conservation,* 44 (2): 4522-4561.

ZACHAR, D. 1982. *Soil erosion*. Developments in Soil Science 10. New York: Elsevier.Scientific Publishing Company.

ZAKOVA, Z.; BERANKOVA, D.; KOCKOVA, E.; KRIZ, P. 1993. Influence of diffuse pollution on the eutrophication and water quality of reservoirs in the Morava river basin. *Water Science and Technology*, 28 (3/5): 79-90.

ZINGG, A.W. 1940. Degree and length of land slope as it affects soil loss in runoff. *Agric. Eng.,* 21:59- 64.

APPENDICES

List of Appendices

1 INPUT VARIABLES FOR SLEMSA

1.1 Provisional values of rainfall energy based on mean annual rainfall; Rhodesian data (Elwell and Stocking, 1973 as quoted by Department of Agricultural Technical Services, 1976)

Mean annual rainfall mm	E $Jm^{-2}yr^{-1}$
400 –500	10400
500 – 600	12200
600 – 700	14000
700 – 800	15800
800 – 900	17600
900 – 1000	19000
1000 –1100	21000
1100 – 1200	23000
1200 - 1500	28000
Greater than 1500	30000

1.2 Mean annual rainfall at the research sites and their energy estimated based on the ratings in given Appendix 1.1

Site	Mean annual RF	Rainfall Energy $Jm^{-2}yr^{-1}$	Years of rainfall
Alemaya			
AU Alluvial			
AU Regosol			
AU Vertisol	845.7	17600	1979-93, 1995-2001
Chiro			
Hirna	795.3	15800	1985-89,95,96
Babile	652	14000	1969-1980
Bedessa	981.1	19000	1984-87,1996-97
Dire Dawa	650	14000	1980-2000
Gelemso	1146	23000	1981-1989
Jijiga			
Amadle			
Dugda Hidi			
Karamara	562.9	12200	1952-89, 1996-2001
Kersa/Lange	898.9	17600	1989-1994
Hamaresa	845.7	17600	See Alemaya
Adele	845.7	17600	See Alemaya

1.3 Estimated topographic factors for SLEMSA at the different research sites

Study sites	Slope gradient, S (%)	Slope length L (m)	Topographic Factor X Value
Adele	10	200	7.53
Amadle	5	80	1.85
AU Alluvial	1	300	0.92
AU Regosol	10	100	5.33
AU Vertisol	1	200	0.75
Babile	12	100	7.04
Bedessa	8	60	2.98
Chiro	25	20	10.72
Dire Dawa	2	300	1.43
Dugda Hidi	4	300	2.77
Gelemso	15	50	7.12
Hamaresa	25	20	10.72
Hirna	15	40	6.36
Karamara	12	100	7.04
Kersa/Lange	10	120	5.83

1.4A Criteria for assigning the basic input values for soil erodibility (F_b) for use in the SLEMSA (Elwell, 1978 cited by Morgan, 1995)

Soil texture	Soil type	F value
Light	Sands Loamy sands Sandy loams	4
Medium	Sandy clay loams Clay loams Sandy clay	5
Heavy	Clay Heavy clay	6

The following adjustments were made to the basic F values based on the soil characteristics.

Soil Condition	**Add**
For light textured soils consisting mainly of sands and silts	(-1)
For restricted vertical permeability within one metre of the surface or for severe soil crusting	(-1)
For ridging up and down the slope	(-1)
For deterioration in soil structure due to excessive soil loss in the previous year (>20t/ha) or for poor management	(-1)
For slight to moderate surface crusting or for soil losses of 10-20t/ha in the previous year	(-0.5)
High swell –shrink potential/ self mulching (Vertic A)	(-0.5)
For deep (>2m) well drained, light textured soils	2
For tillage techniques which encourage maximum retention of water on the surface, e.g. ridging on the contour	1
For first season of no tillage	1
For subsequent seasons of no tillage	2
For tillage techniques which encourage high surface infiltration and maximum water storage in the profile, e.g. ripping, wheel-track planting	1

1.4B Estimation of soil erodibility index (F values) for selected Harerghe soils based on appendix 1.4A

Research sites	% Clay in B Horizon	Textural class	Basic value, †Fb	Description	‡Fm
Adele	45.22	Sandy clay	5	(+1) Ridging on contour; Slightly restricted B horizon (-0.5)	5.5
AU Alluvial	13.9	Sandy loam	4	(-1) Consists of mainly sands and silts; (+2) Deep well drained light textured soil;	5
AU Regosol	27.42	Sandy clay loam	5		5
AU Vertisol	58.22	Clay	6	Self mulching (-0.5)	5.5
Asebe Teferi/Chiro	NA	Clay	6	Self mulching (-0.5); (+1) Ridging on contour; (-0.5) Previous erosion damage	6
Babile	8.36	Sandy Loam	4	(-0.5) Previous erosion damage; (-1) Mainly of sand and silts; Good tillage technique (+1)	3.5
Bedessa	63.8	Clay	6	Self mulching (-0.5); slightly restricted B horizon (-0.5); Ridging on contour (+1)	6
Dire Dawa	22.84	Loam	5	(+2) deep well drained light textured soil; (-1) mainly of sands and silts	6
Gelemso	41.12	Sandy clay	5	(+1) Ridging on contour; Slightly restricted vertical drainage (-0.5); -0.5 previous erosion damage	5
Amadle	58	Silt clay	5	Slight surface crusting –(0.5), High swell- shrink potential –0.5), slightly restricted B horizon (High clay content in B horizon)–0.5	3.5
Dugda Hidi/Chinaksen	51.86	Silt clay	5	Slight surface crusting –(0.5), High swell- shrink potential –0.5), slightly restricted B horizon (High clay content in B horizon)–0.5	3.5
Karamara	29.26	Clay loam	5	Surface crusting –(0.5); calcareous soil (-0.5); (-1) Excessive soil loss in previous year;	3
Kersa/Lange	29.14	Sandy clay loam	5	Contour ploughing, and application of house refuse +1, Erosion evidence (-0.5)	5.5
Hamaresa	56.9	Clay	6	Previous erosion damage (-1), Ridges for moisture retention, (+1)	6
Hirna	60.32	Clay	6	High swell-shrink potential –0.5), slightly restricted B Horizon –0.5; Rock fragments +1, Erosion evidence (-0.5), Moisture retention practice (+1)	6.5

†Fb = Basic soil erodibility value estimated based mainly on the textural classes of the soils

‡Fm = Adjusted soil erodibility value after taking management factors into consideration

1.5 Calculated C values for SLEMSA at the study sites

1.5.1 AU Regosol

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% Cover per landuse	% Cover of total area	I (%Energy intercption)
Jan-Mar	123.38	0.15	Grasses	0.5	25	12.5	1.856
	123.38	0.15	Weeds	0.5	20	10	1.485
							3.341
A-J	273.25	0.33	Maize/sorghum	0.6	40	24.00	7.893
	273.25	0.33	Grasses	0.2	50	10.00	3.289
	273.25	0.33	Beans/weeds	0.2	30	6.00	1.973
							13.154
J-S	347.33	0.42	Maize/Sorghum	0.6	60.00	36.00	15.048
	347.33	0.42	Beans	0.2	70.00	14.00	5.852
	347.33	0.42	Grasses	0.2	70.00	14.00	5.852
							26.753
O-D	86.94	0.10	Maize/Sorghum	0.6	30.00	18.00	1.883
	86.94	0.10	Beans	0.2	15.00	3.00	0.314
	86.94	0.10	Grasses	0.2	40.00	8.00	0.837
							3.034
						Sum I	46.283
						C	**0.062**

1.5.2 AU Alluvial soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	123.38	0.15	Grasses &weeds	1	10	10.00	1.485
							1.485
A-J	273.25	0.33	Sorghum/maize	0.5	40	20.00	6.577
	273.25	0.33	Grasses &weeds	0.5	50	25.00	8.222
							14.799
J-S	347.33	0.42	Sorghum/maize	0.5	60	30.00	12.540
	347.33	0.42	Beans	0.1	70	7.00	2.926
	347.33	0.42	Wheat	0.2	70	14.00	5.852
	347.33	0.42	potato	0.2	40	8.00	3.360
							24.679
O-D	86.94	0.10	Sorghum/maize	0.5	30	15.00	1.570
			Grasses &weeds	0.5	40	20.00	2.093
							3.662
						Sum I	44.625
						C	**0.069**

1.5.3 AU Vertisols

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	123.38	0.15	Grasses &weeds	1	15	15.00	2.227
							2.227
A-J	273.25	0.33	Maize/sorghum	0.5	40	20.00	6.577
	273.25	0.33	Grasses &weeds	0.5	50	25.00	8.222
							14.799
J-S	347.33	0.42	Maize/sorghum	0.5	60	30.00	12.540
			wheat	0.5	70	35.00	14.630
							27.171
O-D	86.94	0.10	Maize/sorghum	0.5	30	15.00	1.570
			Wheat Grasses and weeds	0.5	50	25.00	2.616
							4.185
						Sum I	48.382
						C	**0.055**

1.5.4 Hamaressa soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	123.38	0.15	Chat	0.6	25	15	2.227
		0.15	Trees/grass	0.4	35	14	2.079
						Mean I	4.306
A-J	273.25	0.33	Chat	0.6	30	18	5.919
		0.33	Sorghum	0.2	30	6	1.973
		0.33	Trees/grasses	0.2	50	10	3.289
						Mean I	11.181
J-S	347.33	0.42	Chat	0.6	40	24	10.032
		0.42	Sorghum	0.2	60	12	5.016
		0.42	Trees/grasses	0.2	60	12	5.016
						Mean I	20.065
O-D	86.94	0.10	Chat	0.6	25	15	1.570
		0.10	Sorghum	0.2	20	4	0.419
		0.10	Trees/grasss	0.2	35	7	0.732
						Mean I	2.721
						Sum I	**38.273**
						C	**0.101**

1.5.5 Babile Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	89.32	0.13	Chat	0.2	25	5	0.649
			Trees/Grasses	0.8	5	4	0.519
						Mean I	1.168
A-J	253.22	0.37	Chat	0.2	35	7	2.576
			Sorghum/maize/Groundnut	0.7	40	28	10.303
			Trees	0.1	20	2	0.736
						Mean I	13.615
J-S	287.48	0.42	Chat	0.2	35	7	2.924
			Sorghum/maize/Groundnut	0.7	55	38.5	16.084
			Trees	0.1	30	3	1.253
						Mean I	20.261
O-D	58.15	0.08	Chat	0.2	25	5	0.422
			Sorghum/maize/Groundnut	0.7	30	21	1.774
			Trees	0.1	10	1	0.084
Total	688.15	1.00				Mean I	2.281
						Sum I	**37.325**
						C	**0.107**

1.5.6 Amadle Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	61.44	0.11	Maize/sorghum/Weeds	0.7	15	10.5	1.142
		0.11	Grass	0.3	25	7.5	0.816
						18	1.958
A-J	196.04	0.35	Maize/sorghum/Weeds	0.7	40	28	9.720
		0.35	Grass	0.3	50	15	5.207
						43	14.927
J-S	242.78	0.43	Maize/sorghum/Weeds	0.7	60	42	18.056
		0.43	Grass	0.3	80	24	10.318
						66	28.374
O-D	64.47	0.11	Maize/sorghum/Weeds	0.7	25	17.5	1.998
		0.11	Grass	0.3	50	15	1.712
						32.5	3.710
Total	564.72	1.00				Sum I	**48.969**
						C	**0.053**

1.5.7 Dugda Hidi Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	61.44	0.11	Grass	0.5	30	15	1.632
		0.11	Weeds	0.5	30	15	1.632
						30	3.264
A-J	196.04	0.35	maize/Sorghum	0.5	40	20	6.943
		0.35	Grass	0.5	60	30	10.414
						50	17.357
J-S	242.78	0.43	maize/Sorghum	0.5	60	30	12.897
		0.43	Grass	0.5	80	40	17.196
						70	30.093
O-D	64.47	0.11	maize/Sorghum	0.5	40	20	2.283
		0.11	Grass	0.5	60	30	3.425
						50	5.708
Total	564.72	1.00				Sum I	**56.422**
						C	**0.058**

1.5.8 Lange soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	86.50	0.10	Sorghum/weeds	0.6	10	6	0.573
	87.50	0.10	Maize/weeds	0.3	5	1.5	0.145
	88.50	0.10	Potato/Onion	0.1	5	0.5	0.049
						8	0.766
A-J	248.34	0.27	Sorghum/weeds	0.6	40	24	6.575
	249.34	0.28	Maize/weeds	0.3	40	12	3.301
	250.34	0.28	Potato/Onion	0.1	10	1	0.276
						37	10.152
J-S	474.70	0.52	Sorghum/weeds	0.6	60	36	18.852
	475.70	0.52	Maize/weeds	0.3	60	18	9.446
	476.70	0.53	Potato/Onion	0.1	40	4	2.104
						58	30.402
O-D	96.93	0.11	Sorghum/weeds	0.6	40	24	2.566
	97.93	0.11	Maize/weeds	0.3	40	12	1.296
	98.93	0.11	Potato/Onion	0.1	20	2	0.218
Total	906.48	1.00				38	4.081
						Sum	**45.401**
						C	**0.066**

1.5.9 Hirna Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	106.48	0.13	Weeds	0.8	10	8	1.022
	106.48	0.13	Grass	0.2	20	4	0.511
						12	1.533
A-J	289.71	0.35	Sorghum/weeds	0.8	40	32	11.122
	289.71	0.35	Grass	0.2	50	10	3.476
						42	14.598
J-S	364.55	0.44	Sorghum/weeds	0.8	60	48	20.993
	364.55	0.44	Grass	0.2	70	14	6.123
						62	27.116
O-D	72.81	0.09	Sorghum/weeds	0.8	30	24	2.096
	72.81	0.09	Grass	0.2	50	10	0.873
						34	2.970
Total	833.54	1.00				Sum	46.216
						C	**0.062**

1.5.10 Chiro

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	106.48	0.13	Weeds/Sorghum	0.7	15	10.5	1.341
	106.48	0.13	Grass/trees	0.1	20	2	0.255
	106.48	0.13	Chat	0.2	40	8	1.022
						20.5	2.619
A-J	289.71	0.35	Weeds/Sorghum	0.7	40	28	9.732
	289.71	0.35	Grass/trees	0.1	50	5	1.738
		0.35	Chat	0.2	50	10	3.476
						43	14.945
J-S	364.55	0.44	Weeds/Sorghum	0.7	60	42	18.369
	364.55	0.44	Grass/trees	0.1	80	8	3.499
		0.44	Chat	0.2	50	10	4.373
						60	26.241
O-D	72.81	0.09	Weeds/Sorghum	0.7	30	21	1.834
	72.81	0.09	Grass/trees	0.1	50	5	0.437
		0.09	Chat	0.2	40	8	0.699
Total	833.54	1.00				34	2.970
						Sum	46.775
						C	**0.060**

1.5.11 Bedessa Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	108.61	0.10	Sorghum/weeds	0.4	20	8	0.818
	108.61	0.10	Tef/weeds	0.3	30	9	0.920
	108.61	0.10	Chat/trees	0.3	50	15	1.533
						32	3.270
A-J	391.30	0.37	Sorghum/weeds	0.4	40	16	5.891
	391.30	0.37	Tef/weeds	0.3	30	9	3.314
	391.30	0.37	Chat/trees	0.3	55	16.5	6.075
						41.5	15.280
J-S	477.33	0.45	Sorghum/weeds	0.4	60	24	10.779
	477.33	0.45	Tef/weeds	0.3	70	21	9.432
	477.33	0.45	Chat/trees	0.3	60	18	8.085
						63	28.296
O-D	85.51	0.08	Sorghum/weeds	0.4	40	16	1.287
	85.51	0.08	Tef/weeds	0.3	30	9	0.724
	85.51	0.08	Chat/trees	0.3	50	15	1.207
Total	1062.75	1.00				40	3.218
						Sum	**50.065**
						C	**0.060**

1.5.12 Gelemso Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	112.18	0.10	Chat	0.5	50	25	2.441
	112.18	0.10	Maize/sorghum	0.4	20	8	0.781
	112.18	0.10	Others	0.1	50	5	0.488
						38	3.711
A-J	409.77	0.36	Chat	0.5	60	30	10.702
	409.77	0.36	Maize/sorghum	0.4	40	16	5.708
	409.77	0.36	Others	0.1	55	5.5	1.962
						51.5	18.372
J-S	467.23	0.41	Chat	0.5	70	35	14.237
	467.23	0.41	Maize/sorghum	0.4	60	24	9.762
	467.23	0.41	Others	0.1	60	6	2.441
						65	26.439
O-D	159.49	0.14	Chat	0.5	50	25	3.471
	159.49	0.14	Maize/sorghum	0.4	30	12	1.666
	159.49	0.14	Others	0.1	50	5	0.694
Total	1148.67	1.00				42	5.832
						Sum	**54.354**
						C	**0.059**

1.5.13 Diredawa Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	145.04	0.22	Orchards	0.5	50	25	5.562
	145.04	0.22	Papaya	0.3	30	9	2.002
	145.04	0.22	Vegetables&others	0.2	60	12	2.670
						46	10.235
A-J	204.69	0.31	Orchards	0.5	50	25	7.850
	204.69	0.31	Papaya	0.3	30	9	2.826
	204.69	0.31	Vegetables&others	0.2	60	12	3.768
						46	14.444
J-S	247.94	0.38	Orchards	0.5	60	30	11.411
	247.94	0.38	Papaya	0.3	50	15	5.705
	247.94	0.38	Vegetables&others	0.2	70	14	5.325
						59	22.441
O-D	54.21	0.08	Orchards	0.5	50	25	2.079
	54.21	0.08	Papaya	0.3	30	9	0.748
	54.21	0.08	Vegetables&others	0.2	60	12	0.998
Total	651.88	1.00				46	3.825
						Sum	**50.944**
						C	**0.060**

1.5.14 Karamara Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	% cover of total area	I (%Energy intercption)
Jan-Mar	61.44	0.11	Acatia Shrubs & Grasses	0.8	15	12	1.305
			Chat	0.2	20	4	0.435
						Total	1.741
A-J	196.04	0.35	Acatia Shrubs & Grasses	0.6	40	24	8.331
			Chat	0.2	25	5	1.736
			Sorghum	0.2	35	7	2.430
						Total	12.497
J-S	242.78	0.43	Acatia Shrubs & Grasses	0.6	60	36	15.477
			Chat	0.2	30	6	2.579
			Sorghum	0.2	55	11	4.729
							22.785
O-D	64.47	0.11	Acatia Shrubs & Grasses	0.6	30	18	2.055
			Chat	0.2	20	4	0.457
			Sorghum	0.2	5	1	0.114
Total	564.72	1.00					2.626
						Sum I	**39.648**
						C	**0.093**

1.5.15 Adele soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% Cover per landuse	% Cover of total area	I (%Energy intercption)
Jan-Mar	123.38	0.15	Chat	0.6	30.00	18.00	2.673
	123.38	0.15	Grass	0.4	15	6.00	0.891
							3.564
A-J	273.25	0.33	Maize/sorghum	0.4	40.00	40.00	13.154
		0.33	Chat	0.6	40	40.00	13.154
							26.309
J-S	347.33	0.42	Maize/sorghum	0.4	60	24	10.032
		0.42	chat	0.6	50	30	12.540
							22.573
O-D	86.94	0.10	Maize/sorghum	0.4	30	12	1.256
		0.10	Chat	0.6	30	18	1.883
							3.139
							55.584
						C	**0.058**

2. INPUT VARIABLES FOR USLE

2.1 Estimated mean annual rainfall erosivity R of the USLE for some sites in Harerge, eastern Ethiopia

Weather station	Annual rainfall mm	Rainfall erosivity factor, R†	(Study sites to which the same data was used)
Alemaya	830.9	459	AU Alluvial, AU Regosol, AU Vertisol, Adele and Hamaressa
Asebe Teferi	833.54	460	Chiro; Hirna
Babile	688.15	378	
Bedessa	1062.75	589	
Dire Dawa	651.88	358	
Gelemso	1148.67	637	
Jijiga	564.72	309	Amadle, Karamara, Dugda Hidi
Kersa/Lange	906.48	501	

†R is computed based on the adaptation of the erosivity factor of Wischmeier and Smith (1978) to Ethiopian conditions by Hurni (1985).

2.2 Permeability information for the major soil textural classes (Renard et al., 1991) for use in estimating K value in USLE Wischmeier and Smith Nomograph.

Texture class	Permeability Class	Saturated Hydraulic conductivity mm/hr	†Permeability rating
Clay, Silty clay	6	<1	Very slow
Silty clay Loam, Sandy clay	5	1-2	Slow
Sandy Clay loam, Clay loam	4	2-5	Slow to moderate
Loam, Silty loam, silt	3	5-20	Moderate
Loamy sand, Sandy loam	2	20-60	Moderate to rapid
Sand	1	>60	Rapid

†Wischmeier, et al., 1971.

2.3 Soil structure codes for use in estimation of K value in USLE Wischmeier and Smith Nomograph

Structure codes†	Description
1	Very fine granular
2	Fine granular
3	Medium of course granular
4	Blocky, Platy or massive

†Wischmeier, et al., 1971.

2.4 Estimation of K value of USLE for selected sites in Hareghe, eastern Ethiopia

Study Site	% Silt and very fine sand	% Sand	Textural Class	%OM	Soil permeability index (b)	Soil structure index (a)	K Nomograph‡	§K Calc.
Adele	20.24	36.56	Sandy Clay	1.47	5	3	0.24	0.20
Amadle	37.02	7.80	Silt Clay	2.78	6	2	0.26	0.22
AU Alluvial	12.75	74.60	Sandy Loam	1.17	2	2	0.11	0.06
AU Regosol	19.52	53.05	Sandy Clay Loam	2.78	4	3	0.22	0.18
AU Vertisol	32.60	9.59	Clay	2.16	6	2	0.23	0.20
Babile	14.40	76.65	Sandy Loam	0.84	2	4	0.20	0.16
Bedessa	28.47	5.43	Clay	2.56	6	1	0.20	0.12
Chiro	†ND	ND	Clay	ND	6	2	0.23	0.10
Dire Dawa	40.49	34.85	Loam	0.88	3	2	0.30	0.29
Dugda Hidi	42.00	10.88	Silt Clay	2.51	6	2	0.28	0.27
Gelemso	11.29	48.9	Sandy Clay	1.18	5	4	0.23	0.20
Hamaresa	22.95	23.34	Clay	1.68	6	2	0.21	0.18
Hirna	39.81	6.5	Clay	2.90	6	2	0.24	0.22
Karamara	20.37	49.34	Clay Loam	1.72	4	4	0.25	0.23
Lange	25.50	47.38	Sandy clay Loam	2.03	4	3	0.23	0.22

‡ K Nomograph = K value estimated from Soil erodibility Nomograph (Wischmeier, et. al., 1971)

§K Calc. = K value calculated using equations of Wischmeier and Smith (1978)

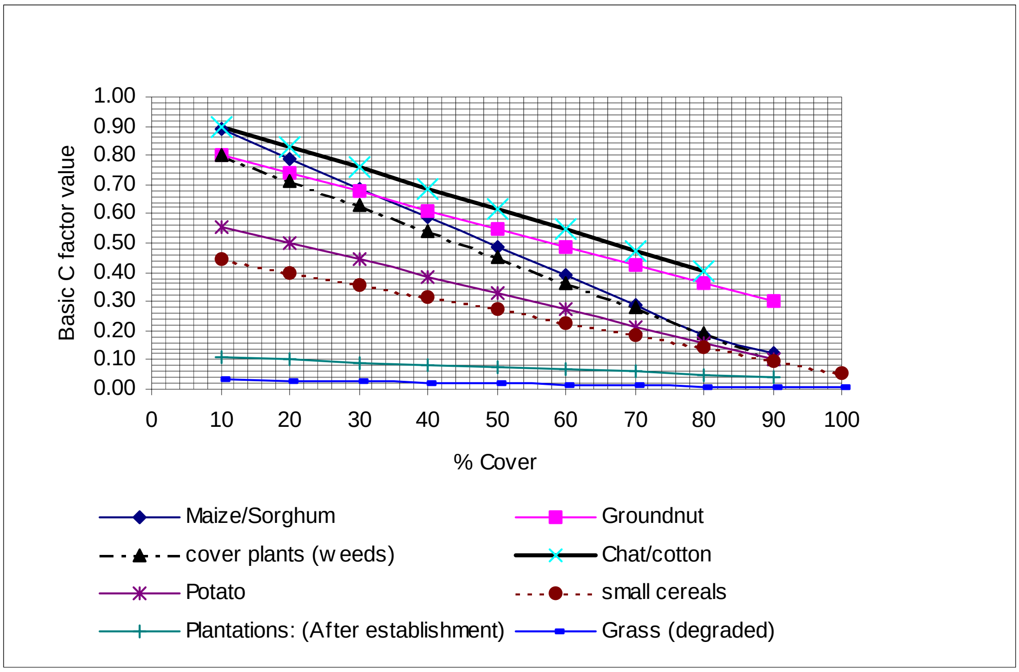
†ND= Not determined

2.5 Cover and management factor C for the USLE

2.5.1 Basic C factor values for the USLE

Practice	Average annual C factor	Remark
Bare soil	1.00	
Forest or dense shrub, high mulch crops	0.001	
Savanna or Prairie grass in good condition	0.01	
Overgrazed savanna or prairie grass	0.1	
Maize, sorghum or millet: High productivity, conventional tillage	0.20-0.55	
Maize, sorghum or millet: low productivity, conventional tillage	0.50-0.90	
Meadow grass	0.01-0.025	
Wheat	0.1-0.40	
Groundnuts	0.30-0.80	
Ethiopian tef	0.25	
Mungbean	0.04	
Coffee after first harvest	0.05	
Plantations: after establishment	0.05-0.1	
Papaya	0.21	
Cotton	0.40-0.70	
Potatoes: rows down slope	0.20-0.50	
Potatoes: rows across slope	0.10-0.40	

Sources: Rooth (1977); Wischmeier and Smith (1978); Hurni (1985); Morgan (1995)



2.5.2 Estimation of the basic USLE -C factor values for some crops from their percent cover based on the range of values presented in Appendix 2.5.1.

2.5.3 Calculation procedures of the weighted C factor values (indicated in Appendix 2.6) for USLE model

The weighted C value for a given crop i during a certain season of the year j is calculated as:

$$C_{wij} = R_{ij}U_{ij}C_{ij}$$

Where

C_{wi} = weighted C value of crop i during season j

R_{ij} = the ratio of season j rainfall to the mean annual rainfall

U_{ij} = ratio of land use for crop i to total land use during season j

C_{ij} = C value for a certain percent cover of crop i during season j

The weighted C value for the total land use during the j^{th} season is

$$C_{ws} = \sum Cw_{ij}$$

Then, the annual weighted C value for each study site is computed as

$$C = \sum C_{ws} = \sum\sum RijUijCij$$

2.6 Calculated C value for USLE Model for the research sites

2.6.1 AU Regosol

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	123.38	0.15	Grasses	0.5	25	0.03	0.002
	123.38	0.15	Weeds	0.5	20	0.70	0.052
							0.054
A-J	273.25	0.33	Maize/sorghum	0.6	40	0.59	0.116
	273.25	0.33	Grasses	0.2	50	0.03	0.002
	273.25	0.33	Beans/weeds	0.2	30	0.63	0.041
							0.159
J-S	347.33	0.42	Maize/Sorghum	0.6	60.00	0.39	0.098
	347.33	0.42	Beans	0.2	70.00	0.28	0.023
	347.33	0.42	Grasses	0.2	70.00	0.01	0.001
							0.122
O-D	86.94	0.10	Maize/Sorghum	0.6	30.00	0.69	0.043
	86.94	0.10	Beans	0.2	15.00	0.75	0.016
	86.94	0.10	Grasses	0.2	40.00	0.02	0.000
							0.059
						Sum C	**0.395**

2.6.2 AU Alluvial soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use by crop a	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	123.38	0.15	Grasses &weeds	1	10	0.45	0.067
							0.004
A-J	273.25	0.33	Sorghum/maize	0.5	40	0.59	0.097
	273.25	0.33	Grasses &weeds	0.5	50	0.45	0.074
							0.171
J-S	347.33	0.42	Sorghum/maize	0.5	60	0.39	0.082
	347.33	0.42	Beans	0.1	70	0.28	0.012
	347.33	0.42	Wheat	0.2	70	0.19	0.016
	347.33	0.42	potato	0.2	40	0.39	0.033
							0.142
O-D	86.94	0.10	Sorghum/maize	0.5	30	0.69	0.036
		0.10	Grasses &weeds	0.5	40	0.54	0.027
							0.063
					45.56	Sum	**0.380**

2.6.3 AU Vertisols

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	123.38	0.15	Grasses &weeds	1	15	0.75	0.111
							0.111
A-J	273.25	0.33	Maize/sorghum	0.5	40	0.59	0.097
	273.25	0.33	Grasses &weeds	0.5	50	0.45	0.074
							0.171
J-S	347.33	0.42	Maize/sorghum	0.5	60	0.39	0.082
		0.42	wheat	0.5	70	0.19	0.040
							0.121
O-D	86.94	0.10	Maize/sorghum	0.5	30	0.69	0.036
		0.10	Wheat Grasses and weeds	0.5	50	0.45	0.023
							0.059
						Sum	**0.462**

2.6.4 Hamaressa soils

Months	Rainfall	Fraction of RF	crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	123.38	0.15	Chat	0.6	40	0.69	0.061
		0.15	Trees/grass	0.4	35	0.03	0.002
							0.063
A-J	273.25	0.33	Chat	0.6	40	0.69	0.136
		0.33	Sorghum	0.2	40	0.59	0.039
		0.33	Trees/grasses	0.2	50	0.02	0.001
							0.176
J-S	347.33	0.42	Chat	0.6	40	0.69	0.173
		0.42	Sorghum	0.2	60	0.39	0.033
		0.42	Trees/grasses	0.2	60	0.02	0.002
							0.207
O-D	86.94	0.10	Chat	0.6	35	0.73	0.046
		0.10	Sorghum	0.2	20	0.79	0.017
		0.10	Trees/grasses	0.2	40	0.02	0.000
							0.063
						Sum I	**0.510**

2.6.5 Babile Soils

Months	Rainfall	Fraction of RF	crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	89.32	0.13	Chat	0.2	25	0.47	0.012
		0.13	Trees/Grasses	0.8	5	0.05	0.005
							0.017
A-J	253.22	0.37	Chat	0.2	35	0.72	0.053
		0.37	Sorghum/maize/Groundnut	0.7	40	0.59	0.152
		0.37	Trees	0.1	20	0.1	0.004
							0.209
J-S	287.48	0.42	Chat	0.2	35	0.72	0.060
		0.42	Sorghum/maize/Groundnut	0.7	55	0.44	0.129
		0.42	Trees	0.1	30	0.09	0.004
							0.193
O-D	58.15	0.08	Chat	0.2	25	0.8	0.014
		0.08	Sorghum/maize/Groundnut	0.7	30	0.69	0.041
		0.08	Trees	0.1	10	0.11	0.001
Total	688.15	1.00					0.055
						Sum	**0.474**

2.6.6 Amadle Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	61.44	0.11	Maize/sorghum/Weeds	0.7	15	0.84	0.064
		0.11	Grass	0.3	20	0.03	0.001
							0.065
A-J	196.04	0.35	Maize/sorghum/Weeds	0.7	30	0.69	0.168
		0.35	Grass	0.3	40	0.02	0.002
							0.170
J-S	242.78	0.43	Maize/sorghum/Weeds	0.7	50	0.49	0.147
		0.43	Grass	0.3	65	0.01	0.001
							0.149
O-D	64.47	0.11	Maize/sorghum/Weeds	0.7	25	0.74	0.059
		0.11	Grass	0.3	50	0.02	0.001
							0.060
Total	564.72	1.00				Sum	**0.443**

2.6.7 Dugda Hidi Soils

Months	Rainfall	Fraction of RF	crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	61.44	0.11	Grass	0.5	20	0.03	0.002
		0.11	Weeds	0.5	20	0.71	0.039
							0.040
A-J	196.04	0.35	maize/Sorghum	0.5	30	0.69	0.120
		0.35	Grass	0.5	40	0.02	0.003
							0.123
J-S	242.78	0.43	maize/Sorghum	0.5	50	0.49	0.105
		0.43	Grass	0.5	70	0.01	0.002
							0.107
O-D	64.47	0.11	maize/Sorghum	0.5	25	0.74	0.042
		0.11	Grass	0.5	40	0.02	0.001
							0.043
Total	564.72	1.00					**0.314**

2.6.8 Lange Soils

Months	Rainfall	Fraction of RF	crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	86.50	0.10	Soghum/weeds	0.6	10	0.89	0.051
	87.50	0.10	Maize/weeds	0.3	5	0.95	0.028
	88.50	0.10	Potato/Onion	0.1	5	0.75	0.007
							0.086
A-J	248.34	0.27	Soghum/weeds	0.6	40	0.59	0.097
	249.34	0.28	Maize/weeds	0.3	40	0.59	0.049
	250.34	0.28	Potato/Onion	0.1	10	0.56	0.015
							0.161
J-S	474.70	0.52	Soghum/weeds	0.6	60	0.39	0.123
	475.70	0.52	Maize/weeds	0.3	60	0.39	0.061
	476.70	0.53	Potato/Onion	0.1	40	0.39	0.021
							0.204
O-D	96.93	0.11	Soghum/weeds	0.6	40	0.59	0.038
	97.93	0.11	Maize/weeds	0.3	40	0.59	0.019
	98.93	0.11	Potato/Onion	0.1	20	0.5	0.005
Total	906.48	1.00					0.062
							0.514

2.6.9 Hirna Soils

Months	Rainfall	Fraction of RF	crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	106.48	0.13	Weeds	0.8	10	0.8	0.082
	106.48	0.13	Grass	0.2	20	0.03	0.001
							0.083
A-J	289.71	0.35	Sorhgum/weeds	0.8	40	0.59	0.164
	289.71	0.35	Grass	0.2	50	0.02	0.001
							0.165
J-S	364.55	0.44	Sorhgum/weeds	0.8	60	0.39	0.136
	364.55	0.44	Grass	0.2	70	0.01	0.001
							0.137
O-D	72.81	0.09	Sorhgum/weeds	0.8	30	0.69	0.048
	72.81	0.09	Grass	0.2	50	0.02	0.000
							0.049
Total	833.54	1.00					**0.434**

2.6.10 Chiro

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	106.48	0.13	Weeds/Sorghum	0.7	15	0.84	0.075
	106.48	0.13	Grass/trees	0.1	20	0.1	0.001
	106.48	0.13	Chat	0.2	40	0.69	0.018
							0.094
A-J	289.71	0.35	Weeds/Sorghum	0.7	40	0.59	0.144
	289.71	0.35	Grass/trees	0.1	50	0.08	0.003
		0.35	Chat	0.2	50	0.62	0.043
							0.189
J-S	364.55	0.44	Weeds/Sorghum	0.7	60	0.39	0.119
	364.55	0.44	Grass/trees	0.1	80	0.05	0.002
		0.44	Chat	0.2	50	0.62	0.054
							0.176
O-D	72.81	0.09	Weeds/Sorghum	0.7	30	0.69	0.042
	72.81	0.09	Grass/trees	0.1	50	0.08	0.001
		0.09	Chat	0.2	40	0.69	0.012
Total	833.54	1.00					0.055
							0.514

2.6.11 Bedessa Soils

Months	Rainfall	Fraction of RF	Crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	108.61	0.10	Sorghum/weeds	0.4	20	0.79	0.032
	108.61	0.10	Tef/weeds	0.3	30	0.44	0.013
	108.61	0.10	Chat/trees	0.3	50	0.35	0.011
							0.057
A-J	391.30	0.37	sorghum/weeds	0.4	40	0.59	0.087
	391.30	0.37	Tef/weeds	0.3	30	0.44	0.049
	391.30	0.37	Chat/trees	0.3	55	0.33	0.036
							0.171
J-S	477.33	0.45	sorghum/weeds	0.4	60	0.39	0.070
	477.33	0.45	Tef/weeds	0.3	70	0.27	0.036
	477.33	0.45	Chat/trees	0.3	60	0.31	0.042
							0.148
O-D	85.51	0.08	sorghum/weeds	0.4	40	0.59	0.019
	85.51	0.08	Tef/weeds	0.3	30	0.44	0.011
	85.51	0.08	Chat/trees	0.3	50	0.35	0.008
Total	1062.75	1.00					0.038
							0.414

2.6.12 Gelemso Soils

Months	Rainfall	Fraction of RF	crop/Veg	Percent land use	% cover per land use	C value per crop/Vegt	Weighted C
Jan-Mar	112.18	0.10	Chat	0.5	50	0.62	0.030
	112.18	0.10	Maize/sorghum	0.4	20	0.79	0.031
	112.18	0.10	Others	0.1	50	0.5	0.005
							0.066
A-J	409.77	0.36	Chat	0.5	60	0.55	0.098
	409.77	0.36	Maize/sorghum	0.4	40	0.59	0.084
	409.77	0.36	Others	0.1	55	0.45	0.016
							0.198
J-S	467.23	0.41	Chat	0.5	70	0.47	0.096
	467.23	0.41	Maize/sorghum	0.4	60	0.39	0.063
	467.23	0.41	Others	0.1	60	0.4	0.016
							0.175
O-D	159.49	0.14	Chat	0.5	50	0.62	0.043
	159.49	0.14	Maize/sorghum	0.4	30	0.69	0.038
	159.49	0.14	Others	0.1	50	0.5	0.007
Total	1148.67	1.00					0.088
							0.528

2.6.13 Diredawa Soils

Months	Rainfall	Fraction of RF	crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	145.04	0.22	Orchards	0.5	50	0.08	0.009
	145.04	0.22	Papaya	0.3	30	0.21	0.014
	145.04	0.22	Vegetables&others	0.2	60	0.4	0.018
							0.041
A-J	204.69	0.31	Orchards	0.5	50	0.08	0.013
	204.69	0.31	Papaya	0.3	30	0.21	0.020
	204.69	0.31	Vegetables&others	0.2	60	0.4	0.025
							0.057
J-S	247.94	0.38	Orchards	0.5	60	0.07	0.013
	247.94	0.38	Papaya	0.3	50	0.21	0.024
	247.94	0.38	Vegetables&others	0.2	70	0.3	0.023
							0.060
O-D	54.21	0.08	Orchards	0.5	50	0.08	0.003
	54.21	0.08	Papaya	0.3	30	0.21	0.005
	54.21	0.08	Vegetables&others	0.2	60	0.4	0.007
Total	651.88	1.00					0.015
							0.173

2.6.14 Karamara Soils

Months	Rainfall	Fraction of RF	crop/Veg	Percent land use	% Cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	61.44	0.11	Acatia Shrubs & Grasses	0.8	25	0.75	0.065
		0.11	Chat	0.2	20	0.83	0.018
							0.083
A-J	196.04	0.35	Acatia Shrubs & Grasses	0.6	40	0.6	0.125
		0.35	Chat	0.2	40	0.69	0.048
		0.35	Sorghum	0.2	35	0.6	0.042
							0.215
J-S	242.78	0.43	Acatia Shrubs & Grasses	0.6	60	0.4	0.103
		0.43	Chat	0.2	50	0.62	0.053
		0.43	Sorghum	0.2	55	0.4	0.034
							0.191
O-D	64.47	0.11	Acatia Shrubs & Grasses	0.6	35	0.65	0.045
		0.11	Chat	0.2	35	0.73	0.017
		0.11	Sorghum	0.2	5	0.95	0.022
Total	564.72	1.00					0.083
							0.572

2.6.15 Adele soils

Months	Monthly Rainfall	Fraction of RF	crop/Veg	Percent land use	% cover per landuse	C value per crop/Vegt	Weighted C
Jan-Mar	123.38	0.15	Chat	0.6	30	0.76	0.068
	123.38	0.15	Grass	0.4	15	0.03	0.002
							0.069
A-J	273.25	0.33	Maize/sorghum	0.4	40	0.59	0.078
		0.33	Chat	0.6	40	0.69	0.136
							0.214
J-S	347.33	0.42	Maize/sorghum	0.4	60	0.39	0.065
		0.42	chat	0.6	50	0.62	0.156
							0.221
O-D	86.94	0.10	Maize/sorghum	0.4	30	0.69	0.029
		0.10	Chat	0.6	30	0.76	0.048
							0.077
							0.581

2.7 Basic P-factor values for the Universal Soil Loss Equation

Erosion control practice	P-factor value
Contouring 0-1° slope	0.60†
Contouring 2-5° slope	0.50†
Contouring 6-7° slope	0.60†
Contouring 8-9° slope	0.70†
Contouring 10-11° slope	0.80†
Contouring 12-14° slope	0.90†
Level bench terrace	0.14
Reverse slope bench terrace	0.05
Outward-sloping bench terrace	0.35
Level retention bench terrace	0.01
Tied ridging	0.1-0.20

†Use 50% of the value for contour bunds or if contour strip cropping is practiced.

After Wischmeier and Smith (1978); Roose, (1977); Chan, (1981) (Quoted by Morgan, 1995)

2.8 Estimation of slope factors and P values for the research sites for use in USLE model

Study sites	Slope gradient (S) %	Slope length L	LS factor	Remark	P factor (USLE)
Adele	10	200	3.50		0.5
Amadle	5	80	0.86		0.5
AU Alluvial	1	300	0.25		0.6
AU Regosol	10	100	2.48		0.6
AU Vertisol	1	200	0.23		0.6
Babile	12	100	3.28	Bunds at 100m interval	0.6
Bedessa	8	60	1.38	Soil Bunds at 60m interval	0.3
Chiro	25	20	4.99	Stone terraces 20m interval	0.14
Dire Dawa	2	300	0.40		0.5
Dugda Hidi	4	300	0.99		0.5
Gelemso	15	50	3.31		0.6
Hamaresa	25	20	4.99	Bunds at 20m interval	0.4
Hirna	15	40	2.96	Stone terraces 50 m interval	0.14
Karamara	12	100	3.28		0.7
Lange	10	120	2.71	Soil Bunds at 20m apart	0.3

2.9 Input variables for the Universal Soil Loss Equation (USLE) adapted for Ethiopia (Hurni, 1985; Nyssen, et al, 2003).

R. Rainfall erosivity

Mean annual rainfall (mm)	100	200	400	800	1200	1600	2000	2400
Annual factor R†	48	104	217	441	666	890	1115	1340

K. Soil erodibility

Soil color	Black	Brown	Red	Yellow
Factor K	0.15	0.20	0.25	0.30

L. Slope length

Length m	5	10	20	40	80	160	240	320
Factor L	0.5	0.7	1.0	1.4	1.9	2.7	3.2	3.8

S. Slope gradient

Slope, %	5	10	15	20	30	40	50	60
Factor S	0.4	1.0	1.6	2.2	3.0	3.8	4.3	4.8

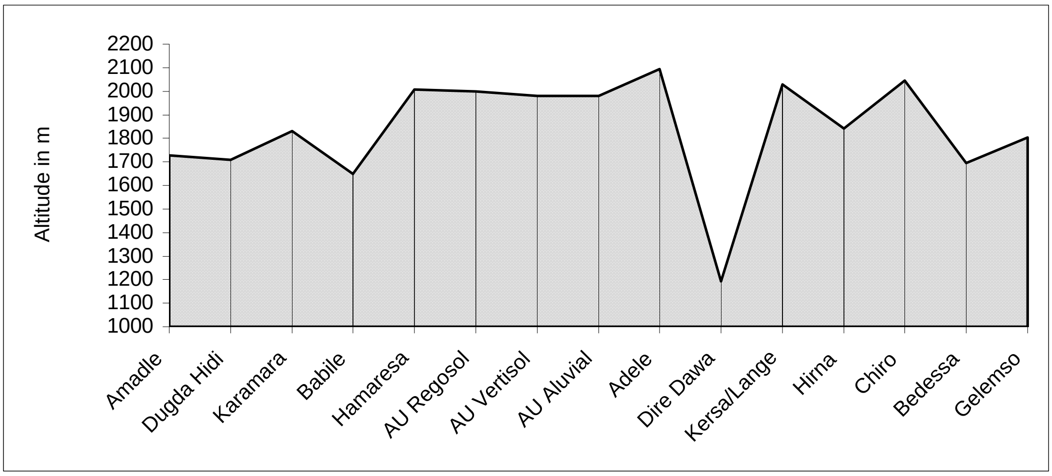
C. Land cover factor

Dense forest	0.001	Dense grass	0.01
Other forests	0.01-0.05	Degraded grass	0.05
Badland hard	0.05	Fallow hard	0.05
Badland soft	0.40	Fallow ploughed	0.60
Sorghum, Maize	0.10	Ethiopian teff	0.25
Cereals, Pulses	0.15	Continuous fallow	1.00

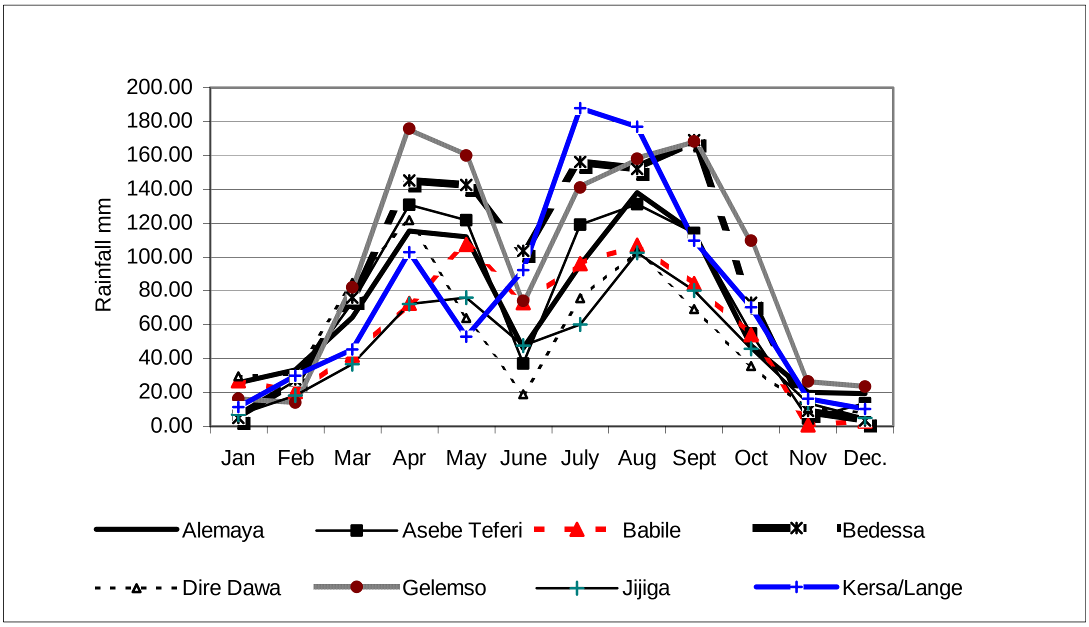
P. Management factor

Ploughing up and down	1.0	Ploughing on contour	0.9
Strip cropping	0.8	Intercropping	0.8
Applying mulch	0.6	Dense intercropping	0.7
Stone cover 80%	0.5	Stone cover 40%	0.8

†R in J cm m^{-2}h^{-1} year^{-1}(Nyssen, et al. 2003); K is also in SI units following Wischmeier and Smith's (1978) conversion coeffient



3. AVERAGE ALTITUDES OF THE STUDY SITES IN HARERGE, EASTERN ETHIOPIA



4. MEAN MONTHLY RAINFALL AT THE STUDY SITES IN HARERGE, EASTERN ETHIOPIA

Altitude in metres above sea level

More than 3700			HIGH WURCH
3700 to 3200		MOIST WURCH	WET WURCH
3200 to 2300		MOIST DEGA	WET DEGA
2300 to 1500	**DRY WEYNA DEGA** *Adele, Alemaya (AU Alluvial, Regosol, Vertisol,), Babile, Chiro Jijiga (Amadle, Dugda Hidi, Karamara) Hamaressa, Hirna, Lange*	**MOIST WEYNA DEGA** *Bedessa* **Gelemso**	WET WEYNA DEGA
1500 to 500	**DRY KOLLA** **Diredawa**	MOIST KOLLA	
Below 500	BERHA		
	Less than 900	**900 to 1400**	**More than 1400**

Annual Rainfall (mm)

5. AGROCLIMATIC ZONES OF THE STUDY SITES (shaded area) WITH REFERENCE TO THAT DESCRIBED FOR ETHIOPIA BY HURNI, 1986)