CHARACTERIZATION AND AMELIORATION OF DEGRADED SOILS IN THE ETHIOPIAN HIGHLANDS

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CHARACTERIZATION AND AMELIORATION OF DEGRADED SOILS IN THE ETHIOPIAN HIGHLANDS

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Abstract

While millions of dollars and billions of hours of food-for-work farm labor have been invested in soil and water conservation practices in the (sub) humid Ethiopian highlands, sediment concentrations in rivers are increasing because land degradation and associated soil erosion remain a persistent problem in the Ethiopian highlands despite the conservation efforts. The objective of this dissertation research was, therefore, to better understand soil degradation and measures that can be taken to ameliorate the hard pans that have formed in degraded soils. The research was carried out in the humid Ethiopian highlands where land degradation is severe.

The detailed study areas were the 113-ha Anjeni and 95-ha Debre Mewi watersheds in the Ethiopian highlands. In both watersheds, 0-45 cm soil penetration resistance (SPR, n=180) and soil physical properties (particle size, organic matter, pH, base ions, cation exchange capacity, silica content, bulk density and moisture content) were determined at 15 cm depth increments for three land uses: cultivated, pasture, and forest. In addition, 32 experimental plots were constructed in the Anjeni watershed to investigate the effects of ripping and liming of soil hardpans on runoff and erosion. The results show that the mean SPR of agricultural fields was

significantly greater (at $p<0.05$) than that of forest lands. Dense layers with above SPR a critical threshold of ≥ 2000 kPa were observed in the cultivated and pasture lands starting at a depth of 15-30 cm but did not occur in the undisturbed forest land. Compared with the original forest soils, agricultural fields were: lower in organic matter, CEC, and exchangeable base cations. They were also more acidic, had a higher bulk density and more fine particles (clay and silt), and contained less soluble silica.

Measurements in the ripped and limed soil in the field experiments in the Anjeni watershed showed that ripping to depths up to 60 cm increased infiltration and decreased runoff. Liming alone, on the contrary, increased runoff likely due to surface sealing. Deep ripping was not effective in reducing sediment yields and there was a tendency for deeper ripping to increase sediment concentration especially in the beginning of the rain phase. Liming decreased sediment concentrations compared with the unlimed plots.

Overall, the findings suggest that land degradation is a process where soil physical and chemical properties in agricultural lands deteriorate after deforestation, causing disintegration of soil aggregates resulting in greater sediment concentration in infiltration water that clog macro-pores, thereby disconnecting deep flow paths found in original forest soils. This, in turn, decreased base flow and increased direct runoff. This process is common in the Ethiopian highlands.

BIOGRAPHICAL SKETCH

Tigist Yazie Tebebu was born and grew up in Gojjam, Ethiopia. After she completed high school at Motta Senior Secondary School, she joined Mekelle University in 2002 and graduated with Bachelor of Science in 2006 in Land Resource Management and Environmental Protection, specializing in Soil and Water Conservation. In 2007, she was employed by Bahir Dar City Municipality Office Department of Urban Agriculture and served as a natural resource management expert. After working for 8 months, she left the office to pursue her graduate study and received her Master of Professional Studies degree from Cornell University in August 2009. For her Master's thesis research, she assessed gully formation and its hydrological controls in the Debre Mewi watershed, located in the Upper Blue Nile Basin.

In 2009, Tigist migrated to the United States of America and, soon after, in 2010 she joined the Soil and Water Lab of the Biological and Environmental Engineering Department in Cornell University to start her Ph.D. Tigist was awarded a State University of New York (SUNY) fellowship and Cornell's Food Systems and Poverty Reduction Integrative Graduate Education and Research Traineeship (IGERT) fellowship during her study.

This dissertation is dedicated to my beloved parents Yazie Tebebu Fenita and Abeba Mekonnen Wubie, my husband Simachew Alehegn Demelash, our beloved daughter Ruth Simachew Alehegn and my late grandfather Mekonnen Wubie Bogale.

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CHAPTER 1: INTRODUCTION

Land degradation occurs worldwide and has become a serious threat to food security in developing countries where people live on the edge of poverty (Eswaren et al., 2001; Bai et al., 2008; FAO, 2011, Bindraban et al., 2012).

Land degradation and associated soil erosion remain a persistent problem in the Ethiopian highlands, reducing farm productivity and affecting the livelihood of people. This land degradation is intimately linked to the expansion of intensive agricultural practices to all types of land including forest lands to meet the food demand of an increasing population (96.5 million with 2.9 % annual growth). Some indigenous practices such as off-contour furrows were practiced by farmers to conserve soil and water; however, these practices are causing waterlogging and promoting gully erosion downhill from the field that aggravates land degradation instead of conservation. Following the recurrent drought and food crises in the 1980's, many efforts have been undertaken to conserve soil and water with support of donors. In this effort, many traditional off-contour furrows were replaced by imported soil and water conservation (SWC) practices such as soil bunds, stone bunds and *Fanyaa Juu* terraces and enclosures (Mitiku et al., 2006). In addition, starting in 2010, a government-led large-scale watershed management program was launched as part of the ambitious Agricultural Growth and Transformation Plan (MOFED, 2010), which annually treats over 3000 community watersheds (> 40,000 hectares of land) with physical and biological SWC measures and involves more than 15 million people (MOA, 2013).

Despite all these conservation efforts, sediment concentrations continue to increase in rivers in the sub-humid and humid Ethiopian highlands (Steenhuis and Tilahun, 2014). This all clearly indicate that past measures have not been effective. It is partly because most practices lack consideration of landscape processes, soil types and agro-ecologic and climatic variations. For instance, most landscape interventions in the humid areas are designed based on the studies carried out in the semi-arid Tigray region situated in the northern part of Ethiopia. Soils in Tigray are generally coarser, covered by rock fragments, and have higher infiltration than those of humid highlands that are more clayey and much wetter. Measures that are successful in increasing available water for crop production in the semiarid region cause waterlogging and related problems in the humid region. This is because of the presence of hardpans in the subsoil that leads to temporary perched water tables when the soil above the restrictive layer saturates. This eventually causes a significant amount of rainwater loss (as surface runoff) and consequently more soil erosion during rainfall periods (Steenhuis et al., 2009; Biazin et al., 2011; Temesgen et al., 2012).

The factors that affect hardpan formation vary widely across locations, soil types and agroclimatic conditions. Studies of the formation and amelioration of hardpans have been largely limited to studies of compaction by heavy machinery during tillage operations. However, heavy machinery cannot explain the extensive hardpan formation in the Blue Nile Basin of the humid Ethiopian highlands where, for the smallholder rainfed farming, most tillage operations are performed either by hand or by the traditional oxen-pulled *Maresha* plow. The few studies on hardpan formation in Ethiopia were limited to the semi-arid areas (Mwendera & Saleem, 1997; Leye, 2007; Biazin et al., 2011; Temesgen et al., 2012b) with one exception of the Temesgen et al. (2012b) study in the humid Choke Mountain area**.** The Choke Mountain study shows the occurrence of hardpans but does not provide sufficient information to understand the drivers for hardpan formation.

Amelioration of the hardpans can allow plants to root more deeply, increase water infiltration and reduce runoff, all resulting in greater amounts of water available for to crop (i.e. green water) and thus increased (and more reliable) yields. The best solution to ameliorate the existing hardpans is breaking down the hard layers. Breakage loosens dense subsoil and improves root penetration and plant growth. This practice can be applied according to the soil, environment and farming systems. Furthermore, the benefits from deep ripping of acidic soils can be increased with liming (Conventry et al., 1987).

In order to design effective SWC practices, landscape processes, and runoff and erosion processes should be better understood.

The main objectives of this research are to better understand runoff and erosion processes in the humid and sub humid Ethiopian highland landscapes. The specific objectives are to investigate the formation of hardpans associated with land use changes, to determine the effects of deep ripping on hardpan soils, and to determine whether liming would improve the effects of deep ripping.

Chapter 2 reviews how understanding of runoff and erosion processes can be applied to improving efficacy of landscape intervention in the (sub) humid Ethiopian highlands. It poses hypotheses based on our previous years' studies in the region, and evaluates the hypotheses using field data from this study. It states that (1) watersheds' hydrological regimes in the humid Ethiopian highlands are similar in space and time; (2) runoff and sediment originate from saturated areas either from discharge of shallow regional ground water in the valley bottom or from degraded areas with limited root zone storage for rainwater above a shallow restrictive layer; and (3) due to deforestation, lateral flow paths have become shallower and shorter which in turn causes the formation of gullies. These hypotheses are evaluated, and principles for landscape interventions to reduce soil loss are devised.

Chapter 3 shows the processes of hardpan formation in the degraded agricultural fields. We investigate how hardpan formation in Ethiopia is directly linked with the conversion of land from a forest ecosystem to agricultural use. It assesses the changes in physical and chemical properties of soils in agricultural lands due to intensive cultivation. The processes of adverse change – from disintegration of soil aggregates, to transportation of fine sediments to clogged macro pores that disconnect deep flow paths originally developed beneath the earlier forest cover - are also discussed in detail.

Chapter 4 evaluates how degraded soils can be improved by deep ripping and liming. The short-term effects of ripping at various depths on runoff and erosion responses are discussed briefly. The potential of liming for adding to the benefits of deep ripping in the long term are also indicated.

These considerations of the landscape and climatic regimes, hardpan formation drivers, and soil remediation strategies contribute to improved soil and water conservation by presenting previously unstudied dynamics in the Ethiopian highlands. Efforts should be made to continue this research in nearby regions and with greater consideration for unique ecological, gully, and biogeochemical conditions in the future.

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CHAPTER 2: IMPROVING EFFICACY OF LANDSCAPE INTERVENTIONS IN THE (SUB) HUMID ETHIOPIAN HIGHLANDS BY IMPROVED UNDERSTANDING OF RUNOFF PROCESSES[1]

Abstract

Despite the millions of dollars invested in soil and water conservation practices in the (sub) humid Ethiopian highlands, and billions of hours of food-for-work farm labor, sediment concentration in rivers is increasing. This paper reports on the research to reverse the current trend. Based on the understanding of the hydrology of highlands, we provide evidence of the sources of surface runoff and sediment and of the mechanisms that govern the erosion processes and approaches and how they affect soil and water conservation practices. We suggest that priority in landscape interventions should be given to re-vegetation of the degraded areas so as to reduce the sediment concentration contributions originating from these areas. Additionally, efforts should be directed to gully rehabilitation in the saturated bottom landscape, efforts that may consist of vegetating shallow gullies and stabilizing head cuts of deeper gullies Finally, rehabilitation efforts should be directed to increase the rain water infiltration in the upland areas through the hardpan layer by connecting the land surface to the original deep flow paths that exist below about 60 cm. It will reduce the direct runoff during the rainy season and increase base flow during the dry season.

Keywords: Monsoon climate, Africa, soil and water conservation practices, mountain hydrology, hardpan soil, landscape interventions

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2.1 Introduction

Land degradation and associated soil erosion remain a persistent problem in the Ethiopian highlands, affecting both individual farmers, neighboring communities and other water users in the landscape and in downstream areas. This land degradation is intimately linked to the expansion of agricultural practices into areas which were previously under forest land cover. During the last fifty years many efforts have been undertaken to conserve soil and water in the Ethiopian highlands, mainly with donor support, to reduce the pressure and impact of agriculture. In this effort, the traditional off-contour furrows, were replaced by imported soil and water conservation (SWC) practices such as soil bunds, stone bunds and *Fanyaa Juu* terraces and enclosures (Mitiku et al., 2006). Most practices in the early 1970s and 1980s were installed with aid of the Food-For-Work natural resource conservation program administered by the Food and Agricultural Organization of the United Nations (Tamene and Vlek, 2008). In 2012 a government-led large scale watershed management program was launched as part of the ambitious Agricultural Growth and Transformation Plan (MOFED, 2010), which annually treats over 3000 community watersheds (> 40,000 hectares of land) with physical and biological SWC measures and involves more than 15 million people (MOA, 2013).

Despite all these conservation efforts, sediment concentrations continue to increase in rivers in the sub-humid and humid (called humid for short) Ethiopian Blue Nile basin (Steenhuis and Tilahun, 2014). Clearly, past measures are not effective and, as Baveye (2013) put it, it is time to think boldly and thus for this case rethink the logic behind the transfer of soil and water conservation practices across regions with different climate and landscapes. In order to design effective landscape interventions, runoff and erosion processes in the landscape should be better understood. For example, the type of runoff process has a direct effect on the placement of soil and water conservation practices. In watersheds, infiltration-excess runoff is generated on the hillsides and, as is currently the case, soil and water conservation practices are located on those hillsides. For saturation-excess runoff, water infiltrates on the hillsides and erosion-inducing runoff occurs in the flatter, downslope part of the landscape. Soil and water conservation practices, in this case, would be more effective at the bottom of the slope.

To date, most studies of landscape interventions to control runoff and erosion processes in the Ethiopian highlands have been carried out in the semi-arid Tigray region situated in the northern part of Ethiopia (Nyssen et al., 2000, 2007, 2009; Gebremichael et al., 2005; Descheemaeker et al., 2006; Aerts et al., 2006; Descheemaeker et al., 2006; Gebreegziabher et al., 2009; Girmay et al., 2009; Haregeweyn et al., 2013; and many others). Historically, many fewer comprehensive studies have been conducted in the humid highlands where landscape processes, soil types, and agro-ecological conditions are different. Soils in Tigray are generally coarser, covered by rock fragments, and have higher infiltration rates than those in the sub (humid) Blue Nile basin that are more clayey and much wetter. Therefore, in the semi-arid northern parts, measures such as enclosures and stone bunds have been successful in increasing the water available for the crops growing in the bottom lands (Nyssen et al., 2009). Landscape intervention in the Machakos region in Kenya, with just under 1000 mm annual rainfall, were also very successful (Tiffen et al. 1994). However, results of the implementation of donor-supported soil and water conservation practices are mixed (at best) in the humid areas where rainfall exceeds potential evaporation and saturation excess (Herweg and Ludi, 1999; Bewket and Sterk, 2002; Mitiku et al., 2006; Dagnew et al., 2015).

The design of soil and water conservation practices for saturation excess in humid Ethiopian highlands has not been studied well. Consequently, our objective is to better understand the hydrological and erosion processes leading to saturation excess runoff in humid monsoon areas and based on this understanding design effective landscape management practices.

2.2 Hypotheses and Theory

Based on interdisciplinary research carried out over the last 6 years, the hydrological and sedimentary processes of the (sub) humid Blue Nile basin at different spatial and temporal scales of observation, we pose the following three-part hypothesis –

(1) **Hydrological similarity of watersheds:** Annual runoff and erosion patterns of the watersheds in the humid Ethiopian highlands are similar in space and time

(2) **Saturation excess:** Runoff and sediment originate from source areas saturated either by a shallow regional groundwater in the valley bottom or from degraded areas with limited root zone storage for rainwater above a shallow restrictive layer

(3) **Flow paths:** Hillslopes with forests transmit infiltrated precipitation through the whole soil profile to the valley bottoms. After deforestation soils become degraded by forming restrictive layers at shallow depth forcing lateral flow to become shallower. This, in turn, reduces travel time, increases runoff and saturated land area, and reduces baseflow. Subsequently, to carry of the increase wet season flow, effective drainage ways are created. These drainage ways are the gullies in the saturated lands.

The first part of the hypothesis on the similarity in time and space is important so we can devise principles for landscape interventions that are applicable to all of the (sub) humid Ethiopian highlands. The second part of the hypothesis indicates that effective landscape interventions should address the saturated source areas in the watershed, while the third part on flow paths explains why gullies are forming and how rehabilitation can be addressed.

2.3 Materials and Methods

Field studies to test the hypotheses were conducted in four watersheds in the Ethiopian highlands (Figure 2-1). Anjeni, Maybar and Andit Tid are Soil Conservation Research Project (SCRP) watersheds, established in the 1980s to monitor soil erosion and efficiency of soil and water conservation measures such as graded *Fanya-Juus*. The fourth watershed, Debre Mewi, was established by Amhara Regional Agricultural Research Institute (ARARI) in 2007 and we adopted it to carry out research on distributed runoff and erosion processes. Rainwater-dependent agriculture is the dominant land use type in all.

The 113 ha Anjeni watershed is oriented north-south and flanked on three sides by plateau ridges. It is located at 37° 31’ E and 10° 40’ N and lies 370 km NW of Addis Ababa, to the south of the Choke Mountains (Figure 2-1b). Mean annual rainfall is 1690 mm and mean daily temperature ranges from 9 °C to 23 °C. In 1985 graded bunds, *Fanya-Juu*, were installed to terrace the hillslopes. *Fanya-Juu* (“throw uphill” in Swahili language) bunds are constructed by digging a trench and throwing the removed soil uphill to form a bund. In time, the space just above the bund has filled up with soil, having settled from ponded water or moved there by tillage, forming a terrace. Alisols, Nitisols and Cambisols are the dominant soil types (Bayabil et al., 2015). More than twelve years data are available in which precipitation, discharge and storm event sediment yields were measured in the periods between 1984 and 1993 and 2012 and 2013 (Table 1).

The 113 ha Maybar watershed is located at 39°39’ E and 10°51’ N, 23 km to the southwest of Dessie in northeast Ethiopia (Figure 2-1c). Mean annual rainfall is 1210 mm and mean daily temperature ranges from 14°C to 20 °C. The watershed drains into the Borkena River, which is a tributary of the Awash River. Phaeozems and Phaeozems associated to Lithosols are the dominant soil types, which are present in shallow layers (Bayabil 2009; Yesuf et al., 2015). Precipitation, discharge and storm event sediment yields are available from 1988-1994, 1996 - 2004 and 2008 (Table 1).

The Andit Tid watershed, situated 180 km northeast of Addis Ababa at 39°43’ E and 9°48’ N, covers 481 ha (Figure 2-1d). On average, it receives 1500 mm rainfall annually and the mean daily temperature is 13 °C. Terraces and small contour drainage ditches were installed by farmers to transport excess rainfall of the field without causing excessive erosion. The watershed is characterized by shallow soil depth particularly at the lower part and Andosols and Regosols are the dominant soil types (Engda, 2009). Precipitation, discharge and storm event sediment yields are available from 1986 to 1992, 1994 to 2001 and 2008 (Table 1).

The Debre Mewi watershed is located 30 km south of Lake Tana, Bahir Dar, Ethiopia at 37°24' E and 11°20’N and covers 523 ha. Studies were conducted in a 95 ha sub watershed (Figure 2-1e). Mean annual rainfall is 1240 mm with a mean daily temperature of 24 °C. A soil and water conservation practices mainly furrows with soil bunds have been implemented over the past three years. Soils have developed from highly weathered and fractured basalt dominated by Nitosols and Vertisols soil types. Precipitation, discharge and storm event sediment yields are available from 2008 to 2014 (Table 1). Additional experimental design details for all watersheds are given below.

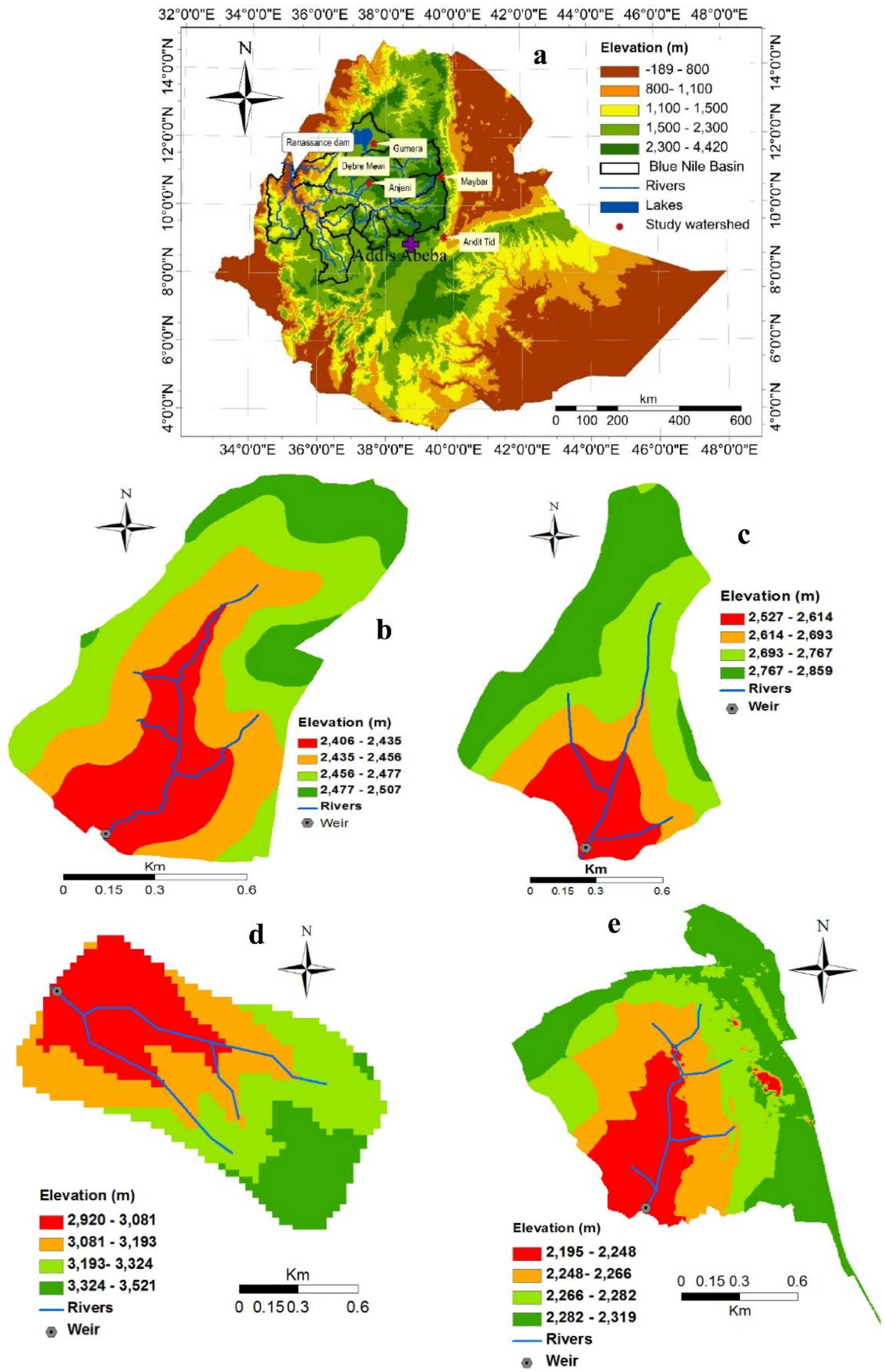


Figure 2-1.The study watersheds in the Ethiopian highlands: a) Map of Ethiopia, b) Anjeni, c) Maybar, d) Andit Tid and Debre Mewi.

Table 2-1. Summary of characteristics of study sites, annual precipitation and observation periods

Watershed	Watershed area (ha)	Dominant soils types	Mean annual rainfall (mm)	Observation periods	Studies
Anjeni	113	Alisols, Nitisols and Cambisols	1690	1984 -1993 and 2012-2013,	Liu et al. (2008); Tilahun et al. (2013); Guzman et al. (2013);Tebebu et al. (2014); Elkamil (2014); Bayabil et al. (2015)
Maybar	113	Phaeozems and Phaeozems associated to Lithosols	1210	1988 –1994; 1996 - 2004 and 2008.	Liu et al. (2008); Bayabil (2009); Bayabil et al.(2010) ; Guzman et al.(2013)
Andit Tid	481	Andosols and Regosols	1500	1986 – 1992; 1994 - 2001 and 2008	Liu et al.(2008); Engida (2009); Tilahun et al. (2013);Guzman et al.(2013)
Debre Mewi	95	Nitosols and Vertisols	1240	2008-2014	Tebebu (2009); Abiy (2009); Tebebu et al. (2010); Zegeye et al. (2010); Tilahun (2012); Langendoen et al. (2013); Tilahun et al. (2014); Dagnew et al. (2014); Zegeye et al. (2014); Tebebu et al. (2014); Dagnew et al. (2015)

2.4 Results and Discussion

The hypotheses is validated first and is followed by a discussion on effective management practices in a landscape with saturation excess runoff in a sub-humid and humid monsoon climate

2.4.1 Hypotheses testing

Based on the results of past studies, the validity of the three-part hypotheses is tested. We will first elaborate on the temporal and spatial similarity in runoff amounts and erosion patterns between different watersheds hundreds of kilometers apart. Next, we will explain runoff mechanisms that are occurring in the landscape. Finally, we will report on the change of flow patterns in a landscape due to land degradation, how these degraded areas are being formed, and why they are increasing with time. These degraded areas are defined according to their hydrological characteristics in that the downward flow through the restrictive layer is limited.

(1) Hydrological similarity of watersheds

Available studies in the Ethiopian highlands with a humid monsoon climate found that despite the large differences in size, soil, and geology, the discharge averaged over relatively short periods at the outlet of different watersheds behaves in a similar manner. The hydrological similarity over 14-day periods in watersheds can be seen by comparing the long-term discharge and sediment concentrations of the three SCRP watersheds (Figure 2-2, 2-3, 2-4), namely Andit Tid, Anjeni, and Maybar, located hundreds of kilometers apart. Liu et al. (2008) showed that for cumulative seasonal effective rainfall of 500 mm or more the proportion of rainfall that becomes runoff is remarkably the same. Figure 2-2 which is redrawn from Liu et al (2008) shows that for all three watersheds, the discharge over a 14-day period as a function of the effective rainfall (defined as precipitation minus potential evaporation). The trend lines for each of the three exhibit a linear relationship of effective precipitation and amount of watershed outflow. The slope of the trend line is 0.5 for the Maybar and Anjeni watersheds (each approximately 100 ha). For the slightly larger Andit Tid watershed (i.e., 400 ha) the slope of the trend line is about 0.6.

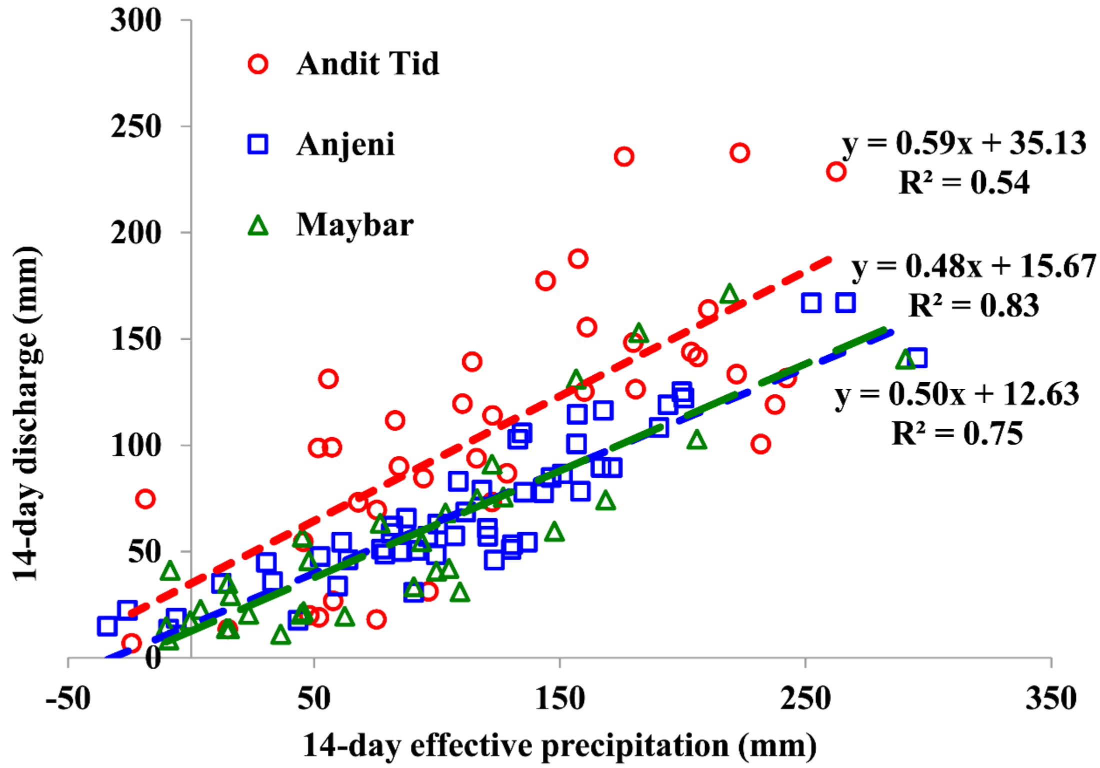


Figure 2-2. Relationship between 14-day discharge and effective precipitation (precipitation minus potential evaporation) after 500 mm of cumulative effective precipitation occurring since the beginning of the rainy phase for three watersheds in the Ethiopian highlands (Liu et al., 2008).

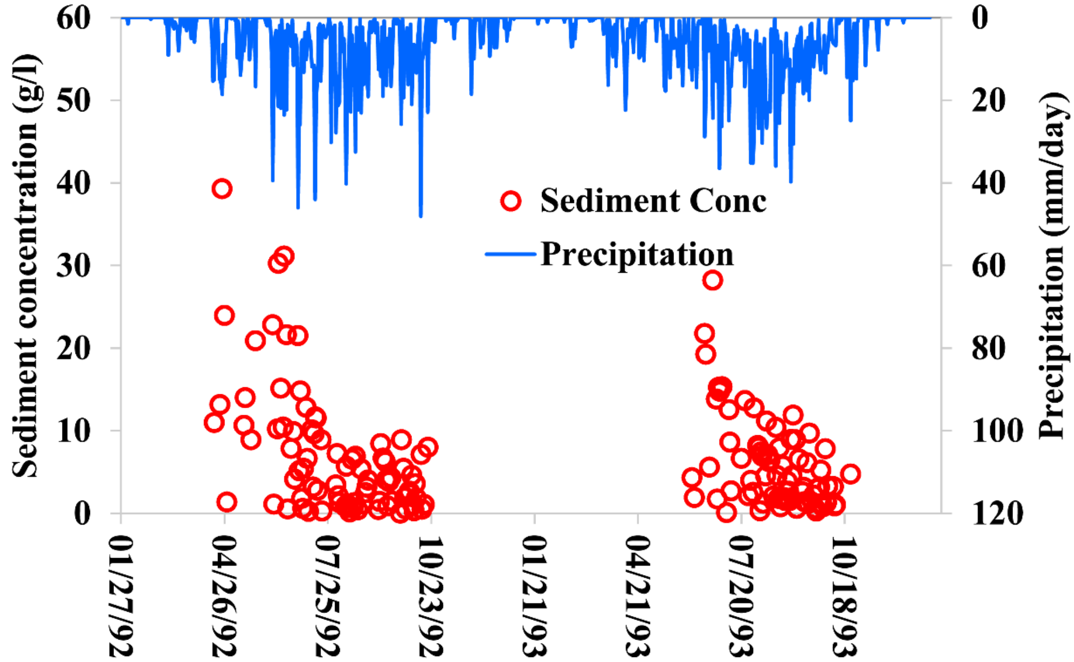


Figure 2-3. Sediment concentration and rainfall for the Anjeni Watershed six years after installing terraces (Elkamil, 2014).

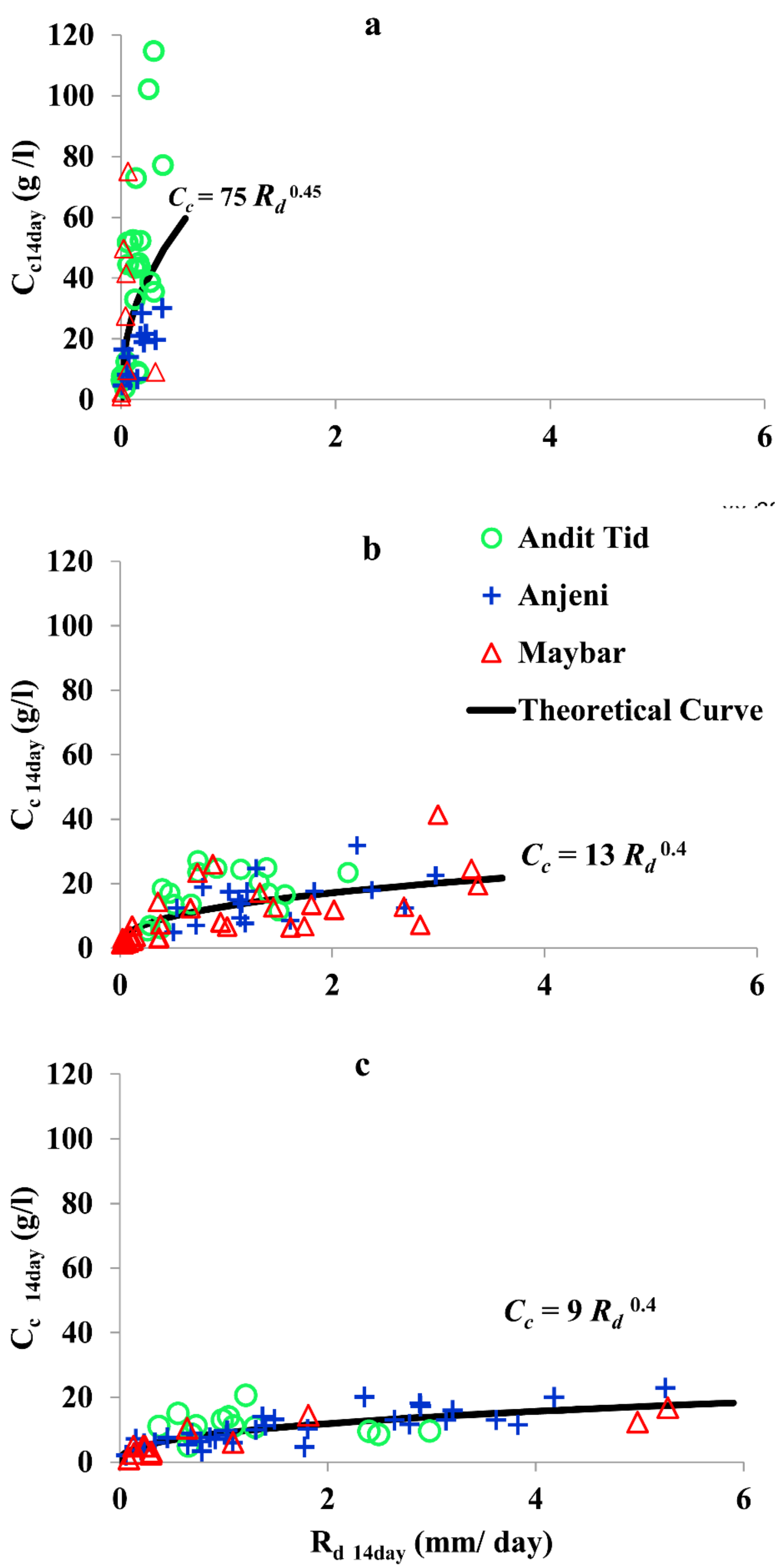

a
b
c
$C_c = 75\ R_d^{\ 0.45}$
$C_c = 13\ R_d^{\ 0.4}$
$C_c = 9\ R_d^{\ 0.4}$
Andit Tid
Anjeni
Maybar
Theoretical Curve
C_{c14day} (g /l)
$C_{c\ 14day}$ (g/l)
$C_{c\ \ 14day}$ (g/l)
$R_{d\ 14day}$ (mm/ day)
0
20
40
60
80
100
120
0
2
4
6

Figure 2-4. Fourteen day averaged discharge, Rd 14day, and sediment concentration, Cc 14 day, for Anjeni, Andit Tid and Maybar watersheds scaled by the fractional agricultural land area: (a) at the beginning of the rainy phase Pce <150 mm, (b) at the middle of rainy phase, 300 mm<Pce<700 mm, and (c) at the end of rainy phase, Pce>700 mm, (Guzman et al., 2013). Pce denotes the cumulative effective precipitation (precipitation minus evaporation) at which each measurement pair occurs. Scaled sediment concentration, Cc, was obtained by quotient of the observed sediment concentration, Cw, to fraction of agriculture land area in the watershed, Ac, (i.e. Cc = Cw /Ac).

The linear relationship between discharge either from interflow or surface flow after a certain threshold in rainfall is exceeded is not uncommon as shown by Chandler and Walter (1998) for Leyte in the Philippines; and by Caballero et al. (2013) for Honduras, Czech Republic and by Wickel et al. (1997 for eastern Amazonia in Brazil). The linear relationship could also explain the closed lake level changes in Haiti and the Dominican Republic. Although the explanation of this linear relationship varies (e.g., Chandler and Walter, 1998), it seems that since rainfall intensity does not affect the relationship, direct runoff from a fixed source area with a shallow ground water table (either perched or regional) is the most likely explanation (Steenhuis et al., 2013). For deep soils without restrictive layers, the source area is a relatively small part of the watershed (Caballero et al 2013; Steenhuis et al., 2013). The opposite is true for watersheds with restrictive layers that have larger contributing areas and less baseflow.

As shown by Enku et al (2015) the Anjeni watershed reaches a point after approximately 500-600 mm of cumulative effective rainfall, where the watershed is in equilibrium and no additional rain will be stored. The difference in rainfall and evaporation is the inflow that contributes to direct runoff (i.e., overland flow and interflow). Thus, the slope of the line is equal to the portion of the rainfall that contributes to direct runoff as shown in

Figure 2-2. This portion of rainfall is approximately 50% for the just over 100 ha Anjeni and Maybar watersheds and nearly 60% for the 400 ha Andit Tid watershed. Baseflow response after the rainstorm takes longer than 14 days, which is indicated by the positive intercept of runoff on the Y axis in the plot. Baseflow is approximately 1 mm/day for the Anjeni and Maybar watersheds (>500 km apart) and 2.5 mm/day for the wetter and larger Andit Tid Watershed.

As shown above and confirmed by modeling studies with a water balance (Tilahun et al., 2013a; Engda et al., 2011), the total annual outflow measured at the watershed outlet is less than total inflow (i.e., precipitation minus evaporation) into the watershed. Because these watersheds are located in the headwaters, some of the rainfall that infiltrates in the headwaters, either topographically drains towards the outlet becoming deep percolation (i.e., bed rock storage, Chandler, 2006) or appears as springs beyond the gage bypassing measurement and as base flow at the gage after the rainy monsoon phase ends.

Similar to the discharge behavior at the watershed outlet, temporal variation in sediment concentrations is comparable among the three watersheds. In all cases, the sediment concentrations were much greater at the beginning than at the end of the rainy monsoon phase. An example was given for the Anjeni watershed by Elkamil (2014) showing elevated concentrations of sediment at the beginning of the rainy phase even six years after terraces were installed (Figure 2-3). This elevation was associated with freshly plowed, degraded soils in which rills are being formed by the excess rainfall that cannot infiltrate the hardpan at depth. Once the greatest intensity storms have passed in July, the rill network can carry the runoff from the remaining storms without the need to form additional rills. Consequently, the sediment concentrations decrease at the end of the rainy phase (Steenhuis et al., 2014b; Tilahun et al., 2013(a, b)). Zegeye et al. (2010) and Tilahun et al. (2015) showed that rill formation stopped in August, and soil loss was greatly decreased from the uplands. The correlation of soil loss with plant cover was very weak (Tebebu et al. 2010) excluding plant cover as the cause for the decrease. Assuming that all sediment loss is originating from the agricultural areas the sediment concentrations can be scaled as the quotient of the observed concentration and the fraction of agricultural land in the watershed. The scaled concentration is plotted in Figure 2-4 as a function of the amount of cumulative precipitation since the beginning of the rainy phase. After scaling with the portion of agricultural land, the sediment concentration curves for the three SCRP watersheds coincide for each of the each of the intervals of cumulative precipitation (Figure 2-4, Guzman et al., 2013), indicating the great similarity in sediment transport between the watersheds

(2) Saturation excess

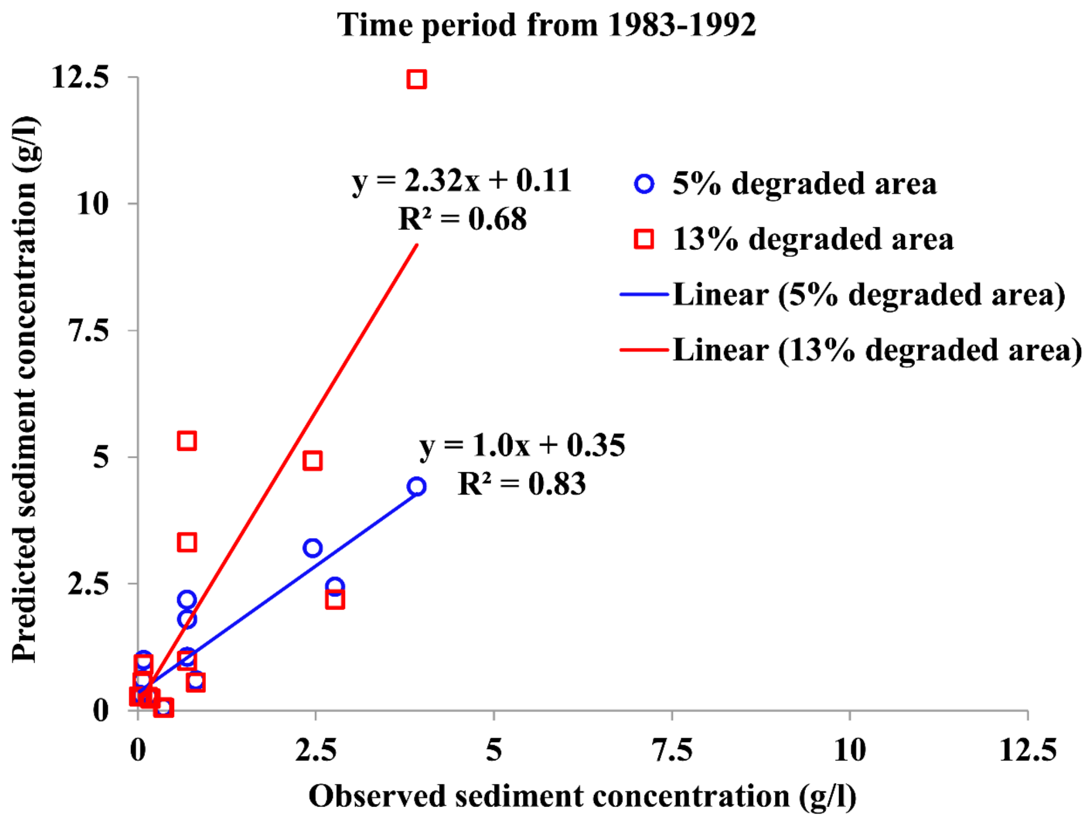
The occurrence of saturation excess can be derived as discussed above from the linear relationship of total precipitation and direct storm runoff in Figure 2-2 for the three watersheds. In addition, comparison of infiltration rates with rainfall intensities allows us to determine the predominance of saturation or infiltration excess as well. Infiltration measurements in the Maybar (Bayabil et al., 2010; and Derib, 2005), Anjeni (Bayabil et al., 2015), Debre Mewi (Tilahun, 2012), and Awramba watersheds shows that the median of the infiltration rate is exceeded less than 10% of the time. Runoff under these conditions then occurs mainly when the soil is saturated near the surface by either a high regional or perched groundwater table on the degraded soils. In contrast to the degraded soils, undisturbed soils have a high lateral conductivity and drain quickly between rain events, especially for steep slopes, and very little overland flow occurs from these lands.

The previous discussion implies that the sources of sediment are the low gradient saturated zones and the degraded soils but not the well-drained hill slopes. This finding was confirmed by runoff plots at several slope positions in the Maybar watershed (Bayabil et al., 2010) where runoff coefficients were inversely proportional to the slope. Water table measurements in this watershed showed that water table depth and both slope and crop type were related. Grass was found on the periodically saturated bottom lands, cropped agricultural land on the mid-slopes with an intermediate (perched) water table, and forest on the steep slopes where a small perched water table could be measured only during the rain storm and shortly thereafter. Similar findings were reported by Taye et al. (2013) in Tigray in the Ethiopian highlands in semi-arid monsoon climate that agrees for experiments with large runoff plots. They found that the crop land had less runoff and erosion located on the relatively steeper hillsides than grass on the land with less slope. Water table information was not available for this study and trampling of cattle could have played a role for the greater runoff from the grassland.

The increase in degraded land has had a direct effect on the amount of runoff and sediment generated. We used the Parameter Efficient Distributed (PED) model to show that the degraded acreage in the watershed increased. In the PED model (for a description see Enku et al., 2014 and Tilahun et al., 2013a, b), direct runoff is simulated as saturation excess runoff from both the periodically saturated bottom lands and the degraded lands using a simple water balance method by assuming that all excess rainfall above the threshold storage (i.e., air filled pore space) becomes direct runoff. Although this is a solid assumption for the areas with the regional groundwater near the surface, it might be not as good for the degraded areas with a perched water table and where some downward infiltration could occur. Thus the area of degraded land used in the model is the minimum area of degraded soils that has a perched water table and generates direct runoff. In the field the degraded area could be larger, however, the quantity of direct runoff generated from it will remain unchanged since it is derived from the outflow hydrograph.

Sediment loss is simulated as a function of the predicted direct runoff from these two areas. Consequently, in the model, an increase in degraded land runoff will result in a greater proportion of direct runoff and hence a greater sediment loss. It is thus possible to estimate the portion of additional runoff from the degraded areas in the watershed by fitting the discharge predicted by the PED model to the outflow signal. By fitting the discharge data of the Gumera River to the PED model, it was found that the direct runoff from the degraded area increased from 5 percent in the 1980's (1983-1992) to 13 percent in the 2000's (1995-2005) (Enkamil, 2014). Then by using the calibrated amount of direct runoff from the degraded areas of the 1980's (5%) and of the 2000's (13%), we predicted the sediment concentration in the runoff water with the same set of input parameters. In Figure 2-5, the predicted and observed sediment concentrations are shown. In the early time period (1983-1992) the 5 percent degraded area gives a good fit between observed and predicted sediment concentration while using the 13% degraded area over predicted the sediment concentrations. In the more recent period (1995-2005) the 13%

degraded area gives the best fit to the observed data (slope of the regression line close to 1) compared with the 5% degraded area that under predicted the sediment concentration. A similar analysis for the Blue Nile basin showed the same trends (Tesemma et al, 2010; Steenhuis and Tilahun 2014) where direct runoff and sediment increased and sediment concentration with time that could be related to an increase in the proportion of degraded areas. This is strengthening this type of analysis.


Time period from 1983-1992
Predicted sediment concentration (g/l)
Observed sediment concentration (g/l)
0
2.5
5
7.5
10
12.5
y = 2.32x + 0.11
R² = 0.68
y = 1.0x + 0.35
R² = 0.83
5% degraded area
13% degraded area
Linear (5% degraded area)
Linear (13% degraded area)

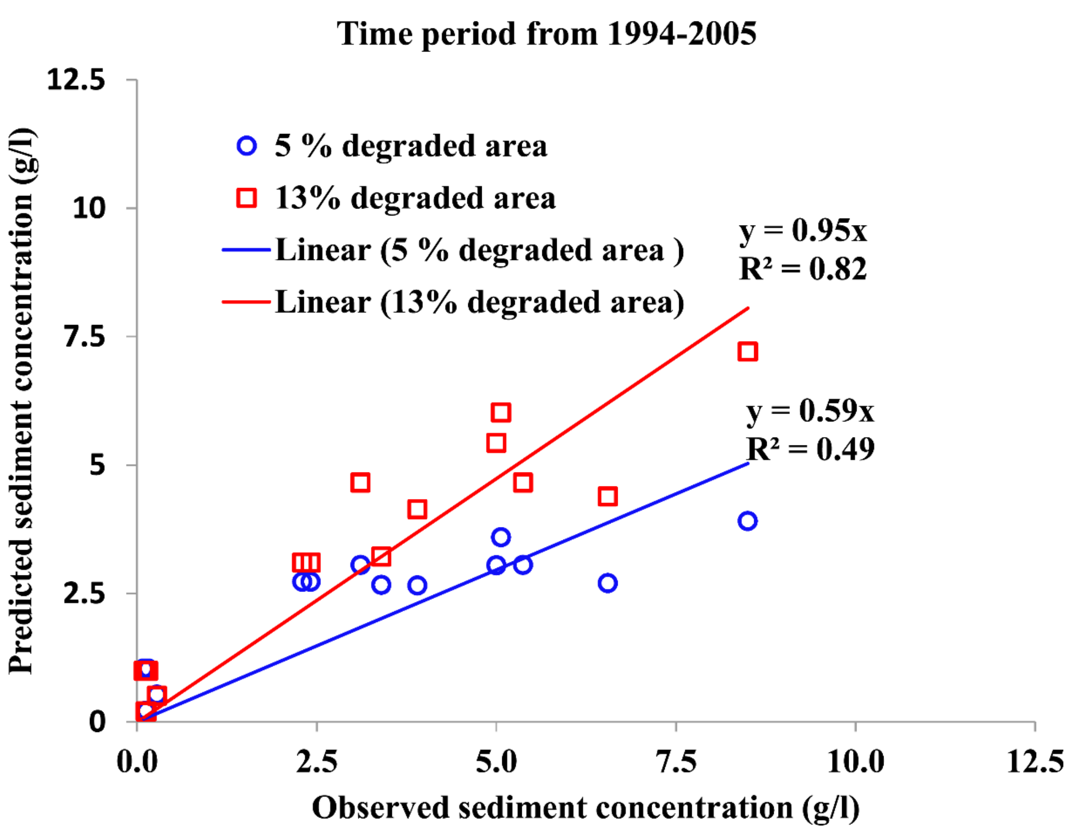

Time period from 1994-2005
Predicted sediment concentration (g/l)
Observed sediment concentration (g/l)
0
2.5
5
7.5
10
12.5
0.0
2.5
5.0
7.5
10.0
12.5
5 % degraded area
13% degraded area
Linear (5 % degraded area)
Linear (13% degraded area)
y = 0.95x
R² = 0.82
y = 0.59x
R² = 0.49

Figure 2-5. Observed and predicted sediment concentration for the Gumera River in northwestern Ethiopia for the period of 1981-1992 (in top figure) and for the period of 1994-2005 (in the bottom figure). The red square markers (and red line) are for the 2000s when 13 percent of the watershed was degraded and the blue circles (and blue line) are for the 1980s when 5 percent of the watershed was degraded.

(3) Flow path of water

In order to determine the change of flow patterns from a forest soil to a degraded soil, it is of interest to speculate how these degraded areas are being formed and why they are increasing with time. Tebebu et al. (2015) compared the penetration resistance of soils in agricultural fields (cultivated and pasture) and never-tilled forest lands surrounding Orthodox Christian churches (with a tradition of keeping a forest around the church and representing the original soil conditions) in Anjeni and Debre Mewi watersheds. In Debre Mewi watershed the mean percentage of clay and silt particles were 85% for the agriculture fields and 64 % for forest lands. In the Anjeni watershed, it was 50, 77, and 74 % in the forest, cultivated and grazing lands, respectively. Mean soil organic matter content in both watersheds was greater for the forest lands (approximately 7.2 %) as compared to that of cultivated of less than 2 %. Mean bulk density of cultivated lands was 1.38 g/cm^3 in Debre Mewi and 1.25 g/cm^3 in Anjeni watershed and for grazing lands 1.4 g/cm^3 in Debre Mewi and 1.2 g/cm^3 in Anjeni. These were much greater than in forest lands with a bulk density of 0.95 g/cm^3 on the average in both watersheds.

Tebebu et al (2015) found hardpan soils in the agricultural fields starting at a depth of 15 to 30 cm (see Figure 2-6). In the top 30 cm cattle on the wet grazing soils caused additional compaction (Figure 2-6). Sub soils in agricultural fields had such a high resistance (> 2000 kPa) that roots had difficulty penetrating them, while the church yards had much smaller or little resistance (< 1500 kPa). Similarly, Temesgen et al. (2009; 2012) found dense subsoil in the agricultural fields of the Enerta watershed, a few kilometers away from Anjeni watershed. Soil penetration resistance of approximately 2000 kPa was found to be a critical threshold value that can limit root capacity to penetrate and restrict soil water movement (Hamza and Anderson 2005). Figure 2-7 shows a typical degraded soil profile. The original soil structure with large vertical pores is seen below 60 cm, while from 0-60 cm the soil is a solid mass with the original cracks filled up with soil. These large pores were established by the roots of the woody vegetation and. are fundamental through which the rapid infiltration of water can occur.

The decrease in organic matter can explain the greater silt and clay content of the cropped and pasture fields compared to the forest. Fine particles are bound together by the organic matter in stable aggregates. Once the organic matter decreases the aggregates disintegrate. The resulting fine particles are easily suspended in the runoff water. We found up to 4% solids in the discharge waters. The sediment laden water infiltrates into the soil and plugs up the large macropores adding additional silt and clay to the profile in addition to the fine particles from the disintegrated aggregates.

The hardpan formation has a direct effect on the resulting peak flow immediately after the occurrence of a storm event, because of a major modification in the length of the flow path of the subsurface flow. Before the soil became degraded, the water infiltrated and followed a long and deep flow path to the stream to become baseflow long after the rain had stopped. However, with the formation of a hardpan, these longer paths are blocked and a much more shallow and direct flow occurs as interflow to the lowlands. Anecdotal evidence of this process is given by the farmers in the Fogera Plain who reported that, in early times, a rainstorm in the headwater of the Gumera would produce elevated stream levels the following day, but presently the flood comes shortly after the rainfall. The change in flow paths requires the landscape to adjust to these increased direct flows by forming effective pathways to carry this water to the stream. These pathways are the gullies that have appeared all over the landscape a few years after the uplands were cleared and became more intensively used in the middle of the 14 year period of the communist regime from 1977 to 1991 in which the fertile bottom lands were taken over by the regime (Tebebu et al., 2010; Ayele et al., 2015).

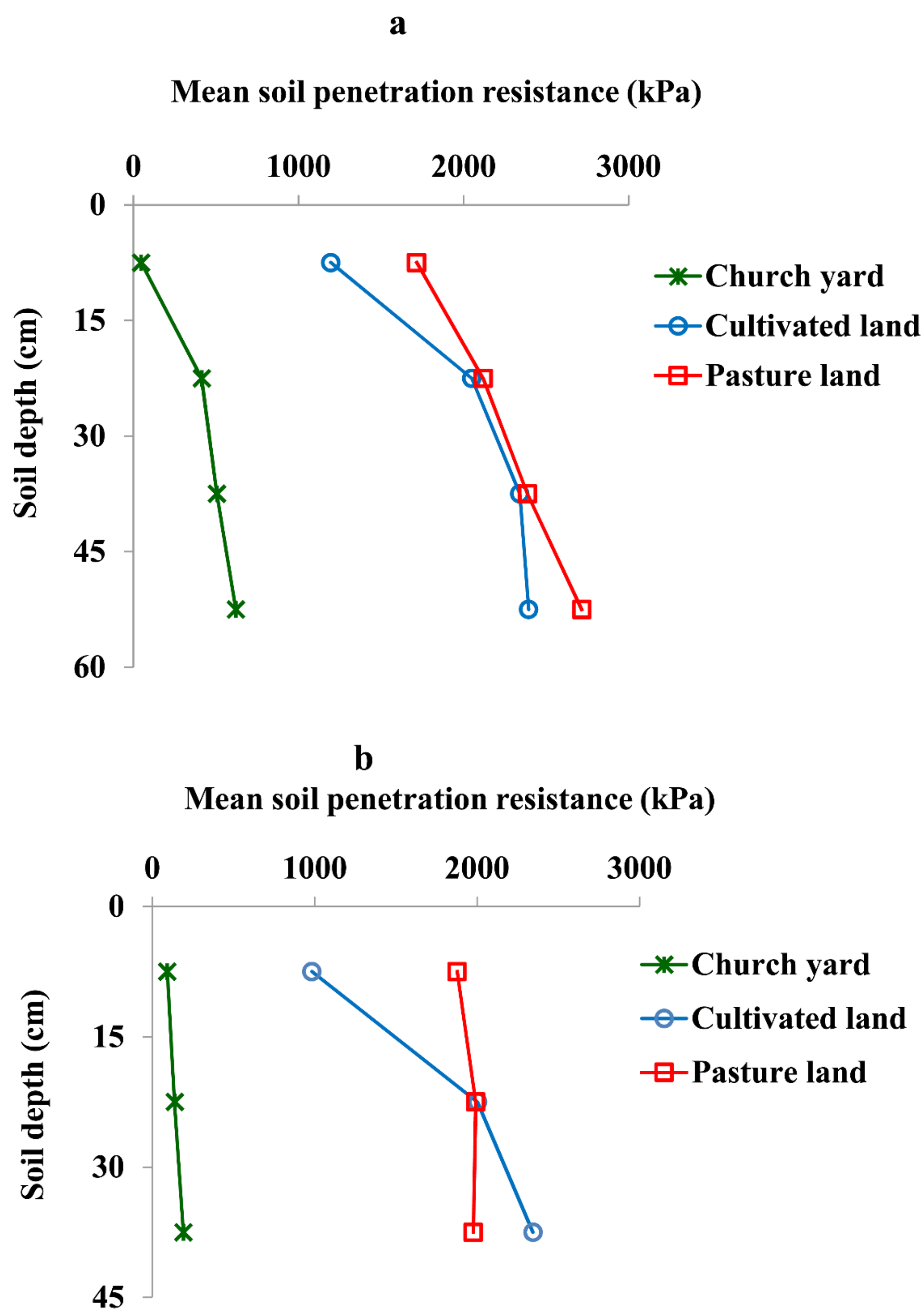


Figure 2-6. Mean soil penetration resistance in cultivated, pasture (grazing land), and forest land (at church yards) in Debre Mewi (a) and Anjeni (b) watersheds measured during the crop growing period (July) when soil was at optimum moisture condition (Tebebu et al., in preparation).

2.4.2 Effective landscape interventions practices

As mentioned in the introduction, despite millions of dollars invested in soil and water conservation practices (Osman and Sauerborn, 2001), sediment concentrations have continuously increased in the rivers of the Ethiopian Highlands. The main reason for the increase is that traditional donor-sponsored landscape interventions are being installed on hillslopes irrespective of the hydrology. Mitiku et al. (2006) and Dagnew et al. (2015) showed that poorly placed soil and water conservation practices concentrate runoff and will increase soil loss. In contrast, effective landscape interventions will decrease soil loss from source areas where the sediment is generated. For the sub-humid and humid Ethiopian highlands, these source areas are the degraded lands and the periodically saturated bottom lands. We will discuss appropriate landscape interventions for the two areas below.

(1) Landscape interventions for degraded soils that have formed a hardpan at shallow depth

Degraded soils are caused in part by clogging of the original macropores that decrease infiltration and increase runoff and erosion from these lands. These degraded areas can take various forms. The most severely degraded areas are bare because the subsoil does not support any crop and likely have the greatest soil losses (exceeded only by the gullies). Agricultural fields can be degraded as well. At the beginning of the rainy monsoon phase, these plowed fields become potential sources for elevated sediment concentration.

In order to rehabilitate these soils, the infiltration rate through the hardpan should be increased. Digging 50 cm deep furrows through the dense layer as part of the recent government sponsored large-scale conservation implementation program, increased infiltration and reduced runoff on soils in which the water table remained below the surface. In contrast, furrows installed in areas that saturated during the rainy phase of the monsoon have already formed gullies two years after installation, because they concentrate all the diffuse overland and subsurface flow to a common point (Dagnew et al., 2015). The most effective soil and water conservation practices are those that increase the infiltration rate of the hardpan and connect the surface with the existing macropore network below 60 cm such that water can flow via the deep flow paths to the outlet. Investigations on the Anjeni plots have demonstrated that maintenance is required for this practice to remain effective. Observations at the Debre Mewi watershed (Dagnew et al., 2015) support this recommendation since in just two years after installation most of the established furrows are already half-filled with deposited sediment.

In the case of a hardpan, a suggested promising method that will not put any land out of production is to rip through the hardpan along the contour at intervals of several meters, and by filling the ripped areas with straw or other organic matter to form high conductive paths to the subsurface (Table 2), as proposed by Saxton et al. (1981), a method that has been shown to increase infiltration into frozen soils significantly (Pikul and Aase, 1998; Schillinger and Wilkins, 1997). Williams et al. (2006) found that rotary sub-soiling decreases runoff as well. In Ethiopia as well, sub soiling of cultivated lands by ripping the compacted soil significantly reduced surface runoff and sediment production (Temesgen et al., 2012). At the same time, the sediment content of the water could be reduced by increasing the pH of the soil through application of lime. Reduction of the sediment concentration in the infiltrating water reduces the possibility of hardpan formation. However, additional research is needed to validate these recommendations. Adding straw may also be good for enhanced denitrification processes in the areas where nitrogen is a problem

Another method to reduce erosion without infiltration furrows or mechanically breaking up the hardpan is to replant the severely degraded areas with fruit trees or elephant grass (Table 2). The roots penetrate the hardpan and form a transport path of the water and at the same time will reduce the concentration of sediment in the infiltration water preventing clogging of the pores (Ziegler. and Giambelluca, 1998). Good examples of conversion of degraded land to forest or orchards can be seen along the road connecting Bahir Dar to Gondar. To aid the establishment of reforested lands, they can be irrigated from groundwater during the dry season which is important if the young fruit trees are to survive. Once established, leaf fall and root turnover will add to the organic matter and soil carbon, which both retains soil moisture and changes soil texture and pH.

No till has proven to reduce erosion. In the studied Debre Mewi plots soil loss only started after the fields were plowed. However, the difficulty with no-till is that it will require herbicides and pesticides to combat the weeds and insects that may cause crop failure (McHugh et al., 2007). In addition, the vegetation or crop residue that is expected to serve as a protective cover or organic material is typically used as animal feed in these smallholder agricultural systems.

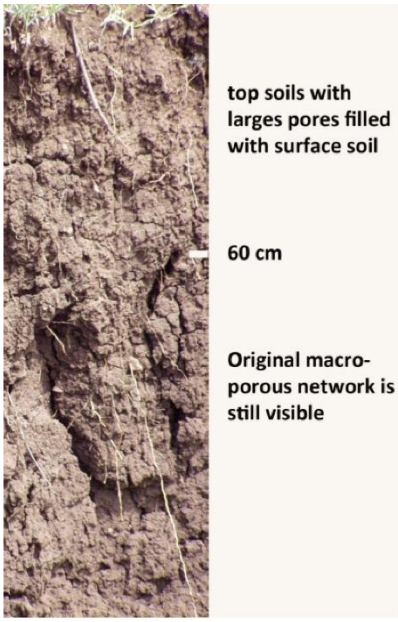


Figure 2-7. A degraded soil profile: the original flow paths are only present in the lower part of the profile (below 60 cm).

(2) Landscape interventions for periodically saturated source areas on less sloping lands near watercourses

The saturated areas of agricultural hillslopes are usually located near watercourses or above barriers where interflow resurfaces. This, for example, is observed in the Debre Mewi watershed where lava intrusion dikes are one of these barriers above which a saturated area is formed (Abiy, 2009). These saturated areas are not a source of sediment when fully covered with wetland plants. However, once cultivated, and especially when overgrazed, these lands become sediment source areas.

In many cases, the saturated areas are also the location where gullies form (Tebebu et al., 2010). Once initiated these gullies expand rapidly, especially at locations where water tables are above the gully bottom. In saturated soil, the strength is reduced. Because of both the absence of bedrock and the minimal soil strength, these gullies can deeply incise into the terrain. In Figure 2-8 shows one of the many rapidly advancing gullies in the Debre Mewi watershed. Banks collapse easily due to high ground water table and become a large source of sediment that is easily being picked up by the water flowing through the gully from the upper part of the watershed. Zegeye et al. (2014) measured that up to 95% of the sediment is contributed by these gullies. As a result, any sediment captured upslope in the watershed does not translate into a reduction in sediment concentration measured downstream. This is confirmed by the study in Debre Mewi of Dagnew et al. (2015) finding that average concentrations downstream of the expanding gullies slightly increase after installation of furrows with bunds to control soil erosion. However, the overall soil loss (at least in the short term) decreased because more rainwater infiltrated and runoff was reduced.

Therefore, effective ways to control gully erosion need to be developed. This is not an easy task, and research should be carried out to develop best management practices at the smallest possible cost to farmers. However, incising channels such as gullies experience a predictable, non-reversible series of adjustment processes (Schumm et al. 1984). Upslope migrating head cuts increase gully depth and slope, destabilizing the gully banks, resulting in widening and downstream deposition (Tebebu, 2009; Tebebu et al., 2010; Langendoen et al., 2013). Hence, it is important to note that gully stabilization should proceed from downstream to upstream by halting the head-ward migration of head cuts (Table 2), which will otherwise severely damage any improvement made on the hillslopes and headwaters.

Table 2-2. Summary of recommended landscape interventions

Landscape intervention	Purpose	Location of application
Ripping the hardpan with filling the ripped areas with straw or other organic matter	Connect the surface with the existing macropore network Increase infiltration rate of the hardpan and reduce runoff and sediment production Enhance denitrification processes in nitrogen deficient areas	Degraded soils with a hardpan at shallow depth mostly in the agricultural hillslopes
Lime application	Increase pH	
Deep furrows with continuous maintenance	Connect the surface with the existing macropore network	
Re-vegetation with fruit trees or elephant grass	Roots penetrate the hardpan and form a transport path of the water Reduce the concentration of sediment in the infiltration water and preventing clogging up of the pores. Add organic matter and soil carbon which both retains soil moisture and changes soil texture and pH	Saturated source areas on less sloping lands Actively incising gully channels Lands with a hardpan soil at shallow depth
Stabilizing gully head cuts from downstream to upstream	Stabilize upslope migrating gully head cuts	Actively incising gully channels in the less sloping saturated areas

Figure 2-8. Gully in the Debre Mewi watershed.

2.5. Conclusions and Recommendations

Combatting the growing sediment loads in the Ethiopian highlands requires understanding the roots of land degradation. This paper is intended to serve as a contribution to the discourse both on the interaction between hydrology, land degradation, and sediment concentrations as well as on the types of landscape interventions that can be implemented to reverse the current trend of unsustainable land use in the (sub) humid monsoonal climate.

To determine the interaction in the degrading landscape with hydrology and sediment concentrations we validated three hypotheses with discharge, sediment and rainfall data of four watersheds in the humid Ethiopian highlands at more than 500 km apart. We found that:

After the watersheds wet up, a hydrological similarity exists in sub-humid and humid watersheds that consist of: a linear relationship between rainfall and direct discharge over 14 day periods. Part of direct discharge is interflow that is transmitted rapidly down the moderate to steep slopes. The remainder is saturation excess runoff from the periodically saturated bottom lands or a perched water table on the degraded hillside Sediment concentrations in discharge are always much greater for a given amount of runoff in the beginning of the rainy phase than at the end. The concentrations at given time between watersheds vary with the proportion of cultivated agricultural area in the watershed. Thus the general hydrological principles of landscape interventions determined from one watershed can be transferred to other watersheds in the (sub) humid Ethiopian highlands

Soil degradation leads to accelerated formation of a near surface restrictive layer and restricts infiltration to the subsoil. As a result, lateral flow paths have become shallower reducing travel time to the outlet, increasing runoff, reducing base flow and a greater regional water table depth saturating more of the valley bottom. To accommodate the increased rate of shallow lateral flow, more effective lateral drainage ways are created. These drainage ways are the gullies in the saturated areas, Saturation excess runoff is common and originates spatially both from areas in which the regional groundwater reaches the surface at the lower slope positions and from the degraded areas with perched water table over the restrictive layer. The effective drainage ways become gullies in the saturated areas with little soil strength and drain the increased flow from the hillsides during the rainy phase as a consequence of the soil degradation. The newly formed gullies are the greatest sources of sediment in the watershed outflow.

Based on these validated hypotheses, we advocate a set of conservation practices that are intended to increase the infiltration rate for the degraded areas on the hillsides and to protect the saturated and severely eroded areas with vegetation so that they can facilitate overland flow without picking up sediment. In many ways, these soil and water conservation practices are different in the wet climates where rainfall exceeds the evaporation during the rainy monsoon phase from those applied in drier areas. For humid areas, drainage of excess rain water takes priority over water conservation in the root zone. Management practices developed in semi-arid monsoon climates such as in Tigray or Machakos area in Kenya should be carefully adapted before recommending for wetter climates

In addition, we have stressed the importance of controlling gully erosion starting at the outlet. The latter suggests that engineers in planning watershed interventions should consider the whole watershed and not start soil and water conservation practices by default at the top of the watershed. This work needs some further testing to refine limits to applicability and to generate wider evidence base. The benefits from which are not just the farmers and agricultural communities in the immediate landscape but also for water users, communities and industries downstream; nowhere is this more important than the rapidly developing Blue/Eastern Nile region.

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CHAPTER 3: CHARACTERIZATION OF DEGRADED SOILS IN THE HUMID ETHIOPIAN HIGHLANDS[2]

Abstract

Hardpan is a major cause of land degradation that affects agricultural productivity in developing countries. However, relatively little is known about the interaction of land degradation and hardpans. The objective of this study was, therefore, to investigate soil degradation and the formation of hardpans in crop/livestock mixed rainfed agriculture systems and to assess how changes in soil properties are related to the conversion of land from forest to agriculture. Two watersheds (Anjeni and Debre Mewi) were selected in the humid Ethiopian highlands. For both watersheds, 0-45 cm soil penetration resistance (SPR, n=180) and soil physical properties (particle size, SOM, pH, base ions, CEC, silica content, bulk density and moisture content) were determined at 15 cm depth increments for three land uses: cultivated, pasture and forest. SPR of agricultural fields was significantly greater than that of forest lands. Dense layers with a critical SPR threshold of $\geq$ 2000 kPa were observed in the cultivated and pasture lands starting at a depth of 15-30cm but did not occur in the undisturbed forest land. Compared with the original forest soils, agricultural fields were: lower in organic matter, CEC, and exchangeable base cations; more acidic; had a higher bulk density and more fine particles (clay and silt); and contained less soluble silica. Overall, our findings suggest that soil physical and chemical properties in agricultural lands deteriorated, causing disintegration of soil aggregates

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resulting in greater sediment concentration in infiltration water that clogged up macro-pores, thereby disconnecting deep flow paths found in original forest soils.

KEY-WORDS*: hardpan; soil penetration resistance; deforestation; soil degradation, East Africa; Horn of Africa*

3.1 Introduction

Land degradation occurs worldwide and is a serious threat to food security in developing countries where people live on the edge of poverty (FAO, 2011; Temesgen et al., 2012a). Land degradation can take on many forms, ranging from desertification to salinized lands in semi-arid lands to low producing compacted soils with low permeability and poor root development in more humid climates (Hawando, 1997; Johnson et al., 1997; Hanson et al., 2004b; Ahmad et al., 2007; Elhaja et al., 2014).

Here, the primary concern is degraded soils in humid climates that form slowly permeable soil layers commonly known as hardpans. According to Soil Science Society of America, hardpans are defined as soil layers with physical characteristics that restrict downward soil water movement and reduce moisture storage capacity. They usually occur between 7.5 and 90 cm deep (Litchfield & Mabbutt, 1962; Hoogmoed & Derpsch, 1985; Radcliffe et al., 1989; Mulholland & Fullen, 1991; Kılıç et al., 2004). Hardpans also limit root's capacity to penetrate the soil profile and to uptake nutrients from the lower strata that are critically needed for improved crop production (Busscher & Bauer, 2003; Raper et al., 2005). For example, a study in Pakistan showed that hardpans caused a reduction of cotton yield by up to 15% (Raza et al., 2007), by reducing nutrient and water uptake and availability. In many coastal plain soils of the southeastern USA, hardpans cause a reduction of corn grain yield by up to 2.4 Mg/ha (Busscher et al., 2001). In addition, during wet periods since infiltration is limited, hardpans make the upper soil layers wetter. This, in turn, results in yield reduction due to root infections (Allmaras et al., 1998) and an increase in runoff and erosion because the soil can store only limited amounts of water before runoff starts. As a consequence, the occurrence of hardpans in the soil profile increases erosion (Tebebu et al., 2015) and sediment concentration in rivers such as in the Blue Nile (Steenhuis & Tilahun, 2014; Steenhuis et al., 2014).

The factors that affect hardpan formation vary widely across locations, soil types and agro-climatic conditions. Litchfield & Mabbutt (1962) and Gerard (1965) among others reported that natural soil formation can over time result in horizons of high density by translocation of clay and loam particles from the layers above. Such processes can be enhanced by several anthropogenic factors such as wheel pressure from farm machinery (Radcliffe et al., 1988; Busscher & Bauer, 2003; Raper et al., 2005), livestock trampling during free grazing (Mulholland & Fullen 1991), and plowing of farmlands at the same depth for many years (Leye, 2007; Temesgen et al., 2009), particularly when the soil is wet (Ahmad et al., 2007). Soil compaction is facilitated by high moisture content (Hamza & Anderson 2005).

Studies of the formation and amelioration of hardpans have been largely limited to studies of the compaction by heavy machinery during tillage operation. However, heavy machinery cannot explain the extensive hardpan formation in the Blue Nile basin of the humid Ethiopian highlands where, for the smallholder rainfed farming, most of all tillage operations are performed either by hand or by the traditional oxen pulled *Maresha* plow. The few studies on hardpan formation in Ethiopia were limited to the semi-arid areas (Mwendera & Saleem, 1997; Leye, 2007; Biazin et al., 2011; Temesgen et al., 2012b) with one exception of the Temesgen et al (2012b) study in the humid Choke Mountain area**.**

This one study in the Choke Mountain shows only the occurrence of hardpans but does not provide sufficient information to understand the drivers for hardpan formation. From earlier studies, it is known that land degradation is associated with the conversion of land from forest ecosystem to agricultural use. For instance, Tebebu et al (2010) showed that the incision and development of gullies at the lower parts of the landscapes are related to the clearance of forests at the hillsides. This is because the removal of vegetation disrupts the local hydrology and increases surface and subsurface runoff from the hillside to the valley bottoms. Similarly, Tebebu et al (2015) reflected that intensive cultivation after the clearance of forests shortens the duration to peak flow in rivers after a storm event because of the major modification in the length of the flow path of the subsurface flow as a result of impermeable layers. Thus, it is reasonable to examine the formation of hardpans associated with land use changes. Consequently, the objectives of this study are to investigate the differences in soil physical and chemical properties under original forest and converted lands and to better understand hardpan formation associated with land use changes.

3.2 Materials and Methods

3.2.1 Description of study areas

This study was carried out in two watersheds in the humid highlands of Ethiopia, namely the Anjeni and Debre Mewi watersheds (Figure 3-1). Like elsewhere in the humid Ethiopian highlands, small holder farmers in these watersheds rely on rainwater to grow crops. Tillage operations are conducted using a traditional oxen pulled, single-tooth cultivator, *Maresha,* at shallow depth of 10-15 cm. Farming systems in both watersheds are a mixture of crop and livestock production. The main land uses are cultivated land (more than 90%), communal grazing land and some natural forest land left mainly around the Orthodox Christian churchyard. The forest land at the church compounds has never been tilled or grazed and is therefore assumed to represent the original soil profile.

The *Anjeni watershed* (10°40' N, 37°31' E) is located 320 km northwest of Addis Ababa south of the Choke Mountains. The watershed is one of the experimental stations established under the Soil Conservation Research Program (SCRP) with the collaboration of the Ethiopian Ministry of Agriculture and the Swiss Agency for Development and Cooperation in the 1980’s (Hurni et al., 2005). The watershed covers 113 ha, is oriented north to south and flanked on three sides (northeast, north and northwest) by plateau ridges with elevation ranges from 2407 to 2507 m (Table 1). On average, the watershed receives 1700 mm rain annually with 16℃ mean daily temperature (Setegn et al., 2010; Bayabil et al., 2015). Soils have developed from basalt and volcanic ash, with dominant soil types being Alisols, Cambisols and Nitosols (Hurni et al., 2005; Tilahun, 2012;

Tilahun et al., 2013). Graded soil bunds have been employed since the mid-1980's to reduce erosion. Most of the grazing (pasture) land in the Anjeni watershed is located on the degraded hill slopes at the northwest side of the watershed while the croplands are in the downslope, midslope and non-degraded upper slope areas of the three sides. The forest land is located on the upper slope at the northwest side.

The second watershed, *Debre Mewi (*37°24' E, 11°20'N), is located 200 km north of Anjeni, approximately 30 km south of Lake Tana, Bahir Dar. The total land area of the watershed is 523 ha; for this study, sampling was done in a 95 ha sub-watershed where elevations ranged from 2187 to 2345 m. Mean annual rainfall in the watershed is 1250 mm and the mean daily temperature is 20℃ (Table 1). Soils have developed from highly weathered and fractured basalt, with Nitosols and Vertisols being the dominant soil types (Abiy, 2009; Tebebu et al., 2010).

Table 3-1. Summary of characteristics of study sites

Watershed	Area (ha)	Mean annual precipitation (mm)	Dominant Soil type	Dominant conservation practice
Anjeni	113	1700	Alisols, Cambisols and Nitosols	Graded soil bunds
Debre Mewi	95	1250	Nitosols and Vertisols	Soil bunds and Fanya-Juu with deep furrows

Since early 2012, intensive soil and water conservation practices have been implemented that consist of soil bunds and *Fanya-Juu* with deep furrows (Dagnew et al., 2015). *Fanya-Juu* ("throw uphill" in Swahili language) bunds are constructed by digging a trench and throwing the removed soil uphill to form a bund. Pasture lands are found in the low lying periodically saturated areas, while cropland is found on the middle and upper slopes where it is intermixed with brush on the shallower soils.

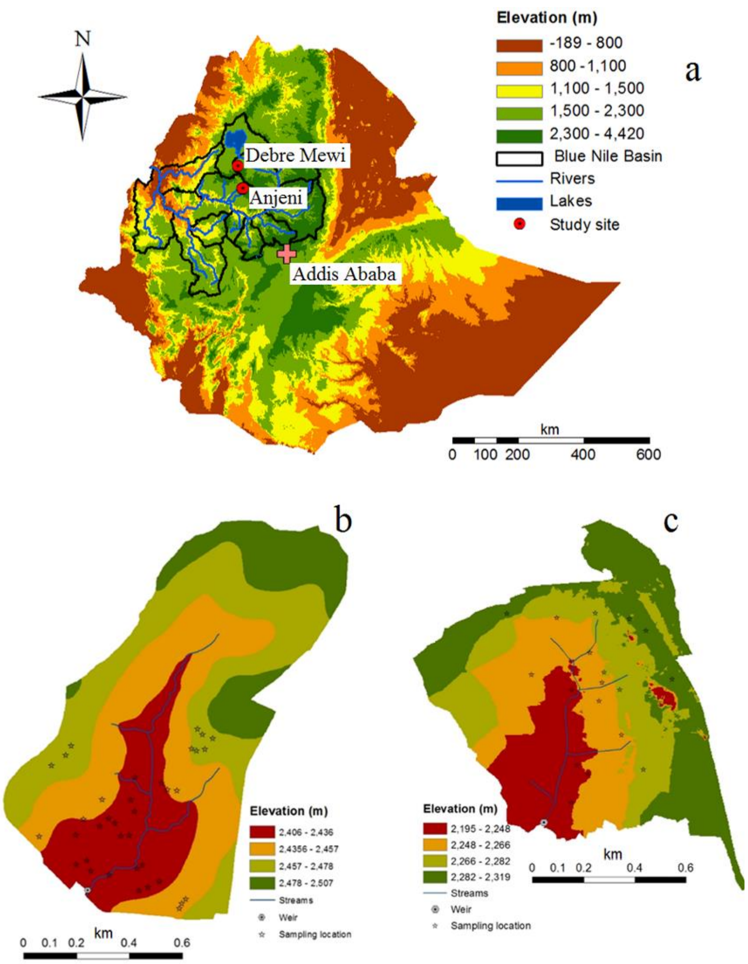

Figure 3-1. Location of study watersheds in the Blue Nile Basin: a) map of Ethiopia, b) Anjeni, and c) Debre Mewi.

3.2.2 Field measurements and soil sampling during the cropping season of 2014

In each watershed, three land uses were selected; cultivated (crop), pasture and adjacent natural forest lands for performing the soil penetration tests and to collect soil samples. In the humid and sub-humid highlands of Ethiopia, most forest lands have been converted to cultivated and pasture lands and very few patches of forest are left. These patches are found in churchyards. Sampling in these protected churchyards can offer an exclusive look into what the original soils in the area must have looked like, and thus can give insight into the effects of forest clearing and land use change on soil degradation in the form of hardpans and the related effects on limited crop water availability, disruption of local hydrology and gully formation.

Since soil penetration resistance varies with moisture content (Hamza & Anderson 2005), sampling was done in the wet and dry season. The wet season set of measurements was performed at the beginning of the growing season in July 2014, following a rain event that brought the soil to field capacity. At this set of measurements, all sampling locations were located with GPS units (horizontal accuracy ~ 2.5 m) to revisit exact locations during the dry season set of measurements. For each season, using a hand held cone penetrometer (DICKEY-john TM Soil Compaction Tester, Ben Meadows Company, Janesville, WI, USA) at 117 and 63 locations, soil penetration resistance (SPR) measurements were taken in Anjeni and Debre Mewi watersheds, respectively. The sampling density was determined systematically based on the watersheds homogeneity and the size of each land use in the watershed.

In the Anjeni watershed, cultivated land is distributed on the three sides and thus for each side, three representative locations were systematically selected at the upper, middle and low slopes. Pasture land is located only on the northwest side and three sampling locations were selected at the three slopes. Due to the limited size of the forest land, only three locations were selected. For each sampling location, SPR measurements were taken from 0-15, 15-30 and 30-45 cm consecutive depths. The sampling design yielded a sub-total of 51, 27 and 9 sampling points at cultivated, pasture and forest lands, respectively. Due to its smaller size and a relative homogeneity in watershed characteristics, lesser number of sampling locations were selected in Debre Mewi. For each of the cultivated and pasture lands, three representative sampling locations were chosen at the upper, middle and lower slopes. In forest land, three locations were selected. Similar to Anjeni, measurements and samples for each location were taken from three consecutive depths at 15 cm increments and the design yielded a subtotal of 27, 27 and 9 sampling points for cultivated, pasture and forest lands, respectively. At the same time during the wet season set of SPR measurements, 500 g disturbed soil samples were collected at all three SPR profiles for analysis of texture, soil organic carbon content (SOC), pH, exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+}), cation exchange capacity (CEC) and silicon. In addition, one soil core (5 cm high, 5 cm diameter) was taken at 5, 20 and 35 cm depth at all SPR profiles for analysis of dry bulk density. Volumetric soil moisture readings at all sampling locations were collected with time domain reflectometry probes (FieldScout TDR 100 Soil moisture meter, Spectrum Technologies, Inc., Aurora, IL, USA) using 20 cm long rod at 0-20, 20-40 and 40-60 cm depth.

The dry season set of SPR measurements with volumetric soil water contents were taken after crop harvest in December 2014 by revisiting the same locations as the wet season set of measurements. Soil sampling was not repeated in the drier season.

3.2.3 Laboratory analyses

Soil laboratory analyses were performed at Adet Agricultural Research Center and Bahir Dar University (Ethiopia) and Cornell University (USA). Disturbed soil samples were air dried, and passed through a 2-mm sieve before analyses. The particle size distribution was determined following Bouyoucos hydrometer procedure (Sahilemedhin & Taye, 2000). Soil organic carbon (SOC) was determined following the Walkley and Black procedure wet digestion method (Sahilemedhin & Taye, 2000). Soil organic matter, SOM, was estimated by multiplying SOC by a factor of 1.724. The pH was measured with the pH-water method using a 1:2.5 soil/water suspension following the procedure described by Sahilemedhin & Taye (2000). Exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}) contents and CEC were determined using inductively coupled plasma (ICP) spectrometry. Similarly, silica content was determined after measuring Silicon using inductively coupled plasma emission spectrometry (ICP_ES) by Thermo, model iCAP 6100. Bulk density was determined after oven drying undisturbed soil cores at 105^{o}C for 24 h.

3.2.4 Statistical analyses

Descriptive statistics (minimum, maximum, mean, standard deviation (SD), and coefficient of variation (CV)) of SPR were determined separately for each land use at each depth for the two watersheds. Statistical data analysis was performed using R (R core Team, 2014) and ‘lme4’ package (Bates et al., 2014). A linear mixed effect analysis was fitted to test the effect of land use change and soil depth on soil degradation. In the fitted model, land use type and soil depth were used as fixed effects and sampling locations was used as random factors. Post hoc mean comparison tests for the significant effects of fixed factors were performed using ‘lsmeans’ package. All significant tests were performed at a significance level of ($p<0.05$) unless specified. In addition, the relationship between SPR and studied soil parameters were determined using nonlinear and linear regression models, and variables with better correlations were identified.

3.3 Results

Assessment of soil penetration resistance across the three land uses is presented first followed by the differences in soil properties among all the three land uses and the relationships between SPR and measured soil physical properties. The discussion mainly focuses on measurements taken in July, since they were taken during the growing season and the difference in moisture contents among the land uses were small. Results from the drier period, measured after crop harvest (in December), are presented in the supplementary material and only discussed briefly in the text.

3.3.1 Soil penetration resistance, bulk density and soil water content

Descriptive statistics of soil penetration resistance (SPR) measurements and selected soil physical characteristics for the three land uses at three soil depths are presented in Figures 3-2, 3-3 and 3-4 and Tables S1, S2 and S3 in the supplementary material.

For the three land uses, SPR varied between 34 kPa for forest soils and 4137 kPa for cultivated lands. Debre Mewi had relatively greater mean SPR values than that of the respective land uses of Anjeni watershed. In Anjeni, observed mean SPR values were 141 kPa (forest land), 1776 kPa (cultivated land), and 1948 kPa (pasture land), while in Debre Mewi observed means were 326 kPa (forest land), 1861 kPa (cultivated land) and 2074 kPa (pasture land) (Figures 3-2a and 3-2b).

As expected, SPR was significantly greater in cultivated and pasture lands than that of the nearby forest churchyard lands in both watersheds (Figures 3-2a and 3-2b). SPR increased with depth in both watersheds for all three land uses (Figures 3-3a and 3-3b). Surface soils of pasture lands had greater SPR than the cultivated lands, however, differences were significant only for Anjeni. Below 15 cm SPR readings from both pasture and cultivated soils were significantly greater than that of forest soils, however, there was no significant difference between pasture and cultivated lands.

An SPR value of 2000 kPa indicates the presence of hardpan, where roots cannot penetrate and soil water movement is restricted (Tayler and Gardner 1963; Hamza and Anderson 2005). Over all, over 58% of the total observations and 70% of the subsoil (below 15 cm) observations in cultivated and pasture lands in the Debre Mewi watershed had SPR values of 2000 kPa or greater, whereas in the Anjeni watershed, only 37% of the total observations and 47% of the subsoil observations in the agricultural (cultivated and pasture) lands were above the critical threshold value. In contrast to the agricultural lands, the forest soils that were never tilled had all SPR measurements distinctly below the critical threshold value of 2000 kPa. The increase of SPR with depth for the forest lands is a natural phenomenon (Litchfield & Mabbutt 1962) where clay particles migrate downward through macropores to a deeper depth than for the agricultural soils because only part of the soil profile takes part in the transport allowing the particles to travel to greater depth before settling out.

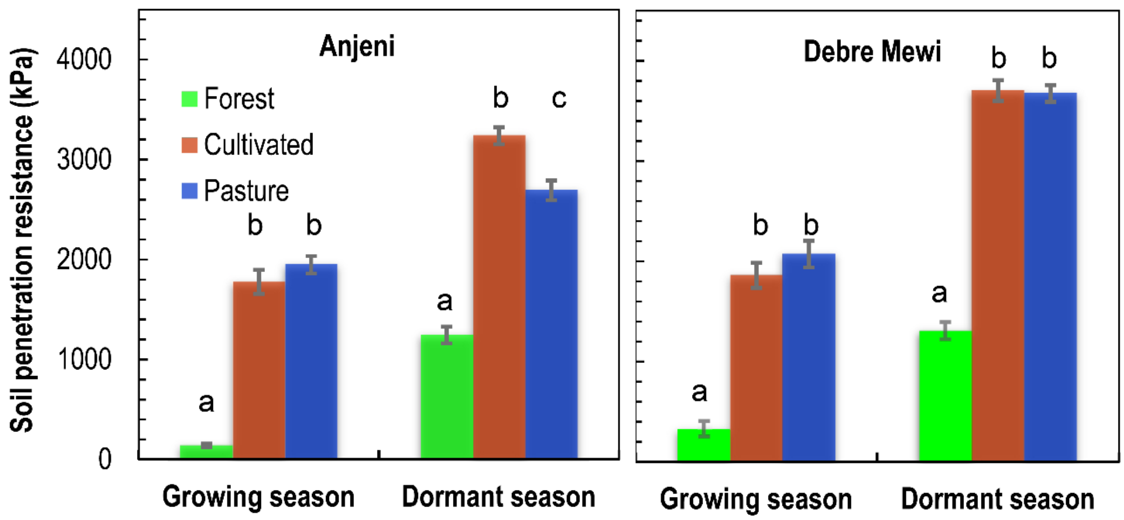

Figure 3-2. Mean soil penetration resistances (SPR) for the three land uses in Anjeni and Debre Mewi watersheds measured in July during crop growing period and in December after crop harvest. Error bars represent a standard error around the mean values. For each watershed, letters followed by different letter are significantly different ($p<0.05$).

Mean bulk density of cultivated and pasture lands were significantly greater than that of forest lands (Figures 3-3c and 3-3d). Mean volumetric soil water content (SWC) during the measurement period (wet season) ranged from 44 to 48% in the Anjeni and 45 to 56% in the Debre Mewi watersheds (Figures 3-3e and 3-3f). Although there were no significant differences for the forest soils, the mean SWC values were greatest at the 40-60 cm depth, which could likely be due to bypass flow through the first 45 cm of soil.

Mean SPR measured in December, after crop harvest, showed an increase for all land uses (Figures 3-2c and 3-2d) in both watersheds. This increase was associated with the decrease in soil water content. On average SPR increased by 82% in forest land, 47% in cultivated land, and 36% in pasture land, where soil water content decreased by 25% in forest, 40% in cultivated, and 70% in pasture lands.

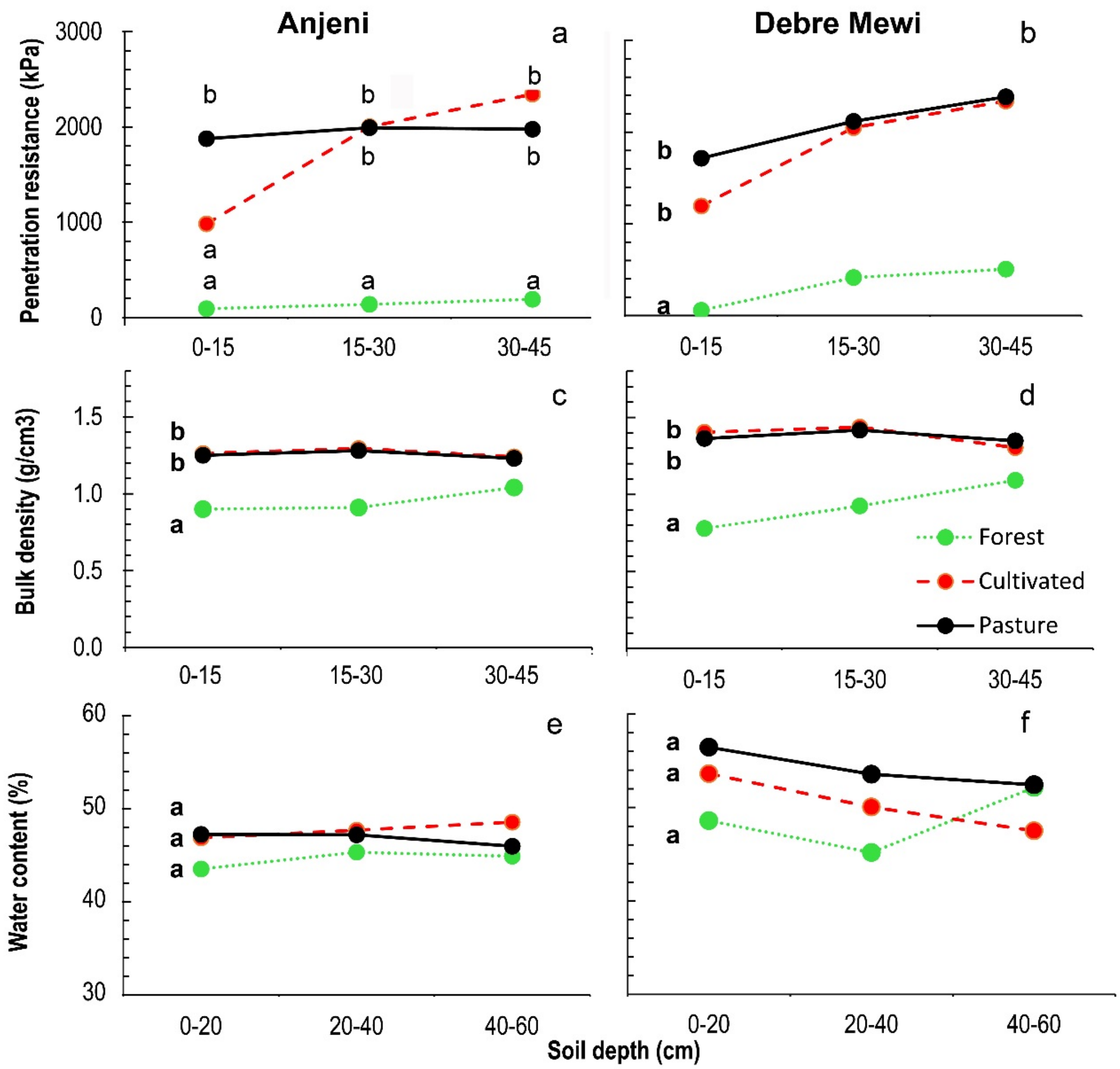

Figure 3-3. Soil properties for forest, cultivated and pasture lands measured in July during crop growing period: soil penetration resistances (SPR), bulk density, and volumetric soil water content (SWC) for Anjeni (a, c and e, respectively) and Debre Mewi (b, d and f) watersheds. SPR and bulk density were measured at 15 cm increments while soil water content was measured at 20 cm increments. For each watershed, values with different letters at a given depth on a given land use are statistically significant at $p<0.05$. For each watershed, bold letters with different letters are significantly different at $p<0.05$ for each depth. Regular letters in 3a refer to significant differences at a particular depth.

3.3.2 Soil properties

To understand the underlying reasons for the increase in SPR (Figures 3-3 and S1 and Table S3 in the supplemental material) after conversion of forest to agricultural land, we examined a number of soil physical and chemical properties including texture, soil organic matter (SOM), divalent exchangeable base cations, cation exchange capacity (CEC), pH and silica content. Mean percentage of fine particles (clay plus silt) was significantly greater in agricultural fields of both watersheds at all sampling depths than that of forest lands adjacent to the agricultural fields (Figures 3-4a and 3-4b). Sand and fine fractions were not significantly different between cultivated and pasture lands. In Anjeni watershed, the mean percentage of fine particles was especially remarkable at the surface soil in the forest (40%) and almost 80% in the agricultural lands after conversion and implementation of soil and water conservation practices.

The mean SOM content for the forest soil (varying between 6 and 11% depending on the depth) was two to three times greater than for cultivated land in both watersheds (Figures 3-4c and 3-4d). Pasture lands had greater SOM than that of the cultivated lands at all sampling depths of both watersheds, and the difference was significant in Anjeni (Figure 4c). The pH for the cultivated and pasture lands showed significantly lower pH (between 3-5 and 3-6) than that of forest soils (near neutral) at all sampling depths in both watersheds (Figures 3-4e and 3-4f). Similarly, CEC was significantly lower in agricultural fields as compared to that of forest lands at all sampling depths of both watersheds (Figures 3-4g and 3-4h). The CEC of pasture and cultivated lands was less than 30 cmol/kg in Anjeni and was relatively greater (around 35 cmol/kg) in pasture lands in Debre Mewi.

Divalent exchangeable base cations (Ca^{2+} and Mg^{2+}) showed a significant difference between agricultural fields and forest lands. However, the amount of monovalent cations (Na^{+} and K^{+}) in both watersheds were negligible. Exchangeable Ca^{2+} was significantly greater in forest lands than that of agricultural fields at all sampling depths in both watersheds (Table S3); however, there was no consistent trend in terms of Mg^{2+} content among land uses in the two watersheds. In Anjeni watershed, mean Mg^{2+} was significantly greater in cultivated lands than pasture lands at both sampling depths. It was relatively similar in pasture and forest lands. In Debre Mewi watershed, pasture land had significantly lower Mg^{2+} than that of cultivated and forest lands, but the latter two land uses had a relatively similar Mg^{2+}.

Soluble silica content analysis was performed for the surface soil samples. Results (Figures 3-5a and 3-5b) show that, in both watersheds, forest land had significantly greater silica content; 120 $cmol_c$/kg in Anjeni and 200 $cmol_c$/kg in Debre Mewi than that of cultivated; 43 $cmol_c$/kg in Anjeni and 131 $cmol_c$/kg in Debre Mewi and pasture land; 65 $cmol_c$/kg in Anjeni and 115 $cmol_c$/kg in Debre Mewi. Silica content in pasture land was significantly greater compared with cultivated land in Anjeni (Figure 3-5a) while it was relatively greater in cultivated land as compared to pasture land (Figure 3-5b).

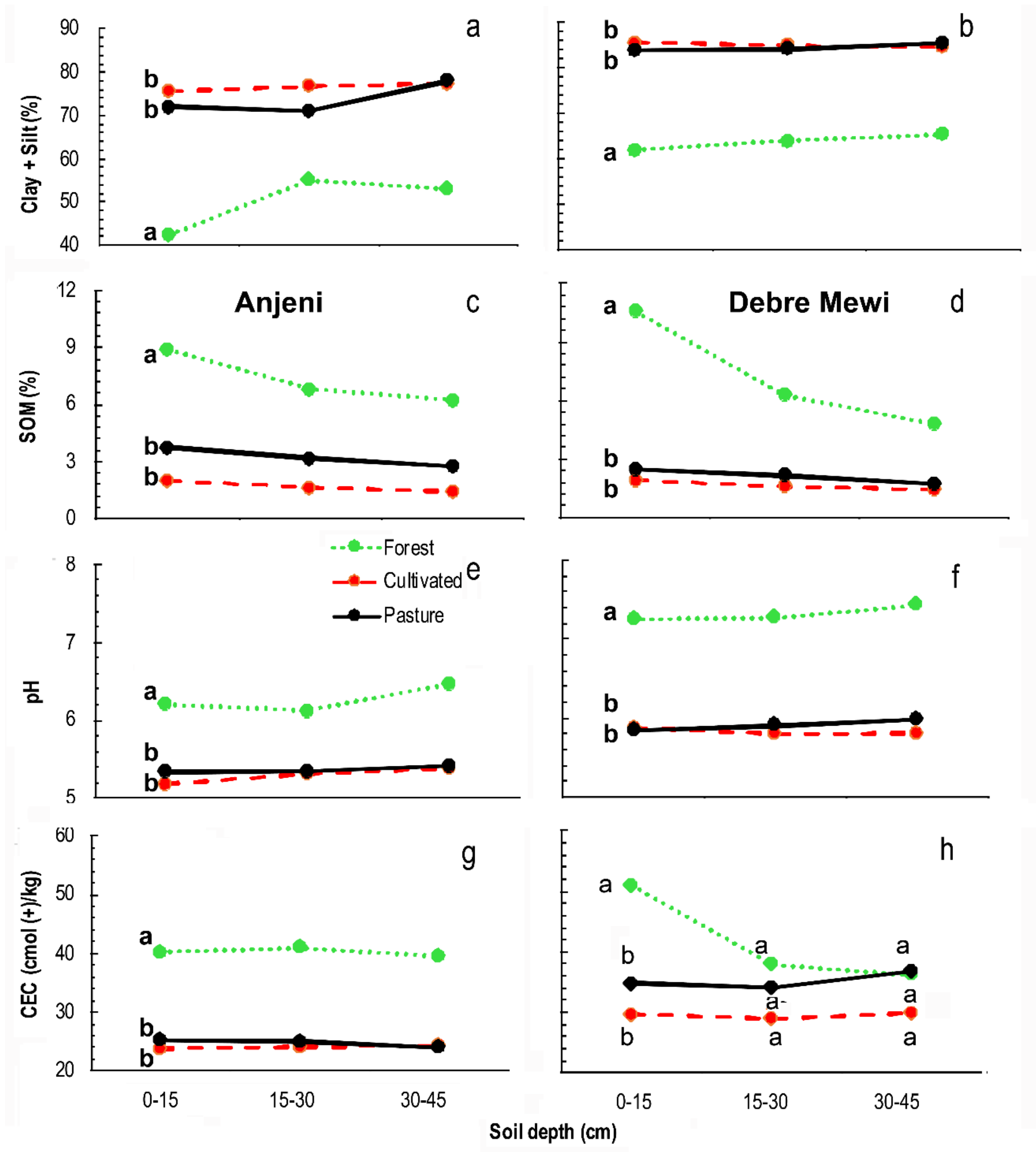

Figure 3-4. Mean values of selected soil parameters; fine particles (clay plus silt content), pH, soil organic matter content (SOM), soil exchange capacity (CEC) for Anjeni (a, c, e, and g, respectively) and Debre Mewi (b, d, f and h, respectively) watersheds. For each watershed, bold letters with different letters are significantly different at $p<0.05$ for each depth for the forest, pasture and cultivated land. Regular letters in 4h refer to a particular depth.

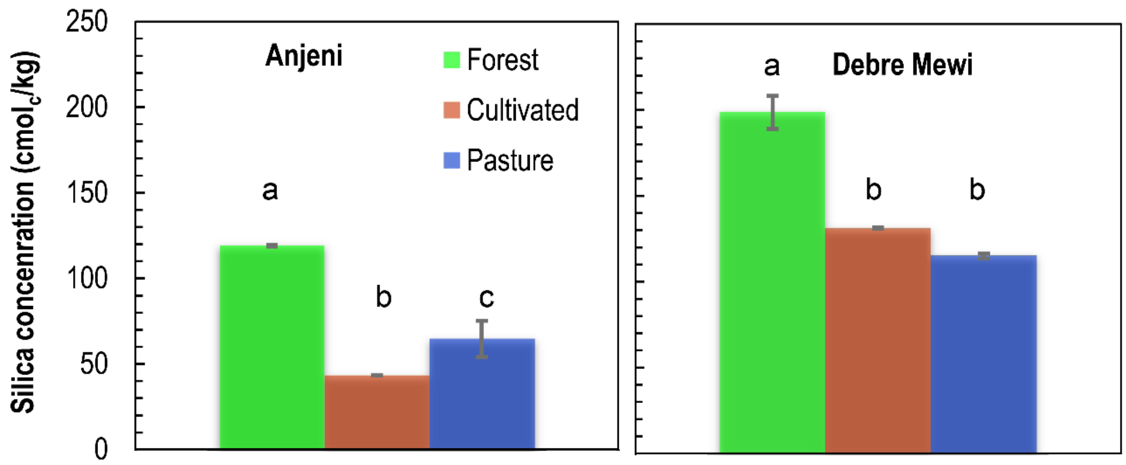

Figure 3-5. Mean silica content at forest, cultivated and pasture lands of the Anjeni and Debre Mewi watersheds. Values with different letters at a given land use are significantly different at $p<0.05$.

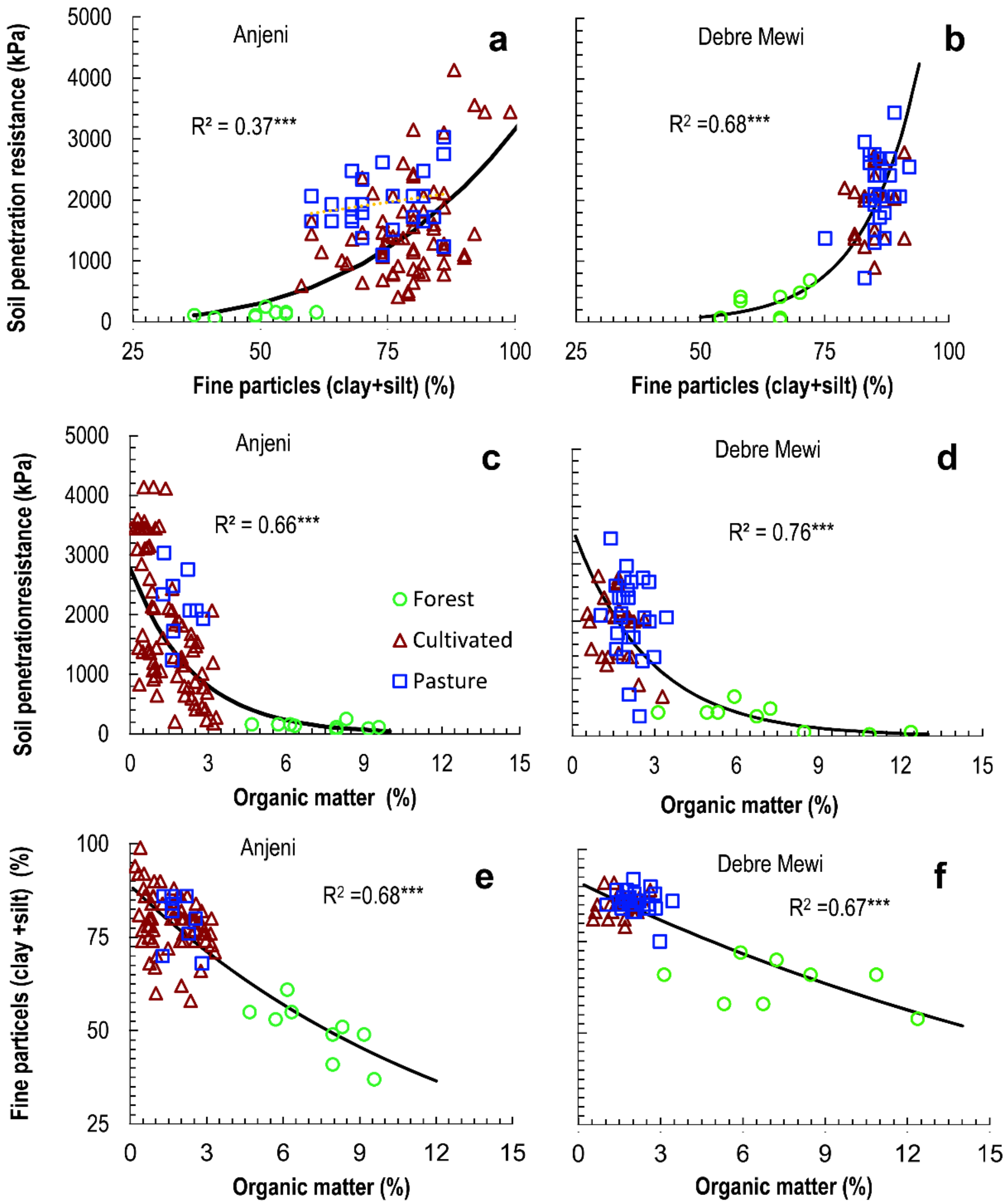

Figure 3-6. The relationship between SPR with SOM and fine particles (clay plus silt content) and fine particles with SOM in Anjeni (a, c and e, respectively) and Debre Mewi (b, d and f, respectively) watersheds. *Significant at p< 0.05 level; ** Significant at p< 0.01 level; and *** Significant at p< 0.001 level.

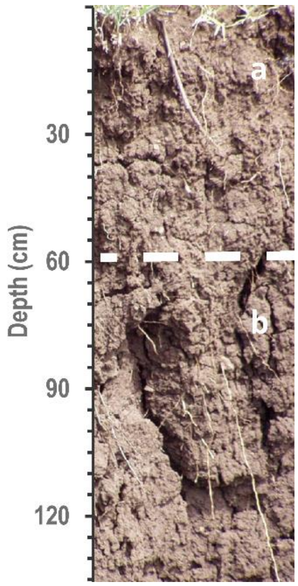

Figure 3-7. A degraded soil profile: the original flow paths are only present in the lower part of the profile (below 60 cm): a) top soils with large pores filled with surface soil, b) original macroporous network is still visible

3.4 Discussion

3.4.1 Assessment of soil penetration resistance

Mean SPR values in the agricultural fields (Figures 3-3a and 3-3b) are within the normal range reported in other studies in Ethiopia. For instance, Temesgen et al. (2012a) found a range of 500-3500 kPa in the cultivated lands of Enerta watershed, located at Choke Mountain in the humid highlands, and Biazin et al. (2011) found a range of 200-1780 kPa in the grazing and cultivated fields of Central Rift Valley in the semi-arid region. Comparison of our measurements to the previous studies indicates that SPR in the humid region is relatively greater than that of the semi-arid region. The significant rise in penetration resistance (2000 kPa or above), starting at a depth of 15-30 cm suggests the occurrence of restrictive soil layers (i.e., hardpans) in the subsoil of agricultural fields. This finding is in agreement with the elevated penetration resistance of soil below 10 cm reaching its maximum at a depth of 18-25 cm in the study of Leye (2007); Temesgen et al. (2012a); Temesgen et al. (2012b) and Biazin et al. (2011). The smaller SPR in forest land indicates the absence of a hardpan in the original soils. The increase of SPR with depth in forest land indicates the existence of natural processes where clay minerals are slowly migrating downward to deeper depths.

The greater SPR in pasture land than that of crop land at the top surface in both watersheds (Figures 3-3a and 3-3b) is either associated with cattle trafficking during wet condition in the pasture or with loosening up the soil in the top 10-15 cm by the *Maresha* plow on cultivated land. Mwendera & Saleem (1997) found greater soil compaction in the farm plots of Debre Zeit with an increased number of cattle passes.

An increment of SPR in the drier season in December measurement as compared to that of the wet season in July (Figures 3-2c and 3-2d) indicates the dependency of SPR on soil water content. Results from Vaz et al. (2011) and Moraes et al. (2013) corroborate our findings by demonstrating that a decrease in soil water content increases SPR.

3.4.2 Relationships of SPR and soil properties

The relationships between SPR and some of the measured soil parameters were well explained by a power type equation as shown in Figure 3-6 and by a linear relationship in Tables S4 and S5 in the supplementary material. The relationship between SPR and fine particles was positive and significant (R^2 = 0.37 in Anjeni, Figure 3-6a, and R^2 = 0.68 in Debre Mewi, Figure 3-6b). This relationship is in agreement with the findings of Zisa et al. (1980) who reported that soils with a large amount of fine particles have smaller pore diameter and higher resistance to penetration than soils with a large amount of coarse particles.

The SPR was significantly (negatively) correlated with SOM (R^2 = 0.66 in Anjeni, Figure 3-6c and R^2 = 0.76 in Debre Mewi, Figure 3-6d). Likewise, the relationship between fine particles and SOM was significant and negative (R^2 = 0.68 in Anjeni, Figure 3-6e and R^2 = 0.68 in Debre Mewi, Figure 3-6f). The negative relationship of SPR with SOM indicates that a reduction of organic matter in the soil decreases the binding potential of soil aggregates that promotes the development of good soil structure. Similarly, Wortmann & Jasa (2003) and Hoorman et al. (2011) stated that soils with lower organic matter content are more susceptible to soil compaction than those with higher organic matter content. Combining results from all land uses showed that the values at the lower tails (i.e. low SPR and low fine particles, low SPR and high SOM, and low fine particles and high SOM) are soils from forest lands.

As expected, bulk density was positively correlated with SPR. The correlation coefficients were significant (R^2 = 0.40 in Anjeni and R^2 = 0.63 in Debre Mewi, Tables S4 and S5). The relationship between pH and basic cations was positive. In particular, the correlation between pH and Ca^{2+} was significant (R^2 = 0.54 in Anjeni and R^2 = 0.76 in Debre Mewi). The relationship of pH with basic cations (Ca^{2+}) mainly show that acidic pH in agricultural fields allows the basic cations, particularly Ca^{2+}, to leach because of the replacement of cations on exchange sites by acidic cations, H^+ and Al species

(Haynes & Swift, 1986). In addition, reduction of CEC in agricultural fields aggravate the reduction of pH.

3.4.3 Effect of land use on soil properties and hardpans formation

In this study, comparison of soil physical and chemical properties between never- tilled forest lands and agricultural fields (Figures 3-3, 3-4, 3-5 and Table S3) suggest that soils in the agricultural fields were originally characterized by high organic matter content, high CEC, high exchangeable base cations, a neutral pH, high soluble silica and low bulk density. But due to a prolonged use of land for agriculture, such soil properties are deteriorated over time. They have become lower in SOM content, exchangeable basic cations (particularly Ca^{2+}), CEC, higher in finer particles (clay and silt content), bulk density and insoluble silica and acidic in pH.

The elevated levels of SOM, soluble silica, pH and divalent ions in forest soils (Figures 3-3, 3-4a and 3-4b) bind soil particles together as aggregates and provide a good soil structure. Decrease in organic matter content and other binding agents in the cultivated and pasture fields breaks up aggregates (Tisdall & Oades, 1982; Zhou et al., 2013) and this is the reason that cultivated and pasture soils have a finer texture than forest soils (Figures 3-3a and 3-3b). Fine particles are likely to be easily dislodged by splashing raindrops than coarse aggregates (McIntyre, 1958), have a lower settling velocity once entrained in the water and stay much longer in suspension than large aggregates (Hjulstrom, 1939). This degradation process is reflected in increasing sediment concentration in the rivers of the Ethiopian highlands during the last 40 years (Steenhuis et al., 2009; Steenhuis & Tilahun, 2014).

In addition, reduced soluble silica in the agricultural fields indicates its availability in the insoluble form. This situation favors binding of clay particles. The process is aggravated by the climatic condition of the region (humid climate). Wet climatic conditions increase clay deposition and silica cementation at the lower profiles (Litchfield & Mabbutt, 1962).

Based on our results above, the enhanced anthropogenic formation of hardpans can be explained as follows: Most of the rainwater infiltrates in unsaturated soils since saturated hydraulic conductivities are extremely high in forest soils and soils derived from volcanic material (Mendoza & Steenhuis, 2002; Hanson et al., 2004; Bayabil et al., 2010). Initially under forest conditions where the organic matter concentrations are high and base cations are not leached, sediment concentrations in the water are extremely low and consists mainly of colloidal matter that infiltrates below 45 cm where the penetration resistance (Figures 3-3a and 3b), bulk density (Figures 3-3c and 3-3d) and the percentage of fine particles (Figures 3-4a and 3-4b) is greater than at the surface. Once the forests are cut down and the soil is plowed, the organic matter and other binding agents decrease and the aggregates become unstable, raindrops pick up the fine sediment that moves down in the profile and settles into the pores. When the downward moving water stops, this sediment plugs pores in the top part (60 cm) of the profile as shown in Figure 3- 7.

In agreement with our findings, other studies have shown that most agricultural activities in the rainfed agricultural system of Ethiopian highlands reduce soil quality. For instance, Emiru & Gebrekidan (2013) and Habtamu et al. (2014) noted that complete removal of crop residues after crop harvest for the purpose of animal fodder and fuel wood consumption increases loss of SOM. Likewise, Temesgen et al. (2009) showed repeated tillage for the purpose of soil turnover causes excessive soil pulverization resulting in poor soil structure. In addition, Mwendera & Saleem (1997) and Tebebu et al. (2010) reported that clearing of vegetation and overgrazing is accelerating soil erosion and runoff. Soil erosion and runoff facilitate strong leaching of exchangeable cations particularly Ca^{2+} and Mg^{2+} (Hodnett & Tomasella, 2002; Emiru & Gebrekidan, 2013) which also results in an increase in soil acidity. Besides, continuous weathering processes (Hodnett & Tomasella, 2002; Amare et al., 2013) and continuous use of ammonium source fertilizers (Emiru & Gebrekidan, 2013) increase soil acidity.

3.5 Conclusions

Agricultural fields in Anjeni and Debre Mewi watersheds have hardpans that impede root growth and restrict soil water movement. Our results show that hardpan formation is linked with the conversion of a forest ecosystem to agricultural use. In the past, when population pressure was low, shifting cultivation with long fallow periods was practiced. Organic matter levels remained high and hardpans did not form. However, recently due to increasing population (96.5 million with 2.9% annual growth), land has become intensively cultivated resulting in a loss of organic matter, leaching of base cations, disintegration of aggregates and increased sediment concentrations in overland flow. The sediment laden water that infiltrates is accelerating hardpan formation by plugging up the large pores. The overall findings of this study imply that hardpans in degraded soils are common in the humid Ethiopian highlands. Management interventions to decrease runoff and soil loss from the uplands should include increasing long-term infiltration rates through the hardpans.

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3.7 Supplementary Material

Table S1: 3-1. Statistical summary of soil penetration resistance (SPR, kPa) and volumetric soil water content (SWC, %) in Anjeni and Debre Mewi watersheds measured under the three land uses during crop growing period. Measurements are at three depths: at 15 cm increments for SPR and 20 increments for SWC.

			Anjeni					Debre Mewi				
Land use	Variable	Depth(cm)	Mean	S.D.	C.V.	Min.	Max.	Mean	S.D.	C.V.	Min.	Max.
Forest	SPR	0-15	92	23	25	69	115	57	20	35	34	69
		15-30	138	23	17	115	161	414	69	17	345	483
		30-45	192	53	28	161	253	506	159	31	414	689
	SWC	0-20	37.3	3.1	8.2	34	40	36.2	2.5	6.8	33.4	38.2
		20-40	38.3	2.5	6.6	36	41	33	2.3	6.8	30.4	34.5
		40-60	40	2	5	38	42	32.4	3	9.3	30.2	35.9
Cultivated	SPR	0-15	983	481	49	184	2114	1195	515	43	276	2068
		15-30	2003	1169	58	414	4137	2049	430	21	1379	2689
		30-45	2344	1014	43	460	3447	2340	321	14	1999	2792
	SWC	0-20	34.3	3.6	11	27.8	44.1	27.7	1.3	4.9	25.8	29.8
		20-40	36.1	4.9	14	28.2	47.6	27	1.8	6.6	24.2	29.5
		40-60	37.7	5.3	14	30	50	27.3	2.9	11	23.3	33.3
Pasture	SPR	0-15	1877	175	9.3	1655	2068	1716	692	40	345	2689
		15-30	1992	418	21	1379	2620	2118	674	32	724	2758
		30-45	45	1977	672	34	1103	2386	586	25	1379	3447
	SWC	0-20	35.5	5.5	16	28	42.9	29.4	4.3	15	23.9	36
		20-40	34.7	4.2	12	29.6	42.3	28	2.6	9.4	23.1	31.7
		40-60	35.8	2.3	6.3	31.4	37.9	28.7	3.4	12	23.7	33.6

Table S1: 3-2. Statistical summary of soil penetration resistance (SPR, kPa) and volumetric soil water content (%) in Anjeni and Debre Mewi watersheds measured under the three land uses after crop harvest. Measurements are at three depths: at 15 cm increments for SPR and 20 increments for SWC.

			Anjeni					Debre Mewi				
Land use	Variable	Depth(cm	Mean	S.D.	C.V.	Min.	Max.	Mean	S.D.	C.V.	Min.	Max.
Forest	SPR	0-15	1069	359	34	655	1276	1069	358.5	33.5	655	1276
		15-30	1379	138	10	1241	1517	1425	79.7	5.6	1379	1517
		30-45	1287	159	12	1103	4068	1425	801.2	56.2	1379	1517
	SWC	0-20	25	2.8	11	22.5	28	25	2.8	12.4	22.5	28
		20-40	39.17	5.3	14	34.5	45	39.17	5.3	29.4	34.5	45
		40-60	44.2	3.7	8	40	47	44.2	3.7	17.9	40	47
Cultivated	SPR	0-15	3326	705	21	1310	4137	3842	155.2	4.0	3482	3999
		15-30	3217	725	23	1241	4137	3930	175.9	4.5	3585	4137
		30-45	3164	903	29	965	1379	3336	79.7	2.4	1999	4137
	SWC	0-20	23.12	10.0	43	10.9	58.75	20.04	1.5	7.6	18.2	22.5
		20-40	34.2	10.9	32	11.2	57.6	34.76	6.3	18.0	27.5	47.3
		40-60	39.97	14.4	36	10.4	68.23	45.3	10.7	23.7	28	63.2
Pasture	SPR	0-15	2903	359	12	2413	3516	3915	123.3	3.2	3723	4068
		15-30	2612	535	20	1724	3447	3516	605.0	17.2	2413	3930
		30-45	2559	597	23	1319	3585	3593	363.8	10.1	2827	3792
	SWC	0-20	18.11	6.6	36	8.7	26.97	25.07	2.6	10.4	20.7	29.2
		20-40	26.78	7.3	27	12.9	36.2	31.28	6.6	21.1	25.3	46.7
		40-60	26.21	9.0	34	8.7	37.05	38.01	8.2	21.6	30.3	53.9

Table S1: 3-3. Mean exchangeable base cations (Ca^{2+}, Mg^{2+}, K^{+} and Na^{+}) as a function of land use. For each watershed at each soil parameter, land uses followed by the same letters are not significantly different at ($p<0.05$).

		Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}
Watershed	Land use		$cmol_c/kg$		
Anjeni	Forest	7.547a	1.408a	0.119a	0.040ab
	Cultivated	0.228b	2.387b	0.056b	0.039a
	Pasture	0.335b	1.112a	0.010c	0.054b
Debre Mewi	Forest	2.031a	4.752a	0.205a	0.060ab
	Cultivated	0.916b	4.314a	0.083b	0.043a
	Pasture	0.880b	2.518b	0.015c	0.087b

Table S1: 3-4. Correlation between SPR and soil properties in the Anjeni watershed (Pearson correlation).

Parameter	SPR	Bulk density	pH	Clay	Silt	Sand	CEC	SOM	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}
SPR (kPa)	1	0.40***	0.13	0.05	0.21*	-0.21*	-0.27**	-0.54***	-0	-0.60***	-0.40***	0.29***
Bulk density (g/cm^3)		1	-0.23*	0.33***	-0.06	-0.42***	-0.37***	-0.54***	-0.1	-0.21*	-0.55**	0.20*
pH			1	-0.32***	0.17	0.34***	0.17	0.13	-0.1	0.01	0.54***	0.09
Clay (%)				1	-0.75***	-0.91***	-0.51***	-0.49**	-0.1	-0.05	-0.43***	-0.03
Silt (%)					1	0.41***	0.19	0.1	0.04	-0.21*	0.02	0.13
Sand (%)						1	0.58***	0.61**	0.13	0.20*	0.58**	-0.03
CEC ($cmol_c$ /kg)							1	0.58***	-0	0.23**	0.60***	0.18
SOM (%)								1	0	0.43***	0.62***	-0.53***
Na^{+} ($cmol_c$ /kg)									1	-0.07	0.08	-0.01
K^{+}($cmol_c$ /kg)										1	0.32***	-0.04
Ca^{2+} ($cmol_c$ /kg)											1	-0.11
Mg^{2+} ($cmol_c$ /kg)												1

*Significant at p< 0.05 level, ** Significant at p< 0.01 level, and *** Significant at p< 0.001 level

Table S1: 3-5. Correlation between SPR and soil properties in the Debre Mewi watershed (Pearson correlation).

Parameter	SPR	Bulk density	pH	Clay	Silt	Sand	CEC	SOM	Na^{+}	K^{+}	Ca^{2+}	Mg^{2+}
SPR (kPa)	1	0.51***	-0.57***	0.61***	-0.30*	-0.66***	-0.2	-0.63***	0.16	-0.59***	-0.55***	-0.24
Bulk density (g/cm3)		1	-0.63***	0.64***	-0.34**	-0.68***	-0.47***	-0.81***	0.02	-0.57***	-0.66***	-0.28*
pH			1	-0.66***	0.27*	0.75***	0.54***	0.66***	-0.1	0.61***	0.76***	0.28*
Clay (%)				1	-0.76***	-0.92***	-0.50***	-0.77***	-0	-0.56***	-0.62***	-0.15
Silt (%)					1	0.45***	0.27*	0.49***	0.23	0.25*	0.26*	-0.18
Sand (%)						1	0.53***	0.77***	-0.1	0.63***	0.70***	0.32*
CEC (cmolc /kg)							1	0.52***	-0.1	0.05	0.50***	0.06
SOM (%)								1	0.04	0.64***	0.71***	0.25*
Na^{+} (cmolc /kg)									1	-0.23	-0.23	-0.35**
K^{+} (cmolc /kg))										1	0.64***	0.70***
Ca^{2+} (cmolc /kg)											1	0.42***
Mg^{2+} (cmolc /kg)												1

*Significant at p< 0.05 level, ** Significant at p< 0.01 level, and *** Significant at p< 0.001 level

CHAPTER 4: CAN DEGRADED SOILS BE IMPROVED BY DEEP RIPPING AND LIMING? A FIELD EXPERIMENT IN THE HUMID ETHIOPIAN HIGHLANDS

Abstract

Loss of organic matter after deforestation leads to breakup of aggregates, increased splash displacement of soil particles, and hardpan formation in the subsoil and causes perched water tables. Perched water tables prevent infiltration of water and increase soil erosion. Deep ripping is the best approach to break down the hard layers and increase infiltration. However, in the highlands of Ethiopia, there is little information on the effect of ripping hardpan soils. The objective of this study was, therefore, to determine the effects of deep ripping on degraded soils with a hardpan and whether liming would improve its effectiveness. A field study was conducted in the Anjeni watershed. A total of 32 experimental runoff plots were installed across the watershed. Deep ripping at 15 (CT15), 30 (DT30), 45 (DT45), and 60 (DT60) cm depths were applied with and without lime amendments. Results showed that as ripping depth increased the amount of runoff decreased significantly. DT60 produced the lowest amount of runoff. However, liming increased runoff responses, on average by 10 %. In contrast to the declining runoff amounts, an increase in ripping depth increased the amount of soil loss measured. Liming significantly decreased soil loss up to 35 %. Overall, the findings suggest that deep ripping in hardpan soils improved rainwater infiltration resulting in lower runoff production even in the short term but increased soil loss due to more soil disturbance. Although plots with deep ripping plus liming had greater runoff production than other plots, soil loss was less.

***KEY-WORDS**: Hardpan soil, deep ripping, liming, runoff, soil loss, soil amelioration*

4.1 Introduction

Land degradation has become a serious threat to food security in the world (Eswaren et al., 2001; FAO 2011, Bindraban et al., 2012). It affects especially the small holder farmers in developing countries who cannot buy additional food when the crops grown are insufficient (Hermans Neuman et al 2017).

Land degradation can occur in many forms such as erosion, salinization, and accelerated hardpan formation within soil (Oldeman 1994; Hari et al 2001; Hamza and Anderson, 2005,). Land degradation reduces the soil's capacity to regulate water flow through the soil profile, reducing crop yield due to poor root development (Johnson et al., 1997; Hanson et al., 2004b; Ahmad et al., 2007, Kuhan, 1994).

In this manuscript, our primary concern is amelioration of degraded soils in humid monsoon climates that have formed slowly permeable soil layers commonly known as hardpans. Hardpans are defined as soil layers with physical characteristics that restrict downward soil water movement and reduce moisture storage capacity (Soil Science Society of America, 2015, Hoogmoed & Derpsch, 1985; Radcliffe et al., 1989; Mulholland & Fullen, 1991; Kılıç et al., 2004). They usually occur between 7.5 and 90 cm deep. In the Ethiopian highlands, these hardpans form after conversion of land from forest to cropland. Plowing of the croplands causes the soil to lose organic matter (Ashagrie et al., 2007; Solomon et al., 2002; Carlos et al, 2001). Once the organic matter decreases below 3%, soil aggregates lose their cohesion and disintegrate (Ashagrie et al., 2007, Tebebu et al., 2016). The soil becomes finer (Tebebu et al. 2017) as cementing agents leach out. Since finer particles settle slower than the coarse aggregates, sediment concentrations increase in the infiltrating water, the rate of hardpan formation increases above a slow natural rate (Tebebu et al. 2016).

The presence of hardpans in the subsoil leads to temporary perched water tables when the soil above the restrictive layer saturates. This eventually causes a significant amount of rainwater loss as surface runoff and consequently more soil erosion during rainfall periods (Steenhuis et al., 2009; Biazn et al., 2011; Temesgen et al., 2012). In addition, hardpans impede root growth below the plow depth, thereby reducing plants' capacities to obtain water and nutrients during periods when soil moisture and nutrient reserves in an accessible lower profile could be critical to crop production (Busscher and Bauer 2003, Raper et al., 2005).

Currently, in the Ethiopian highlands, the indigenous strategy farmers use to prevent water logging and surface runoff due to hardpans employs off-contour furrows to guide excess water off the plot without causing significant erosion (Gebreegziabher et al., 2009; Nyssen et al., 2011; Engida et al., 2011). On average, farmers construct these furrows as 10-15 cm deep and 20 cm wide during land preparation (Nyssen et al, 2010; Oicha et al., 2010; Opolot, 2012). Densities depend on the water logging with closer spacing downhill than uphill (Zegeye et al 2010). These practices are counterproductive during a dry spell (or at the end of) the monsoon season when plants need the soil water to survive but the furrows have channeled away the previous rains too quickly

In addition, since the indigenous practices are seen by conservation experts as promoting gully erosion downhill from the fields, the government and international donors have been implementing practices since the 1980s (Osman and Sauerborn 2001). Starting in 2010, the Ethiopian government intensified its effort forcing farmers to install soil and water conservation practices for two months per year (Dagnew et al., 2015). Annually, more than 15 million farmers are compelled to contribute free labor (MOFED, 2010). These practices consist mainly of 40-50 cm deep infiltration furrows on the contour with excavated soil thrown uphill. These practices aid in infiltration in the uplands of rain water because they connect the surface soil with the underlying soil with macro pores present from the time before deforestation. (Tebebu 2015, Zimale et al., 2017). However, these practices have a limited life span because they are not maintained by farmers due to the labor involved and the limited benefit.

Amelioration of the hardpans can allow plants to root more deeply, increase water infiltration and reduce runoff, all resulting in greater amounts of water available for the crop (i.e. green water) and thus increased (and more reliable) yields. The best solution to ameliorate the existing hardpans is breaking down the hard layers. Deep ripping, sometimes called “subsoiling” is an important practice used to shatter soils having dense subsurface horizons. It loosens dense subsoil and improves root penetration and plant growth. This practice can be adapted according to the soil, environment and farming systems. A review by Hamza and Anderson (2005) showed that addition of organic matter, mechanical loosening such as deep ripping, and rotation of crops and pasture plants with strong tap roots can penetrate and break down compacted layers.

Deep ripping has become a common management practice in many countries. Studies in Western Australia (Delroy and Bowden 1986), New Zeland (Blaneaves and Mare, 1989), and South Africa (Bennie and Botha, 1986) found that deep ripping increased crop yield by increasing the rate of root extension, root development and efficiency of fertilizer use. Similarly, Munkholm et al., 2001) found that loosening of a compacted layer by deep tillage resulted in lower penetration resistance and bulk density. Similar studies in India have shown that deep tillage is effective in enhancing the downward movement of water (Nitant and Singh, 1995; Laddha and Totawat 1997).

Moreover, studies in the Australian soils have shown that application of lime increases benefits from deep ripping of acidic soils (Conventry et al., 1987). Liming is expected to decrease the amount of raindrop splash and therefore prevent re-formation of hardpan after it has been ripped.

Increasing infiltration to the deeper soils in the humid Ethiopian highlands is beneficial as intended ripping and liming decreases surface runoff and sediment loads (Dagnew et al 2015, 2016). Most soils in the Ethiopian highlands are characterized as acidic (Demelash and Stahr, 2010, Bayabil et al., 2015, Amare et al. 2013). Therefore, increasing infiltration by deep ripping and combining that with liming should be beneficial as found in other countries. Therefore, this study sought to determine the effects of deep ripping on hardpan soils and to determine whether liming would improve the effects of deep ripping.

4.2 Materials and Methods

4.2.1 Site description

This experiment was carried out in Anjeni watershed located 320 km northwest of Addis Ababa to the south of Choke Mountains at 10°40' N and 37°31' E. Anjeni watershed is one of the experimental stations for the Soil Conservation Research Program (SCRP) established in the 1980's with collaboration between the Ethiopian Ministry of Agriculture and Swiss Agency for Development and Cooperation (Hurni et al., 2005). The watershed covers 113 ha, oriented north to south and flanked on three sides by plateau ridges with elevation ranges from 2407 to 2507 m above sea level. The watershed has a unimodal rainy season and the rainy months are from mid-

May to Mid-October. On average, it receives 1690 mm rain annually with 16℃ mean daily temperature (Setegn et al., 2008). Soils have developed from basalt and volcanic ash, dominated by Alisols, Cambisols and Nitosols types (Hurni et al., 2005; Legesse, 2009; Tilahun et al., 2011, Zeleke, 2000). Soils are characterized by acidic pH and low organic matter content (Tebebu et al., 2015)

In this watershed, small holder farmers (similar to almost all of the humid Ethiopian highlands) are relying on rainwater to grow crops. The farming system is a mixture of crop and livestock production. Cultivated lands have been intensively cultivated which has left most of the fields degraded. Farmers apply conventional tillage using the *Maresha* plow with a plowing depth of 10-15 cm. To reclaim such degradation, graded fanya-juu terraces were employed in the mid-1980's. This practice increased infiltration and reduced soil loss greatly initially. The effectiveness decreased gradually and after approximately five years, runoff and infiltration were at the same rate as before implementation (Guzman et al, 2017)

4.2.2 Field experiment

To assess the effect of deep ripping on runoff and erosion response of degraded soils, 32 experimental runoff plots were installed across the watershed. These plots are located along three transects with different levels of soil degradation (Figure 4-1). Plot installation and data collection methods were similar to the method that Bayabil et al (2016) used. In Bayabil et al.'s study period 2012/13 plots were installed close to the terraces but in this study period (2014), plots were 6m away from terraces to avoid water logging issues. In 2012/13, barley plus charcoal and lupine plantations with conventional tillage treatments were applied for all plots except that lupine plots in 2013 which were left untilled. Detailed spatial attributes of each transect are presented in Table 4-1. Transect-1 has deep soil, greater exchangeable acidity, and moderate soil penetration resistance; Transect-2 has moderately deep soil and the lowest soil penetration resistance; and Transect-3 have degraded soil with greatest soil penetration resistance. Transect-1 and Transect-2 had 12 plots each. Four plots were located at each of upper slope, midslope, and downslope locations. Transect-3 has 8 plots, four located at the upper and four at midslope. Each plot size was 4.5 m^2 (1.5 m by 3 m). For each location, plots were ripped at four depths; codes CT15, DT30, DT45, and DT60 symbolize uniform depths of 15; 30; 45 and 60 cm, respectively. Ripping was accomplished by handheld hoe. To determine if benefits of ripping improved with liming, lime was applied in Transect-1 in mid-June based on the recommendation of Amhara Regional Agriculture Research Institute (ARARI) lime recommendation manual and local practice. The amount of lime needed was determined after testing the soil acidity. For each plot, barley (a widely grown crop in the watershed) was seeded right after the application of lime following local farmers' cultural practices. All plots were fertilized with 100 kg/ha of di-ammonium phosphate (DAP; containing 46 %, 23 % and 21 % of nitrogen, phosphorus and potassium, respectively) and 100 kg/ha of urea (100 % nitrogen). DAP was applied during seeding period while urea was applied a month after sowing.

Plot rainfall, runoff and erosion data were collected throughout the monsoon phase using the methods described by Bayabil et al. (2016). Previous years' (2012 and 2013) data were used to show the trend in runoff and erosion response characteristics along transects.

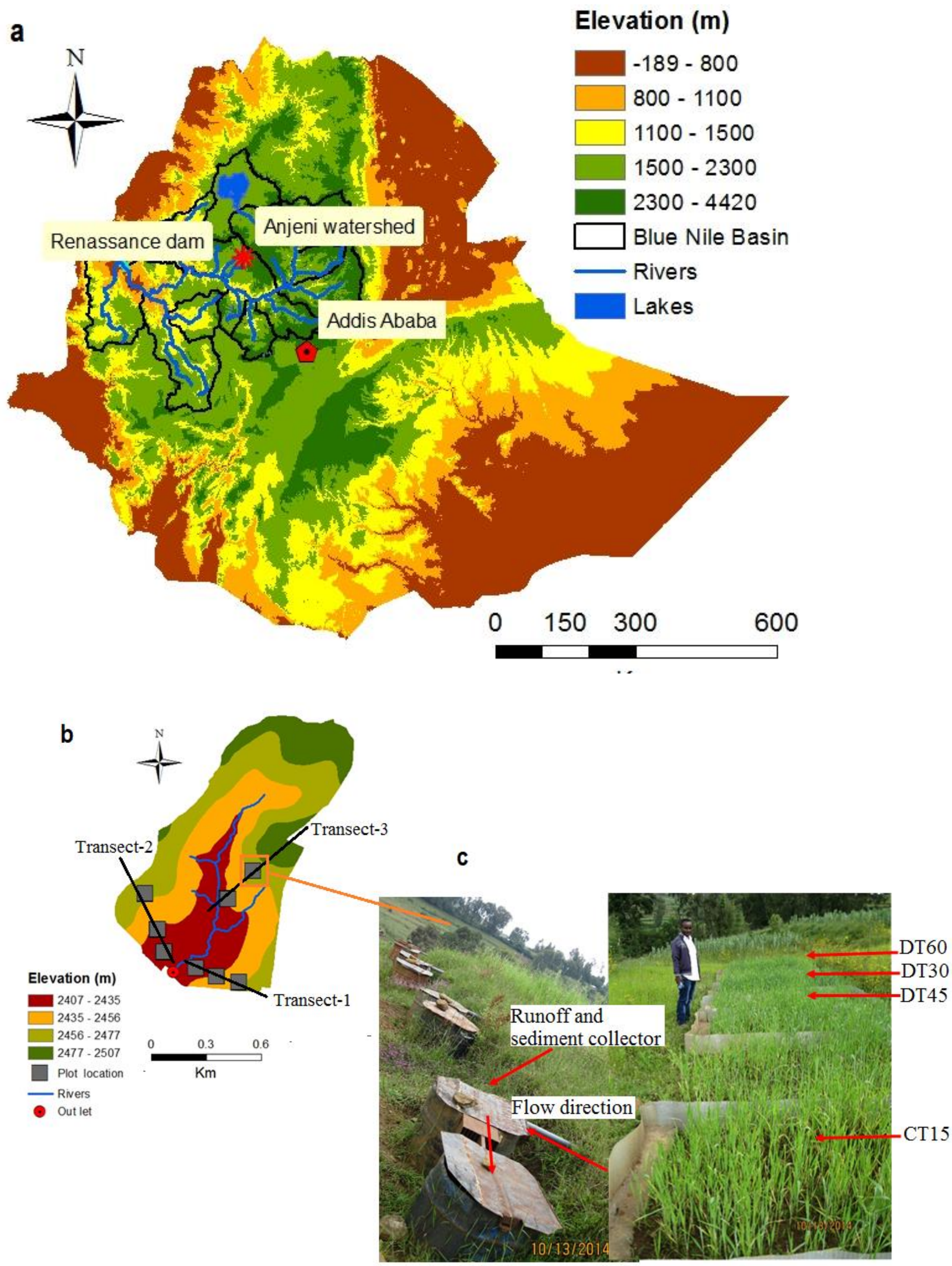


Figure 4-1. Anjeni watershed in the Blue Nile Basin in the Ethiopian highlands: Maps of Ethiopia (a) and Anjeni watershed (b). The relative locations of each runoff plot (CT15, DT30, DT45 and DT60 plots, ripped at 15 cm, 30 cm, 45 cm and 60 cm deep, respectively) (c). Transect-1 (deep soil) is lime amended plots; Transect-2 (moderately deep soil) and Transect-3 (most degraded) are without lime.

Table 4-1. Characteristics of Transects

	Location		
Parameter	Transect-1	Transect-2	Transect-3
Slope (%)	14.5	11.8	15.6
Bulk density (g/cm3)	1.26	1.17	1.31
SPR (kPa)	1305	949	2578
Soil depth (m)	1.2	1.1	0.5
OM (%)	1.1	1.2	1.4
Exchangeable acidity (meq/100g)	1.87	1.25	1.05
Texture	Clay	Clay	Clay loam
Number of plots	12	12	8
Treatment	Ripping with lime	Ripping without lime	Ripping without lime

OM: organic matter; SPR: soil penetration resistance

4.2.3 Statistical analyses

The effect of lime and ripping on runoff and erosion response was determined using R (R Development Core Team, 2014). A general linear model was fitted using ‘glm’ package. Transect, lime amendment, and tillage depth were used as fixed factors. To determine significant factors, post hoc mean comparison tests were performed using ‘lsmeans’ package. All significance tests were performed at a significance level of ($p<0.05$) unless specified.

4.3 Results

4.3.1 Rainfall, runoff and sediment yield characteristics

We will first show the temporal rainfall distribution of the watershed for three consecutive years with the five-year average. Next, we will show the baseline patterns of runoff and sediment responses with different levels of soil degradation, before treatment. Finally, we will present how deep ripping and liming of degraded soil changed runoff and sediment responses.

The monthly rainfall distribution for the monsoon phases in 2012 - 2014 and the five-year rainfall average are shown in Figure 4-2. The rainfall in 2012 was relatively smaller and amounted 1034 mm and the 2013 season received the greatest amount, 1485 mm. The total rainfall in 2014 was 1133 mm, slightly lower than the five-year average of 1256 mm. In all years, the greatest amount of rainfall was recorded in the months of July and August (Figure 4-2).

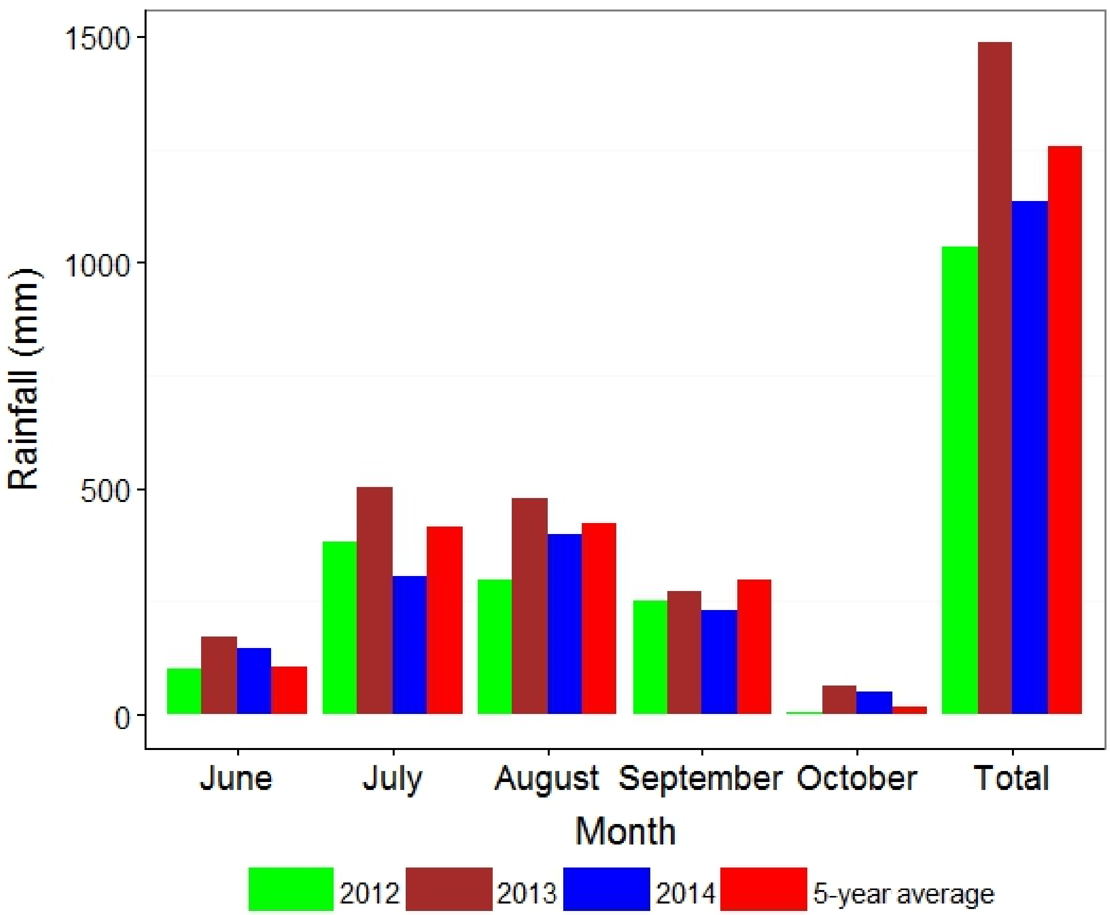


Figure 4-2. Mean monthly rainfall distribution for five years average (1989-1993) and monthly rainfall distribution of year 2012, 2013 and 2014 in Anjeni watershed during the crop growing period.

Time series runoff and sediment response results showed that, except for some storm events, plots under different levels of degradation and location responded in a similar pattern (Figure 4-4a and b). On average in 2012, 2013 and 2014, more than 40, 24, and 46 percent, respectively, of rainfall was lost as surface runoff.

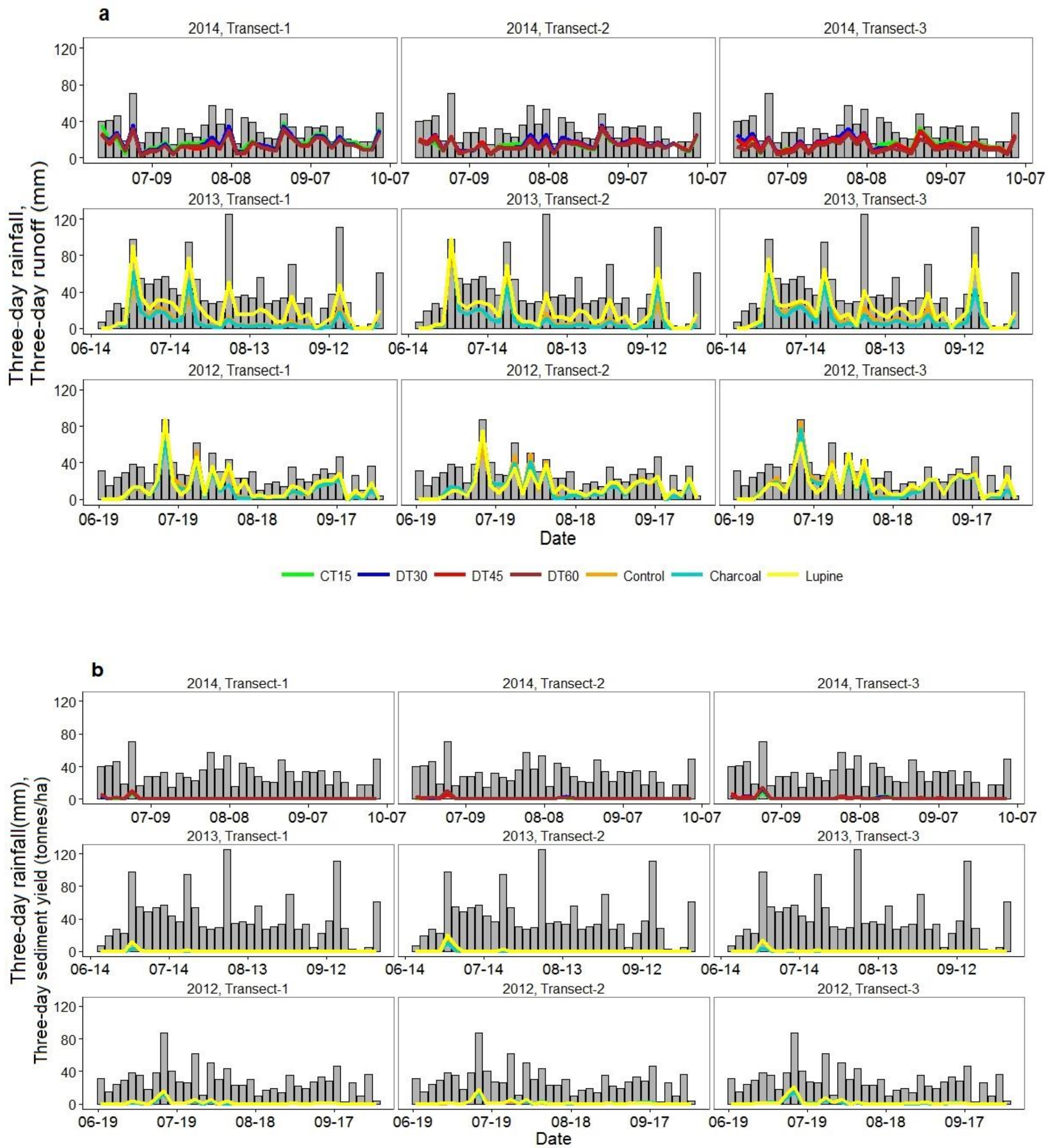
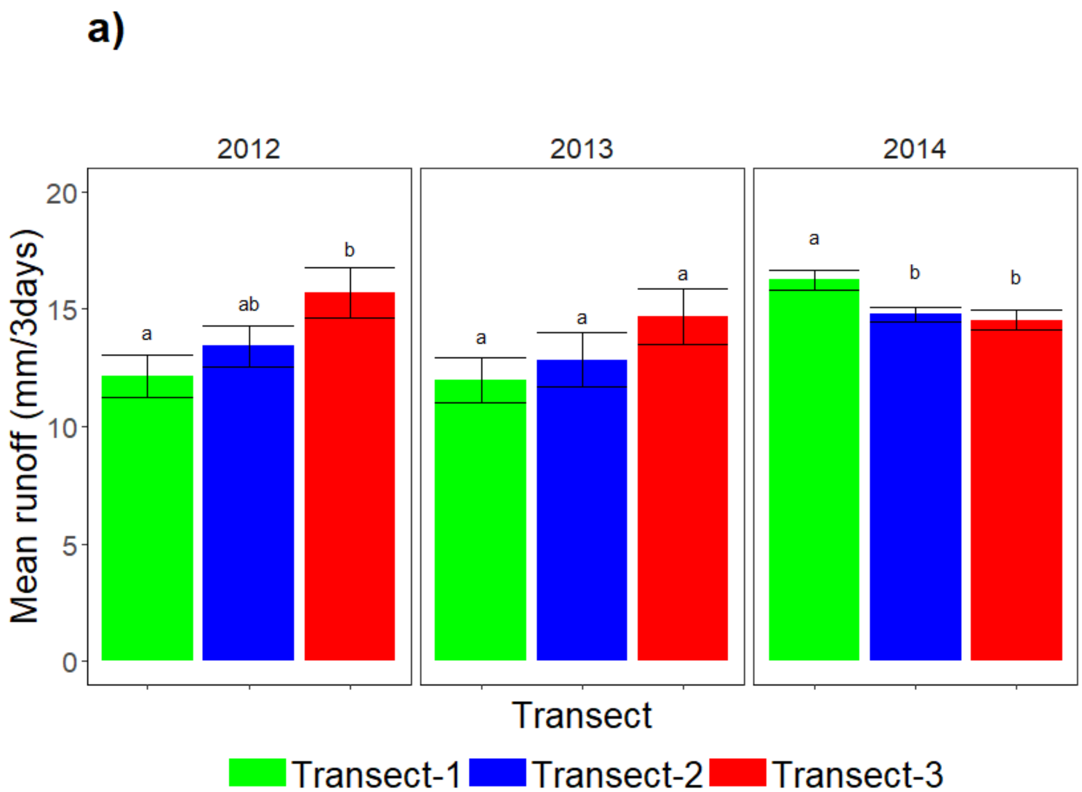


Figure 4-3.Three-day average rainfall and plot runoff responses (a) and three-day average rainfall and plot soil loss (b) among transects in 2012, 2013 and 2014 monsoon phase. The grey bar graph is rainfall.

However, comparison of three-day mean runoff responses among transects with different management options and levels of degradation showed a slight variation. In 2012 and 2013, when plots were treated with barley with charcoal and lupine plantation, the greatest mean runoff response was observed in Transect-3 (the most degraded location). In 2014 after plots were ripped, the greatest amount of runoff was observed in Transect-1 (relatively deep soil that was treated with lime (Figure 4-4a). Unlike the runoff response, the greatest soil loss was observed in Transect-3 in both before ripping in 2012 and after ripping in 2014 (Figure 4-5a and b).



b)

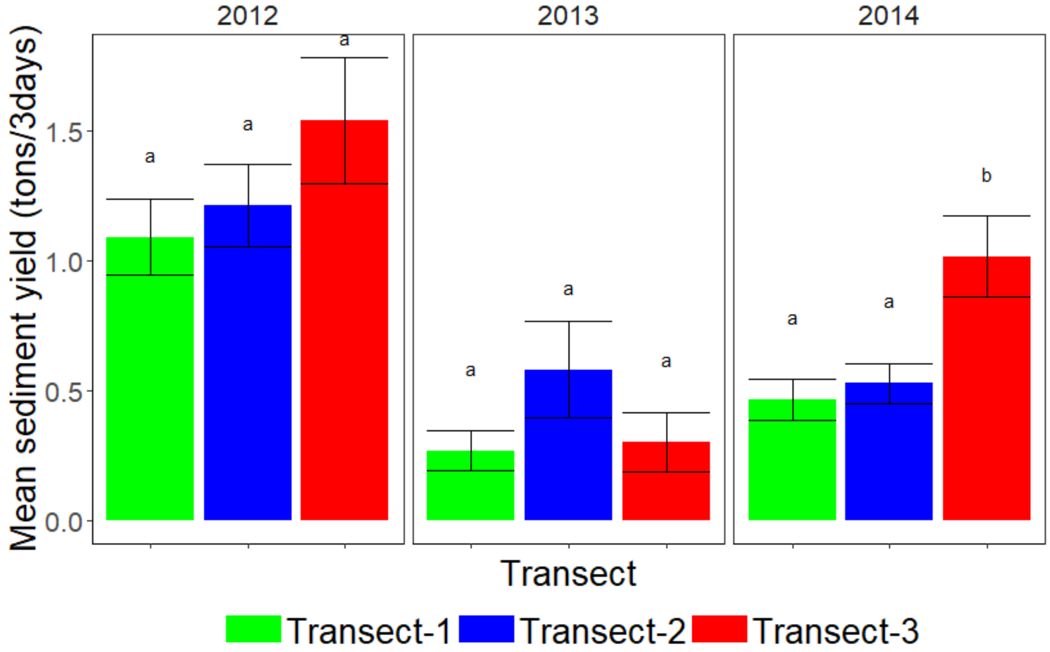


Figure 4-4.Three-day average plot runoff responses (a) and soil loss (b) among transects in 2012, and 2013 (before ripping and liming) and 2014 (after ripping and liming) monsoon phase. For each Transect, treatment followed by same letter is not significantly different at $p < 0.05$.

Table 4-2. Summary of mean runoff, coefficient runoff and sediment yield for transects for three years

Year	Location	Mean runoff (mm/3 days)	Mean runoff coefficient	Mean sediment yield (ton/ha/3 days)
2014	Transect-1	15.91	0.47	0.51
2014	Transect-2	14.76	0.45	0.53
2014	Transect-3	14.52	0.45	1.02
2013	Transect-1	11.97	0.22	0.27
2013	Transect-2	12.83	0.22	0.58
2013	Transect-3	14.67	0.28	0.30
2012	Transect-1	12.14	0.33	1.09
2012	Transect-2	13.41	0.39	1.21
2012	Transect-3	15.69	0.48	1.54

The following section focuses on how degraded soils can be improved with the application of deep ripping and liming based on year 2014 study results.

4.3.2 Effect of liming and ripping on runoff production

Analyses of runoff responses and sediment yield as they are affected by ripping depth are presented in Figures 4-6 to 4-9. As expected, ripping these degraded soils reduced runoff response. Comparison of runoff response under different ripping depths showed that as ripping depth increased the amount of runoff produced generally decreased (Figure 4-5) for all three transects. The smallest mean three-day runoff was observed in plots ripped to 60 cm deep (DT60). Likewise, runoff coefficients were the lowest in DT60. DT60 produced significantly lower amounts of mean runoff than conventional tillage (CT15) and 30 cm deep ripped (DT30) (Figure 4-5a).

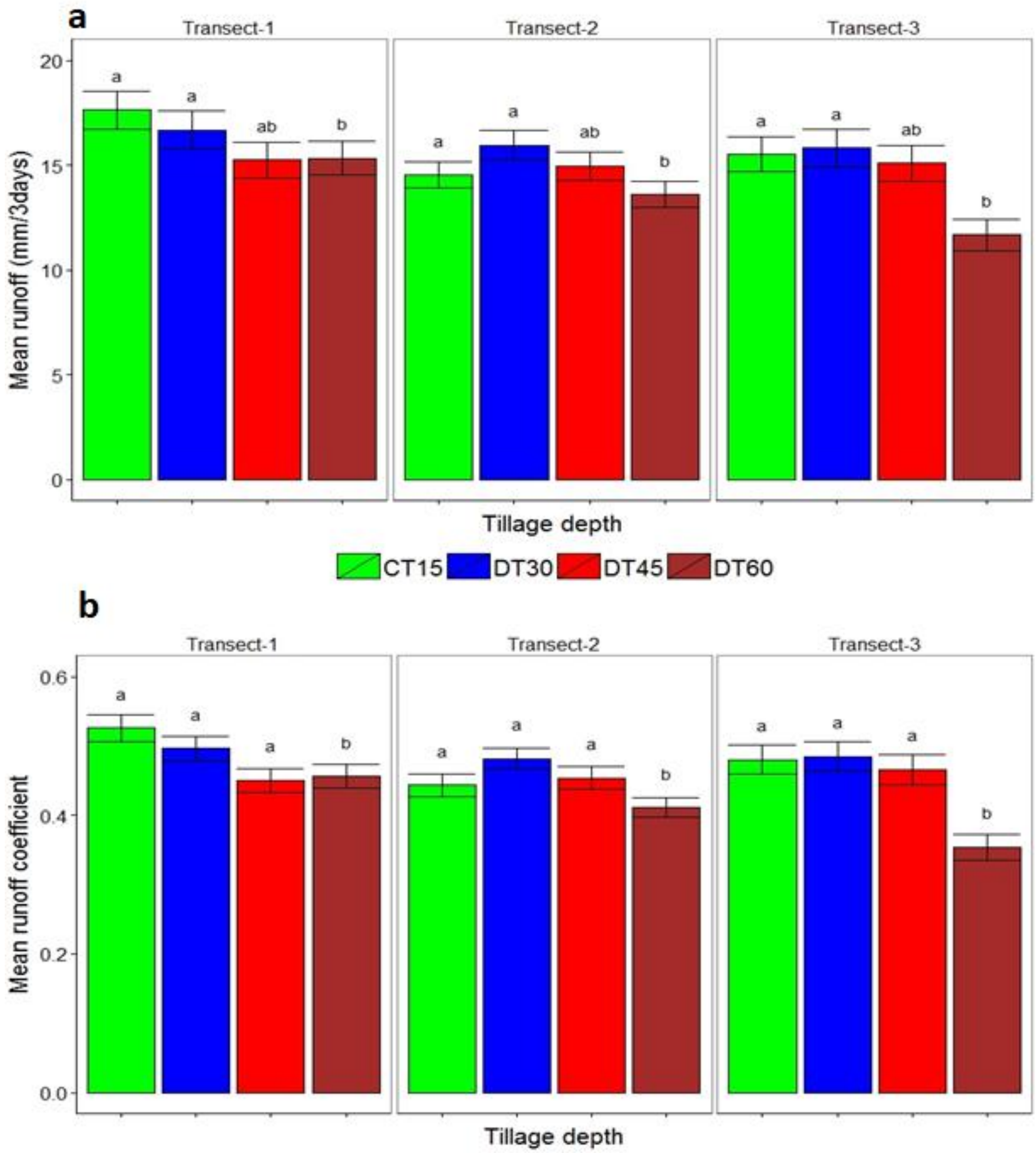


Figure 4-5. Three-day mean plot runoff (mm) (a) and mean runoff coefficient (b) under lime amended (Transect-1) and non-amended (Transect-2 and 3) plots for the monsoon phase of 2014. CT15 = conventional tillage, DT30 = ripped 30 cm deep, DT45= ripped 45 cm deep and DT60 = ripped 60 cm deep). For each Transect, treatment followed by same letter is not significantly different at $p < 0.05$.

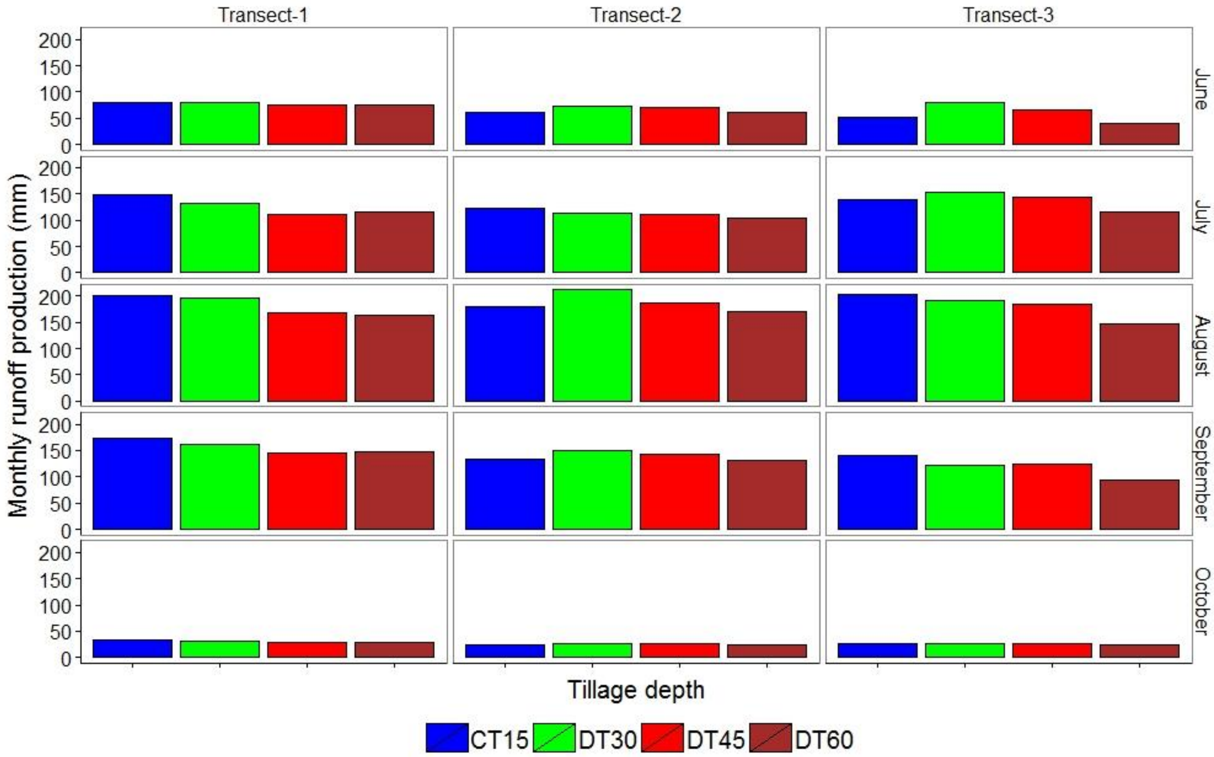


Figure 4-6. Monthly total runoff coefficient for lime amended (Transect-1) and non-amended (Transect-2 and 3) plots for the monsoon phase of 2014. CT15 = conventional tillage, DT30 = ripped 30 cm deep, DT45= ripped 45 cm deep and DT60 = ripped 60 cm deep).

Comparison of monthly total runoff response results showed that DT60 reduced runoff production within all transects relative to CT15. The reduction is considerable in Transect-3 (Figure 4-6). Similarly, the relationship between cumulative rainfall and cumulative runoff in plots ripped to different depths indicated that DT60 plots produced the smallest amount of runoff. The effect was more pronounced with an increase in cumulative rainfall, particularly after 300 to 450 mm rainfall occurred (Figure 4-7).

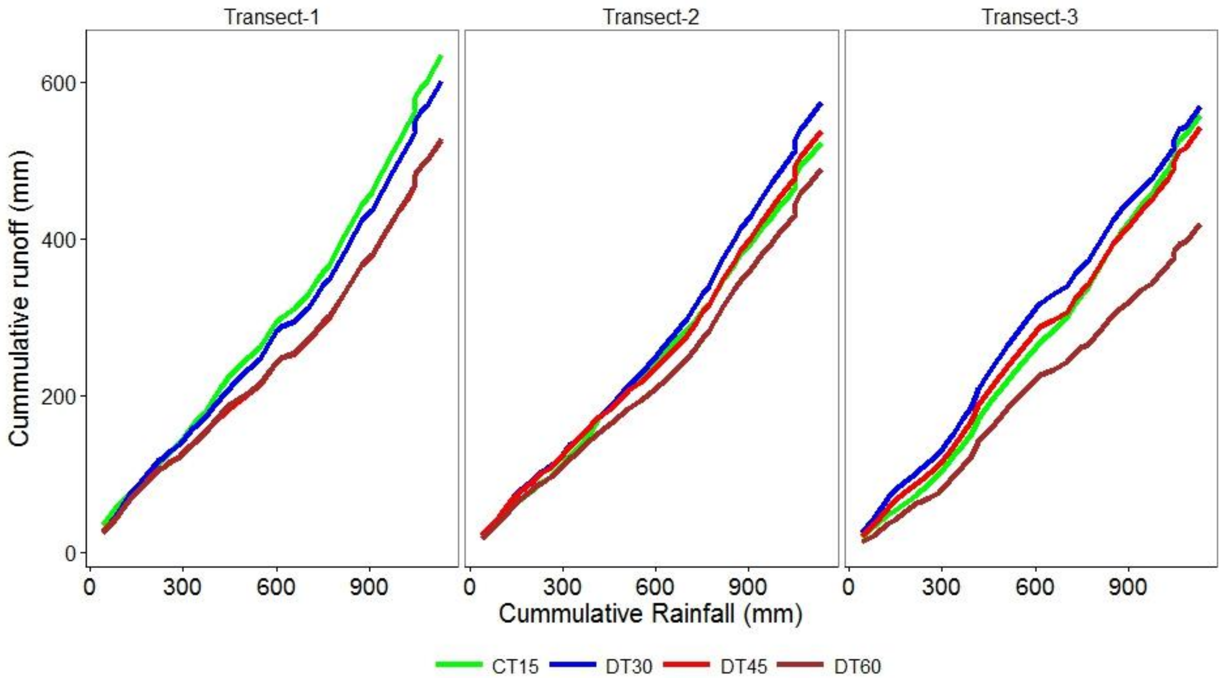
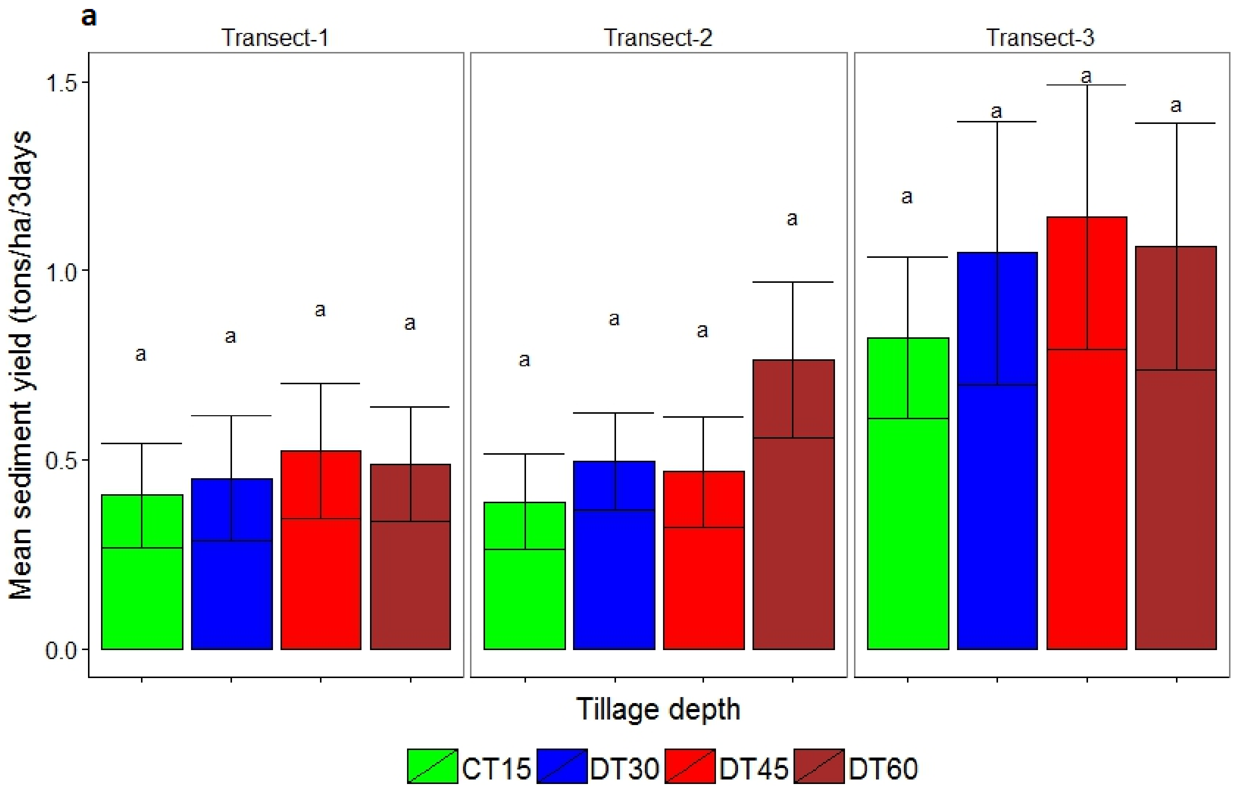


Figure 4-7. Cumulative rainfall vs. cumulative runoff under different ripping depth (CT15 = conventional tillage, DT30 = ripped 30 cm deep, DT45= ripped 45 cm deep and DT60 = ripped 60 cm deep) in lime amended (Transect-1) and non-amended (Transect-2 and 3) plots for the monsoon phase of 2014.

4.3.3 Effect of liming and ripping on sediment production/soil loss

Even though we expected that liming could increase the benefits of ripping in the short term, application of lime on hardpan soils increased the amount of runoff produced considerably. On average, liming increased runoff response by 10 % (Figure 4-5a). Likewise, the runoff coefficient on lime amended plots is significantly greater than that of non-amended plots.

On the other hand, analysis of soil loss under lime amended and non-amended plots showed that Transect-1 produced lower soil loss than unlimed, initially more degraded Transect-3, and about the same soil loss as initially less degraded Transect-2 (Figure 4-8a). Average soil loss in non-amended plots ranged from 1 to 50 tonnes/ha/yr and liming decreased this loss up to 35 %.



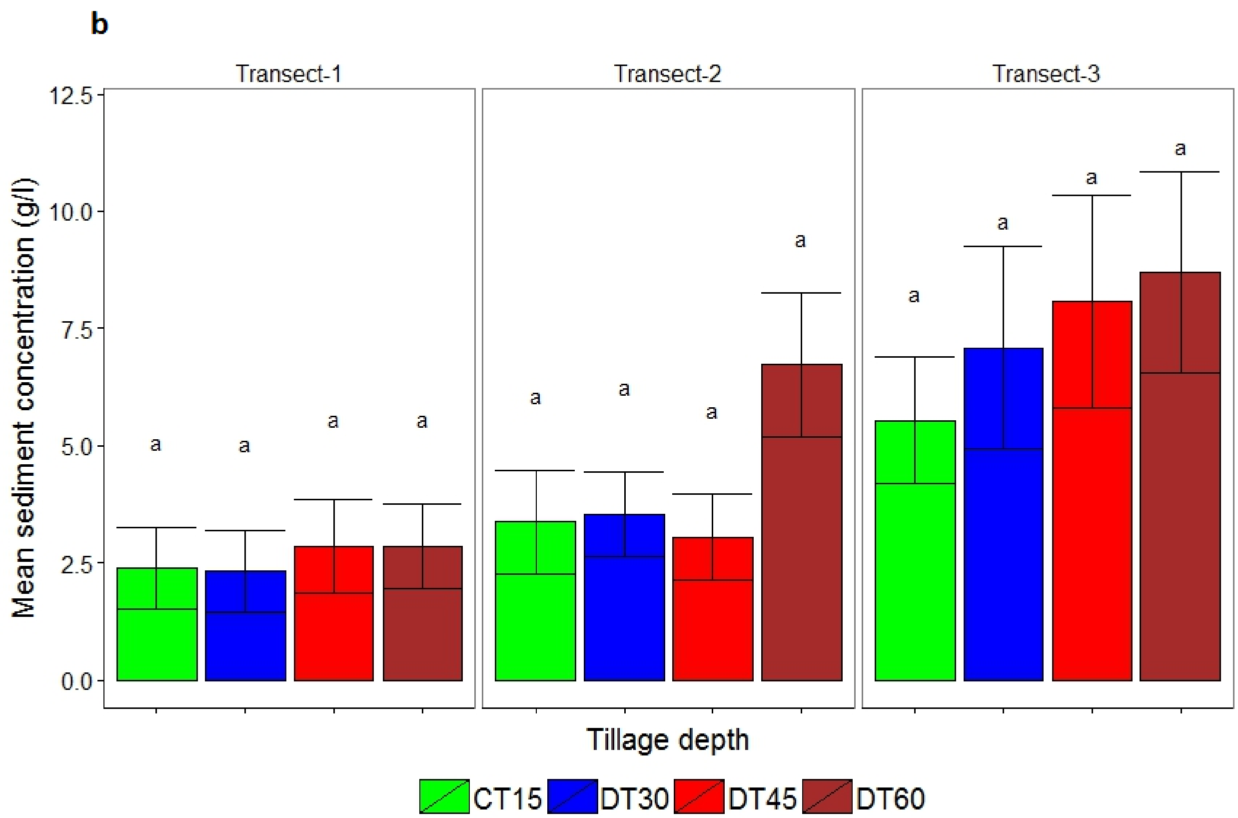
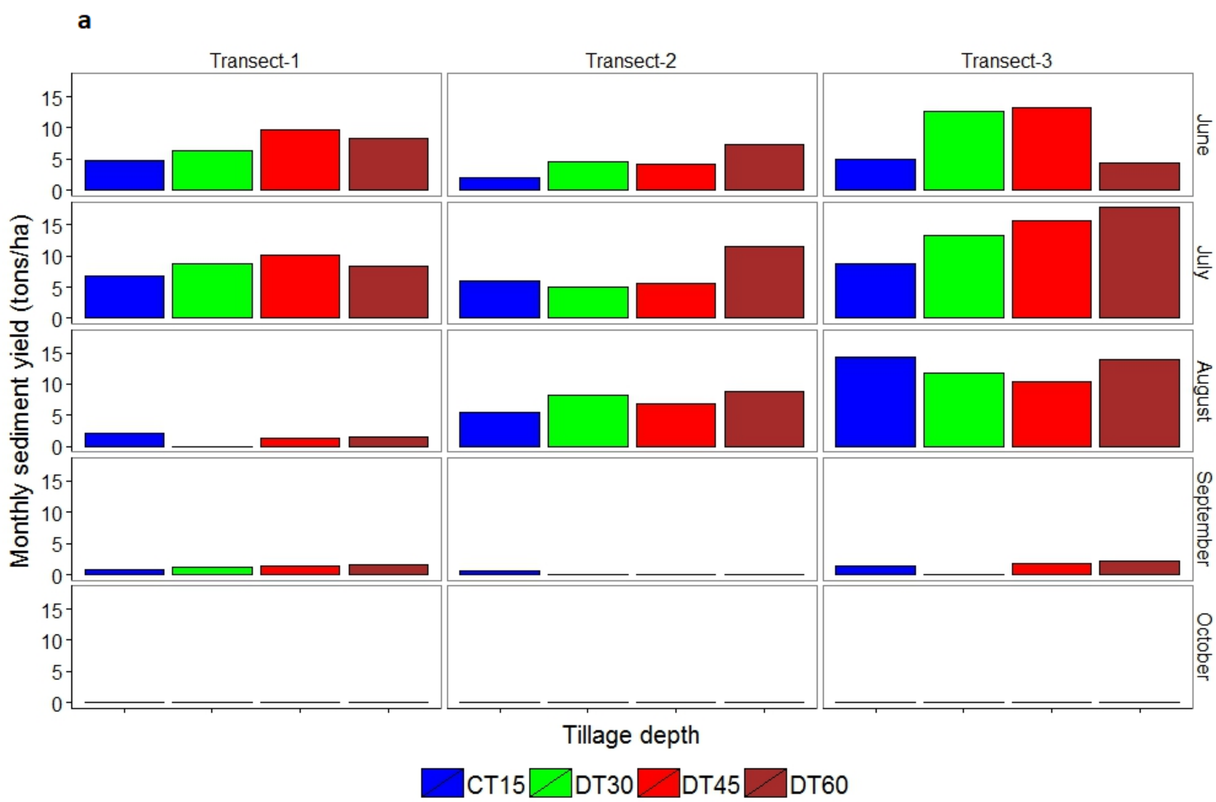


Figure 4-8. Mean sediment production (a) and sediment concertation (b) under different ripping depth (CT15 = conventional tillage, DT30 = ripped 30 cm deep, DT45= ripped 45 cm deep and DT60 = ripped 60 cm deep) in lime amended (Transect-1) and non-amended (Transect-2 and 3) plots for the monsoon phase of 2014. Ripping depth for each transect followed by same letter are not significantly different at $p < 0.05$.

Comparison of mean monthly soil loss for both lime amended and non-amended plots showed that the greater amount of soil loss was observed in the months of June and July. At the latter season in August, variation was observed and soil loss continued to occur in non-amended plots but in the case of lime amended plots, it was almost negligible (Figure 4-9a).



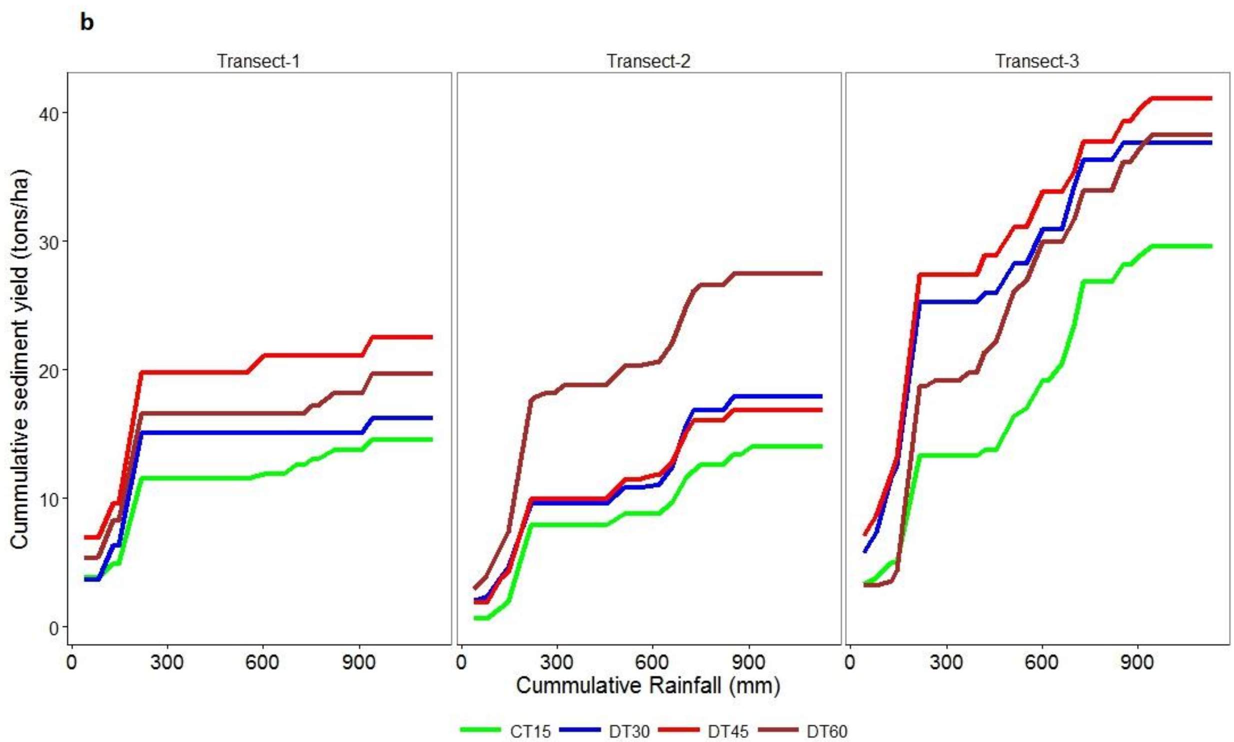


Figure 4-9. Monthly total sediment production (a) and cumulative sediment yield vs. cumulative runoff (b) under different ripping depth (CT15 = conventional tillage, DT30 = ripped 30 cm deep, DT45= ripped 45 cm deep and DT60 = ripped 60 cm deep) in lime amended (Transect-1) and non-amended (Transect-2 and 3) plots for the monsoon phase of 2014.

In addition, an increase in ripping depth increased the amount of soil loss significantly. The relationship between cumulative rainfall and cumulative sediment production in plots ripped under different depths indicated that CT15 plots caused the lowest sediment production in all transects (Figure 4-9b). In all transects, the effect was more pronounced with an increase in the cumulative rainfall, particularly after 300 mm rainfall occurred.

4.4 Discussion

The reduction of runoff under deeper ripped plots for both lime amended and non-amended plots indicate that deep ripping can improve water permeability and subsurface drainage system of degraded soils. In agreement with our findings, Asmamaw et al. (2012) found improve moisture retention, high infiltration, and low soil evaporation in ripped hardpan soils of northwestern Ethiopia. Similarly, Leye (2007) showed that ripping resulted in lower surface runoff and better crop yields as compared to conventional tillage because of greater water productivity and greater crop transpiration. Similarly, Schillinger and Wilkins (1997) found that ripping significantly improved water infiltration in the soil and reduced soil erosion. Similarly, Araya et al. (2012) found a reduction of runoff in plots tilled under 25-30 cm compared to plots tilled under conventional tillage at 10 to 15 cm depths because of the increased capacity for furrows to retain a large proportion of runoff.

The greater soil loss under deeply ripped plots compared to the shallowly ripped plots indicates that disturbance of soil during ripping causes the soil profile to be more prone to soil erosion by water.

Our expectation that liming improves the benefits of ripping to reduce runoff responses in the short term was not supported by this study. Conversely, the results indicated that liming significantly increased runoff response.

The results from (2012 and 2013) studies conducted on approximately the same plots treated with barley with charcoal and lupine plantation showed that Transect-1 produced the least amount of runoff. In contrast, Transect-1 having the greatest runoff response in 2014 after ripping suggested that liming affects the runoff process. The greater runoff due to liming is likely linked to its short-term effect. A study by Castro and Logan (1991) reported that structural degradation of soil is expected to occur in short term due to liming. This situation is likely to be aggravated by the late application date and application method. Application of lime was performed mid-June after the monsoon rain had started. However, according to the recommendation of the regional research center and local practices in the study area, liming is usually performed at least 3 months before sowing a crop. This time period allows lime to mix with the soil and to react with soil exchange acidity (Fageria and Baligar, 2008). Similarly, Kibet et al. (2016) observed that liming improves soil properties after thirty years of application. In addition, it is well known that application of lime as surface dressing during the rainy season can cause crusting (Shainberg et al., 1989). This situation is aggravated by the textural class of the soil in the watershed. Soils in Anjeni watershed are dominated by clay that limits infiltration of rainwater.

Despite this study result, we expect that liming could improve the benefits of ripping and soil quality in later years. This is because liming reduces the leaching loss of cations in highly weathered tropical soils. In addition, calcium in liming material helps in the formation of soil aggregates (Castro and Logan, 1991), hence improving soil structure and pore size distribution that may have deteriorated due to tillage operations and cropping systems (Chan and Heenan,1998). Similarly, Haynes and Swift (1988) found that liming increased microbial biomass which improves chemical and biochemical processes of the soil.

On the other hand, the reduction of soil loss due to liming can be related to the improvement of soil quality. This result is in line with Castro and Logan (1991) who found that liming significantly decreased erosion on degraded tropical soils, in particular soils with low organic matter contents. Muller (1993) showed that dispersion of soil colloids was significantly reduced by liming in the soils of Western Australia.

Moreover, the greater amount of runoff in the months of July, August, and September corresponded to the amount and the intensity of rainfall the plots received. In addition, later in the rainy season, most of the lands are fully saturated resulting in saturation excess runoff. Similar findings were reported in the studies of Tebebu et al. (2010), Bayabil et al. (2010), Tilahun et al., (2013), and Guzman et al. (2013).

The greater soil loss in the months of July and August was also because the ripping operations in July made the soil profile directly susceptible to erosion. Similar results were observed at the outlet of the watershed (Bayabil et al., 2016). In agreement with this, Tilahun et al. (2015) and Vanmaecke (2010) showed a greater soil loss at the beginning of the rainy season when the soil is disturbed and bare. The findings of this study (very prominently in Figure 4-9) suggest that the time immediately following ripping of the hardpan is the most critical period where the highest amount of soil loss occurs and that pattern needs higher attention.

4.5 Conclusions

The results of this study show that ripping hardpan soils reduced runoff responses but increased erosion in the short term. As ripping depth increased the amount of rainfall abstracted increased. Ripping hardpans allows rainfall more time to infiltrate deeper into the soil profile. In contrast, liming degraded soil reduced the effectiveness of deep ripping to abstract rain water. The increased runoff due to liming can be because liming can cause some short-term structural degradation of soil. On the other hand, it improved the benefits of deep ripping on soil erosion. The reduction of soil erosion due to liming is because liming is expected to decrease the amount of raindrop splash and therefore prevent formation of hardpan after it has ripped.

The overall findings of this study suggest that hardpans in the Ethiopian highlands can be ameliorated using deep ripping. Liming can improve the benefits of deep ripping to reduce runoff and erosion response in the long term. During the first few years, caution is required to reduce the negative response which liming has on the effects of deep ripping on runoff and erosion responses).

4.6 References

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CHAPTER 5: CONCLUSIONS

Land degradation and associated soil erosion remain a persistent problem in the Ethiopian highlands affecting the livelihoods of people. Several soil and water conservation practices have been implemented, however, the effects are far below expectations and land degradation is still increasing at alarming rate. The failure of SWC practices is partly due to lack of understanding in landscape processes, soil types, and agro-ecologic and climatic variations during design and implementation (Steenhuis and Tilahun, 2014; Bayabil et al., 2010).

In this dissertation, we detail the runoff and erosion processes in the humid Ethiopian landscape and suggest effective landscape interventions. In addition, we examined hardpans formation associated with land use changes and evaluated the effectiveness of deep ripping and liming on managing degraded soils.

In the first part of this dissertation research (Chapter two), we assessed the hydrological and sedimentary processes of the (sub) humid Ethiopian highlands at different spatial and temporal scales of observation. Studies in four watersheds (Anjeni, Maybar, Andit Tid and Debre Mewi) showed that annual runoff and erosion patterns of the watersheds in the humid Ethiopian highlands are similar in space and time. Runoff and sediment originate from source areas saturated, either by a shallow regional groundwater in the valley bottom or from degraded areas with limited root zone storage for rainwater above a shallow restrictive layer. After deforestation soils became degraded and formed restrictive layers at shallow depths. This, in turn, increased lateral flow, shortened travel time, increase runoff and enlarged saturated land area, and reduced base flow.

In Chapter three, we investigated the extent of soil degradation and the formation of hardpans in crop/livestock mixed rainfed agriculture systems of Anjeni and Debre Mewi watersheds. Our findings showed that the formation of hardpan soil is associated with the conversion of land from forest ecosystems to agriculture use. Soil physical and chemical properties in agricultural lands deteriorated, causing disintegration of soil aggregates resulting in greater sediment concentration in infiltration water that clogged up macro-pores, thereby disconnecting deep flow paths found in original forest soils.

In Chapter four, the effect of ripping hardpan soils on runoff response and sediment yield was investigated. In addition, we tested whether liming would improve the effectiveness of ripping. Measurements of runoff and sediment yield in the runoff plots of Anjeni watershed indicated that deep ripping hardpan soils improved rainwater infiltration resulting in lower runoff production even in short-term but increased soil loss due to more soil disturbance. However, liming increased runoff responses, on average by 10 % and decreased soil loss up to 35 %.

In all, this dissertation shows that deforestation in itself does not cause soil degradation but soil degradation is a consequence of a number of processes that starts with loss of organic matter that binds the soil together in aggregates. Once these aggregates have broken down, the natural rate of horizon formation is greatly increased resulting in hardpan formation that is still ongoing, damaging each year more land and increasing sediment concentration in the water. This sediment is filling up the newly constructed reservoirs for hydro-electric power and robbing the small-holder farmers from the food they need to feed the family. It is imperative that this degradation cycle be broken, first by recognizing the underlying causes of land degradation and then to research for solutions instead of indiscriminately installing millions of soil bunds that after a few years are ineffective.

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