# Effects of land use and management practices on soil loss and soil properties in the Upper Blue Nile basin, Ethiopia

## (エチオピア青ナイル川上流域における土地利用と管理策が土壌流亡および土壌特性に及ぼす影響)

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**The United Graduate School of Agricultural Sciences**
**Tottori University, Japan**

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A dissertation submitted to
The United Graduate School of Agricultural Sciences, Tottori University
in partial fulfillment of the requirements for the Degree of Doctor of
Philosophy in Global Arid Land Science

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The United Graduate School of Agricultural Sciences
Tottori University, Japan
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# List of Abbreviations and Acronyms

| | |
|---|---|
| ADSWE | Amhara Design and Supervision Works Enterprise |
| ANOVA | Analysis Of Variance |
| BD | Bulck Density |
| CEC | Cation Exchange Capacity |
| CV | Coefficient of Variation |
| DMY | Dry Matter Yield |
| DZ | Deposition Zone |
| EC | Electrical Conductivity |
| EZ | Erosion Zone |
| FAO | Food and Agricultural Organization |
| GL | Grazing Land |
| $K_{av}$ | available Potassium |
| LT | Local Time |
| MR | Mean Ranks |
| OM | Organic Matter |
| $P_{av}$ | available Phosphorous |
| pH | power of Hydrogen |
| SC | Sediment Concentration |
| SD | Standard Deviation |
| SL | Soil Loss |
| SLM | Sustainable Land Management |

| | |
|---|---|
| SLMP | Sustainable Land Management Project |
| SOC | Soil Organic Matter |
| SOM | Soil Organic Matter |
| SPSS | Statistical Package for Social Science |
| SSC | Suspended Sediment Concentration |
| SWC | Soil and Water Conservation |
| SY | Sediment Yield |
| TN | Total Nitrogen |
| UBNB | Upper Blue Nile Basin |
| USA | United States of America |
| USDA | United States Department of Agriculture |

# Chapter 1

## General Introduction

## 1.1 Background

### 1.1.1 Soil and its ecological functions

Soil is one of the most complex biomaterials on earth (Young and Crawford, 2004), and a key component of the terrestrial ecosystem operating at the interface of the lithosphere, biosphere, hydrosphere, and atmosphere (Szabolcs, 1994). It is a precious and essential natural resource underpinning all terrestrial life (Bini, 2009), that can make the difference between survival and extinction for most land-based life (Doran, 1996); a vital part of ecosystems and earth system functions that support the delivery of primary ecosystem services (Robinson et al., 2017). Soil functions and ecosystem services are dependent on key soil properties and their interaction (Figure 1.1), and are mostly influenced by its use and management interventions (Adhikari and Hartemink, 2016).

Healthy soil, in particular, is the foundation of agriculture and an essential resource to ensure human needs such as food, feed, fiber, clean water, and clean air (Amundson et al., 2015). A well managed soil is an important carbon pool in terrestrial ecosystems (Janzen et al., 1997), and it is globally viewed as having the potential to sequester significant quantities of carbon derived from atmospheric carbon dioxide (Rabbi et al., 2014).

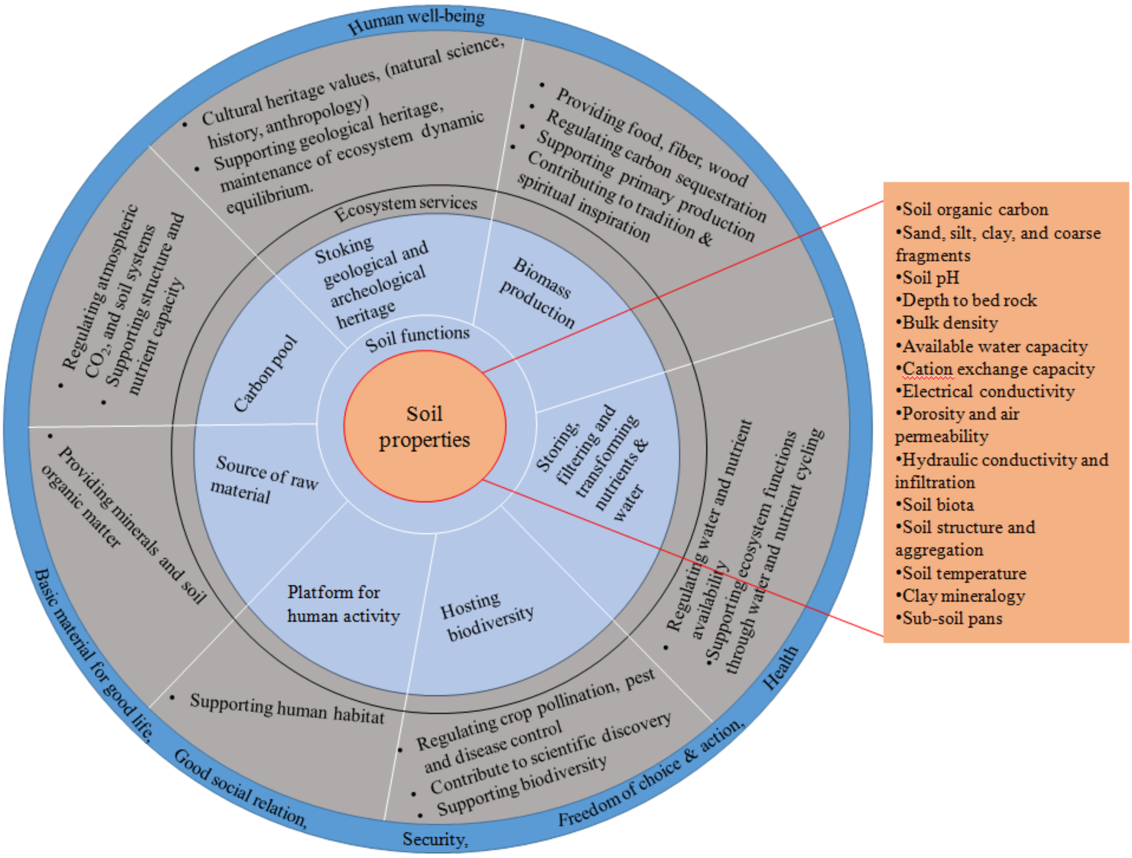

**Figure 1.1** A conceptual diagram linking key soil properties to ecosystem services through soil functions for the well-being of humans (Source: Adhikari and Hartemink, 2016).

### 1.1.2 Soil degradation: Processes, causes, and consequences

In the Anthropocene, soil quality (the ability of the soil to perform a particular ecosystem function) is threatened worldwide by human-induced degradation processes (Bridges and Oldeman, 1999; Lal, 2001), including physical (e.g., soil erosion, compaction, and waterlogging), chemical (e.g., nutrient depletion and acidification), and biological (e.g., depletion of soil fauna and flora, and organic matter) processes (Lal and Stewart, 1990b, Figure 1.2). These degradation processes have increasingly become major problems in many regions of the world where human activity and related land use changes primarily caused accelerated soil erosion, which has substantial implications for nutrient and carbon cycling, land productivity, and in turn, worldwide socio-economic conditions (Borrelli et al., 2017). As clearly illustrated in Figure 1.3, soil degradation is a complex phenomenon driven by complex interaction among socioeconomic and biophysical factors (Lal and Stewart, 1990a**)**. For instance, over the past centuries, population growth, urbanization, and industrialization have induced a prolonged decline in the extent of forest cover in many regions across the globe (Rudel et al., 2005). The conversion of forest to cultivable lands, and associated practices causes modifications to the hydroclimatology cycle as well as increased runoff and soil erosion (Souza-Filho et al., 2016) which further lead to marked edaphic changes and greater erosion vulnerability at soil surface horizons (Beliveau et al., 2015).

Problems associated to soil erosion and land degradation, however, are most pressing in developing countries, where the livelihoods of large proportions of the population are directly dependent on the soil (Tully et al., 2015), and where population pressure (population to land ratio) is steadily rising. In these countries, additional lands are being used for intensive cultivation and grazing at the cost of degrading natural forests and grasslands (Sunderlin et al., 2005). In some of such countries, soils have lost 60% to 80% of their soil organic carbon (SOC) pool over 30 years period as a result of the extractive practices of subsistence farming, which have adverse effects on soil quality and lower its ability to resist drought and degradation processes (Lal, 2006).

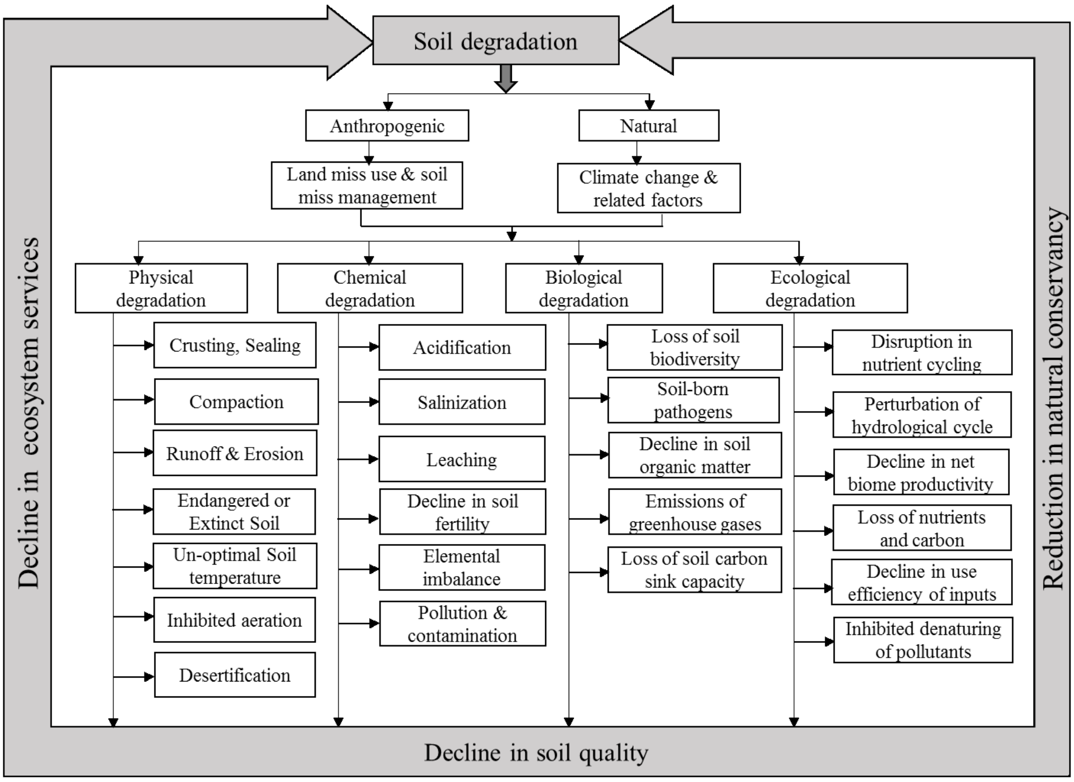

**Figure 1.2** Causes and types of soil degradation processes (Source: Lal and Stewart, 1990b; Lal, 2015).

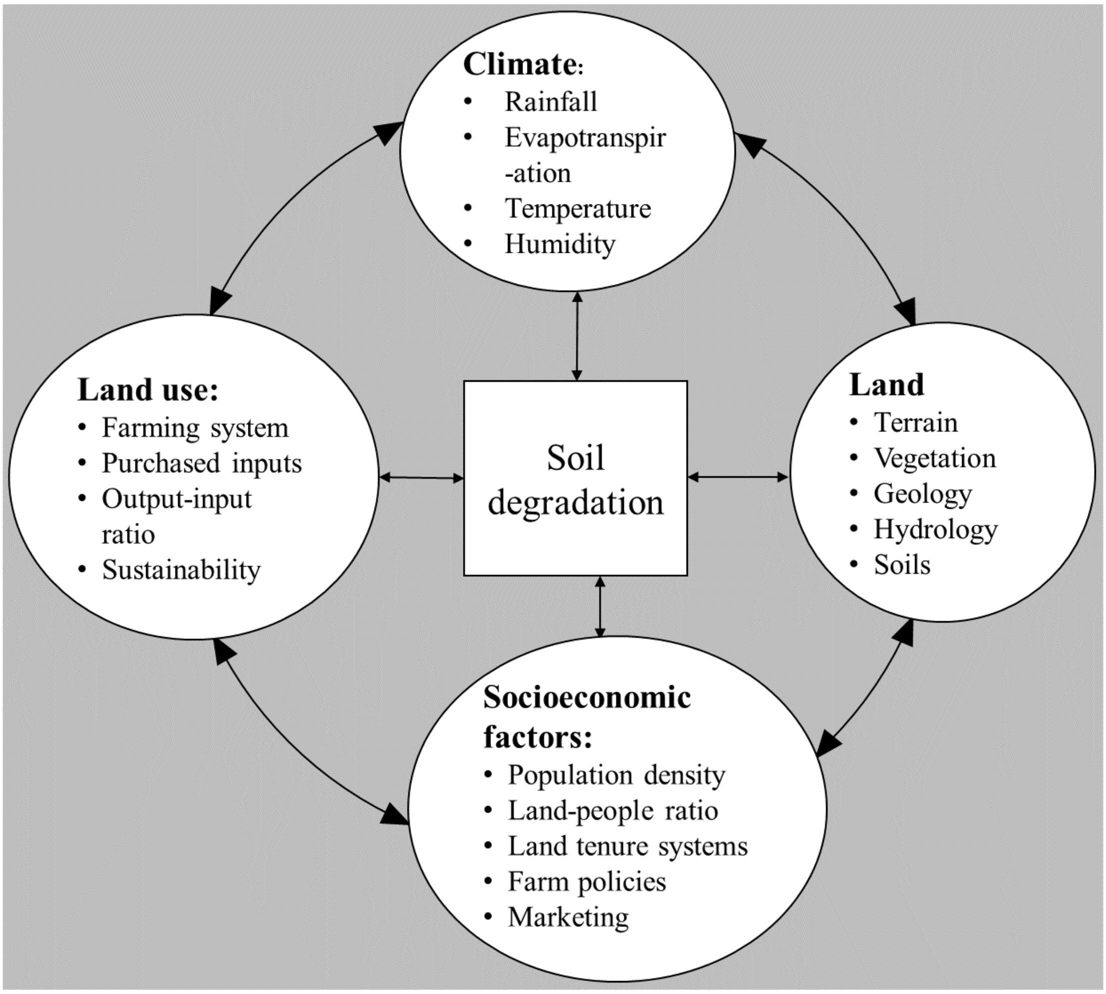

**Figure 1.3** Interactions of factors that determine soil degradation (Source: Lal and Stewart, 1990a).

The costs of soil erosion by water are beyond the removal of valuable topsoil (soil degradation), they are combined with the severity of many other on-site, and off-site consequences (Telles et al., 2011). The linkage between the major causes and consequences (on-site and off-site impacts) of soil erosion, mainly through human-induced erosion and sedimentation processes, is illustrated in Figure 1.4. However, because the consequences of soil erosion are very location-specific, with each geographical location is characterized by a specific mix of biophysical and socioeconomic variables (Enters, 1998), short-term and long-term categories given in Figure 1.4 could be quite arbitrary and subject to change for different spatial and temporal scales. This, therefore, requires a comparative approach in which soil erosion rates and costs are compared from the perspectives of landscape and climate heterogeneity, for prioritization of locations and suggest appropriate remedial measures.

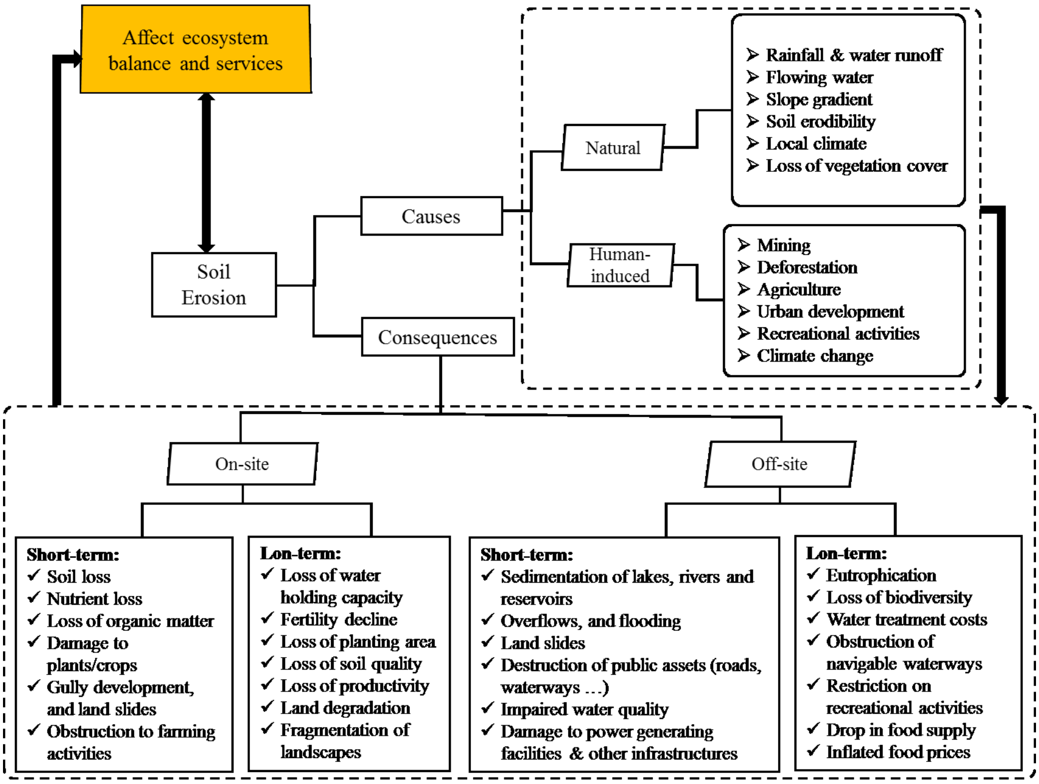

**Figure 1.4** A conceptual diagram linking causes and consequences of soil erosion (Source: Telles et al., 2011).

### 1.1.3 Soil erosion and land degradation in Ethiopia

Soil erosion is one of the most critical environmental problems in Ethiopia, caused mainly by the rapid population increase, deforestation, low vegetative cover, and unbalanced crop and livestock production (Taddese, 2001). It is most pressing in the highlands which account for 43% of the country's total area, 95% of the cultivated area, and support about 88% of the human and 75% of the livestock populations (Shiferaw and Holden, 1999), and where small scale rainfed agriculture is the main source of livelihood for about 87% of country's population (Hurni et al., 2015), and subsistence farmers cannot cope with soil and nutrient losses (Lal, 2001) Average soil loss rates from croplands have been estimated at 42 t $ha^{-1}$ $yr^{-1}$ but may also re ach up to 300 t $ha^{-1}$ $yr^{-1}$ in individual fields (Hurni, 1993b) which far exceeds the rates of soil formation. The estimates reported about 33 years ago (FAO, 1986) indicated that some 50% of these highlands were significantly eroded, of which 25% are seriously eroded, and 4% have reached a point of no return. As a result of this, about 70 % of population and an area of over 40 million ha are affected by land degradation in these highlands (Melaku, 2013), indicating the scale and extent of the problem challenging the region and the country.

Favorable agricultural and ecological conditions have drawn many people to settle in these highlands, leading to high population densities that sometimes exceed 300 people per km$^2$, deforestation, and overexploitation of natural resources (Nyssen et al., 2009; Kassie et al., 2010; Haregeweyn et al., 2017) which in turn lead to increased runoff and soil erosion (Figure 1.5) with an adverse impact on aquatic and terrestrial ecosystem functions (Figure 1. 6). This situation is more particularly critical in areas experiencing high rates of soil loss and soil degradation as a result of intense rainfall, steep and undulating topography, and the problem has been exacerbated by the use of agricultural systems that reduce the protective soil cover provided by native or natural vegetation (Nyssen et al., 2004).

Previous studies quantitatively demonstrated that soil erosion and degradation are grave in the central and northwestern highlands (Figure 1.5) of the country (Hakkeling, 1989; Sonneveld et al., 2011; Hunni et al., 2015) where the amount and erosivity of rainfall is very high (Fenta et al., 2017), free grazing is widespread, and soils are fragile. The estimated soil loss rates in this region, based on field assessment of rill and inter-rill erosion (Herweg, 1999; Bewuket and Teferi, 2009; Kindiye, 2013; Admasu et al., 2014; Amare et al., 2014), are all exceeded both the suggested soil loss tolerance of 18 Mg ha$^{-1}$ yr$^{-1}$ (Hurni, 1983a) and the estimated soil formation rates ranging from 2 to 22 Mg $ha^{-1}$ $yr^{-1}$ (Hurni, 1983b). Such high soil erosion rates have had critical on-site consequences to the farmers — decline in both the current and potential crop and livestock yields — and external or off-site effects which indirectly affect the rest of the society: pollution and sedimentation of hydroelectric dams, Lakes, and reservoirs (Gebreselassie et al., 2015). The off-site environmental consequences of land degradation due to soil erosion also include its effect on the biodiversity and many ecosystem services (Figure 1.1): supporting (e.g. nutrient cycling, soil formation), regulating (e.g. flood regulation, water purification), cultural, spiritual, and recreational services for the present and future generations (Nkonya et al., 2011).

For instance, the Upper Blue Nile Basin (UBNB, Figure 1.5) also known as the drainage basin of Abbay River (the largest tributary of the Nile river) with the total area of 173,000 $km^2$ (about 16% the country's total area), is amongst the actively eroded regions, about 39% of the basin area is experiencing severe to very severe (>30 t $ha^{-1}$ $yr^{-1}$) soil erosion risk (Mengistu et al., 2015; Haregeweyn et al., 2017). This results in sedimentation and major threats for irrigation canals and hydroelectric power projects in the basin and the downstream countries (Sudan and Egypt). As reported in Hurni et al. (2015), upland erosion in this basin is contributing a sediment yield of at least 300 million tonnes/yr at the location of the Grand Ethiopian Renaissance Dam that has been under construction since 2011. A major benefit of the dam will be hydropower production to fully support the development of both rural and urban areas of Ethiopia, though there are also transboundary benefits and impacts expected.

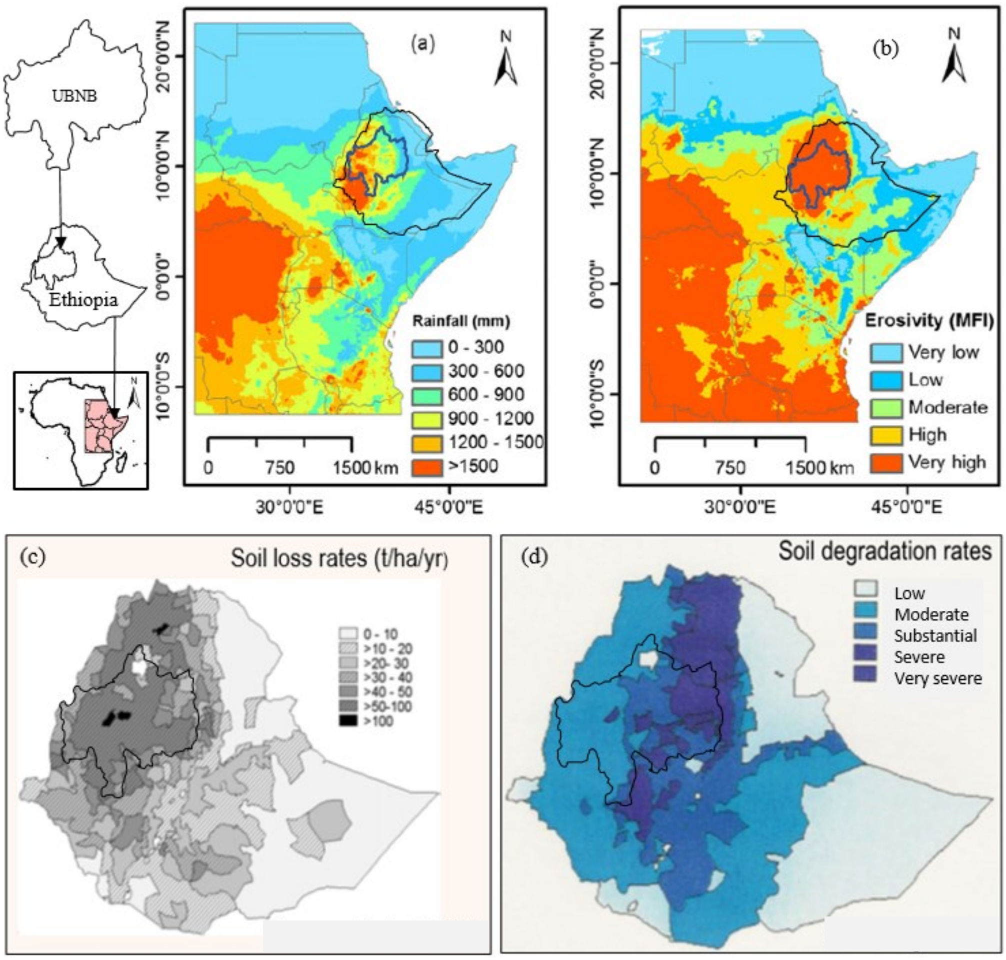

**Figure 1.5** Spatial distribution of (a) mean annual rainfall and (b) erosivity in the eastern Africa region (Fenta et al., 2017), and rates of (c) soil loss (Sonneveled et al., 2011) and (d) soil degradation (Hakkeling, 1989) in Ethiopia.

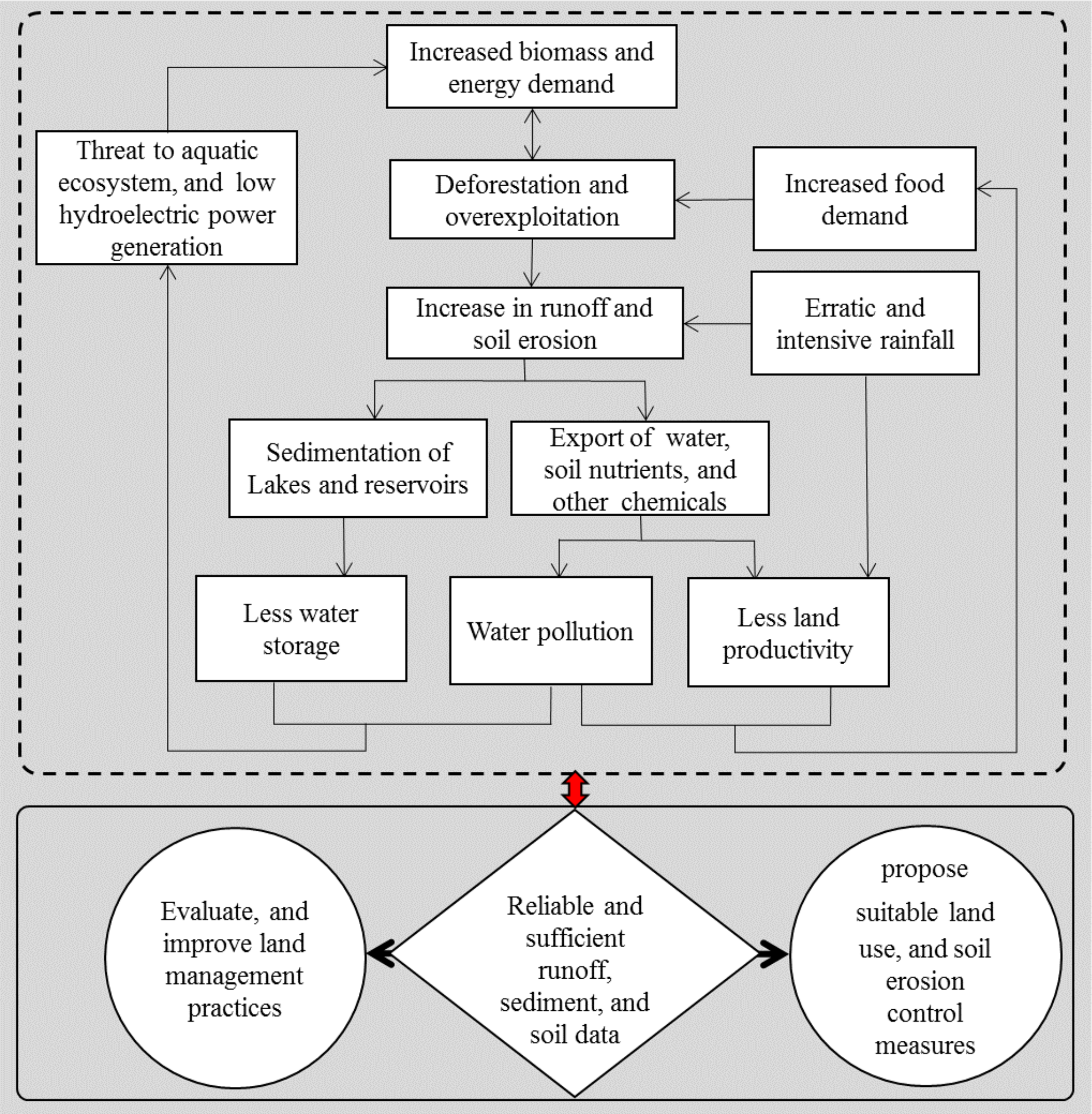

**Figure 1.6** A conceptual diagram linking the overall impact of population pressure on land and water resources in the Ethiopian highlands, and the need for reliable and sufficient data about runoff, sediment and soil for planning sustainable land use and management practices (redrawn from Zenebe, 2009).

Another important location in the northwestern highlands of Ethiopia, that has been at risk of upland soil erosion (Setegn et al., 2009) and sedimentation (Lemma et al., 2017), is the Lake Tana: the largest Lake in Ethiopia, source of the Blue Nile River, the important

Lake for the country in many aspects such as agriculture, biodiversity, tourism, fishery, and hydroelectric power production at *Tis Abay* and *Tana-Beles* stations (Monsieurs *et al.*, 2015). Despite the awareness for the overall impact of soil erosion have become increased, tackling natural and human induced destructive process in the landscapes of Ethiopia (Figure 1.6) and sustaining ecosystem services from the terrestrial and aquatic ecosystems is persistent to be a great challenge, and this requires reliable and sufficient information on the interaction among socioeconomic and biophysical components (Lal and Stewart, 1990a; Kalaugher et al., 2013).

### 1.1.4 Sustainable land management in Ethiopia

The issue of soil and water conservation (SWC) activities for sustainable land management (SLM) was neglected until the early 1970s despite the increasing land degradation. But, the awareness of the problem was incited by the devastating famine in Wollo (northeastern part of Ethiopia) in 1973–74, and efforts to install conservation measures on erodible lands were thus initiated following the 1975's land reform and by establishing peasant associations as an instrument for mobilizing labor and assignment of local responsibilities for rehabilitation efforts (Shiferaw and Holden, 1999). The efforts in the 1970's, however, gave emphasis for the drought-prone areas (where drought increases soil vulnerability to erosion when rain does fall), and they were implemented on an *ad hoc* basis (dealing problems as they happen) until it was replaced by a watershed-based approach by the involvement of the World Food Program and others since the early 1980s, the later was implemented by providing food-for-work incentives for conservation activities (Haregeweyn et al., 2015).

Over the years, the watershed-based approach has promoted various SWC measures such as the creation of soil or stone bunds, *fanya juu* or bench terraces, cut-off drains, drainage canals, check dams, and grass strips (Tefera and Sterk, 2010). Soil erosion, however, continues to be a problem, and SWC efforts targeting wider geographic regions began with the implementation of the Sustainable Land Management (SLM) Project in 2008: A two phase project initiated to address two of Ethiopia's most important developmental and environmental problems (severe land degradation and decline in agricultural productivity). This project was funded by the International Development Association (IDA), the Global Environmental Facility (GEF), the Least Developed Countries Fund **(**LDCF**)**, and Multi donor Trust Fund (MTDF) of the World Bank group, and others (SLMP, 2013; Yemane, 2019). By this program, various SWC practices and technologies were adopted and screened based on land use and agro-ecological conditions

(Table 1.1) with a detailed guideline and training of developmental agents (Hurni et al; 2016). Since then, these practices have been implemented in seven regions and 187 watersheds to prevent or control land degradation by pursuing integrated and cross-sectoral approaches. Results of the regional-scale assessment of land management by Hurni et al. (2015) showed that 1% to 75% of the rainfed agricultural areas of the highlands were covered by structural SLM measures (Figure 1.7).

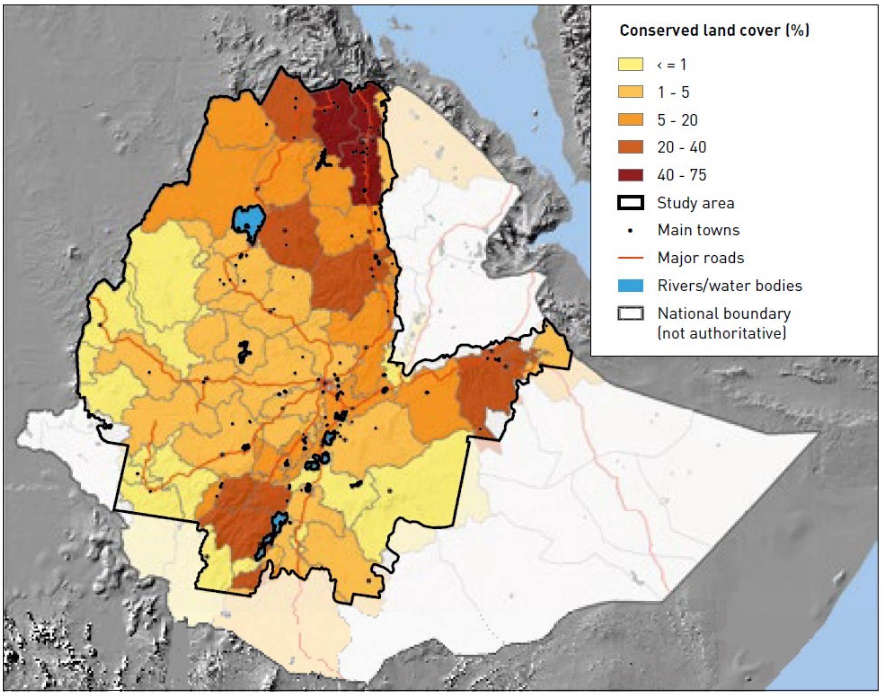

**Figure 1.7** The share of the existing conservation structures by land cover classes in Ethiopian highlands**.** For most of the zones, the structures only occur on croplands, in central Tigray, Eastern Tigray, South Tigray, North Wello and South Wello, however, structures exist on cropland, bushland, grassland, and degraded hills (Source: Hurni et al., 2015).

In addition to the creation of cross-slope barriers (structures) mentioned above, it is now being increasingly recognized by the government of Ethiopia that the use minimum tillage, reduction of household livestock numbers, a ban on free grazing, planting of different shrub and tree species, and the establishment of area exclosures should be done to effectively control soil erosion by running water and improve the physico-chemical and hydro-biological properties of soils, and to maintain sustainable functions and services of both terrestrial and aquatic ecosystems.

**Table 1.1** List of different types of SLM (SWC) practices for different land use and local situations in Ethiopia (Sources: Hurni et al., 2016).

| Land use types | SLM (SWC) practices | Type | Suitable agro-ecology (local situation) | | |
|---|---|---|---|---|---|
| | | | Elevation[a] (m a.s.l) | Annual rainfall[b] (mm) | Slop range (%) |
| Croplands | Broadbed and furrow | Agronomic | 1, 2, 3, 4, & 5 | 2 & 3 | Gentle |
| | Conservation tillage | Agronomic | 1, 2, 3, 4, & 5 | 1, 2, & 3 | All |
| | Mulch | Agronomic | 1, 2, 3, & 4 | 1, 2, & 3 | All |
| | Trash line | Agronomic | 1, 2, 3, & 4 | 1, 2, & 3 | Gentle |
| | Grass strip | Vegetative | 1, 2, 3, 4, & 5 | 2 & 3 | Gentle |
| | Vetiver | Vegetative | 1, 2, 3, & 4 | 2 & 3 | All |
| | Alley cropping | Vegetative | 1, 2, 3, & 4 | 2 & 3 | 0–50 |
| | Bench terrace | Structural | 1, 2, 3, 4, & 5 | 1, 2, & 3 | <50 |
| | Graded bund | Structural | 1, 2, 3, 4, & 5 | 2 & 3 | 3–50 |
| | Graded fanya juu | Structural | 1, 2, 3, 4, & 5 | 2 & 3 | 3–50 |
| | Level bund | Structural | 1, 2, 3, 4, & 5 | 1 & 2 | 3–50 |
| | Level fanya juu | Structural | 1, 2, 3, 4, & 5 | 1 & 2 | 3–50 |
| Grass land | Cut and carry | Vegetative | 1, 2, 3, 4, & 5 | 1, 2, & 3 | All |
| | Controlled grazing | Overall | 1, 2, 3, 4, & 5 | 1, 2, & 3 | Gentle |
| | Grass land improvement | Overall | 2, 3, & 4 | 2 & 3 | All |
| Forest | Tree planting | Vegetative | 1, 2, 3, 4 & 5 | 1, 2, & 3 | All |
| | Hillside terrace | Structural | 2, 3, 4 & 5 | 1 & 2 | 50–100 |
| | Microbasin | Structural | 2, 3, 4 & 5 | 1 & 2 | All |
| | Trench | Structural | 2, 3, & 4 | 1 & 2 | All |
| All land uses | Checkdam | Structural | 1, 2, 3, 4 & 5 | 1, 2, & 3 | All |
| | Water harvesting | Structural | 1, 2, 3, 4 & 5 | 1 & 2 | All |
| | Cutoff drain | Structural | 1, 2, 3, 4 & 5 | 1, 2, & 3 | 3–50 |
| | Waterway | Structural | 1, 2, 3, 4 & 5 | 2 & 3 | 3–50 |
| | Gully rehabilitation | Overall | 1, 2, 3, 4 & 5 | 1, 2, & 3 | 0–30 |
| | Re-vegetation | Overall | 1, 2, 3, 4 & 5 | 1, 2, & 3 | All |
| | Area closure | Overall | 1, 2, 3, 4 & 5 | 1, 2, & 3 | All |

[a] numbers indicate different elevation zones, 1: below 500; 2: 500–500; 3: 1500–2300; 4: 2300–3200; 5: 3200–3700

[b] numbers indicate different rainfall zones, 1: below 900; 2: 900–1400; 3: > 1400

## 1.2 Problem statement

While the substantial investment of financial and labor resources for the planning and implementation sustainable land management in many regions of Ethiopia, relevant studies on the impacts of management interventions have been concentrated in the dryer areas of the northern highlands. Such relevant studies are particularly limited for the central and western highlands of the country such as the Upper Blue Nile basin where soil erosion by water is a major threat to sustainable ecosystem functions (Figure 1.6). In this region, promising SLM practices (exclosure, reduced tillage, combined structural and vegetative practices) have been given less policy and research attention, and very little is known about the changes in soil quality properties following the implementation of such and other SLM practices.

Moreover, some of the previous studies in Ethiopia made the use of plot scale results for spatial analysis of soil erosion and its consequences i.e., plot scale results have often been extrapolated to watershed scales which could produce misleading results especially in areas where biophysical factors are highly variable over space and time. Also, large scale implementation of SLM practices have mostly been done without a preliminary assessment of the potential and susceptibility to soil erosion, i.e., not based on the framework of land degradation neutrality response hierarchy—the approach that would help appropriate identification of intervention areas where avoidance of land degradation is achievable, followed by areas where mitigation through adoption of SLM practices is suited, and lastly areas suitable for restoration or rehabilitation (Cowie et al., 2018). This is due partly to insufficient policy attention and difficulties inherent in collecting sufficient and reliable runoff, soil, and sediment data at wider spatial and temporal scales.

## 1.3 Objectives of the study

This study was, therefore, aimed to improve our current understanding of the impact of land use and management practices on runoff and soil loss rates in the Upper Blue Nile basin, at different spatial and temporal scales, and to identify SLM practices that can reduce soil erosion and thereby enhance the in situ soil quality properties. The three main objectives were to (1) analyze the variability of watershed scale soil loss (sediment yield) using a paired watershed approach; (2) quantify the effects of land use and selected SLM practices on runoff and soil loss in different agro-ecologies; and (3) evaluate the variation in key soil properties as influenced land use and management practices.

The results of these objectives provide useful information for policymakers and land managers involved in the promotion of large-scale implementation of suitable land use and management practices in the Upper Blue Nile basin as well as in other regions with similar climatic and topographic settings. This study, based on the key findings, further offers appropriate recommendations to be taken in to consideration by future land management, research, and related works.

## 1.4 Description of the study area

### 1.4.1 Location and climate

This study was carried out at three sites (Dibatie, Aba Gerima, and Guder) in the Upper Blue Nile basin of Ethiopia (Figure 1.8 and Table 1.2). These sites are representative of the different agro-ecologies of the basin [lowland (Dibatie), midland (Aba Gerima), and highland (Guder)], and located within the tropical to humid tropical climatic zones, with elevation ranging from 1487 to 2882 m above sea level (a.s.l.). All the three sites are characterized by two distinctive seasons: a dry season that extends from November to April and a wet season from May to October. Based on the 18 years (1999–2016) of rainfall records obtained from the nearby meteorological stations for the respective sites, the mean annual rainfall is 1022 mm, 1343 mm, and 2454 mm at Dibatie, Aba Gerima, and Guder, respectively (Table 1.2). At all three sites, about 85% the annual rain falls during the four wettest months (June to September, Figure 1.9). Different from the rainfall pattern, minimum, average, and maximum temperatures decreases as elevation increases across the sites (Table 1.2 and Figure 1.9).

According to the local climate zone classification, based on elevation and mean annual precipitation (Hurni et al., 2016), the Dibatie, Aba Gerima, and Guder sites, respectively, are belong to Moist Kolla (500–1500 m a.s.l., mean annual precipitation of 900–1400 mm), Moist Weyna Dega (1500–2300 m a.s.l., mean annual precipitation of 900–1400 mm), and Wet Dega (2300–3200 m a.s.l., mean annual precipitation of ≥1400 mm) agro-ecological zones (Table 1.1).

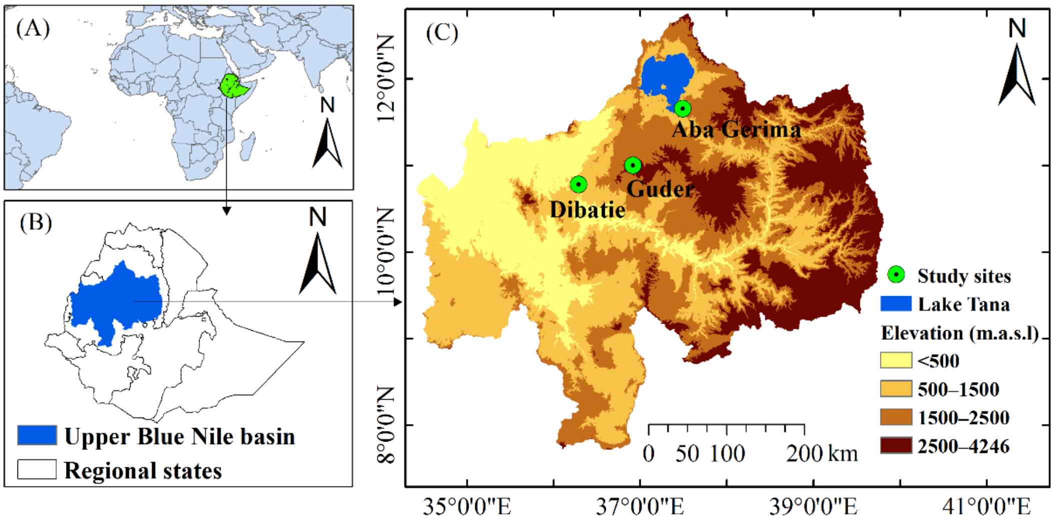

**Figure 1.8** Location maps of the study area: (A) Ethiopia in Africa; (B) the Upper Blue Nile basin in Ethiopia; (C) the study sites in the Upper Blue Nile basin.

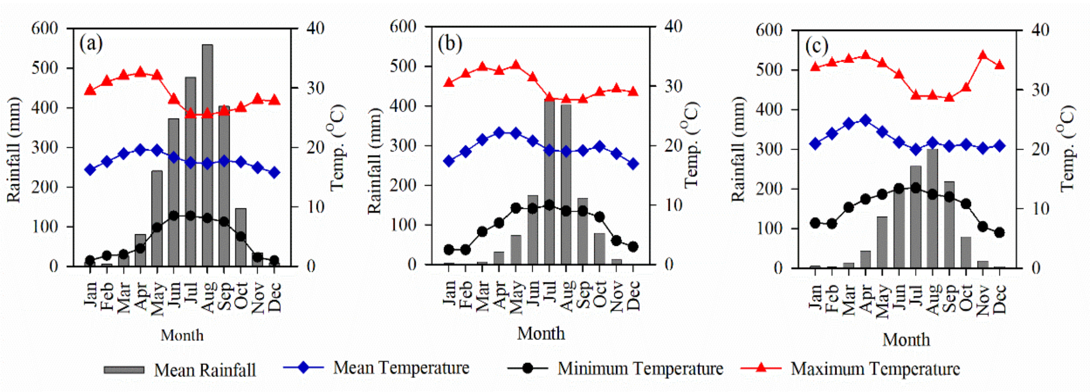

**Figure 1.9** Monthly average rainfall and temperature, and monthly minimum and maximum temperatures at Guder (a), Aba Gerima (b), and Dibatie (c) sites during 1999–2016.

**Table 1.2** Characteristics of the three sites in the Upper Blue Nile basin of Ethiopia.

| Feature | Dibatie | Aba Gerima | Guder |
|---|---|---|---|
| Location | 10°45′38″N–10°46′59″N<br>36°16′34″E–36°17′46″E | 11°38′51″N–11°40′34″N<br>37°29′35″E–37°30′52″E | 10°59′34″N–11°01′01″N<br>36°54′09″E–36°55′55″E |
| Elevation (m a.s.l) | 1487–1718 | 1912–2126 | 2489–2882 |
| Mean annual rainfall (mm) | 1022 | 1343 | 2495 |
| Mean daily temperature (°C) | 24.0 | 23.5 | 19.5 |
| Climatic zone | Humid tropical | Humid subtropical | Moist subtropical |
| Agro-ecological zone[a] | Moist Kolla | Moist Weyna Dega | Wet Dega |
| Major soils | Vertisols, Luvisols | Luvisols, Leptosols | Acrisols, Luvisols |
| Major land use types | Cropland, grazing land, degraded bushland | Cropland, grazing land, degraded bushland | Cropland, grazing land, degraded bushland |
| Farming system | Mixed crop–livestock | Mixed crop–livestock | Mixed crop–livestock |
| Major crops | Finger millet, teff, maize, groundnut, and chili pepper | Finger millet, tef, maize, and khat | Tef, barley, wheat, and potato |
| Major livestock types | Cattle, sheep, goats, donkeys | Cattle, sheep, goat, donkeys | Cattle, sheep, horses |

[a] Local agro-ecological zones, Source: Hurni et al. (2016).

### 1.4.2 Major soil types

The major soil types (FAO classification system) differ across the study sites (Mekonnen, 2016), (Table 1.2). At Guder, Acrisols (equivalent to Ultisols in the USDA soil taxonomy), characterized by the accumulation of low-activity (i.e., highly weathered) clay in the subsoil, low cation exchange capacity, and low base saturation, are dominant, followed by Luvisols (i.e., Alfisols), which are very deep, well-drained soils with clay accumulation in the subsoil. At Aba Gerima, Luvisols are dominant, followed by Leptosols (i.e., Entisols), very shallow soils formed over hard rock that are particularly susceptible to erosion. At Dibatie, Vertisols, which are characterized by a high content of clay minerals that shrink and swell during dry and wet seasons, respectively, are dominant, followed by Luvisols.

### 1.4.3 Land use and farming systems

The landscape at the three sites is fragmented as a result of different traditional land use practices over many decades. The major land use types are cultivated lands, grazing lands, and degraded bushlands (Sultan et al., 2018). At all sites, there is a larger proportion of cultivated lands than non-cultivated ones (grazing lands and degraded bushlands). Based on observations during filed works, grazing lands at the Aba Gerima site are frequently and heavily grazed, and are, thus, more susceptible to soil erosion when intense rain events occur.

In all sites, the farming system is mixed crop–livestock, characterized by small scale, rainfed and continuous cropping practices. Major crops include tef (*Eragrostis tef*), barley (*Hordeum vulgare*), wheat (*Triticum aestivum*), and potato (*Solanum tuberosum*) at the Guder site, whereas finger millet (*Eleusine coracana*), maize (*Zea mays*), and tef are the major crops at Aba Gerima and Dibatie sites. In addition to these staple crops, khat (*Catha edulis*) in Aba Gerima, and groundnut (*Arachis hypogaea L.*) and chili pepper (*Capsicum annuum*) in Dibatie are also cultivated as cash crops. Livestock types are more or less similar at the three sites: cattle (*Bos primigenius*) and sheep (*Ovis aries*) are dominant at all three sites, followed by horse (*Equus caballus*) at Guder, and goat (*Capra hircus*) and donkey (*Equus africanus*) at the Aba Gerima and Dibatie sites (Table 1.2).

### 1.4.4 Land management practices

Various SLM or SWC practices (Table 1.1) have been implemented by governmental and non-governmental organizations for the last few decades to reduce the on-site and off-site effects of runoff and soil erosion in the Upper Blue Nile basin. The most widely applied measures in the study sites, i.e., those examined by this study, are the construction of soil bund (an embankment of soil accompanied by a ditch on the uphill side) and *Fanya Juu* (an embankment of soil accompanied by a ditch on the downhill side) for cultivated lands, and trenches (rectangular pits arranged in staggered manner along the contour with the embankment on the downhill side) for non-cultivated lands (Figure 1.10).

In addition to construction of the physical barriers, some cheap and promising practices are now being recognized to effectively control soil erosion, and improve in-situ soil quality properties. These includes strengthening of soil bunds with grasses to reduce soil loss and made the land occupied by the barrier productive (Amare et al., 2014), conservation tillage to reduce soil compaction and improve soil structure (Temesgen et al., 2012), and exclosure for restoration of soils in degraded communal lands (Mekuria et al., 2007).

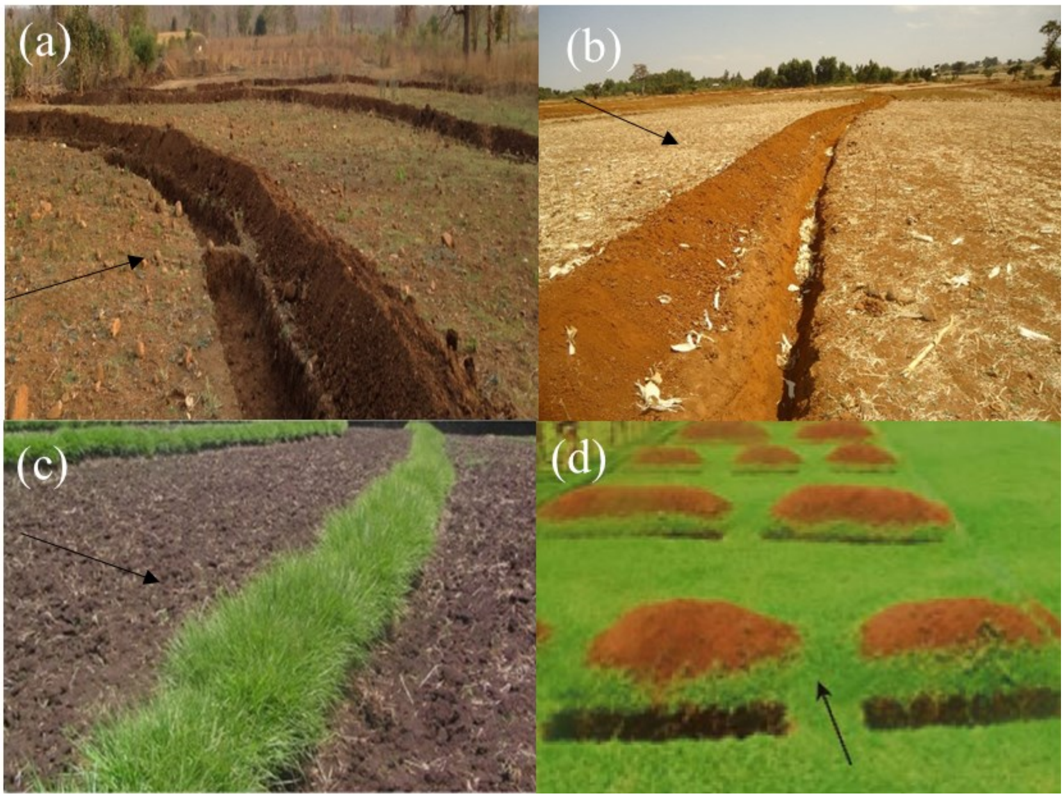

**Figure 1.10** Cross slope soil and water conservation measures adopted and implemented in the highlands of Ethiopia: Soil bund (a), *Fanya juu* (b), and soil bund combined with grass (c) in cultivated lands; and trenches (d) in grass land. The arrows indicate the slope direction.

At the Guder site, small-scale farmers have recently adopted a *taungya* system using wattle trees (*Acacia decurrens*) that stabilize the soil during and after the growing season (Figure 1.11). Plantation of this tree is getting expanded in to other areas at the cost of cultivated lands mainly because of its economic benefits: provides additional income for farmers and others involved at different activities from seedling preparation to charcoal production (Achamyeleh, 2015; Nigussie et al., 2017). The change from cultivated land to this plantation, however, has some trade-offs concerning hydrologic processes and soil erosion: high runoff and low soil loss paradox both at plot and watershed scales (Kindiye, 2016; Sultan et al., 2017) due to bare and sealed ground surface created at later stages (Figure 1.11b). Because larger areas under such plantations could have significant impact on physico-chemical and hydro-biological properties of soils, reliable and sufficient information is required to carefully plan and design appropriate management options, part of this thesis provided a suitable clue in this regard.

**Figure 1.11** Acacia decurrens plantation at Guder site: (a) dense canopy cover at its early stages versus (b) bare and sealed ground surface created at its later stages.

## 1.5 Organization of the thesis

This thesis is comprised of five chapters (Figure 1.12). The first chapter (Chapter 1) presents the introductory sections (background, problem statement, objectives, and the study area). It explains the pressing problems related to soil erosion based on the existing literatures, site observations, and proven facts, and indicates the rationale of this study. Chapter 2 examines the variation in sediment yield (watershed scale soils loss) within and between two adjacent watersheds and two consecutive years in the tropical humid highland of the Upper Blue Nile basin, Ethiopia. Chapter 3 examines the effects of the land use and management practices on runoff and soil loss in three different agro-ecologies (lowland, midland, and highland) that are typical representative of the different biophysical and socioeconomic conditions of the basin. Chapter 4 investigates the variation of soil properties as influenced by land use and management practices within and across the three agro-ecologies. The last chapter (Chapter 5) presents the general conclusions and recommendations based on the key findings from the three main chapters (chapters 2, 3, and 4).

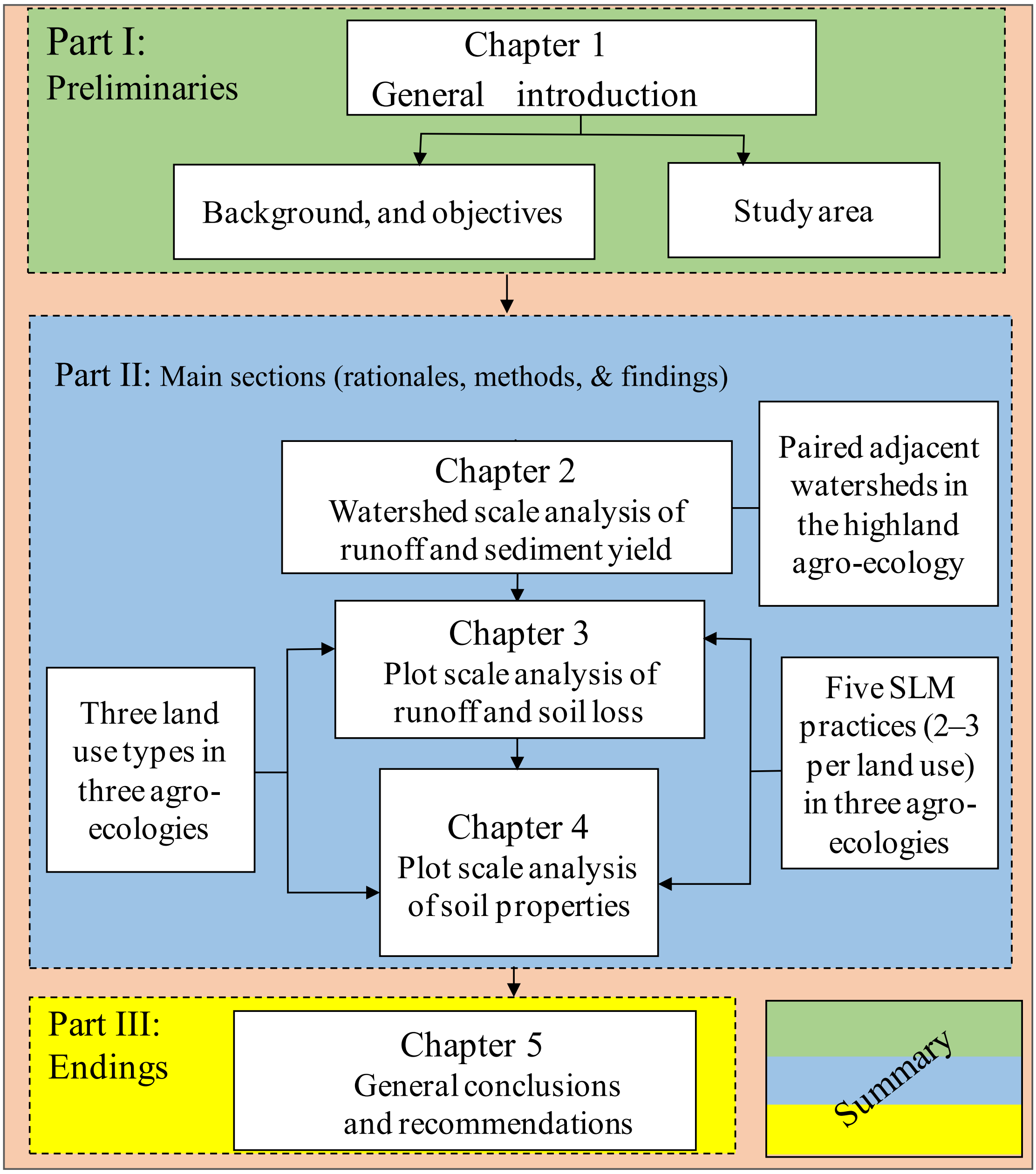

**Figure 1.12** Structure of the thesis.

# Chapter 2

## Analyzing the variability of sediment yield: a case study from paired watersheds in the Upper Blue Nile basin, Ethiopia

This chapter is published as:

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## 2.1 Introduction

Several plot scale studies have been conducted to evaluate soil erosion rates and the performance of some selected SWC measures on slopes in different parts of the Ethiopian highlands (Herweg and Ludi, 1999; Temesgen et al., 2012; Taye et al., 2013; Adimassu et al., 2014; Amare et al., 2014). These studies have monitored runoff and the sediment yield (*SY*) caused by sheet and rill erosion in small bounded runoff plots, mainly in croplands. Results from these studies have often been implicitly or explicitly extrapolated to watershed scales, which has been shown to produce misleading results (de Vente and Poesen, 2005) because processes not captured by plot-scale measurements (e.g., gully erosion, bank erosion, mass wasting) are dominant contributors of soil loss at watershed scales (Rijsdijk, 2005). Furthermore, the sediment supply in watersheds is heterogeneous in both time and space because it depends on the climate, land use, and landscape characteristics such as slope, topography, soil type, vegetation, and drainage conditions (Marttila and Kløve, 2010; Verbist et al., 2010). Therefore, watershed-scale estimates of *SY* and its spatial and temporal variation are needed for a variety of purposes, including the design of erosion-control structures (Russell et al., 2001) and evaluation of the effects of various land use and management practices (Gao et al., 2007; Sadeghi et al., 2008).

Improved site-specific knowledge of the variability of watershed-scale *SYs* are needed to design more effective erosion control strategies in Ethiopia's severely eroded areas, particularly in the humid tropical highlands of the Upper Blue Nile basin where high erosion rates exist owing to erosive rainfall, steep and undulating topography, and agricultural practices that reduce protective soil cover (Hurni et al., 2005). About 39% of the basin experiences severe or very severe erosion (Haregeweyn et al., 2017) that causes excessive sedimentation and threatens the sustainability of downstream reservoirs, including the Grand Ethiopian Renaissance Dam.

Despite the magnitude of the problem, few assessments of watershed-scale spatial and temporal variability of *SY* exist in this basin, probably because of technical difficulties inherent in measuring the suspended sediment concentration (*SSC*) in discharge at sufficiently high temporal and spatial resolution (Verbist et al., 2010). Therefore, in the present study we monitored discharge and *SSCs* during two consecutive rainy seasons in paired watersheds located in the Upper Blue Nile basin. The main objective was to examine controls on spatial and temporal variations of discharge and *SY* in these two comparably-sized watersheds.

## 2.2 Materials and methods

### 2.2.1 Site characteristics and experimental setup

For this study, adjacent paired watersheds (Akusity and Kasiry) were selected within the Guder area of the Upper Blue Nile basin (Figure 2.1, and Table 2.1). These studied watersheds are located between 10° 57′ 23″N and 11° 11′ 21″ N and between 36° 40′ 01″E and 37° 05′ 21″ E, and are a typical representative of the biophysical conditions (i.e., vegetation cover, rainfall pattern, land use, and management practices) in the northwestern Ethiopian highlands. The elevation in the Guder area ranges from 2400 to > 3000 m a.s.l., but the elevation for the particular study site is ranging between 2492 m a.s.l. at the outlet of the Kasiry watershed, and 2882 m a.s.l. at the highest point on the divide between the two watersheds.

The study site falls within the humid tropical climatic zone (Sultan et al., 2017), and corresponds to the *Dega* zone (i.e., cool, greater than 2400 m above sea level) in the local climate classification system, characterized by a dry season that extends from November to April, and a wet season from May to October. Based on the 17 yr record (1999-2015) at the Injibara station (located about 5 km from the study area), the mean annual rainfall is 2454 mm (about 85% during the wet season), and the mean daily temperature ranges from

9.4-25°C. Annual rainfall in 2014 (2635 mm) was above average and in 2015 (2239 mm) it was below average. Note that the higher annual rainfall in 2014 was caused by large rainfall amounts in February, March, and April (out of the sediment monitoring period of this study), whereas the contribution during these months was much smaller in 2015.

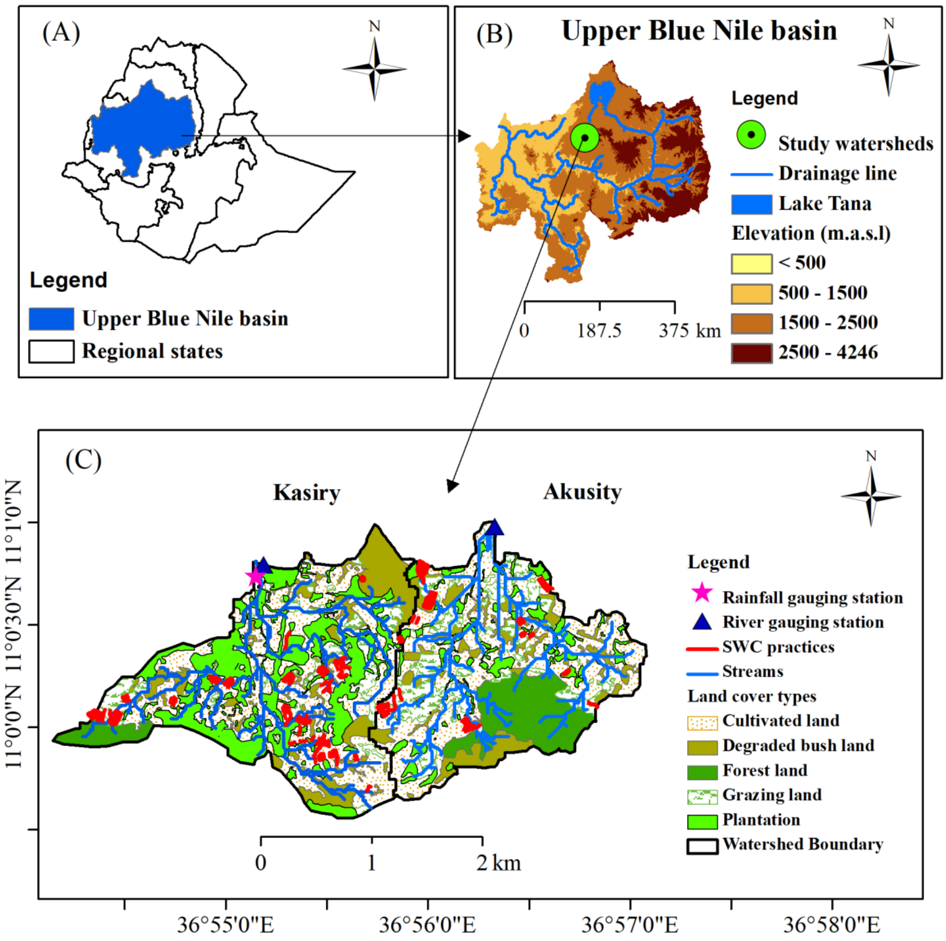

**Figure 2.1** Map of the study area: (A) Location of the Upper Blue Nile basin within Ethiopia. (B) Topography and locations of the Akusity and Kasiry watersheds within the Upper Blue Nile basin. (C) Land cover types.

**Table 2. 1** Characteristics of the paired watersheds within the Guder watershed.

| Feature (units) | Akusity | Kasiry |
|---|---|---|
| Sampling years | 2014 and 2015 | 2014 and 2015 |
| Location of sampling stations | 11°01′00″ N, 36°56′16″E | 11°00′44″ N, 36°55′11″E |
| Elevation (m a.s.l.) | 2554–2882 | 2492–2880 |
| Mean daily temperature (°C) | 9.4–25.0 | 9.4–25.0 |
| Mean annual rainfall (mm) | 2454 | 2454 |
| Agro-ecological zone | Humid tropical | Humid tropical |
| Total area (ha) | 343 | 399 |
| Area with slope >30% (% of total) | 36 | 31 |
| Total number of households | 56 | 105 |
| Drainage density (km/km$^2$) | 9.1 | 14.3 |
| Major soil types | Luvisol and Leptosol | Acrisol and Vertisol |
| Major crops | Barley, tef, wheat, and potato | Barley, tef, wheat, and potato |
| Proportion of land use types (% of total area): | | |
| Cultivated land | 41 (141 ha) | 39 (156 ha) |
| Grazing land | 18 (61 ha) | 10 (38 ha) |
| Degraded bushland | 14 (49 ha) | 17 (70 ha) |
| Tree plantation[a] | 10 (35 ha) | 30 (120 ha) |
| Forest | 17 (57 ha) | 4 (15 ha) |
| SWC coverage[b] (%) | 4 | 8 |

[a] Planted tree species are Acacia decurrens and eucalyptus.

[b] The proportion of the watersheds treated with different soil and water conservation (SWC) measures, excluding plantations.

Gauging stations were installed at the outlets of the Akusity and Kasiry watersheds to monitor discharge and the *SY*. These stations were located in relatively stable and straight cross sections of the rivers to minimize sediment deposition in the channel (Yeshaneh et al., 2014). Each monitoring station was equipped with an automatic pressure transducer

(TD-Diver; van Essen Instruments, Delft, the Netherlands), a staff gauge mounted at the side of the stream bed and strongly fixed in place with a concrete base, and a depth-integrated sediment sampler (Figure 2.2). Flow stage, flow velocity, discharge, and the *SSC* were measured for 117 days during the wettest months (from 1 July to 25 October) in 2014 and 2015.

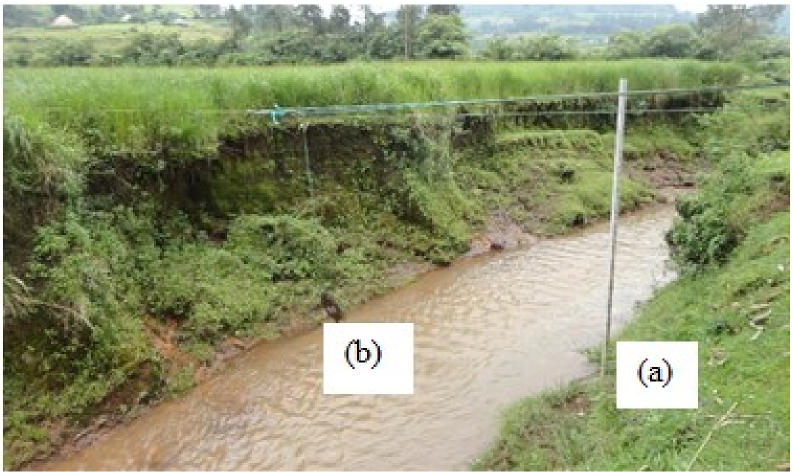

**Figure 2.2** A river gauge station at the outlet of the Akusity watershed equipped with different measuring materials: (a) a staff gauge with a TD-Diver pressure transducer at the bottom, and (b) a depth-integrated suspended sediment sampler suspended from a cable stretched across the stream.

### 2.2.2 Streamflow and suspended sediment measurements

We measured discharge by monitoring stages automatically (10-min intervals) using the TD-Diver water level sensor, and manually three times per day (at 07:00, 13:00, and 18:00) using the graduated staff gauge (Figure 2.2). The manual staff gauge was also monitored when peak flows or large changes in streamflow were observed. The relationship between the corresponding manual and automatic flow depth records was strong and significant ($R^2 = 0.87$ and $P < 0.001$ for Akusity; $R^2 = 0.81$ and $P < 0.001$ for Kasiry). We subsequently corrected the continuous automated flow readings using regression equations developed from linear relationships between manual and automatic flow depths for the two watersheds.

Surface streamflow velocities were measured using the manual (float) method (Zenebe et al., 2013) at various flow stages, including peak flows as special incidents. These surface velocity measurements were then converted to the mean stream velocity using an adjustment coefficient (0.88) suggested for smooth streambeds (Turnipseed and Sauer, 2010). The corresponding discharge, for each float velocity measurement, was determined by the velocity–area method. The corrected continuous automated flow depth (stage) data was then transformed into a discharge based on standard stage-discharge rating curves for each watershed.

Samples of suspended sediment (about 1 L) were collected for each of the 117 days of each sampling year. All samples were collected at the center of the stream at the same time as the manual flow depth records (07:00, 13:00, and 18:00 each day and when peak flows or larger changes in streamflow were observed) using a depth-integrated sampler and plastic bottles (Bouchez et al., 2011). We collected a total of 1602 samples during the sampling period, but only 1263 of the samples (609 for Akusity and 654 for Kasiry) were analyzed for *SSC*. The remaining 339 samples (21% of the total) were discarded for the following reasons: (1) some of the repeated samples taken during the end of the rainy season were not analyzed because they clearly had extremely low sediment concentration values (7%); (2) some of the bottles were damaged during transport to the laboratory and the water sample leaked (8%); and (3) labels on bottles were lost or too faded to identify (6%). Of these discarded samples, 9% were from the early part of the rainy season and 12% were from the late part of the season. Nevertheless, we believe that the 1263 samples were sufficient to analyze the variability of *SSCs* over the rainy season. These samples were filtered using grade 42 Whatman filter paper and the collected sediments were then oven-dried at 105°C for 24 h and weighed on a digital balance with a precision of 0.001 g. The *SSC* for each sample was then determined by dividing the mass of the suspended sediment by the sample volume.

### 2.2.3 Discharge and sediment rating curves

The samples we obtained generally covered only a limited number of events during each sampling season. Thus, we used the measured values for these samples to establish *Q–SSC* rating curves fit with power functions. We then used the power functions to estimate *SSCs* for the continuous discharge series calculated from the TD-Diver readings (Asselman, 2000; Vanmaercke et al., 2010; Guzman et al., 2013).

We hypothesized that the sediment supply in the watersheds would be highly variable during different parts of the rainy season. Thus, we assumed that a single rating curve developed by plotting all *Q* and *SSC* observations in a single graph would be inappropriate for prediction and might even fail to explain the spatial and temporal variations in the sediment supply. We therefore grouped the data into different periods (P1, P2, and P3; Table 2.2) based on differences in the runoff and sediment supply patterns observed in previous plot-based experiments in the Kasiry watershed (Kindye, 2016; Sultan et al., 2017). This grouping was done to create more reasonable *Q–SSC* rating curves (Table 2.3) that could subsequently be used to calculate the *SY* by accounting for the spatial and temporal variation of the sediment supply and transport in the watersheds. Previous studies also showed that such a classification of the sampling period is the best strategy to provide a better fit to the data and better represent the various flows through the watershed during the rainy phases in monsoonal basins (Liu et al., 2008; Vanmaercke et al., 2010; Guzman et al., 2013).

**Table 2.2** Groups of sampling dates used to create multiple discharge and sediment rating curves.

| Period | Length of period | No. of days | Description |
|---|---|---|---|
| All | 1 July to 25 Oct. | 117 | Entire sampling period |
| P1 | 1 July to 10 Aug. | 41 | Low runoff, but high sediment supply |
| P2 | 11 Aug. to 20 Sept. | 41 | High runoff, but low sediment supply |
| P3 | 21 Sept. to 25 Oct. | 35 | Low runoff and low sediment supply |

### 2.2.4 Calculating sediment yield and the role of peak flows

We calculated *SYs* for the continuous discharge series using the *Q–SSC* rating curves (Table 2.3). We then calculated the daily *SY* according to the method of Vanmaercke et al. (2010) as follows:

$$SY = \sum_{n=i}^{n} (Q_i \times SSC_i \times 600) \qquad (2.1)$$

where *SY* is the daily sediment yield (t day$^{-1}$); *n* is the number of observations per day at 10-min intervals (we assumed a constant discharge during each interval); $Q_i$ is the equivalent volume (L s$^{-1}$) of runoff discharge (m$^3$ s$^{-1}$) for observation *i*; and $SSC_i$ is the suspended sediment concentration (g L$^{-1}$) for observation *i*. We calculated the total *SY* for a rainy season by summing the daily values, and calculated the area-specific *SY* (t $ha^{-1}$) by dividing the total *SY* by the area of the corresponding watershed.

**Table 2.3** Parameters of the discharge–sediment rating curves.

| Station | Season | Date group | n | a | b | R2 |
|---|---|---|---|---|---|---|
| Akusity | 2014 | All samples | 287 | 1.74 | 0.59 | $0.33^{*}$ |
| | | P1 | 75 | 5.69 | 0.95 | $0.65^{**}$ |
| | | P2 | 128 | 2.56 | 0.85 | $0.57^{*}$ |
| | | P3 | 84 | 0.47 | 0.28 | 0.23 |
| | 2015 | All Samples | 322 | 2.68 | 0.93 | 0.25 |
| | | P1 | 108 | 6.84 | 1.12 | $0.56^{**}$ |
| | | P2 | 85 | 4.85 | 0.65 | $0.43^{*}$ |
| | | P3 | 129 | 0.21 | 0.23 | 0.22 |
| Kasiry | 2014 | All Samples | 276 | 1.25 | 0.59 | $0.40^{*}$ |
| | | P1 | 49 | 2.49 | 0.81 | $0.58^{**}$ |
| | | P2 | 103 | 1.31 | 0.58 | $0.40^{*}$ |
| | | P3 | 124 | 0.64 | 0.37 | 0.24 |
| | 2015 | All samples | 378 | 0.68 | 0.71 | 0.16 |
| | | P1 | 119 | 2.84 | 0.97 | $0.73^{**}$ |
| | | P2 | 134 | 1.41 | 0.58 | $0.50^{*}$ |
| | | P3 | 125 | 0.18 | 0.21 | $0.32^{*}$ |

Table 2.2 defines the date groups used in this analysis.
*n* is the number of samples in each sampling period and *a* and *b* are regression coefficients for the power function $SSC = aQ^b$.
** = significance level of $P < 0.01$.
* = significance level of $P < 0.05$.

We evaluated the role of peak flow events for sediment export by calculating the proportion of the seasonal *SY* contributed by the most important peak flow events observed during the two rainy seasons. In doing so, we considered three events with the highest rainfall and discharge in each sampling season, and calculated the *SY* contributed over a certain duration (from the start of the rising curve to the end of the falling curve). We then divided this amount by the seasonal *SY* to express the proportion of that total (as a percentage) contributed by each event.

### 2.2.5 Data analysis

To evaluate the variability in sediment supply and *SY* from the two paired watersheds, we considered *Q* and *SSC* data measured at the same time in the two watersheds. All the *Q*–*SSC* rating curves were calculated as power functions using regression to quantify the strength of the relationship. We used a double mass-curve to clarify the relationship between the cumulative *SY* and runoff yield as a function of time during the two sampling years. As the data was not normally distributed, we used a non-parametric test (Mann-Whitney U test) in SPSS statistics (version 23) to evaluate the significance of spatial variation (between watersheds) in runoff and *SY* rates in the two sampling years.

## 2.3 Results and discussion

### 2.3.1 Spatial variability of SSC

The observed mean *SSC* values for both watersheds in the this study (Table 2.4) are within the range of values (0.11–8.7 g $L^{-1}$) reported by other studies in the Upper Blue Nile basin (Guzman et al., 2013; Yeshaneh et al., 2014; Moges et al., 2016), but are generally smaller than those (10–100 g $L^{-1}$) reported for peak flow events for semi-arid tropical highlands of Northern Ethiopia (Vanmaercke et al., 2010). It should be noted that *SSC* was not measured for some important peak flow events by this study, as they occurred during the night or at other times when we were not available to obtain samples. It is a common phenomenon in the Ethiopian highlands that some peak flow events that can transport higher masses of sediments often occur at night and are difficult to measure (Vanmaercke et al., 2010). This suggests that appropriate methods of nighttime sampling would be crucial to more accurately understand the *SSC* variance for streamflow events in different watersheds.

As expected, a Mann-Whitney U test (Table 2.4, by comparing the mean ranks of the data) indicated that the *SSC* differed greatly between the paired watersheds. In both years, *SSC* was significantly (Z < -1.96 and *P* < 0.05) higher for Akusity, though the corresponding discharge was higher for Kasiry. This can be attributed to differences in main characteristics between the two watersheds (Table 2.1), which directly or indirectly affect the runoff response and sediment transport. For instance, the coverage of *Eucaltptus* and *Acacia decurrens* tree plantations differed greatly between the two watersheds (30% in Kasiry, but only 10% in Akusity). A plot scale study by Sultan et al. (2017) reported higher runoff coefficients in these plantations (18% of the received rainfall for *Eucalyptus* and 32% for *Acacia decurrens*), whereas the respective *SSC* values (1.21 g $L^{-1}$ for *Eucalyptus* and 0.44 g $L^{-1}$ for *Acacia decurrens*) reported by Kindye (2016) were much lower than those for croplands (5.5–11.7 g $L^{-1}$). Hence, the higher *SSC* values in Akusity can be linked to the dominancy of cultivated land connected to streams (Figure 2.1) and less coverage by plantations that can exponentially decrease the intensity of splash erosion processes (Puigdefábregas, 2005) and concentrated flow erosion (Gyssels and Poesen, 2003).

**Table 2.4** The descriptive statistics and Mann-Whitney U test results of the measured discharge (*Q*) and the associated suspended sediment concentration (*SSC*) in the two watersheds (stations) and years.

| Season | Station | n | $Q$ (m$^3$ s$^{-1}$) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | SD | CV | Median | Mann-Whitney U test | | | |
| | | | | | | | Mr. | U | Z | P |
| 2014 | Akusity | 287 | 0.19 | 1.51 | 387 | 0.11 | 271 | 36556 | −1.511 | 0.131 |
| | Kasiry | 276 | 0.36 | 1.44 | 277 | 0.13 | 292 | | | |
| 2015 | Akusity | 322 | 0.31 | 2.09 | 674 | 0.04 | 205 | 13887 | −17.591 | 0.000 |
| | Kasiry | 378 | 0.52 | 2.48 | 302 | 0.44 | 474 | | | |
| | | | *SSC* (g L$^{-1}$) | | | | | | | |
| 2014 | Akusity | 287 | 1.04 | 3.49 | 306 | 0.10 | 293 | 35993 | −1.972 | 0.037 |
| | Kasiry | 276 | 0.51 | 2.38 | 415 | 0.09 | 268 | | | |
| 2015 | Akusity | 322 | 2.20 | 4.26 | 201 | 0.31 | 393 | 44257 | −6.178 | 0.000 |
| | Kasiry | 322 | 0.92 | 3.74 | 381 | 0.24 | 298 | | | |

*n*: number of observations in each season, SD: standard deviation, CV: coefficient of variation (%), Mr: mean rank. Letters (Z and P) are outputs of the Mann-Whitney U test indicating the significant difference (at $Z < -1.96$ and $P < 0.05$) in *Q* and *SSC* between the two watersheds in the two sampling seasons.

The *a* coefficients of the *Q*–*SSC* rating curves were clearly higher for Akusity than for Kasiry (Table 2.3 and Figure 2.4; except for period P3 in 2014), and this further indicates that sediment transport caused by flow events was higher in Akusity, probably owing to a higher proportion of cultivated lands and less coverage by plantations and areas where SWC measures have been implemented (Table 2.1). This finding had been reported by other researchers (Guzman et al., 2013) who studied *Q*–*SSC* relationships for small watersheds in the sub-humid Ethiopian highlands. As suggested by Asselman (2000), the values of the *a* and *b* coefficients for the *Q–SSC* rating curves are a measure of the sediment transport regime of river flows: steep rating curves (with high *a* and *b* coefficient values) are characteristic of river sections that drain intensively weathered or loose sedimentary materials, which can be transported even at relatively low discharge rates. In contrast, flat rating curves (with low *a* and *b* coefficient values) are characteristic of rivers with little sediment transport. In rivers with steep rating curves, an increase in discharge results in a large increase in *SSC*, indicating that the erosive ability of the water is high during periods with high discharge or that important sediment sources become available when the water level rises (Vanmaercke et al., 2010).

### 2.3.2 Temporal variability of SSC

The results also clearly demonstrated that the magnitudes of the measured *SSC* varied between years. The results of the descriptive statistics (Table 2.4) showed that the mean *SSC* values were clearly higher in 2015 than in 2014 for both watersheds, which can be attributed to differences in the corresponding *Q*, which was also clearly higher in 2015. In 2015, the *SSC* was 1.8 (Kasiry) and 2.1 (Akusity) times the values in 2014. This could be explained by large differences in the range of daily rainfall amounts (0.29–54.5 mm in 2014 versus 0.80–97.3 mm in 2015; Figure 2.3a), which would affect both the amount of runoff and the associated sediment transport capacity. Consequently, we see large variations in both magnitude and trends of *Q* and *SSC* within and between the rainy seasons (Figure 2.3).

Although *Q* showed contrasting trends in the two sampling seasons (i.e., *Q* was higher during the end of the rainy season near P3 in 2014, but was higher during the beginning near P1 in 2015; Figure 2.3b), the corresponding *SSC* showed similar trends during the two rainy seasons in both watersheds (i.e., higher at the beginning of the rainy season and lower towards the end; Figure 2.3c). This agrees with findings from the Indian monsoon area (Kale and Hire, 2004). The trend of decreasing *SSC* toward the end of the rainy season can be attributed to a limited sediment supply (because much of the easily erodible material would already have been exhausted earlier in the season) and decreased sediment transport capacity from lower Q owing to increased protection from the vegetation cover. Through the analysis of hysteresis loops, several studies have shown that *SSC* is dynamic during runoff events, which is linked to the supply and exhaustion of sediment from sources (Steegen et al., 2000; Moliere et al., 2004; Rovira and Batalla, 2006; Rodríguez-Blanco et al., 2010). Studies from the Upper Blue Nile basin (Zegeye et al., 2010; Yeshaneh et al., 2014) reported that the *SSC* during runoff events is higher in the beginning of the rainy season than towards the end, mainly owing to a greater contribution of bare and loose soil conditions in the upslope contributing areas that consist of primarily cultivated land. Thus, for a given *Q*, a range of *SSC* values can be obtained, depending on whether the event occurs at the beginning or the end of the rainy season. This implies that great care must be applied when studying the relationship between *Q* and *SSC* in watersheds where biological and physical factors are subjected to change during the rainy season. This finding further indicates that a single *Q*–*SSC* relationship for a season may be misleading in this geographic location because of vegetation changes that occur during a single season, and that single events can have disproportionate effects on the sediment yield during a season.

The temporal variability of *SSCs* in the two watersheds was further demonstrated by differences in the *Q*–*SSC* rating curves developed for different periods during the sampling seasons (Table 2.3 and Figure 2.4). The $R^2$ values for the regressions varied considerably, ranging from 0.22–0.65 in Akusity and from 0.16–0.73 at Kasiry (Table 2.3). These values help demonstrate a weak to strong association between discharge and *SSC* (Asselman, 2000; Vanmaercke et al., 2010; Guzman et al., 2013).

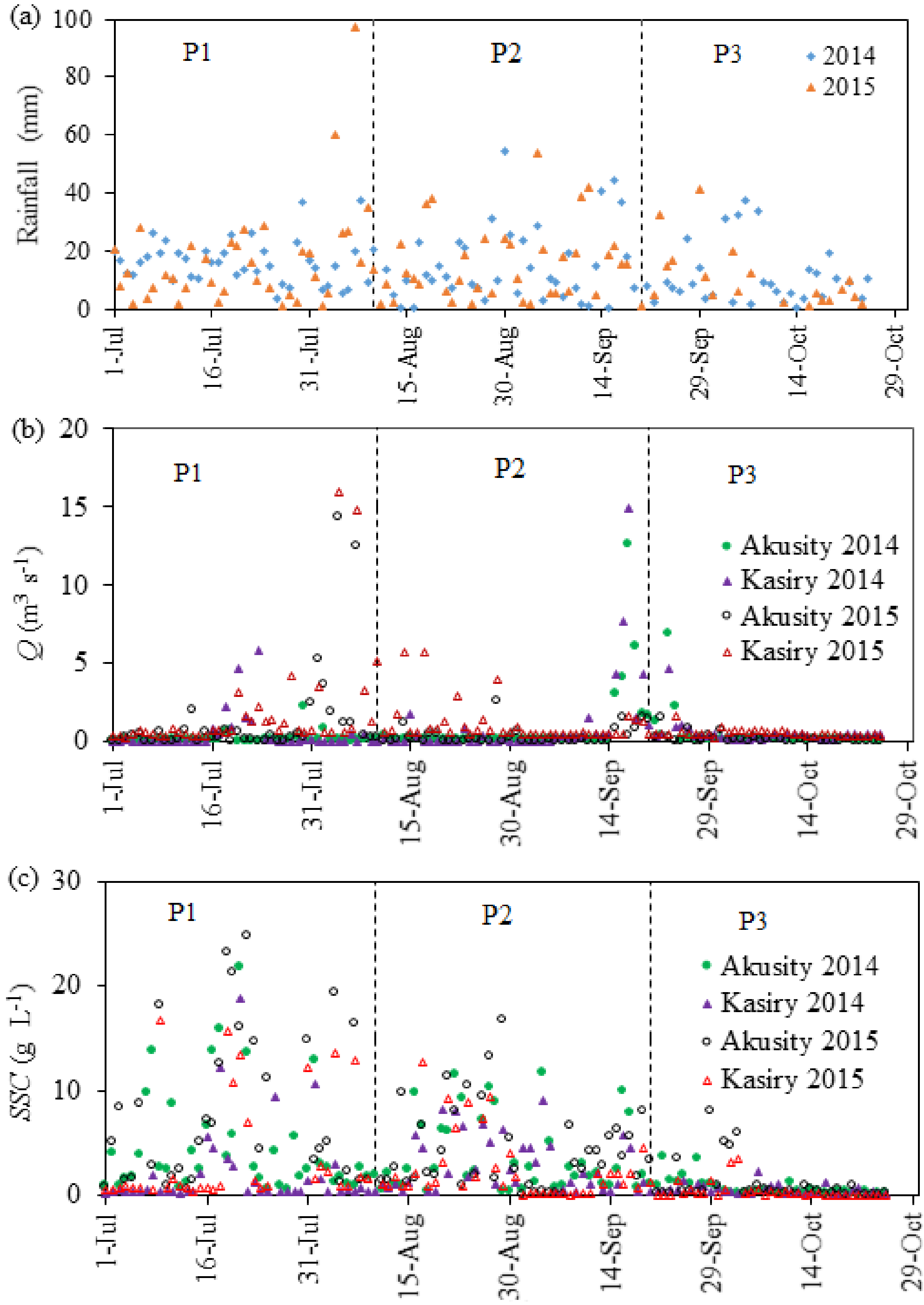

**Figure 2.3** Patterns of daily (a) rainfall, (b) streamflow discharge (*Q*), and (c) suspended sediment concentration (*SSC*) in the Akusity and Kasiry watersheds during the 2014 and 2015 sampling seasons.

Regressions using data from the entire sampling season were generally weak in 2014 and not statistically significant in 2015 largely because of the extreme variability of *SSC* (the CV ranged from 201–415%) for the flows during the rainy season (Table 2.4). A more recent study of watersheds of various sizes in Ethiopia's Upper Blue Nile basin (Moges et al., 2016) also demonstrated that sediment concentrations for a given discharge are variable over the rainy season, and that this strongly affected the relationship between *Q* and *SSC*. Other studies (Moliere et al., 2004; Alexandrov et al., 2007; Liu et al., 2008; Guzman et al., 2013) also showed that a single rating curve is subject to high data scatter because the relationship between *Q* and *SSC* often differs between different parts of the rainy season (see Table 2.3). Thus, dividing the sampling season into different periods (i.e., P1, P2, and P3 in Table 2.2) produces statistically significant relationships with $R^2$ values that range from 0.56–0.73 for P1 (all with $P<0.01$), and 0.40–0.57 for P2 (all with $P<0.05$). Only one of the four relationships for the end of the rainy season (P3) was significant at the $P<0.05$ level.

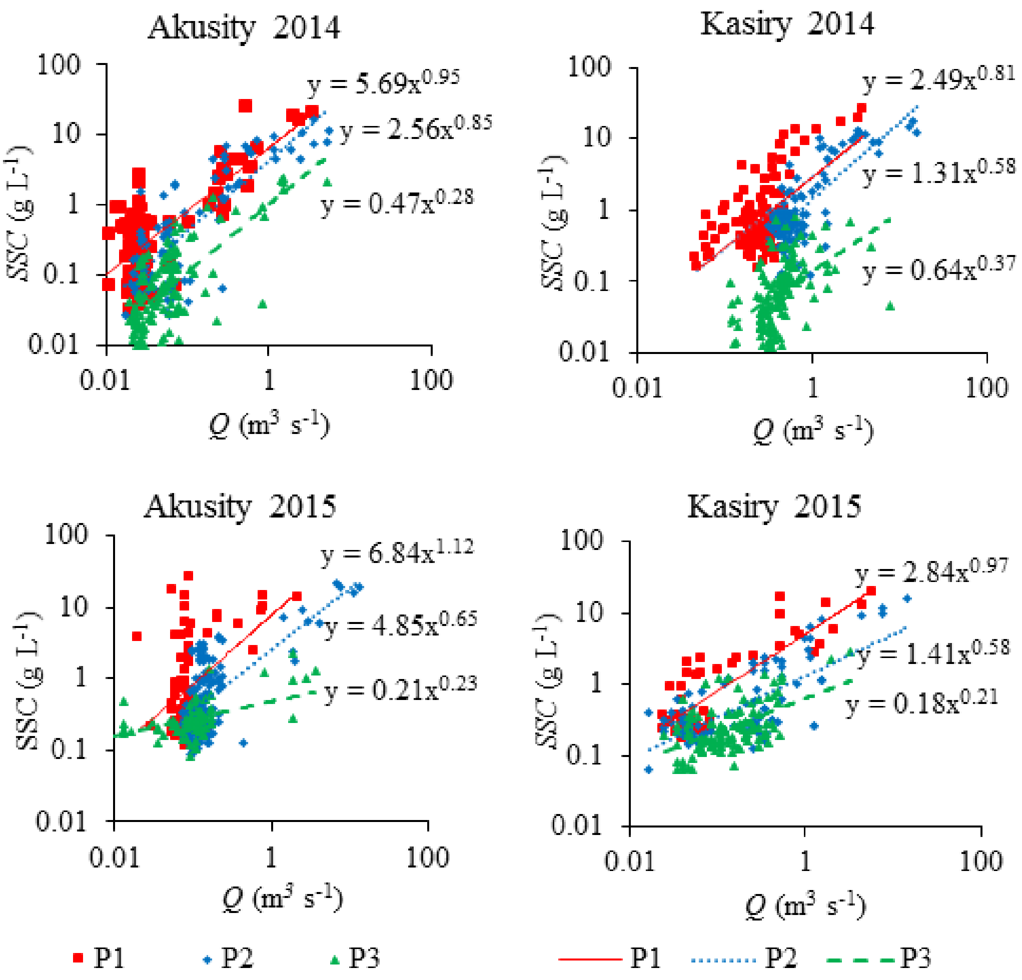

**Figure 2.4** Relationships between discharge (*Q*) and the suspended sediment concentration (*SSC*) at the Akusity and Kasiry stations during the 2014 and 2015 sampling seasons. Letters (P1-P3) represents the three different periods of the measuring seasons. The $R^2$ and P-values for each curve are given in Table 2.3.

As noted in several previous studies in different parts of the world (Asselman, 2000; Steegen et al., 2000; Alexandrov et al., 2007; Rodríguez-Blanco et al., 2010; Vanmaercke et al., 2010), high temporal and spatial variability in the sediment supply in watersheds resulted in poor *Q*–*SSC* relationships when all data was pooled for analysis; thus, predicting sediment concentration from a single rating curve is less reliable and less accurate than dividing the data into separate groups for periods with distinct physical and biological characteristics.

### 2.3.3 Variability in daily SY

The *SY* was calculated at a daily scale using the *Q–SSC* rating curves and the descriptive statistics of the data (Table 2.5) showed that the magnitudes were greatly varied in the two years and watersheds (the CV ranged from 313–685%). It is apparent from the table that the mean *SY* values and variability (CV) are clearly higher in the 2015 than in the 2014 for both watersheds. This was partly explained by the difference in the magnitude and timing of peak flow events during the two sampling seasons. In 2014, peak flow events occurred late in the main rainy season (mid-September), resulting in lower *SYs*. This part of the rainy season is characterized by low sediment supply owing to a combination of depletion of the available sediment by previous storm events and improved vegetation cover that protects the surface soil against detachment by rain drops and against erosion by surface flows. In 2015, however, peak flow events occurred early in the main rainy season (early August) during a period with a high sediment supply and less vegetation cover, resulting in much higher daily *SYs*. These results agree with previous findings in the highlands with monsoonal climate showing that sediment transport by runoff events was higher near the beginning of the rainy season than near the end (Kale and Hire, 2004; Zegeye et al., 2010; Guzman et al., 2013; Taye et al., 2013; Yeshaneh et al., 2014).

**Table 2.5** The descriptive statistics and Mann-Whitney U test results for daily runoff and sediment yield (*SY*) calculated at the Akusity and Kasiry stations during the two rainy seasons.

| Season | Station | n | Runoff (mm) | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Mean | SD | CV | Median | Mann-Whitney U test | | | |
| | | | | | | | Mr. | U | Z | P |
| 2014 | Akusity | 117 | 3.25 | 3.20 | 102 | 2.09 | 84 | 2882 | −7.653 | 0.000 |
| | Kasiry | 117 | 4.77 | 3.31 | 69 | 2.53 | 151 | | | |
| 2015 | Akusity | 117 | 3.15 | 3.33 | 103 | 4.16 | 67 | 969 | −11.348 | 0.000 |
| | Kasiry | 117 | 8.00 | 4.10 | 51 | 7.28 | 168 | | | |
| | | | *SY* (t $ha^{-1}$) | | | | | | | |
| 2014 | Akusity | 117 | 0.22 | 1.28 | 582 | 0.01 | 125 | 5855 | −1.913 | 0.056 |
| | Kasiry | 117 | 0.07 | 0.22 | 313 | 0.01 | 109 | | | |
| 2015 | Akusity | 117 | 0.61 | 4.18 | 685 | 0.06 | 132 | 5125 | −3.321 | 0.001 |
| | Kasiry | 117 | 0.23 | 1.35 | 586 | 0.02 | 102 | | | |

*n:* number of days in each season, SD: standard deviation, CV: coefficient of variation (%), Mr: mean rank. Letters (Z and P) are the outputs of the Mann-Whitney U test indicating the significance difference (at $Z < -1.96$ and $P < 0.05$) in daily runoff and *SY* between the two watersheds in the two seasons, by comparing mean ranks.

We also found that the daily runoff and *SY* differed significantly ($Z < -1.96$ and $P < 0.05$) between the two watersheds in both sampling seasons (except *SY* in 2014). This might be resulted from the impact of peak flow events from watersheds with different proportion of protective vegetation covers (Table 2.1). In both watersheds and years, the variability of

*SY* (CV = 313–685%) was an order of magnitude higher than that for runoff (CV = 51–103%) (Table 2.5). This extreme variability in *SY* can be explained by the changes in sediment supply during the rainy season and the occurrence of peak flow events, particularly those that occurred with a higher *SSC* (up to 265 g $L^{-1}$, calculated using the *Q*–*SSC* rating curves).

The role of peak flow events in determining the amount and variability of *SY* can be seen in double-mass curves (Figure 2.5). Herweg and Ludi (1999) and Amare et al. (2014) noted that the length and the slope of double-mass curves are a good indicator of the strength of the relationship between runoff and soil loss during the rainy season (i.e., short and steep curves represent a stronger relationship). We found very different patterns for the double-mass curves for the two sampling sites. The double-mass curves for Akusity are both shorter and steeper than for Kasiry in both seasons. This indicated that much of the sediment from Akusity was transported by the occurrence of few powerful peak flow events during the period of high sediment supply early in the growing season.

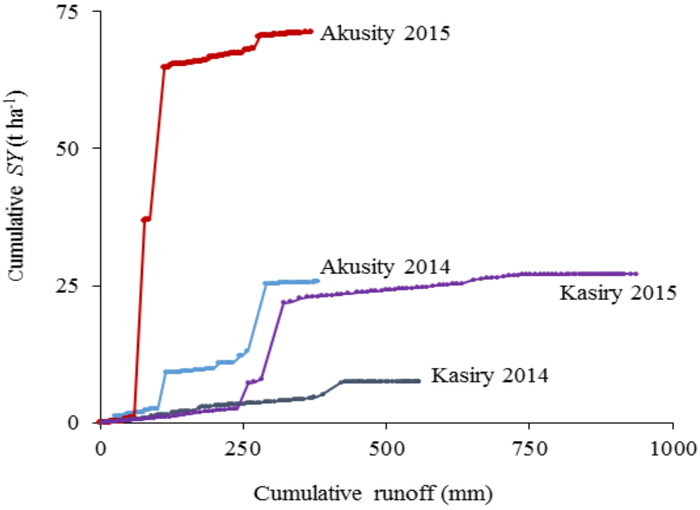

**Figure 2.5** Cumulative sediment yield (*SY*) and runoff relationships for the two watersheds during the two rainy seasons (1 July to 25 October in 2014 and 2015).

### 2.3.4 Variability in seasonal SY

We calculated the total *SY* for both years (Table 2.6) and for some selected peak flow events (Table 2.7) during the rainy season and found clear spatial (between watersheds) and temporal differences (within and between years). Both the total *SY* (kt $\mathrm{yr}^{-1}$) and area specific *SY* (t $\mathrm{ha}^{-1}\,\mathrm{yr}^{-1}$) were clearly larger at Akusity than at Kasiry despite the lower runoff (Table 2.6). This can be attributed to one or more of several factors: (i) lower areal coverage both by SWC measures and plantations at Akusity (Table 2.1), (ii) a slightly higher areal coverage by steep slopes and associated Leptosols at Akusity, which may have facilitated a more rapid runoff response, leading to concentrated flows and higher erosion at lower positions on the slopes and in drainage channels, (iii) slightly more cultivated land connected to drainage systems at Akusity that may have produced high sediment transport, especially during heavy rainfall events that produced concentrated surface flows over intensively plowed soils (Yeshaneh et al., 2014), and (iv) the shape of the Akusity watershed is more circular, which would produce a faster runoff response and higher sediment delivery during peak flow events (Table 2.7) which is in consistent with the findings by other researchers (Haregeweyn et al., 2008; Vanmaercke et al., 2010; Verbist et al., 2010).

**Table 2.6** Seasonal rainfall, runoff, and sediment yield (*SY*) during the two sampling years.

| Watershed | Year | Rainfall (mm) | Runoff (mm) | SY |  |
|---|---|---|---|---|---|
|  |  |  |  | Total (kt $yr^{-1}$) | Area specific (t $ha^{-1}$ $yr^{-1}$) |
| Akusity | 2014 | 1586 | 368 | 8.8 | 25.7 |
|  | 2015 | 1800 | 422 | 24.4 | 71.2 |
|  | Avg. | 1693 | 395 | 16.6 | 48.5 |
| Kasiry | 2014 | 1586 | 558 | 3.01 | 7.6 |
|  | 2015 | 1800 | 936 | 10.8 | 27.2 |
|  | Avg. | 1693 | 747 | 6.9 | 17.4 |

The average area specific *SY* in Kasiry (17.4 t $ha^{-1}$; Table 2.6) was of the same order of magnitude (3.97–25.6 t $ha^{-1}$) reported by similar studies in the Ethiopian highlands (Haregeweyn et al., 2008; Guzman et al., 2013; Yeshaneh et al., 2014) and elsewhere in the world (Rodríguez-Blanco et al., 2010; Verbist et al., 2010). The value obtained in

Akusity (48.5 t $ha^{-1}$), however, was far greater even than the range of magnitudes (22.7–37.8 t $ha^{-1}$) reported for medium-sized watersheds in the northern highlands of Ethiopia (Vanmaercke et al., 2010). Marttila and Kløve (2010) noted that such variability in *SY* among watersheds is expected because of differences in climate, land use, and landscape characteristics such as the slope, topography, soil type, vegetation, and drainage conditions.

The seasonal *SY* in 2015 was more than two times that in 2014 (Table 2.6), which can be attributed mainly to the difference in the magnitude and timing of the peak flow events in the rainy seasons (see also sections 2.3.2 and 2.3.3). In 2015, largest peak flow events occurred early in the rainy season, whereas in 2014 they occurred late in the rainy season (Table 2.7 and Figure 2.3). This could imply that peak flow events and their timing can control the amount of seasonal *SY* in this geographic region. For instance, the two peak flow events that occurred late in the rainy season of 2014 (on 16/09/2014 and 17/09/2017) accounted for 51% of the seasonal *SY* in Akusity and 47% in Kasiry. In contrast, the two peak flow events that occurred early in the rainy season of 2015 (on 04/08/2015 and 07/08/2015) accounted for 89% in Akusity and 68% in Kasiry. This

**Table 2.7** The contributions of the three peak flow events to watershed-scale seasonal runoff and area specific sediment yield (*SY*) amounts.

| Watershed | Date of event | Duration (hours: minutes) | Daily rainfall (mm) | $Q_{peak}$ ($m^{-3} s^{-1}$) | Runoff (mm) | $SSC_{peak}$ ($g\ L^{-1}$) | *SY* ($t\ ha^{-1}$) | Contribution to runoff (% of total) | Contribution to *SY* (% of total) |
|---|---|---|---|---|---|---|---|---|---|
| Akusity | 2014/8/7 | 4:10 | 20.20 | 17. 75 | 12.77 | 33.46 | 3.02 | 3.47 | 11.75 |
| | 2014/9/16 | 2:10 | 33.60 | 12.35 | 6.41 | 21.68 | 0.93 | 1.74 | 3.62 |
| | 2014/9/17 | 4:50 | 36.70 | 41.17 | 29.79 | 60.35 | 12.18 | 8.10 | 47.39 |
| | 2015/8/4 | 5:00 | 36.99 | 31.93 | 17.64 | 265.20 | 36.09 | 4.18 | 50.69 |
| | 2015/8/7 | 4:00 | 97.29 | 22.34 | 23.83 | 175.27 | 27.60 | 5.65 | 38.76 |
| | 2015/9/16 | 3:20 | 21.65 | 10.10 | 7.53 | 43.63 | 2.29 | 1.78 | 3.22 |
| Kasiry | 2014/7/22 | 3:20 | 26.50 | 7.51 | 5.03 | 27.48 | 0.43 | 0.90 | 5.66 |
| | 2014/9/16 | 4:40 | 33.60 | 21.47 | 10.21 | 7.76 | 0.56 | 1.83 | 7.37 |
| | 2014/9/17 | 4:30 | 36.70 | 35.14 | 27.72 | 10.32 | 3.03 | 4.97 | 39.87 |
| | 2015/8/4 | 5:40 | 36.99 | 20.44 | 14.27 | 53.01 | 4.58 | 1.52 | 16.90 |
| | 2015/8/7 | 5:50 | 97.29 | 23.22 | 31.87 | 67.50 | 13.80 | 3.40 | 50.92 |
| | 2015/9/11 | 5:00 | 38.62 | 12.50 | 12.34 | 25.01 | 1.56 | 1.32 | 5.76 |

agrees with the findings of Vanmaercke et al. (2010), who suggested that sediment export from watersheds is characterized by high temporal variability that is mainly controlled by the magnitude and timing of peak flow events. Similarly, for the temperate-humid zone of northwestern Spain, Rodríguez-Blanco et al. (2010) reported that the variability of *SY* was correlated with the number and magnitude of runoff events and that most of the sediment was transported over short periods of time.

## 2.4 Conclusions

Our study clearly demonstrated substantial variability in the suspended sediment concentration during discharge flow events in two humid tropical watersheds, and this variation was attributed to the spatial and temporal variation in biological and physical factors (rainfall, magnitude and timing of peak flow events, land cover, and SWC measures). This suggests that sediment supply and transport vary widely over space and time, and that it will be necessary to study discharge–sediment relationships at appropriate spatial and temporal scales to accurately determine the dynamics of sediment yield in watersheds. The *Q–SSC* rating curves showed weak relationships when data from the whole season were pooled for the regression analysis, but improved when the data were separated into groups based on periods with distinct characteristics. This provides additional evidence that the sediment transport capacity of the flows varies over time, and that developing a single rating curve to estimate *SY* in such watersheds may not be appropriate.

The *SY* varied widely during the two year study period and between watersheds in a given year (7.6 and 27.1 t $\mathrm{ha}^{-1}$ for Kasiry in 2014 and 2015*,* with corresponding values of 25.7 and 71.2 t $\mathrm{ha}^{-1}$ for Akusity), and a small number of peak flow events accounted for a larger percentage of the seasonal *SY* that determined both the amount and the variability of *SY* within watersheds. Hence, our results suggest that careful and site-specific sampling, combined with measurements of peak flow events, will be crucial to accurately assess the dynamics of sediment yield at a watershed scale in humid tropical environments, which will be crucial to support the planning of appropriate measures to control soil erosion and its consequences.

# Chapter 3

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# Effects of land use and sustainable land management practices on runoff and soil loss in the Upper Blue Nile basin, Ethiopia

This chapter is published as:

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## 3.1 Introduction

Soil erosion by running water is a major environmental challenge in Ethiopia (Taddese, 2001), and the problem is particularly important in the Upper Blue Nile basin of the country because of the potentially high erosion rates caused by heavy and erosive rainfall (Fenta et al., 2017), steep topography, and agricultural practices that reduce protective soil cover (Hurni et al., 2005). Soil loss rates (37–246 t $ha^{-1}$ $yr^{-1}$) reported by studies in the basin (Bewket and Teferi, 2009; Kindiye, 2013; Adimassu et al., 2014; Amare et al., 2014; Kindiye, 2016) are about 5 to 14 times greater than estimated rates of soil formation (6–18 t $ha^{-1}$ $yr^{-1}$) in most areas in the region (Hurni, 1983a) and the acceptable soil loss limit (1–6 t $ha^{-1}$) recommended for Ethiopia (Hurni, 1983b). Such high soil loss rates can result in a significant reduction in the productive capacity of agricultural lands because the soil that is removed by erosion typically contains about three times more nutrients than the soil left behind and is 1.5 to 5 times richer in organic matter (Pimentel et al., 1995).

Accelerated soil erosion in the basin also has off-site consequences that substantially threaten Lake Tana and other reservoirs that contribute to Ethiopia's agriculture, biodiversity, tourism, fisheries, and hydroelectric power production (Setegn et al., 2009). For example, a sediment budget study by Lemma et al. (2017) revealed that the annual sediment deposition in Lake Tana is 36.97 Megaton (Mt), for an estimated lifetime of the lake of 764 to 1032 years, which is shorter than the lifetime estimated in earlier studies (Engida, 2010; Zimale et al., 2016). A comprehensive assessment by Haregeweyn et al. (2017) also showed that 39% of the Upper Blue Nile basin is subject to severe to very severe erosion, which could potentially threaten the sustainability of downstream reservoirs, including the Grand Ethiopian Renaissance Dam.

In response to these problems, the Ethiopian government initiated a soil and water conservation (SWC) program in the 1970s emphasizing drought-prone areas. This program was implemented on an *ad hoc* basis until it was replaced by a watershed-based approach in the 1980s (Kebede, 1991; Dejene, 2003; Haregeweyn et al., 2015). However, soil erosion continues to be a major problem, and efforts targeting wider geographic regions began with implementation of the Sustainable Land Management (SLM) program in 2008 (Schmidt and Tadesse, 2017). The SLM program has promoted various practices, such as the construction of soil or stone bunds, *fanya juu* (a terrace system described in section 1.4.4), bench terraces, trenches, cut-off drains, drainage canals, and check dams, as well as the planting of different shrub or tree species and establishing area exclosures

(Tefera and Sterk, 2010), see also Table 1.1.

Studies conducted in different areas of the Ethiopian highlands have reported a remarkable reduction in soil erosion through the use of SLM measures. For example, substantial reductions in runoff and soil loss resulting from the use of stone bunds (Gebrermichael et al., 2005; Nyssen et al., 2007b; Taye et al., 2013; Taye et al., 2015) and area exclosures (Mekuria et al., 2007; Girmay et al., 2009; Yayneshet et al., 2009) have been reported in the semi-arid region of Ethiopia. A significant reduction in soil loss has also been reported by few studies in the western and central highlands of Ethiopia (Herweg and Ludi, 1999; Adimassu et al., 2014; Amare et al., 2014); these assessments, however, emphasized croplands, although many efforts are also underway to reduce soil erosion through area exclosure and vegetation restoration in non-croplands at various scales. In general, despite the huge investment of financial and labor resources for planning and implementation of SLM practices in the humid and tropical regions of the Upper Blue Nile basin, little or no rigorous research has been conducted to assess the extent to which runoff and soil loss (SL) are reduced in different land use types and agro-ecologies. In particular, promising measures such as the use of exclosures and combined measures have been given little attention by previous studies, which have tended to focus on structural measures used in croplands. Relevant studies are particularly rare in areas where rainfall is intense and runoff occurs over highly erodible soils (Nyssen et al., 2007a). This lack of research may be, at least in part, a result of the financial difficulties involved in establishing experimental facilities and collecting data over wide spatial and temporal scales.

In the present study, we monitored runoff and soil loss (SL) from 42 runoff plots during two consecutive rainy seasons (2015 and 2016) in three agro-ecologically different sites of the Upper Blue Nile basin of Ethiopia. The main objective was to better understand the effect of land use types and SLM practices on runoff and SL in different agro-ecologies and thereby provide site-specific information that can support policy development to promote large-scale implementation of suitable SLM practices in the Upper Blue Nile basin. The specific objectives were to (1) quantify runoff and SL from three dominant land use types—cropland, grazing land, and degraded bush land; and (2) evaluate the effectiveness of five SLM practices—soil bund, soil bund reinforced with grass, *Fanya juu,* exclosure, and exclosure with trenches—in reducing runoff and SL in different agro-ecologies of the basin.

## 3.2 Materials and methods

### 3.2.1 Experimental setup

To assess the extent of soil erosion, and evaluate and support SLM in the Upper Blue Nile basin of Ethiopia, we selected three sites in different agro-ecologies of the basin (highland, midland, and lowland) and set up a field experiment (Figure 3.1). A total of 42 runoff plots (14 at each agro-ecological site) were established on three land use types: cropland (CL1 and CL2), grazing land (GL), and degraded bushland (DBL).

The characteristics of the different treatments investigated for each land use type are shown Table 3.1. Four treatments were investigated in each cropland at all sites: (1) control (C), plots with conventional practices and no SLM measures; (2) soil bund (SB), plots with a soil embankment built by excavating a ditch along the contour (the material excavated from the ditch is moved downhill to build the embankment); (3) *fanya juu* (F), a type of terrace built from soil, similar to a soil bund, but with the ditch below the embankment (i.e., the excavated material from the ditch is moved uphill); and (4) soil bund reinforced with grass (SBG), a soil embankment integrated with different grass types (desho grass [*Pennisetum pedicellatum*] at Guder, elephant grass [*Pennisetum purpureum*] at Aba Gerima, and Vetiver grass [*Vetiveria zizanioides*] at Dibatie). Three treatments were investigated on non-croplands (GL and DBL): (1) control (C), plots with no supportive measures on which both browsing and grazing animals were allowed to graze; (2) area exclosure (E), fenced plots where animals were excluded to allow the natural vegetation to regenerate; and (3) exclosure with trenches (E+T), fenced plots accompanied by rectangular staggered trenches with the excavated soil material embanked downslope (see Figure 1.10 in section 1.4.4).

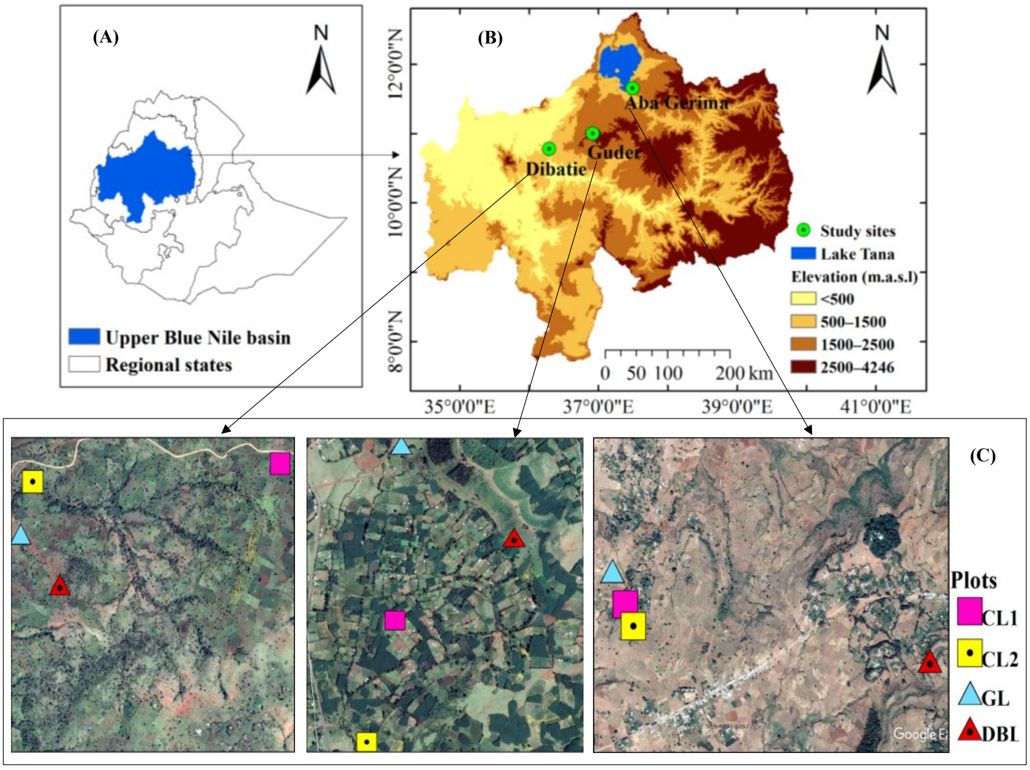

**Figure 3.1** Locations of the runoff plots of different land use types (C) in the three sites (Didatie, Guder, and Aba Gerima) of the Upper Blue Nile basin (B) of Ethiopia (A). CL1: gently sloped cropland; CL2: steeply sloped cropland; GL: steeply sloped grazing land; DBL: steeply slope degraded bushland. Plot locations are displayed on georeferenced Google Earth images taken on 22 October 2013 for Dibatie, 16 November 2016 for Aba Gerima, and 19 November 2017 for Guder.

Depending on the land use type, slope gradient, and type of construction, 3 to 20 structures (SB, F, SBG, and trenches) were built in each treatment plot where structural SLM measures were applied (Table 3.1). For croplands, SLM measures were installed following the approach of Herweg and Ludi (1999) and Amare et al. (2014). Detailed information about the number, design, and dimensions of the SB, F, SBG, and trench structures is given in Sultan et al. (2018). For all treatments, the area of the bounded runoff plots (Figure 3.2) was similar, each being about 180 $m^2$ (6 m × 30 m). To prevent inflow and outflow of runoff, three sides (upper, left, and right) of the plots were bounded with a waterproof metal board 35 cm in height that was inserted 15 cm into the soil so that 20 cm remained above the surface. A trapezoidal runoff collector trench 5 m long, 1 m deep, and 3 m wide at the top and 1.5 m wide at the bottom was located at the downslope end of each plot and lined with a thick geomembrane plastic sheet (Figure 3.2). The capacity of the collector trench, 9.7 $m^3$, was determined by considering the maximum daily rainfall and the highest runoff coefficient, 46%, observed in highly degraded fallowed and bare lands in the Ethiopian highland (Herweg and Ludi, 1999).

In the cropland plots, tilling was done manually with hoes only once at the time of sowing and other agronomic activities were implemented based on the farmer’s typical practice at each site. The crops grown in the first year (2015) of the experiment differed across the study sites (barley at Guder, finger millet at Aba Gerima, and chili pepper at Dibatie) so they were suitable for the current crop rotation. In the second year (2016), however, the same crop (tef) was grown on all cropland plots. Except for brief intervals during tillage and related activities, all cropland plots were fenced to prevent damage to experimental structures and facilities by free-moving animals, especially during dry periods. Hence, it should be noted that the control cropland plots (C) may not represent farmers' typical traditional practices. We believe, however, that the results will help in the overall evaluation and support current and future governmental efforts (i.e., banning free grazing, using minimum tillage, and reduced removal of crop residues on croplands) to reduce soil erosion and increase carbon sequestration (Mekonnen et al., 2013). Plots on non-croplands (GL and DBL) were established on communal lands; hence, the control (C) plots were not fenced and unrestricted grazing by animals was allowed over the study period. Local farmers were involved throughout the research process from the set-up of the experiment, to help understanding between the research and the community.

**Table 3.1** Characteristics of the study plots and SLM practices in the different land use types and agro-ecologies.

| | | | | | | | Structural features of SLM practices (SB, F, SBG, and trench)[b] | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Site (agro-ecology) | Land use | Slope (%) | Elevation (m a. s .l) | Soil texture class | dBD[a] (g $cm^{-3}$) | Treatment tested | Total number per plot | Area coverage ($m^2$ $plot^{-1}$) | Area coverage ($m^2$ $ha^{-1}$) | Proportion (% of total area) |
| Guder (highland) | CL1 | 5 | 2560 | Clay loam | 1.18 | C, SB, F, and SBG | 3 | 28.8 | 1600.0 | 16 |
| | CL2 | 15 | 2590 | Clay loam | 1.30 | C, SB, F, and SBG | 4 | 38.4 | 2133.3 | 21 |
| | GL | 15 | 2564 | Clay loam | 1.14 | C, E, and E+T | 15 | 39.9 | 2216.7 | 22 |
| | DBL | 35 | 2632 | Loam | 1.11 | C, E, and E+T | 20 | 53.2 | 2955.6 | 30 |
| Aba Gerima (midland) | CL1 | 5 | 1983 | Clay loam | 1.27 | C, SB, F, and SBG | 3 | 28.8 | 1600.0 | 16 |
| | CL2 | 15 | 1997 | Sandy loam | 1.22 | C, SB, F, and SBG | 4 | 38.4 | 2133.3 | 21 |
| | GL | 15 | 1939 | Clay loam | 1.39 | C, E, and E+T | 15 | 39.9 | 2216.7 | 22 |
| | DBL | 35 | 2105 | Sandy loam | 1.43 | C, E, and E+T | 20 | 53.2 | 2955.6 | 30 |
| Dibatie (lowland) | CL1 | 5 | 1586 | Clay | 1.11 | C, SB, F, and SBG | 3 | 28.8 | 1600.0 | 16 |
| | CL2 | 15 | 1498 | Clay | 1.14 | C, SB, F, and SBG | 4 | 38.4 | 2133.3 | 21 |
| | GL | 15 | 1513 | Clay | 1.24 | C, E, and E+T | 15 | 39.9 | 2216.7 | 22 |
| | DBL | 35 | 1586 | Clay | 1.14 | C, E, and E+T | 20 | 53.2 | 2955.6 | 30 |

CL1: gently sloped cropland, CL2: steeply sloped cropland, GL: steeply sloped grazing land, DBL: steeply sloped degraded bushland, C: control, SB: soil bund, F: *Fanya juu*, SBG: soil bund reinforced with grass, E: exclosure, E+T: exclosure with trenches, dBD: dry bulk densities.

[a] Dry bulk densities are the averages of values measured during the study periods (i.e., once each year in 2015 and 2016).

[b] Structural features of SLM measures include the total number of each type of structure (SB, F, SBG, and trench) built within each treated plot, the corresponding total area occupied by the structures at plot ($m^2$) and hectare (ha) scales, and the percentage share (%) of the total area.

**Figure 3.2** A partial view of the experimental setup on different land use types. Detailed information is given in Table 3.1. The photos of CL1, CL2, and DBL (from the Aba Gerima site) and GL (Guder) were taken around mid-August 2016. Abbreviations are defined in Table 3.1.

### 3.2.2 Rainfall measurement

Manual and tipping-bucket rain gauge stations were installed at each site to collect data about the number of rainy days and rain events and rainfall amount and intensity (Table 3.2). The number of rainy days (days with rainfall of >0.1 mm, Bewket and Conway (2007)) and daily rainfall amount were determined on the basis of data collected using manual rain gauges during the study period (2015 and 2016). The number of events and rain intensity were calculated from the tipping-bucket station (Data Logging Rain Gauge, Onset Part No: RG3-M). To calculate intensity, the number of consecutive tips, each 0.2 mm, was counted for every rain event using the HOBOware 3.7.14 software; 30 minutes was chosen as the minimum inter-event time to separate two events, as has been suggested for the Lake Tana basin (Haile et al., 2011). Then, the rainfall intensity was calculated following Huang et al. (2013) by dividing the rainfall amount (mm) by the duration (h) from the start of the tips to the end for each event. The tipping buckets failed to record data during the measuring season of 2015 at Guder and 2016 at Aba Gerima, but we believe that the available data (Table 3.2) are quite sufficient to understand the characteristics of rainfall during the two study seasons and across the three sites.

**Table 3.2** Number of rain events and corresponding mean intensity (± standard deviation) observed from the tipping-bucket rain gauges, and number of rainy days, cumulative rainfall, and mean daily rainfall amount (± standard deviation) observed from the manual rain gauges during the four wettest months of the study periods at the three study sties.

| Season | Site | June | July | Aug | Sept | Oct | Total |
|---|---|---|---|---|---|---|---|
| 1. Number of events | | | | | | | |
| 2015 | Guder | * | * | * | * | * | * |
| | Aba Gerima | 22 | 33 | 44 | 35 | 14 | 148 |
| | Dibatie | 15 | 21 | 25 | 20 | 14 | 95 |
| 2016 | Guder | 37 | 61 | 47 | 41 | 34 | 220 |
| | Aba Gerima | * | * | * | * | * | * |
| | Dibatie | 28 | 31 | 27 | 24 | 26 | 136 |
| 2. Mean event rain intensity (mm $h^{-1}$) | | | | | | | |
| 2015 | Guder | * | * | * | * | * | |
| | Aba Gerima | 43.29±87.74 | 16.46±41.79 | 8.47±13.21 | 9.39±9.37 | 10.36±10.10 | |
| | Dibatie | 9.02±15.37 | 7.81±6.79 | 6.95±9.83 | 9.60±10.04 | 9.57±7.62 | |
| 2016 | Guder | 6.79±5.51 | 5.1±4.94 | 6.10±5.13 | 8.27±8.60 | 9.9±6.85 | |
| | Aba Gerima | * | * | * | * | * | |
| | Dibatie | 8.78±8.92 | 4.32±4.16 | 7.94±8.13 | 7.73±8.45 | 11.27±7.25 | |
| 3. Number of rainy days (*n*) | | | | | | | |
| 2015 | Guder | 25 | 29 | 31 | 25 | 17 | 127 |
| | Aba Gerima | 9 | 21 | 26 | 18 | 9 | 83 |
| | Dibatie | 10 | 11 | 11 | 8 | 7 | 47 |
| 2016 | Guder | 28 | 30 | 31 | 30 | 31 | 150 |
| | Aba Gerima | 21 | 30 | 30 | 21 | 14 | 116 |
| | Dibatie | 22 | 27 | 25 | 22 | 18 | 112 |
| 4.Cumulative rainfall amount (mm) | | | | | | | |
| 2015 | Guder | 284 | 395 | 530 | 465 | 133 | 1800 |
| | Aba Gerima | 254 | 380 | 394 | 205 | 127 | 1360 |
| | Dibatie | 150 | 246 | 183 | 175 | 127 | 881 |
| 2016 | Guder | 324 | 440 | 445 | 297 | 184 | 1691 |
| | Aba Gerima | 246 | 408 | 441 | 210 | 113 | 1419 |
| | Dibatie | 183 | 288 | 247 | 146 | 138 | 1002 |
| 5. Mean daily rainfall amount (mm) | | | | | | | |
| 2015 | Guder | 9.48±10.17 | 11.45±9.16 | 16.46±18.63 | 14.18±14.68 | 4.31±6.60 | |
| | Aba Gerima | 9.77±19.43 | 13.20±14.40 | 12.70±15.89 | 6.93±8.89 | 4.09±9.61 | |
| | Dibatie | 6.56±14.95 | 7.94±13.52 | 5.90±11.74 | 5.83±11.69 | 4.11±8.95 | |
| 2016 | Guder | 10.79±10.44 | 14.20±8.98 | 14.36±9.98 | 9.92±6.25 | 5.94±4.55 | |
| | Aba Gerima | 8.20±14.13 | 13.18±12.52 | 14.23±19.36 | 7.01±8.26 | 3.65±8.91 | |
| | Dibatie | 6.11±7.76 | 9.29±9.49 | 7.73±10.83 | 4.88±8.43 | 4.45±6.83 | |

*The Tipping buckets failed to record the data.

### 3.2.3 Runoff and soil loss measurements

Runoff and soil loss data were collected on a daily basis whenever rainfall generated runoff. The methodological framework employed to calculate runoff and associated soil loss (SL) is shown in Figure 3.3. Runoff was calculated from the geometry of the collector trench. That is, the runoff water depth (trench water level, in m) was measured in the collector trench on daily basis (every morning at 8:00 LT) at six fixed points marked at equal intervals in the trench. The mean depth was used to model runoff volume. At the beginning of the experiment, every trench was calibrated by adding measured volumes of water and measuring the corresponding depths; the relationship between the depth and corresponding volume records was strong and significant ($R^2 > 0.98$ and $P < 0.001$). We subsequently calculated runoff volume using regression equations (rating curves) developed from linear relationships between mean depth and the corresponding runoff volume for each trench**.** To obtain the actual runoff volume, the volume of rainfall dropped directly on the collector trench was calculated on the basis of the rainfall and (mm) and surface area of the collector trench. The actual runoff was then calculated as a difference between the runoff volume and direct rainfall volume.

To analyze sediment concentration (SC), on a daily basis (every morning at 8:00 LT), the runoff collected in the trench was vigorously mixed with a floor brush until all settled sediment was mixed with the water and then a 1 L sample was taken. After measuring runoff depth and sampling, we removed the runoff water from each trench manually with plastic buckets. The geomembrane plastic was also carefully cleaned and checked for any damage. We collected a total of 5205 samples during the 2015 and 2016 sampling seasons (2711 at Guder, 1472 at Aba Gerima, and 1022 at Dibatie) and measured the SC (g $L^{-1}$). All of the runoff samples were filtered through Whatman 42 filter paper, which was then oven dried at 105 °C for 24 h. The SC was determined by weighing the filter and sediment together on a digital balance (precision = 0.001 g) and then the weight of the filter was subtracted. The daily soil loss (SL, t $ha^{-1}$, Figure 3.3) was then calculated as the product of actual runoff volume (L) and sediment concentration (SC, g $L^{-1}$), and the seasonal SL was obtained by summing the daily values. The effectiveness of SLM practices in reducing runoff and soil loss was calculated following the approach of Sultan et al. (2018), where the effectiveness for each SLM practice was calculated relative to runoff and SL in the corresponding control plot.

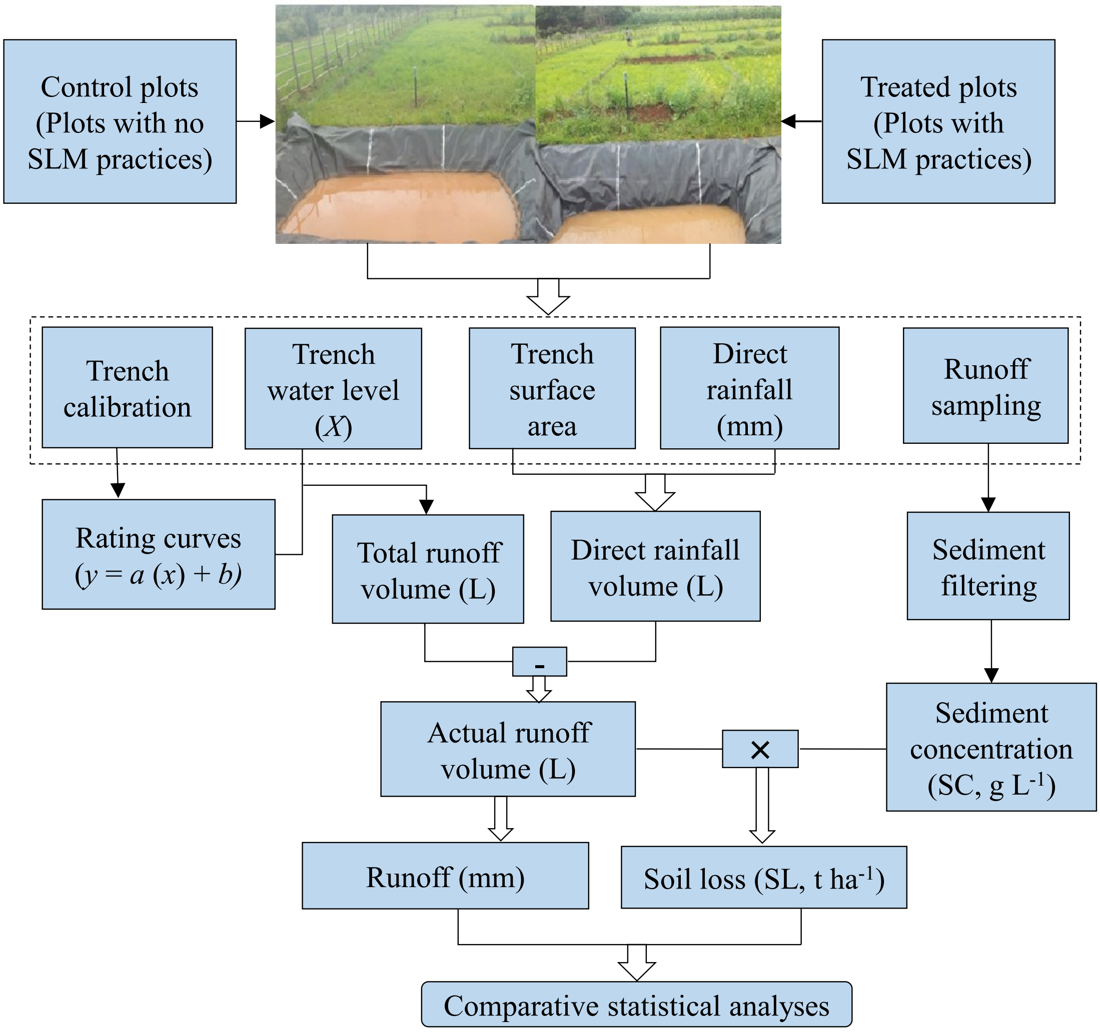

**Figure 3.3** The methodological framework employed to measure runoff and soil loss from bounded plots: trench calibration, trench water level measurement, runoff sampling, and sediment filtering.

### 3.2.4 Statistical analysis

For the statistical analysis, we considered daily runoff and SL data from each measuring season (2015 and 2016). Descriptive statistical parameters (mean, median, standard deviation, coefficients of variation, skewness, and kurtosis) were calculated for runoff and soil loss. Parametric statistical tests could not be used for this study because the distributions of all data sets were significantly non-normal. Hence, a Mann-Whitney U test (a non-parametric test that performs well with non-normally distributed data) was used to evaluate the significance of differences in runoff and soil loss from different land use types and treatments. We also performed regression analyses of the daily runoff and SL data sets in which control plots (conventional practices) were compared with treated plots (plots with SLM practices) to evaluate the statistical relationship between the data collected from plots with and without SLM interventions. Data analyses were carried out with Excel and SPSS 23.0 software (SPSS Inc., Chicago, IL, USA).

## 3.3 Results and discussion

### 3.3.1 Seasonal runoff and soil loss

The amount of runoff and SL observed during the two study seasons in the different land use types and treatments are presented in Figure 3.4. Across all 42 monitored plots at the three agro-ecological sites, seasonal runoff ranged from 52 to 810 mm in 2015 and from 37 to 898 mm in 2016, and SL ranged from 0.07 to 39.67 t ha$^{-1}$ and from 0.01 to 24.70 t ha$^{-1}$. The highest runoff and SL amounts were observed for the control treatments at all sites, whereas the lowest were observed for SBG plots in croplands and E+T plots in non-croplands. The runoff generally increased in the order Dibatie (lowland)<Aba Gerima (midland) < Guder (highland), following the pattern of rainfall amount, whereas SL increased in the order Dibatie (lowland) < Guder (highland) < Aba Gerima (midland), following the pattern of rainfall intensity (Table 3.2, and Figure 3. 4).

The range of runoff values during both seasons in the current study is clearly higher than the range (1–688 mm) reported by other studies in the Upper Blue Nile basin (Herweg and Ludi, 1999; Alemayehu et al., 2013; Amare et al., 2014). This difference may partly be attributed to the heavy daily rainfall amounts (69–97 mm) that generated extremely higher runoff amounts from land uses associated with a relatively higher dry bulk density, especially from heavily grazed non-croplands (Figure 3.4). The SL values, however, are generally smaller than the range of values (6–167 t ha$^{-1}$) reported by previous studies, possibly because of differences in climatic and other biophysical factors in the Upper Blue Nile basin that result in spatial and temporal variability in soil erosion. For example, extreme spatial and temporal variability in rainfall distribution over the basin is clearly indicated in Abtew et al. (2009) and Rientjes et al. (2013). (Haregeweyn et al., 2017) also found large spatial variation of the most important factors (rain erosivity, soil erodibility, and vegetation cover) that greatly influence the rate of soil erosion in this basin.

The highest SL values reported by the previous studies, however, were measured from intensively ploughed and open cropland plots, which was not the case in the current study: plots on croplands were fenced throughout the study period and tilled only once at the time of sowing (see section 3.3.1). Hence, the relatively lower SL values from croplands in this study are in line with the possibility that crop residue and organic matter buildup are greater under protected conditions, which may have resulted in improved topsoil conditions and lower soil erosion rates. This finding may indicate that a substantial reduction in SL from croplands can be achieved by applying minimum tillage and prohibiting free grazing.

The seasonal SL rates for three land use–site combinations (CL2 of Guder, and GL and DBL of Aba Gerima) were markedly higher than the maximum tolerable limit (6 t $ha^{-1}$) suggested for Ethiopia (Hurni, 1983b), but in other cases SL rates were by far lower than this limit. Most likely, this result can be explained by differences in biophysical and human factors affecting top soil conditions and hydrological responses in these plots. For example, the relatively higher SL from Guder CL2 in 2016 can be attributed to higher seasonal runoff amounts due to surface compaction resulting from tef cultivation. This finding is in agreement with Hurni (1985), who calculated that the C-factor value of soil loss for tef fields in the central and eastern highlands of Ethiopia is 0.25, a value far greater than the values calculated for other land use types. This can most probably be attributed to the deterioration of soil physical properties (bulk density, total porosity, and soil structural stability) owing to excessive tillage operations applied to prepare fine and smooth seedbed to grow tef (Tesfahunegn, 2015).

The high SL rates from GL and DBL of Aba Gerima during both seasons can be explained by the high intensity rainfall events that occurred early during the rainy season (June and July, Table 3.2), when the protective vegetation cover is low and sediment supply is relatively high, on a ground surface that had been loosened by the hooves of grazing animals (Stavi et al., 2016), which is especially likely during the dry period. Studies from the Upper Blue Nile basin (Zegeye et al., 2010; Amare et al., 2014; Yeshaneh et al., 2014) also showed that sediment transport during runoff events is higher at the beginning of the rainy season than it is towards the end, mainly because bare and loose soil conditions are common earlier in the season.

Regardless of land use and slope gradients, the SL rates at the Dibatie site during both seasons were clearly lower than the acceptable limit (6 t $ha^{-1}$), largely because of the lower rainfall and runoff amounts. The SL rates can also be explained partly by the expanding and shrinking properties of the soils at that site (Vertisols), because rapid downward movement of rainwater can occur as a result of the formation of wide and deep cracks, especially when rain events occur after a prolonged dry period (Favre et al., 1997). This downward movement results in turn in less runoff and transportation of soil materials.

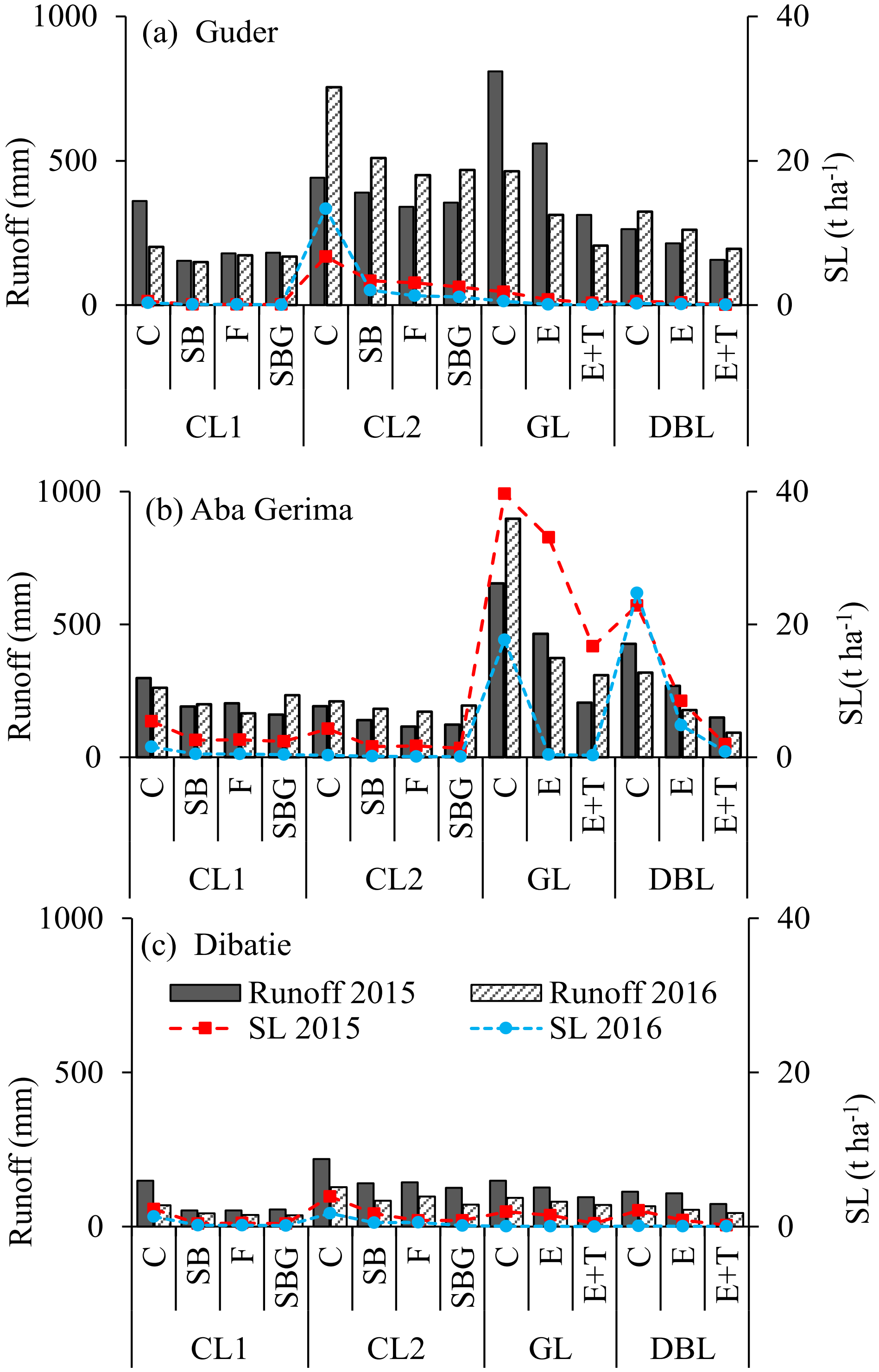

**Figure 3.4** Seasonal runoff and soil loss (SL) rates from different land use types under different treatments at the Guder, Aba Gerima, and Dibatie sites. Abbreviations are defined in Table 3.1.

### 3.3.2 Effects of land use on runoff and soil loss

In the control plots for each site and measuring period, Mann-Whitney U test results showed significant differences in runoff, sediment concentration (SC), and SL across the different land use types (Table 3.3). The runoff and SL differences across land use types were more pronounced in the highland (Guder) and midland (Aba Gerima) agro-ecologies than in the lowland (Dibatie), probably owing to variability in biophysical factors, including soil, rainfall, and vegetation cover, across the studied land use types. The lower variability at Dibatie can be explained partly by the similarity in soil textural class (clay) across all land use types (Table 3.1) and the low grazing intensity on non-croplands. The effect of slope steepness, one of the topographic factors affecting runoff and soil loss, was not clearly observed in the three agro-ecological sites, implying that the influence of this factor was most likely dependent on land use type and other dominant factors. Similarly, Wickama et al. (2015) stated that the magnitude of soil erosion variation from one location to another may depend on the dominant biophysical conditions on the ground.

Among the three dominant land use types, GL generally had significantly higher runoff than the other land use types at Guder and Aba Gerima, largely because the rainfall thresholds (5 and 9 mm) required to generate runoff were lower and the seasonal runoff coefficients (35 and 40) were higher in these areas (Sultan et al., 2018), which were frequently grazed and had a relatively compacted surface (Table 3.1). In this regard, many studies have shown that soils of grazed lands are characterized by high dry bulk densities, caused by human- and cattle-induced compaction, and they therefore have higher runoff coefficients than soils of other land uses (Wei et al., 2007; Alemayehu et al., 2013; Taye et al., 2013; Toohey et al., 2018). At Dibatie, however, the runoff was generally not significantly different across the three land use types during the study periods, at least partly because the main biophysical factors were similar across the land use types. Qiang et al. (2016) also found minimal differences in runoff among five different land use types on slopes with different gradients (5% and 15%) but with similar soil texture and protective vegetation coverage.

Significant differences in SL between croplands and non-croplands were observed across the sites. At Guder and Dibatie, the daily SL in CL2 (15% slope) was significantly higher than that in non-croplands ($P < 0.05$; Table 3.3). This result is probably attributable to the fact that croplands are subject to cultivation and soil compaction activities that would result in higher runoff and sediment concentration values. Studies of other areas (Girmay et al., 2009; Mohammad and Adam, 2010; El Kateb et al., 2013; Xiao-Yin et al., 2015; Qiang et al., 2016) have reported that soil erosion in cultivated fields is markedly higher than that in other land uses. Ploughed crop fields are commonly bare in the Ethiopian highlands and therefore vulnerable to splash and runoff erosion (Virgo and Munro, 1978). Many studies have also shown that plowing generally increases soil erosion potential because the process breaks down soil aggregates, reduces infiltration capacity, and increases surface runoff (Basic et al., 2004; Biazin et al., 2011; Temesgen et al., 2012; Tesfahunegn, 2015).

At Aba Gerima, however, SL in non-croplands (GL and DBL) was significantly higher than that in croplands, largely because of the higher dry bulk density (Table 3.1) induced by intensive grazing and the unprotected soil surface, which could easily be eroded when intense rain events occurred. Higher soil loss values (17–38.7 t $ha^{-1}$) have been observed from intensively grazed lands than from croplands (7.7–9.7 t $ha^{-1}$) in intense summer rain areas of the northern highlands of Ethiopia (Nyssen et al., 2009; Taye et al., 2013). Significant soil erosion resulting from intensive grazing, removal of protective vegetative cover, and surface trampling by livestock has been reported elsewhere in the highlands of Ethiopia (Mwendera and Saleem, 1997a; 1997b). The significantly lower SL from croplands, at the Aba Gerima site in the current study, might also be the result of minimal human and livestock intervention during the study periods, another indication that free and intensive grazing plays an important role in increasing soil erosion rates in intense rain areas of the Upper Blue Nile basin. In general, the results of this study demonstrate that the effect of land use on runoff and SL is variable across different agro-ecologies and therefore site-specific experimentation is paramount to generate model input parameters for soil erosion estimates and decision-making purposes.

**Table 3.3** The mean, median, standard deviation (SD), and mean rank (MR) of daily runoff, SC, and SL data sets for control (C) plots at Guder, Aba Gerima, and Dibatie during the two study seasons.

| Site | Season | Land use | $n$ | Runoff (mm) | | | | SC ($g\ L^{-1}$) | | | | SL ($t\ ha^{-1}$ ) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Mean | Median | SD | MR | Mean | Median | SD | MR | Mean | Median | SD | MR |
| Guder | 2015 | CL1 | 113 | 3.19 | 2.51 | 3.23 | 118$^{c}$ | 0.21 | 0.03 | 0.72 | 58$^{d}$ | 0.007 | 0.003 | 0.032 | 72$^{c}$ |
| | | CL2 | 113 | 4.41 | 4.23 | 4.21 | 128$^{b}$ | 1.34 | 0.58 | 2.02 | 137$^{a}$ | 0.067 | 0.015 | 0.143 | 124$^{a}$ |
| | | GL | 112 | 7.23 | 6.12 | 6.47 | 137$^{a}$ | 0.23 | 0.20 | 0.13 | 90$^{b}$ | 0.016 | 0.013 | 0.016 | 100$^{b}$ |
| | | DBL | 122 | 2.15 | 1.97 | 0.87 | 76$^{d}$ | 0.15 | 0.15 | 0.01 | 76$^{c}$ | 0.004 | 0.001 | 0.007 | 56$^{d}$ |
| | 2016 | CL1 | 113 | 1.79 | 1.40 | 1.81 | 72$^{d}$ | 0.07 | 0.02 | 0.14 | 52$^{d}$ | 0.004 | 0.001 | 0.014 | 52$^{c}$ |
| | | CL2 | 100 | 7.55 | 6.21 | 6.18 | 146$^{a}$ | 1.88 | 0.36 | 7.16 | 130$^{a}$ | 0.141 | 0.015 | 0.560 | 125$^{a}$ |
| | | GL | 101 | 4.59 | 3.37 | 4.35 | 129$^{b}$ | 0.12 | 0.08 | 0.15 | 111$^{c}$ | 0.007 | 0.003 | 0.014 | 81$^{b}$ |
| | | DBL | 119 | 2.27 | 1.61 | 2.20 | 94$^{c}$ | 0.16 | 0.16 | 0.01 | 120$^{b}$ | 0.003 | 0.003 | 0.003 | 85$^{b}$ |
| Aba Gerima | 2015 | CL1 | 50 | 5.95 | 3.08 | 7.29 | 61$^{b}$ | 1.78 | 0.51 | 4.82 | 62$^{b}$ | 0.108 | 0.022 | 0.330 | 52$^{b}$ |
| | | CL2 | 55 | 3.46 | 2.10 | 4.01 | 46$^{c}$ | 1.39 | 0.18 | 4.70 | 51$^{c}$ | 0.078 | 0.005 | 0.367 | 42$^{d}$ |
| | | GL | 54 | 12.10 | 4.85 | 14.71 | 69$^{a}$ | 1.82 | 0.34 | 8.67 | 52$^{c}$ | 0.793 | 0.013 | 4.977 | 48$^{c}$ |
| | | DBL | 64 | 6.38 | 2.90 | 8.47 | 57$^{b}$ | 5.13 | 3.92 | 4.24 | 73$^{a}$ | 0.431 | 0.186 | 0.743 | 66$^{a}$ |
| | 2016 | CL1 | 44 | 5.96 | 3.57 | 5.83 | 52$^{b}$ | 0.77 | 0.25 | 1.58 | 53$^{c}$ | 0.036 | 0.010 | 0.096 | 68$^{b}$ |
| | | CL2 | 56 | 3.76 | 2.45 | 1.88 | 42$^{c}$ | 0.15 | 0.07 | 0.26 | 37$^{d}$ | 0.005 | 0.002 | 0.011 | 34$^{c}$ |
| | | GL | 47 | 19.10 | 19.42 | 12.29 | 85$^{a}$ | 1.63 | 0.84 | 2.95 | 65$^{a}$ | 0.393 | 0.103 | 0.810 | 75$^{a}$ |
| | | DBL | 71 | 4.50 | 3.62 | 5.66 | 55$^{b}$ | 4.75 | 0.37 | 12.04 | 56$^{b}$ | 0.348 | 0.009 | 1.038 | 63$^{b}$ |
| Dibatie | 2015 | CL1 | 39 | 3.83 | 2.58 | 3.55 | 40$^{a}$ | 1.51 | 1.51 | 0.03 | 54$^{a}$ | 0.071 | 0.011 | 0.109 | 43$^{b}$ |
| | | CL2 | 42 | 5.21 | 3.31 | 5.77 | 42$^{a}$ | 1.36 | 0.37 | 3.17 | 44$^{b}$ | 0.092 | 0.015 | 0.281 | 50$^{a}$ |
| | | GL | 42 | 3.54 | 1.49 | 5.00 | 40$^{a}$ | 2.05 | 0.14 | 7.30 | 36$^{c}$ | 0.052 | 0.002 | 0.178 | 37$^{c}$ |
| | | DBL | 41 | 2.75 | 0.95 | 3.99 | 39$^{a}$ | 0.89 | 0.45 | 1.14 | 45$^{b}$ | 0.054 | 0.005 | 0.133 | 42$^{b}$ |
| | 2016 | CL1 | 42 | 1.64 | 1.34 | 1.14 | 32$^{b}$ | 1.00 | 0.20 | 2.74 | 37$^{b}$ | 0.030 | 0.004 | 0.092 | 35$^{b}$ |
| | | CL2 | 36 | 3.55 | 2.10 | 5.26 | 47$^{a}$ | 1.09 | 0.42 | 1.48 | 49$^{a}$ | 0.051 | 0.010 | 0.095 | 43$^{a}$ |
| | | GL | 36 | 2.58 | 1.85 | 1.81 | 42$^{a}$ | 0.04 | 0.03 | 0.06 | 27$^{c}$ | 0.001 | 0.001 | 0.003 | 30$^{c}$ |
| | | DBL | 32 | 2.07 | 2.01 | 0.94 | 45$^{a}$ | 0.12 | 0.04 | 0.29 | 33$^{c}$ | 0.003 | 0.001 | 0.007 | 27$^{c}$ |

*n*: Number of observations for each season and study site; MRs within the same column with different letters indicate that the difference in runoff, SC, and SL between land use types were statistically significant ($|Z| > 1.96$, and $P < 0.05$), according to the Mann-Whitney U test. Land use abbreviations are defined in Table 3.1.

### 3.3.3 Effectiveness of SLM practices in reducing runoff and soil loss

The effectiveness of SLM practices in reducing runoff and SL was calculated from the relative seasonal runoff and SL values (Table 3.4). The average relative reduction in runoff due to SLM practices ranged from 11% to 58% at Guder, 20% to 68% at Aba Gerima, and 11% to 55% at Dibatie. The corresponding reduction in SL ranged from 39% to 86% at Guder, 57% to 94% at Aba Gerima, and 38% to 87% at Dibatie (Table 3.4). These results clearly demonstrate that the effectiveness of SLM practices was generally higher for SL reduction than for runoff, probably because of the limited storage capacity for the infiltration of excess runoff. Sultan et al. (2018) found a runoff conservation efficiency for structural SLM practices ranging from 25% to 50% at these three sites. Elsewhere in Ethiopia, SLM measures have also been reported to be much more effective in reducing SL than in reducing runoff (Herweg and Ludi, 1999; Taye et al., 2013; Adimassu et al., 2014; Amare et al., 2014).

The Mann-Whitney U test results (Figure 3.6) showed that the median runoff and SL from treated plots (plots with SLM practices) were significantly ($|Z| > 1.96$, $P < 0.05$) smaller as compared to runoff and SL from untreated plots (plots without SLM practices) at all sites and during both measuring seasons. These results further demonstrate the substantial effectiveness of SLM practices in reducing soil erosion regardless of land use and agro-ecology. Studies in the northern highlands of Ethiopia (Gebrermichael et al., 2005; Nyssen et al., 2007b; Taye et al., 2015) have also found significant reductions in runoff and SL resulting from the use of structural SLM practices. Previous studies of croplands in the Upper Blue Nile basin (Herweg and Ludi, 1999; Adimassu et al., 2014; Amare et al., 2014) obtained similar findings, although studies that include different land use types and agro-ecologies (like ours) are rare in this basin.

**Table 3.4** Relative reduction in seasonal runoff and soil loss (SL) due to the different SLM practices in different land use types at the three study sites.

| Land use | SLM practice | Guder 2015 | Guder 2016 | Guder Mean | Aba Gerima 2015 | Aba Gerima 2016 | Aba Gerima Mean | Dibatie 2015 | Dibatie 2016 | Dibatie Mean |
|---|---|---|---|---|---|---|---|---|---|---|
| Relative reduction in runoff (%)[a] | | | | | | | | | | |
| CL1 | SB | 56 | 26 | 42 | 36 | 24 | 30 | 65 | 38 | 51 |
| | F | 50 | 14 | 32 | 32 | 37 | 35 | 65 | 45 | 55 |
| | SBG | 50 | 17 | 33 | 31 | 46 | 34 | 63 | 46 | 55 |
| CL2 | SB | 22 | 33 | 27 | 27 | 13 | 20 | 36 | 34 | 35 |
| | F | 23 | 40 | 32 | 40 | 18 | 29 | 34 | 24 | 29 |
| | SBG | 20 | 38 | 29 | 36 | 8 | 22 | 42 | 45 | 43 |
| GL | E | 31 | 33 | 32 | 29 | 58 | 44 | 15 | 13 | 14 |
| | E+T | 61 | 56 | 58 | 69 | 66 | 67 | 36 | 25 | 30 |
| DBL | E | 19 | 3 | 11 | 37 | 45 | 41 | 4 | 18 | 11 |
| | E+T | 40 | 28 | 34 | 65 | 71 | 68 | 35 | 33 | 34 |
| Relative reduction in SL (%)[a] | | | | | | | | | | |
| CL1 | SB | 82 | 74 | 78 | 52 | 69 | 61 | 83 | 88 | 86 |
| | F | 79 | 71 | 75 | 52 | 68 | 60 | 79 | 86 | 83 |
| | SBG | 76 | 84 | 80 | 56 | 73 | 65 | 83 | 91 | 87 |
| CL2 | SB | 50 | 85 | 67 | 57 | 63 | 60 | 57 | 70 | 63 |
| | F | 54 | 90 | 72 | 60 | 61 | 61 | 57 | 80 | 68 |
| | SBG | 62 | 92 | 77 | 64 | 69 | 66 | 79 | 94 | 86 |
| GL | E | 57 | 84 | 71 | 17 | 98 | 57 | 23 | 53 | 38 |
| | E+T | 82 | 89 | 86 | 58 | 98 | 78 | 75 | 79 | 77 |
| DBL | E | 29 | 48 | 39 | 63 | 80 | 72 | 50 | 59 | 55 |
| | E+T | 80 | 87 | 84 | 91 | 97 | 94 | 80 | 91 | 86 |

[a] The relative runoff and SL were calculated by dividing the absolute seasonal values (Figure 3.4) from treated plots (plots with SLM) by those from the control plots (plots with no SLM). The quotient was then multiplied by 100; i.e., the runoff and SL from the control plots are assumed to be 100%. The relative reduction due to each SLM practice was then calculated by subtracting the relative runoff and SL values from 100. Abbreviations are defined in Table 3.1.

Furthermore, differences in runoff between plots with different SLM practices on croplands (SB, F and SBG) were not generally significant during the study period, probably because of similarities in runoff storage capacity (Taye et al., 2015). However, SL values differed significantly among plots treated with SB, F, and SBG, especially in 2016; the SBG values were significantly lower than those of SB and F, largely as a result of well-established grass cover (Figure 3.5), which provided good soil protection. Amare et al. (2014) also found that soil bunds combined with different grasses performed better than soil bunds alone in controlling soil and water losses in the Upper Blue Nile basin. Our results imply that the integration of structural and vegetative SLM practices is the most effective strategy for reducing SL in croplands. This combination could have the additional benefit to farmers of providing a considerable amount of forage biomass in areas occupied by bunds and not suitable for crop cultivation.

In non-croplands, the differences in median runoff between plots with different treatments (E vs. E+T) were generally significant in both seasons, whereas the differences in SL were statistically significant only in the first year (Figure 3.6). These results clearly demonstrate that the effectiveness of exclosures was better in the second year than in the first, most likely because of the restoration of protective vegetation cover in fenced plots (Figure 3.5). This result further suggests that the use of exclosures alone is quite suitable where the only concern is soil loss, whereas exclosures with trenches are suitable when the concern is both runoff and soil loss. Mekuria and Aynekulu (2013) reported that in grazing lands in Northern Ethiopia exclosures have a significant positive effect on the restoration of degraded soils, and Yayneshet et al. (2009) and Simona et al. (2018) reported that exclosures are effective for restoring plant species composition, diversity, biomass, cover, and structure of both herbaceous and woody vegetation. In addition, Zhang et al. (2015) reported that water filtration, sediment conservation, and slope protection were most effective in areas with high vegetation coverage. A recent study in southwestern Iran (Yaghobi et al., 2018) also indicated that exclosure treatments significantly reduced soil and organic carbon loss in rangelands. Hence, our findings provide additional evidence that exclosure management is a promising strategy for reducing soil erosion in non-agricultural landscapes and can help to maintain ecosystem functions in the Upper Blue Nile basin and other similar environments.

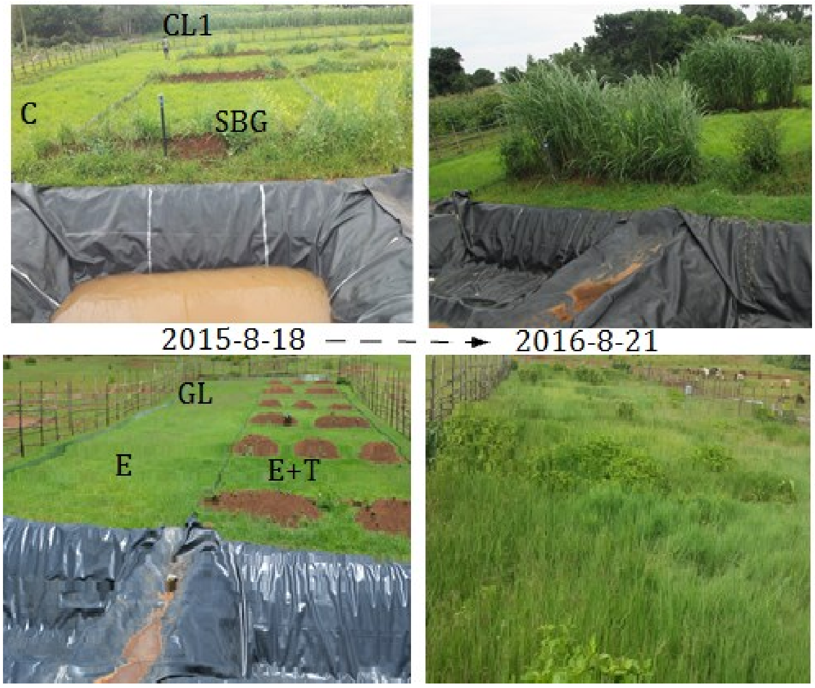

**Figure 3.5** Evolution of SLM practices between the two study seasons for cropland (top) and grazing land (bottom) at the Aba Gerima site. Abbreviations are defined in Table 3.1.

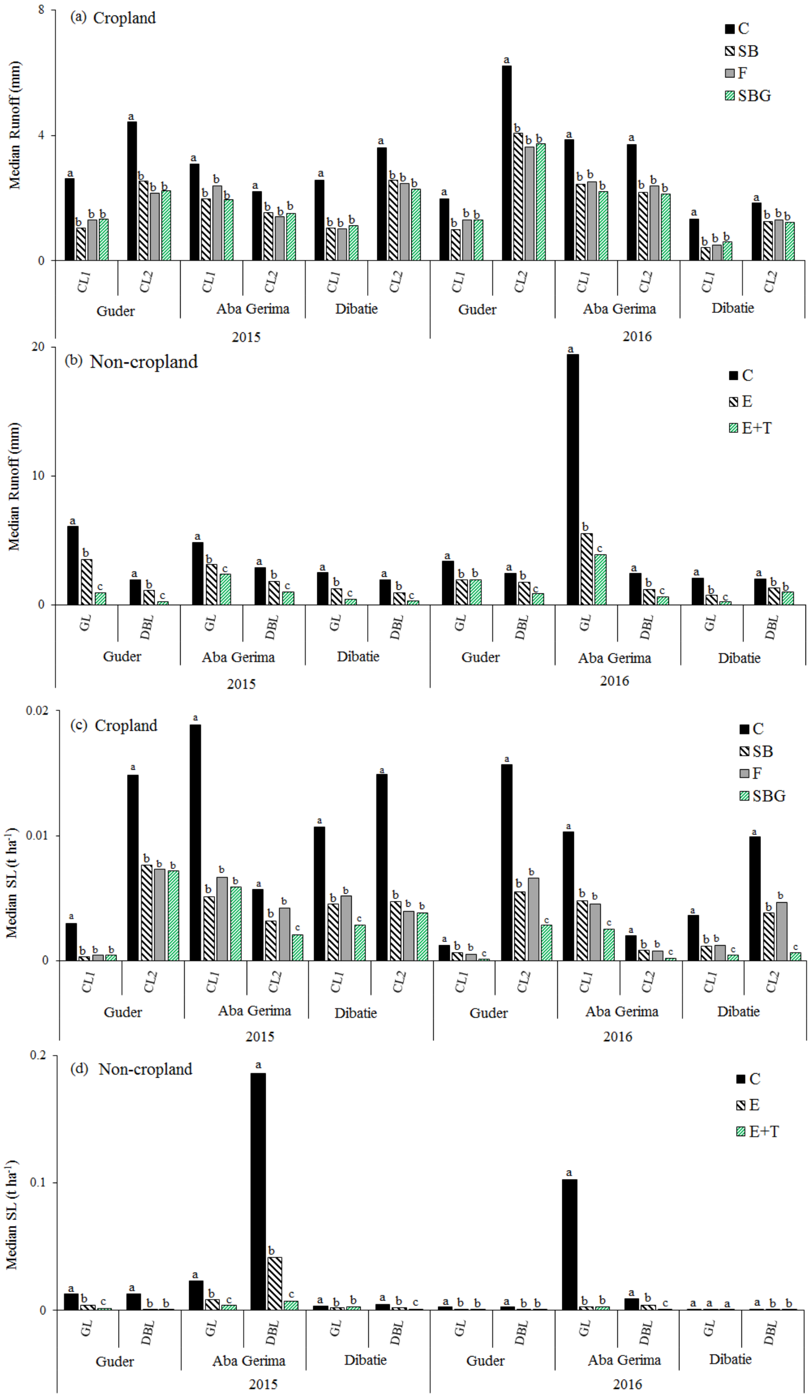

**Figure 3.6** The median runoff and SL from different land use types and treatments at the Guder, Aba Gerima, and Dibatie sites during the 2015 and 2016 study periods. For each land use type at each site, bars with the different letters indicate that the differences in daily runoff or SL between the different treatments were statistically significant ($|Z| > 1.96$ and $P < 0.05$; Mann-Whitney U test). Abbreviations are defined in Table 3.1.

### 3.3.4 Temporal variability in runoff and soil loss

Most CV (%), skewness, and kurtosis values for daily runoff and SL were extremely high (Figure 3.7), mostly because of the variability in rainfall (Table 3.2) and protective vegetative cover in the rainy season. Case studies in Guder (Kindiye, 2016; Sultan et al., 2017) indicated that runoff and SL clearly varied as the rainy season progressed. A watershed scale analysis at the same study site (Figure 2.3, chapter 2) also demonstrated that runoff and sediment concentration (SC) magnitudes varied greatly during different parts of the rainy season and were greatly influenced by the magnitude and timing of intense rain events.

As shown in Figure 3.7, SL was extremely variable over the rainy season at all sites (CV = 75–653, skewness *Z* values = 4–38, and kurtosis *Z* values = 3–188), and much more variable than runoff (CV = 41–159, skewness *Z* values = 0–23, and kurtosis *Z* values = 0–91). This extreme variability in SL can be explained partly by changes in the sediment supply during the rainy season and the occurrence of intense rain events, particularly near the beginning of the rainy season. The rapid development of protective vegetative cover as the rainy season progressed (Herweg and Ludi, 1999) may also explain the extreme variability in SL. Thus, great care must be taken when analyzing SL data collected in locations where biophysical factors exhibit high temporal variability.

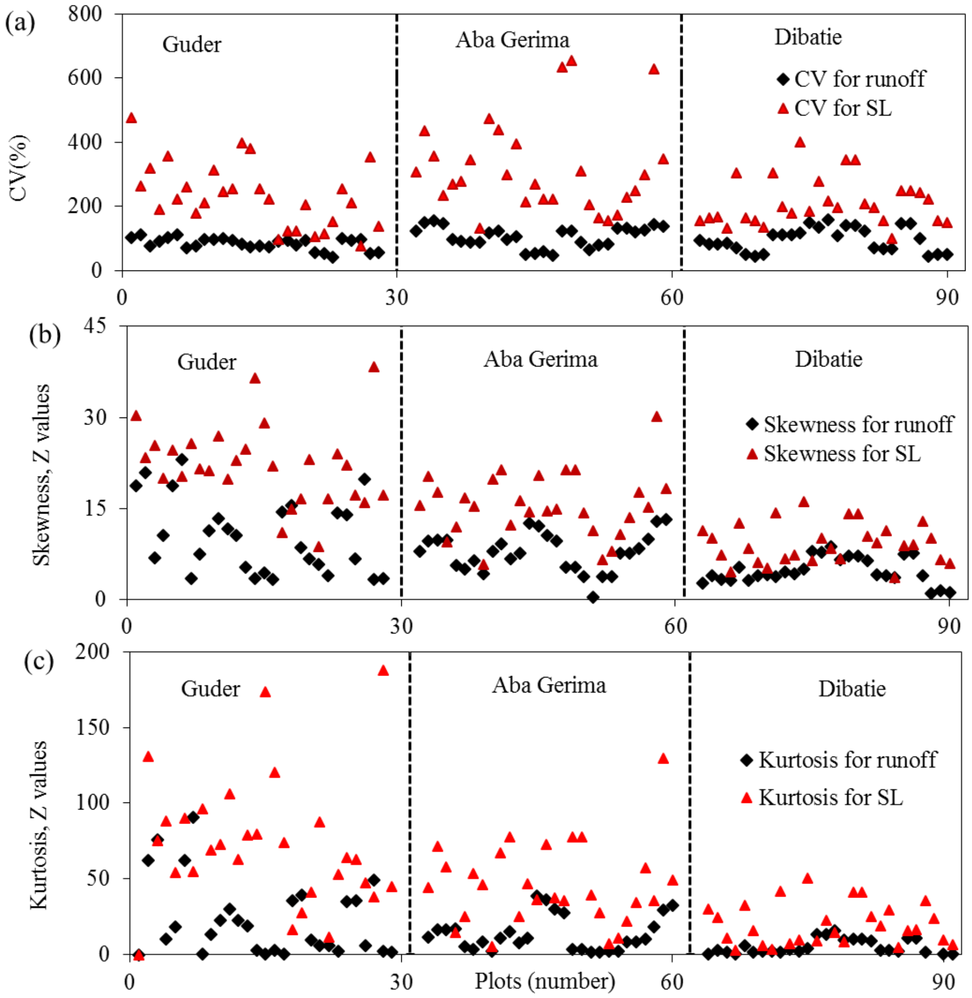

**Figure 3.7** Descriptive statistics for daily runoff and SL data: (a) coefficient of variation (CV) and Z values for (b) skewness and (c) kurtosis: Number of plots on the x-axis represent the plots defined in Table 3.1 (14 plots at each site) from which the data collected during both sampling seasons were pooled (i.e., 28 data sets at each site). The high Z values for skewness and kurtosis indicate that both runoff and SL varied significantly ($|Z| > 1.96$ and $P < 0.05$) over the rainy season.

Our results also demonstrate that SL greatly varied between the two years, with the seasonal rates generally being higher in the first year than in the second (Figure 3.4), regardless of the rainfall and runoff amounts. Higher SL in the first year was partly attributable to the residual effects from previous traditional land use activities (multiple tillage and heavy grazing) that likely deteriorated the physical properties of the topsoil (Mwendera and Saleem, 1997a; Basic et al., 2004).The considerable soil disturbance during plot installation and the absence of protective cover on bunds of excavated subsoil in 2015 (Figure 3.5, left) might also explain the higher SL values. Peng et al. (2014) observed that deteriorated, freshly exposed, and disturbed subsoil materials are highly susceptible to the detaching and cutting actions of raindrops and flowing water.

Clear differences between the two study years in runoff and SL among the different treatments in different land use types is graphically illustrated in double-mass curves (Figure 3.8). Shorter lines and smaller slopes in the curves indicate that runoff and SL increased less with number of days with rainfall compared with longer lines and higher slopes (Herweg and Ludi, 1999; Amare et al., 2014). At all sites, the change in slope between the two seasons is more important than the change in line length, mainly because runoff amounts were comparable but SL was lower in 2016. This situation was more pronounced in the treated plots, indicating that the effect of SLM practices was not immediate; rather, they gradually became more effective in reducing SL with the development of protective vegetative cover in the fenced plots and bunds (Figure 3.5). Hence, the relatively steeper slopes of the double-mass curves for SB, F, SBG, and E+T in the first year (Figure 3.8) can be explained by the absence or general lack of protective materials on exposed areas (Prosdocimi et al., 2016), which accounted for 16% to 30% of the total plot area (Table 3.1). This finding suggests that it is important to support conservation structures composed of soil with covers that provide protection against the detachment and cutting actions of rainfall and runoff so as to achieve the intended immediate effectiveness in soil erosion reduction.

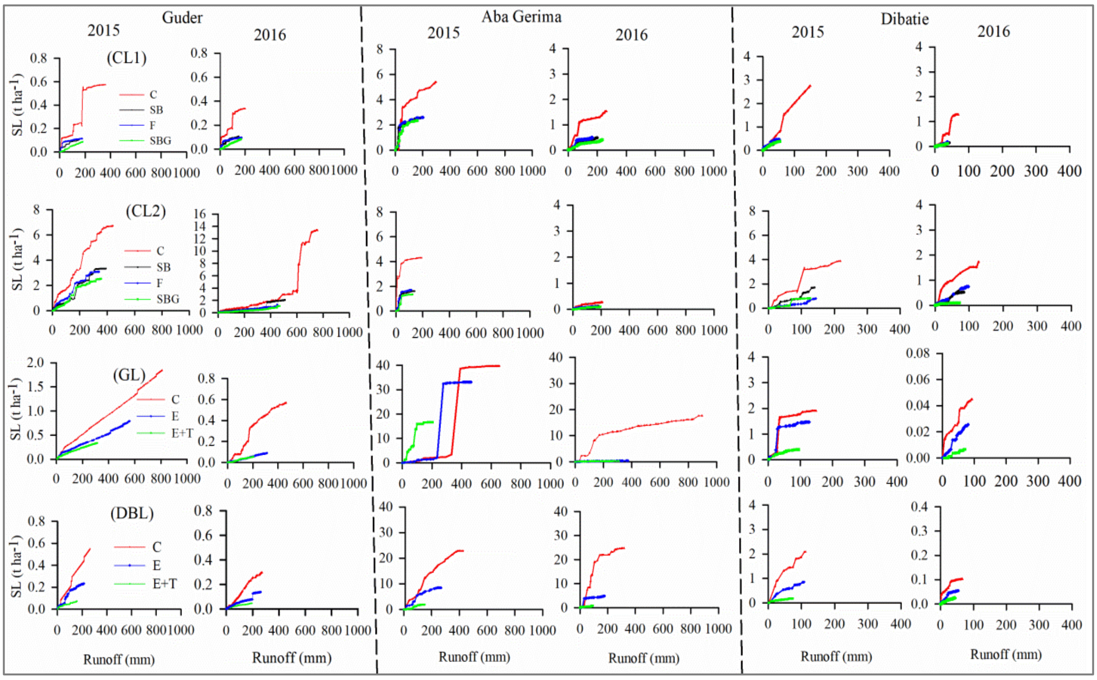

**Figure 3.8** Cumulative runoff and soil loss (SL) relationships for the different treatments and land use types at the Guder, Aba Gerima, and Dibatie sites during the 2015 and 2016 sampling seasons; each dot represents the daily runoff and SL amounts along the progression of rainy season (June to October). The abbreviations are defined in Table 3.1.

The variation in the effects of SLM practices between the two seasons can also be observed in regression curves fitted to daily runoff and SL data from the control and treated plots (Figure 3.9, Table 3.5). The daily runoff from treated plots amounted to 21% to 86% of that from the corresponding control plots in 2015 versus 28% to 87% in 2016. The corresponding SL values, however, were 1% to 86% in 2015 versus 1% to 27% in 2016 (Table 3.5). The regression curves (Figure 3.9, left) and parameters for runoff (Table 3.5) showed statistically significant relationships between treated and untreated plots in both seasons ($R^2$ values of 0.42–0.99 and $P < 0.01$). The same relationships for SL were significant for 21 regression curves in the first year ($R^2$ range of 0.35–93 and $P < 0.01$ for the 14 curves, and $R^2$ range of 0.12–0.41 and $P < 0.05$ for the rest of Six) and only for four curves in the second year ($R^2 = 0.52$ and $P < 0.01$ for one curve, and $R^2$ range of 0.15–0.30 and $P < 0.05$ for the rest of three).

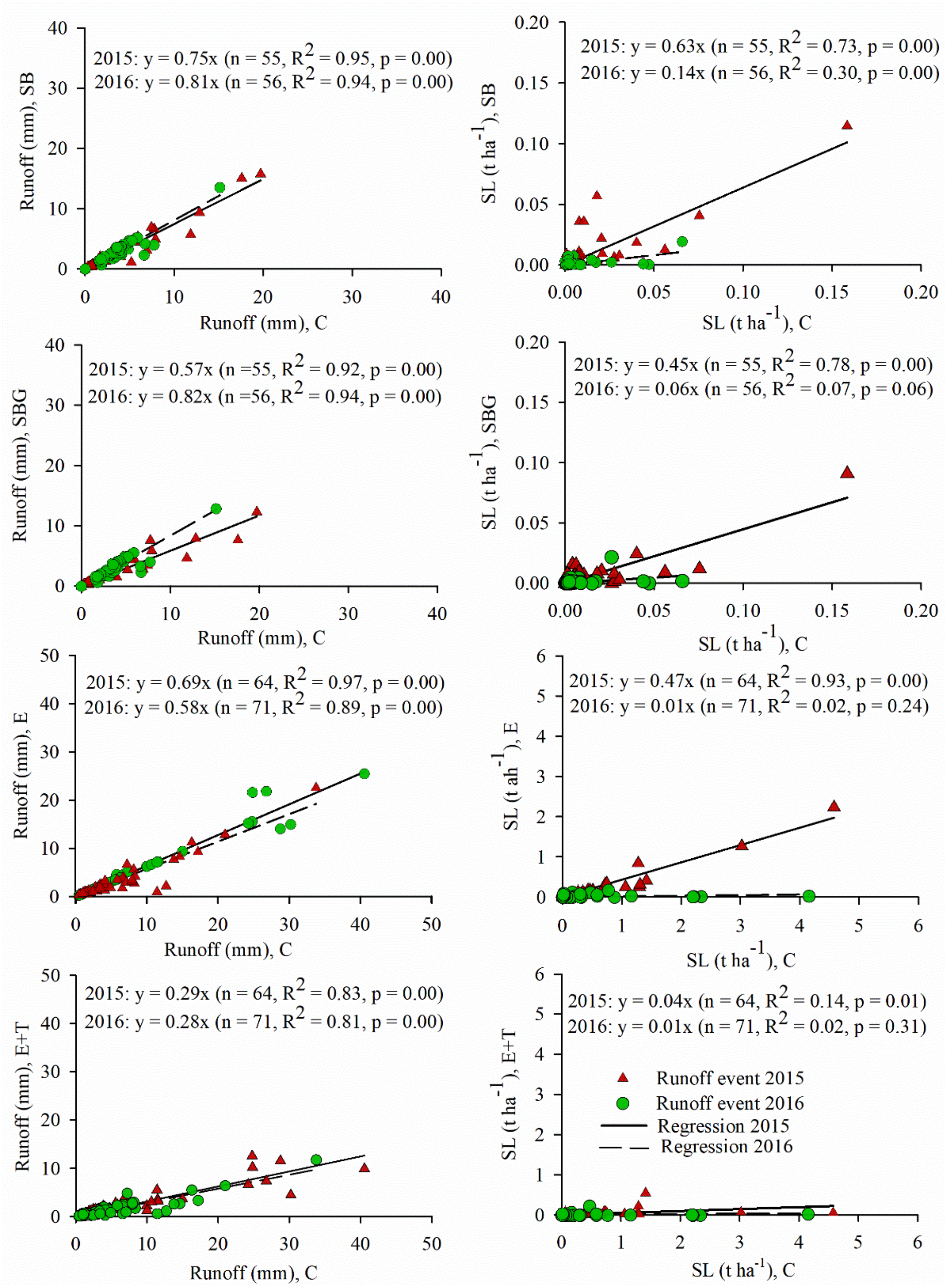

**Figure 3.9** Regression curves fitted to daily runoff (left) and SL (right) data for control (C) versus treated (SB and SBG for CL2, and E and E+T for DBL) plots at the Aba Gerima site. *Fanya juu* was not included in this analysis because it showed similar results as the soil bund at all sites during both seasons (Figure 3.6). The detailed calculations and parameters of these regression curves are given in Table 3.5. Abbreviations are defined in Table 3.1.

**Table 3.5** Parameters of linear regression curves fitted to daily runoff and soil loss (SL) data from plots with & without SLM practice (Figure 3.9).

| Site | Land use | SLM practice | 2015 | | | | | 2016 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | *n* | Runoff (mm) | | SL (t ha$^{-1}$) | | *n* | Runoff (mm) | | SL (t ha$^{-1}$) | |
| | | | | *a* | R$^2$ | *a* | R$^2$ | | *a* | R$^2$ | *a* | R$^2$ |
| Guder | CL1 | SB | 113 | 0.46 | $0.96^{**}$ | 0.05 | $0.25^{*}$ | 113 | 0.78 | $0.94^{**}$ | 0.03 | 0.04 |
| | | SBG | 113 | 0.40 | $0.81^{**}$ | 0.02 | 0.03 | 113 | 0.49 | $0.60^{**}$ | 0.01 | 0.02 |
| | CL2 | SB | 113 | 0.86 | $0.94^{**}$ | 0.70 | $0.78^{**}$ | 100 | 0.50 | $0.66^{**}$ | 0.02 | 0.02 |
| | | SBG | 113 | 0.77 | $0.96^{**}$ | 0.37 | $0.60^{**}$ | 100 | 0.46 | $0.66^{**}$ | 0.01 | 0.02 |
| | GL | E | 112 | 0.67 | $0.99^{**}$ | 0.49 | $0.89^{**}$ | 101 | 0.45 | $0.62^{**}$ | 0.01 | 0.02 |
| | | E+T | 112 | 0.30 | $0.88^{**}$ | 0.15 | $0.50^{**}$ | 101 | 0.53 | $0.65^{**}$ | 0.01 | 0.00 |
| | DBL | E | 122 | 0.73 | $0.59^{**}$ | 0.05 | 0.01 | 119 | 0.64 | $0.71^{**}$ | 0.03 | 0.00 |
| | | E+T | 122 | 0.43 | $0.42^{**}$ | 0.01 | 0.00 | 119 | 0.34 | $0.55^{**}$ | 0.01 | 0.01 |
| Aba Gerima | CL1 | SB | 50 | 0.75 | $0.93^{**}$ | 0.60 | $0.77^{**}$ | 44 | 0.62 | $0.79^{**}$ | 0.27 | $0.52^{**}$ |
| | | SBG | 50 | 0.64 | $0.92^{**}$ | 0.26 | $0.61^{**}$ | 44 | 0.71 | $0.77^{**}$ | 0.09 | $0.15^{*}$ |
| | CL2 | SB | 55 | 0.75 | $0.95^{**}$ | 0.63 | $0.73^{**}$ | 56 | 0.81 | $0.94^{**}$ | 0.14 | $0.30^{*}$ |
| | | SBG | 55 | 0.57 | $0.92^{**}$ | 0.45 | $0.78^{**}$ | 56 | 0.82 | $0.94^{**}$ | 0.06 | 0.07 |
| | GL | E | 54 | 0.71 | $0.98^{**}$ | 0.86 | $0.99^{**}$ | 47 | 0.83 | $0.95^{**}$ | 0.01 | 0.06 |
| | | E+T | 54 | 0.21 | $0.85^{**}$ | 0.19 | $0.77^{**}$ | 47 | 0.34 | $0.51^{**}$ | 0.01 | 0.00 |
| | DBL | E | 64 | 0.69 | $0.97^{**}$ | 0.47 | $0.93^{**}$ | 71 | 0.58 | $0.89^{**}$ | 0.01 | 0.02 |
| | | E+T | 64 | 0.29 | $0.83^{**}$ | 0.04 | $0.14^{*}$ | 71 | 0.28 | $0.81^{**}$ | 0.01 | 0.02 |
| Dibatie | CL1 | SB | 39 | 0.27 | $0.77^{**}$ | 0.07 | $0.35^{**}$ | 42 | 0.36 | $0.68^{**}$ | 0.02 | 0.05 |
| | | SBG | 39 | 0.30 | $0.79^{**}$ | 0.05 | $0.12^{*}$ | 42 | 0.32 | $0.65^{**}$ | 0.01 | 0.00 |
| | CL2 | SB | 42 | 0.62 | $0.94^{**}$ | 0.33 | $0.48^{**}$ | 36 | 0.59 | $0.98^{**}$ | 0.07 | 0.07 |
| | | SBG | 42 | 0.51 | $0.68^{**}$ | 0.22 | $0.24^{*}$ | 36 | 0.39 | $0.94^{**}$ | 0.01 | 0.00 |
| | GL | E | 42 | 0.85 | $0.97^{**}$ | 0.77 | $0.97^{**}$ | 36 | 0.82 | $0.96^{**}$ | 0.14 | $0.17^{*}$ |
| | | E+T | 42 | 0.51 | $0.86^{**}$ | 0.39 | $0.45^{**}$ | 36 | 0.71 | $0.93^{**}$ | 0.05 | 0.10 |
| | DBL | E | 41 | 0.79 | $0.95^{**}$ | 0.34 | $0.41^{*}$ | 32 | 0.87 | $0.97^{**}$ | 0.13 | 0.08 |
| | | E+T | 41 | 0.53 | $0.69^{**}$ | 0.45 | $0.44^{**}$ | 32 | 0.67 | $0.88^{**}$ | 0.05 | 0.03 |

*n* is the number of daily observations in each sampling period and *a* is the regression coefficient for the linear function, $y = ax$ (Figure 3.9). Note that the R$^2$ values < 0.005 are rounded to 0.00. $^{**}P < 0.01$; $^{*}P < 0.05$. Abbreviations are defined in Table 3.1.

The slope (*a*) and $R^2$ values of the regression curves are a measure of the effectiveness of water and soil conservation SLM practices. Steep curves (higher *a* and $R^2$ values) indicate comparable runoff and SL amounts from plots with and without SLM practices. This further demonstrates lower effectiveness of SLM practices, probably caused by a decline in the storage capacity for infiltration excess runoff (Taye et al., 2015), as well as by a considerable loss of sediment from uncovered exposed parts of bunds during the first year (Adimassu et al., 2014; Amare et al., 2014). In contrast, flat curves (lower *a* and $R^2$ values) indicate higher effectiveness of SLM practices, which as noted above, was more pronounced for SL in 2016 (Table 3.5). This result provides additional evidence supporting the sowing or planting of suitable fast-growing grass species in any areas not directly involved in runoff storage and production once construction of structural SLM practices is complete. Elephant grass planted to reinforce soil bunds (Figure 3.5, top right) grows quickly, and part (≥ 16%, depending on the slope gradient) of the cultivable land occupied by structural SLM practices could be compensated partly by biomass yield that could be harvested about twice per season. Likewise, the attainment of dense grass cover (Figure 3.5, bottom right) and a relatively low SL in exclosures in 2016 (Figure 3.8) suggests that soil erosion control in non-croplands can best be achieved by allowing natural vegetation to remain undisturbed for as long as possible. However, further investigation is needed in consideration of ecological succession and other possible effects such integrated measures might have, for example, effects on soil properties, biomass, and biodiversity.

## 3.4 Conclusions

The results of this study revealed that magnitudes of runoff and SL were variable across different agro-ecologies and land use types in the Upper Blue Nile basin of Ethiopia. Analysis of runoff and SL data showed that erosion was generally higher in the midland (Aba Gerima) agro-ecology than in the highland and lowland agro-ecologies, largely because of the occurrence of intense rain events during June and July, when the sediment supply is high and protective vegetative cover is low. This study also showed that free grazing on steeply sloped non-croplands in intense rain areas leads to greater losses of water and soil as compared to other land uses. This result is likely attributable to grazing pressure and continuous removal of protective cover and organic materials. In contrast, the soil loss rates for fenced plots were generally below the permissible limit, indicating a positive effect of banning or limiting free grazing.

The studied SLM practices significantly reduced runoff and soil loss as compared to conventional practices, implying that it is worth investing in the use of SLM to control soil erosion. Nonetheless, the effectiveness of all of the studied SLM practices was more important in the reduction of soil loss than of runoff, which probably can be attributed to the limited storage capacity to capture infiltration excess runoff water. Additional strategies may be needed to manage excess runoff water so as to reduce on-site and off-site consequences.

Of the SLM practices investigated on croplands, soil bunds reinforced with grass performed best in controlling soil loss, indicating the effectiveness of integrating structural and vegetative measures to control soil erosion from cultivated lands. On non-croplands, however, exclosures and exclosures with trenches generally exhibited similar effects on soil loss but different effects on runoff, implying that exclosures alone might be suitable where soil loss is the main concern. Exclosures and trenches, however, may be needed where runoff and soil loss are both a concern. Soil loss reduction was better in 2016 than in 2015 for soil bunds reinforced by grass and exclosures, most likely because of improvements in protective vegetative cover. Vegetation restoration is therefore considered one of the best SLM practices for improving protective capacity against soil erosion. However, further investigation is needed in consideration of ecological succession and other possible effects such integrated measures might have, for example, effects on soil properties, biomass, and biodiversity.

Over all, this study provides useful information for policymakers and land managers involved in the promotion of large-scale implementation of suitable SLM practices in the Upper Blue Nile basin as well as in other regions with similar climatic and topographic settings.

# Chapter 4

# Variability of soil properties as influenced by land use and management practices in the Upper Blue Nile basin, Ethiopia

This chapter is submitted to journal as:

Ebabu, K., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Aklog, D., Masunaga, T., Tsubo, M., Sultan, D., Fenta, A.A. and Yibeltal, M. (2019). Variability of soil properties as influenced by land use and management practices in the Upper Blue Nile basin, Ethiopia. Soil & Tillage Research

## 4.1 Introduction

Ethiopia is among the developing sub-Saharan African countries where population pressure is enormously increasing land use intensity, in most cases beyond the bounds of soil resilience, and where soil erosion by water is a principal cause of nutrient depletion (Misra et al., 2003) and nutrient imbalances (Haileslassie et al., 2005) in soils. The degree of soil degradation due to soil erosion by water, however, differs across the landscapes of Ethiopia, mainly because of large variations in topography, climate, lithology, and land use, which in turn cause high spatial variability in soil properties and the soil's susceptibility to degradation (Sanchis et al., 2008; Dessalegn et al., 2014; Teferi et al., 2016). For example, studies in the Upper Blue Nile basin of Ethiopia (Bewket and Teferi, 2009; Nyssen et al., 2009; Kindiye, 2013; Taye et al., 2013; Adimassu et al., 2014; Amare et al., 2014; Kindiye, 2016) have reported soil loss rates ranging from 37 to 246 t ha$^{-1}$ yr$^{-1}$, reflecting spatial variation in soil erosion rates and the associated soil degradation. Similarly, average soil erosion-associated losses of primary soil nutrients (N, P, and K) in the northern and central highlands of Ethiopia vary from 0.02 to 0.91 kg ha$^{-1}$ yr$^{-1}$ for available phosphorus ($P_{av}$), and from 0.78 to 47.81 kg ha$^{-1}$ yr$^{-1}$ for total nitrogen (TN), depending on the land use and biophysical factors such as rainfall, vegetation cover, and soil type (Haileslassie et al., 2007; Haregeweyn et al., 2008; Girmay et al., 2009; Adimassu et al., 2014). Studies conducted in different parts of the world have shown that nutrient depletion and soil degradation rates are greatly influenced by soil properties, land use types, and land management practices (Gafur et al., 2003; Pardini et al., 2003; Visser et al., 2005), all of which show characteristically high spatial and temporal variability in the landscapes of Ethiopia (Bewket and Stroosnijder, 2003; Gelaw et al., 2014). Therefore, to achieve understanding of soil quality and to develop management strategies for sustainable ecosystem functions, knowledge of how key soil properties vary in different environments under various land use and land management interventions is essential (Doran, 1996).

In Ethiopia, owing to concerns about increasing soil degradation and the associated loss of productivity, plans for sustainable land management (SLM) have been developed with two main objectives: (1) to maintain soil quality (Shahab et al., 2013), and (2) to integrate ecological systems with socio-economic and political principles in the management of land for agricultural and other purposes with the aim of achieving intra- and intergenerational equity (Hurni, 1996; Pender et al., 2006). SLM programs targeting wide geographical regions began to be implemented in 2008 (Schmidt and Tadesse, 2017).

These programs promote practices such as the construction of soil or stone bunds, *fanya juu*, bench terraces, trenches, cut-off drains, drainage canals, and check dams, as well as the planting of different shrub and tree species and the establishment of area exclosures (Tefera and Sterk, 2010), see the detail in sections 1.1.4 and 1.4.4

Remarkable reductions in soil loss through the use of SLM practices have been reported in different parts of the Ethiopian highland (Herweg and Ludi, 1999; Gebrermichael et al., 2005; Nyssen et al., 2007b; Amare et al., 2014). Nonetheless, few studies have considered the extent to which variations in soil properties are influenced by land use and management practices, and they have been concentrated in the dry areas of Northern Ethiopia where soils are greatly degraded (Mekuria et al., 2007; Nyssen et al., 2007a; Haregeweyn et al., 2008; Girmay et al., 2009; Yayneshet et al., 2009). Moreover, the high costs of implementing land management practices and conducting soil laboratory analyses, especially of multiple soil samples collected across wide areas over time, also discourage such studies.

The current study was conducted to investigate the effects of land use and management practices on selected soil properties in three different agro-ecological zones of the Upper Blue Nile basin. The specific objectives were (1) to analyze selected soil physicochemical properties across lowland, midland, and highland agro-ecological zones and among three main land use types (cropland, grazing land, and degraded bushland), and (2) to evaluate changes in soil quality properties following the implementation of SLM practices (*fanya juu*, soil bunds reinforced with grass, exclosures, and exclosures with trenches). To obtain site-specific and appropriate information useful in evaluating the design and implementation of suitable SLM practices, data for the study were generated from experimental plots established in 2015.

## 4.2 Materials and methods

### 4.2.1 Soil sampling

In the current study, soil samples from the three sites (agro-ecological zones) were collected from plots established in three land use types (cropland, grazing land, and bushland) in which different management practices (control, *fanya juu,* or soil bund reinforced with grass in cropland plots, and control, exclosure, or exclosure with trenches in bushland and grazing land plots) had been implemented (Figure 4.1 and Table 4.1). The sampled plots (Figure 4.1), each with an area of 180 $m^2$ (6 m × 30 m), were originally established in 2015 for runoff and soil loss monitoring (Table 3.1). So that relative changes in soil quality indicators following the implementation of SLM practices could be evaluated, samples were collected twice during the monitoring period: immediately after the start of the experiment (August 2015), and three years later (February 2018), by which time the vegetation cover in the experimental plots had clearly increased. All samples were collected from the 0–20 cm soil layer, which is considered to be appropriate for evaluating the temporal and spatial variations in soil properties in the Upper Blue Nile basin (Bewket and Stroosnijder, 2003; Abegaz et al., 2016), and because we expected the responses of soil properties to land management interventions to be greater in this layer than in the subsurface horizons.

During the entire three-year period, all sampling plots except for the control plots in non-croplands were fenced (Figure 4.1), and all cropland plots were manually tilled with hoes, but only at the time of sowing, so that information could be obtained about the use of land management strategies (banning free grazing, using minimum tillage, and reduced removal of crop residues) proposed by the Government of Ethiopia to reduce soil loss and improve soil quality in ecologically sensitive areas.

The sampling layout and whether single or composite samples were collected differed depending on the sampling year, land use type, and the management practices used (Table

4.1). In general, at each site, different land management practices were implemented in 2015 in three adjacent plots in each land use type (Figure 4.1). Because the observed topsoil conditions were generally the same in the adjacent plots of each land use type at the time the SLM practices were implemented, in 2015 a composite sample was collected for each land use type by thoroughly mixing auger samples collected at different points within the three plots (total area, 540 $m^2$; 18 m × 30 m × 3) (Figure 4.1). It was assumed that the surface soil properties of the composite sample from adjacent plots would be representative and thus useful as baseline information against which changes in soil properties after SLM intervention could be evaluated.

In 2018, each plot was sampled separately for each land use type (Figure 4.1), because the different land management practices led to increased heterogeneity and different surface soil conditions over the three years. Depending on the land use type and management practice implemented, 1 (from plots without SLM structures; **Figure 4.1a, d, and e**) to 14 (from plots with SLM structures; **Figure 4.1b, c,** and **f**) composite samples were prepared from 9 to 42 point samples collected with a hand auger. The number and locations of the sampling points in plots with SLM structures were selected by considering erosion and deposition zones and by taking into account possible variability in soil properties due to the implemented structural soil and water conservation measures.

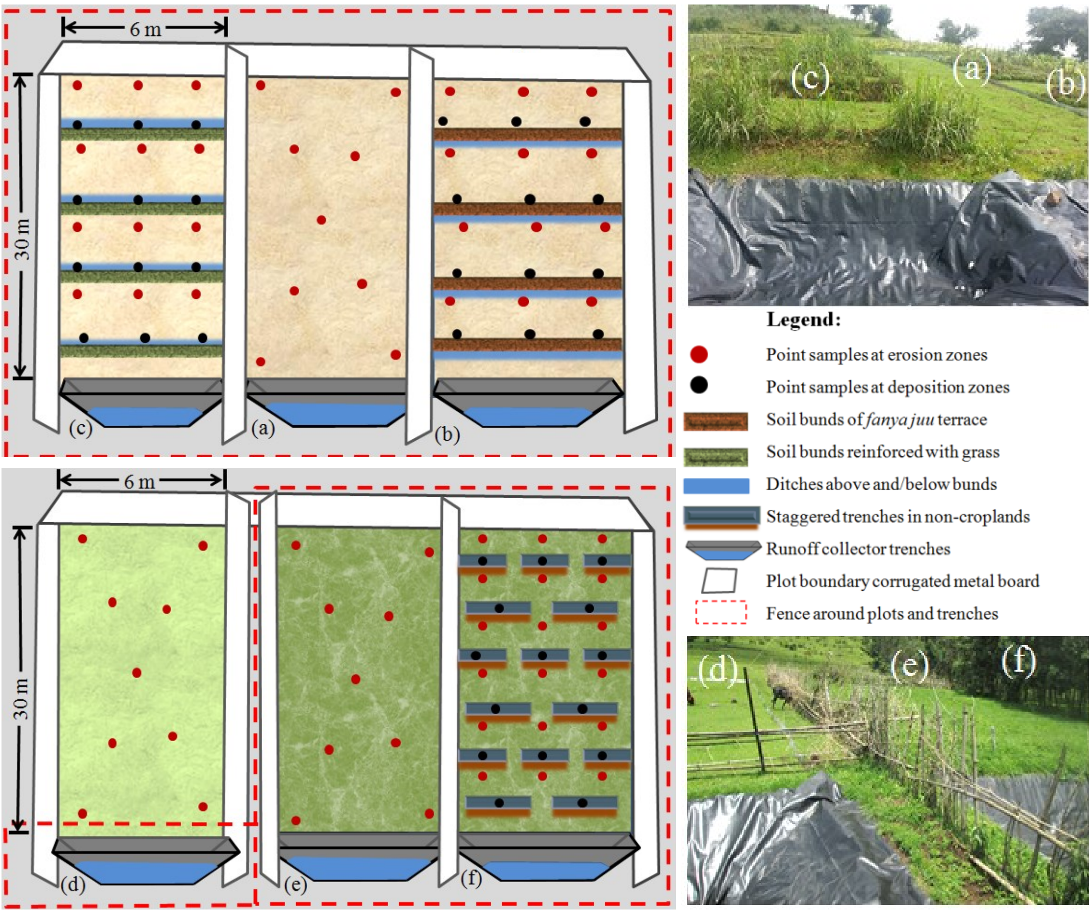

**Figure 4.1** A simplified representation of the soil sampling design in plots of cropland [control (a), *fanya juu* (b), and soil bund with grass (c)] and non-cropland [control (d), exclosure (e), and exclosure with trenches (f)]. See also Figure 4.3, section 4.3.4, for additional photos of plots.

**Table 4.1** Features of the experimental plots in different land use types in the three agro-ecological zones.

| Site (agro-ecology) | Land use | Slope (%) | Elevation (m a. s .l) | Management practice (plots) | Runoff (mm)[b] | SL (t $ha^{-1}$)[b] | SL reduction (%) | DMY (t $ha^{-1}$) | # of point samples[c] | # of composite samples[c] |
|---|---|---|---|---|---|---|---|---|---|---|
| Guder (highland) | CL[a] | 10 | 2575 | C | 378 | 5.25 | – | – | 18 | 2 |
| | | | | F | 285 | 1.16 | 78 | – | 42 | 14 |
| | | | | SBG | 293 | 0.95 | 82 | – | 42 | 14 |
| | GL | 15 | 2564 | C | 637 | 1.21 | – | – | 9 | 1 |
| | | | | E | 437 | 0.44 | 64 | 7.14 | 9 | 1 |
| | | | | E+T | 260 | 0.20 | 83 | 5.84 | 33 | 8 |
| | DBL | 35 | 2632 | C | 294 | 0.40 | – | – | 9 | 1 |
| | | | | E | 238 | 0.26 | 35 | 0.96 | 9 | 1 |
| | | | | E+T | 176 | 0.06 | 85 | 1.24 | 40 | 8 |
| Aba Gerima (midland) | CL[a] | 10 | 1990 | C | 241 | 2.88 | – | – | 18 | 2 |
| | | | | F | 164 | 1.23 | 57 | – | 42 | 14 |
| | | | | SBG | 177 | 1.06 | 63 | – | 42 | 14 |
| | GL | 15 | 1939 | C | 777 | 28.67 | – | – | 9 | 1 |
| | | | | E | 419 | 16.75 | 42 | 6.17 | 9 | 1 |
| | | | | E+T | 257 | 8.50 | 70 | 9.03 | 33 | 8 |
| | DBL | 35 | 2105 | C | 373 | 23.76 | – | – | 9 | 1 |
| | | | | E | 223 | 6.65 | 72 | 3.60 | 9 | 1 |
| | | | | E+T | 121 | 1.39 | 94 | 3.60 | 40 | 8 |
| Dibatie (lowland) | CL[a] | 10 | 1542 | C | 141 | 2.29 | – | – | 18 | 2 |
| | | | | F | 83 | 0.50 | 78 | – | 42 | 14 |
| | | | | SBG | 72 | 0.36 | 84 | – | 42 | 14 |
| | GL | 15 | 1513 | C | 121 | 0.98 | – | – | 9 | 1 |
| | | | | E | 104 | 0.75 | 23 | 6.94 | 9 | 1 |
| | | | | E+T | 82 | 0.21 | 79 | 5.19 | 33 | 8 |
| | DBL | 35 | 1586 | C | 90 | 1.10 | – | – | 9 | 1 |
| | | | | E | 81 | 0.45 | 59 | 6.48 | 9 | 1 |
| | | | | E+T | 59 | 0.10 | 91 | 5.60 | 40 | 8 |

CL, cropland; GL, grazing land; DBL, degraded bushland; C, control (conventional); F, *fanya* *juu*; SBG, soil bund reinforced with grass; E, exclosure; E+T, exclosure with trenches; SL, soil loss; DMY, aboveground dry matter yield of grass, measured in 2016.

[a] Slope, elevation, runoff, SL, and SL reduction values in cropland plots are the average of measurements made at two locations (5% and 15% slope); the number of samples represents the total number of samples collected at the two locations.

[b] Seasonal runoff, SL, and SL reduction values are the averages of values measured during 2015 and 2016 to evaluate the effect of land use and SLM practices on these parameters (Table 3.4).

[c] In plots with SLM structures (F, SBG, and E+T), 50% of the samples were collected from erosion zones and 50% from deposition zones (Figure 4.1); erosion zones were sampled 2 m away from trenches in non-croplands and 3 m away from bunds in croplands; sampling points in deposition zones were in the ditches behind the structures. Point and composite samples collected in 2015 from these plots are not included in the total.

A total of 162 composite samples (54 samples from each agro-ecological zone) were collected for laboratory analysis; 12 were collected in the initial year (2015) and 150 in the final year (2018) of the study. In addition to auger sampling, 90 undisturbed samples were collected with a standard core sampler (100 cc metal cylinder with a height of 5 cm) for determining the bulk density (BD) of soils in each plot; 36 core samples were collected in 2015, and 54 were collected in 2018.

### 4.2.2 Soil laboratory analysis

Composite soil samples were prepared (air-dried, ground, sieved to 2 mm, and packaged) at the Soil Laboratory of Bahir University, Ethiopia, and transported to Amhara Design and Supervision Works Enterprise (ADSWE) for analysis. All samples were analyzed for the following soil quality indicators: texture (subdivided into sand, silt, and clay contents), pH, electrical conductivity (EC), cation exchange capacity (CEC), soil organic carbon (SOC), total nitrogen (TN), available phosphorous ($P_{av}$), and available potassium ($K_{av}$). Texture was measured by hydrometer after shaking each soil sample in a sodium hexametaphosphate (Calgon) solution (Bouyoucos, 1962). pH and EC were determined on the basis of the potentiometric principle (Peech, 1965): pH was measured in a 1:25 soil/water solution with a pH meter, and EC was measured in a saturated soil paste with a conductivity meter. CEC was determined by washing the soil with ammonium acetate ($NH_4OAc$) solution (Ross and Ketterings, 2011). The SOC percentage was determined by the Walkley-Black chromic acid wet oxidation method (Nelson and Sommers, 1996), and the TN percentage was determined by digestion, distillation, and titration procedures using a Kjeldahl apparatus (Bremner, 1996). The concentrations of two essential primary nutrients, $P_{av}$ and $K_{av}$, were estimated after extraction by the sodium bicarbonate method (Olsen, 1954) and sodium acetate method (Hosseinpur and Samavati, 2008), respectively. In addition to these eight properties determined by routine laboratory chemical procedures, BD was calculated from the mass to total volume ratio of core samples oven-dried at 105 °C for 24 h.

### 4.2.3 Data analysis

The statistical package for social sciences (SPSS) version 23 for Windows was used to analyze the data. Descriptive statistics were determined to evaluate the variability of soil properties in the different agro-ecological zones as influenced by land use and management practices. Depending on the distribution of the data, parametric or non-parametric inferential statistical tests were used to evaluate the degree of variability in the soil quality indicators among agro-ecological zones and land use types. The Mann-Whitney U test, a non-parametric test, was used to compare the mean ranks of soil properties among agro-ecological zones, because these data were not normally distributed. One-way analysis of variance (ANOVA, a parametric test) and the Scheffé post hoc multiple comparisons test were used to compare mean values of soil properties among land use types within each agro-ecological zone.

## 4.3 Results and discussion

### 4.3.1 Variation of soil properties across agro-ecological zones

The Mann-Whitney U test results for the data from 2018 showed significant variation in most soil properties across the three agro-ecological sites (zones) in the Upper

Blue Nile basin (**Table 4.2**). The median values of four soil properties (sand content, EC, SOC, and TN) were significantly higher ($|Z| > 1.96$, $P < 0.05$) at Guder than at Aba Gerima and Dibatie, whereas the clay content and $K_{av}$ were greater at Dibatie than at the other sites. This substantial variation in soil quality indicators across the three sites is mainly attributable to differences among the sites in climate, soil parent material, and vegetation (Table 1.2), which strongly influence soil formation and physico-chemical characteristics (Brady and Weil, 2014). For instance, the significantly higher SOC and TN contents of soils at Guder compared with those at Aba Gerima and Dibatie may be attributable to a lower soil organic matter (SOM) decomposition rate caused by lower temperatures (Table 1.2), which may in turn result in less $CO_2$ production (Ontl and Schulte, 2012) and, thus, higher SOC levels. The lower SOM decomposition rate might also reflect the negative relationship between SOM decomposition rates and iron oxide concentrations in Acrisols (Bayer et al., 2001), as well the preservation of SOM through its complexation with variable charge minerals and due to limited biological activity in low-temperature areas (Deckers, 1993). These results show that variations in climatic and lithological factors across landscapes may result in important variation in the carbon storage capacity of the soil and in associated soil attributes. Hence, management practices should be carefully planned by taking into account different environmental settings.

The observed variation in soil parameter values across the three sites may also be related to spatial variability in soil degradation processes (Bewket and Stroosnijder, 2003). For example, the seasonal plot-scale soil loss (SL) rates observed at Guder and Dibatie (Table 4.1) were far smaller than the maximum acceptable limit (6 t ha$^{-1}$) recommended for Ethiopia (Hurni, 1983). Furthermore, the values of some soil quality indicators (SOC, TN, and $K_{av}$) observed at these two sites are close to or within the suggested optimal ranges for plant productivity (See Table 4.5, section 4.3.4). These results support the inference that the soils at these sites have higher levels of SOM, which affects physical, chemical, and biological properties of the soil (Ontl and Schulte, 2012). Conversely, the lower levels of SOC, TN, and $K_{av}$ at Aba Gerima may be partly attributable to the high runoff and soil loss rates at that site associated with intensive rainfall (Ebabu et al., 2019) together with excessive grazing, which can cause increased soil compaction and SOM loss (Teferi et al., 2016).

**Table 4.2** Statistical analysis results for selected topsoil (0–20 cm depth) properties in the different agro-ecological zones in the Upper Blue Nile basin. $n = 50$, except for BD ($n = 18$).

| Soil property (units) | Sites | Mean | SD | CV (% | Median | MR | Mann-Whitney U test results | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | Pair | *U* | *Z* | *P* |
| Clay (%) | Guder | 18.60 | 9.79 | 53 | 16.00 | 43 | 1 | 854 | –2.741 | 0.006 |
| | Aba Gerima | 24.92 | 10.28 | 41 | 25.00 | 58 | 2 | 70 | –8.155 | 0.000 |
| | Dibatie | 60.08 | 15.96 | 27 | 66.00 | 74 | 3 | 149 | –7.603 | 0.000 |
| Silt (%) | Guder | 36.40 | 4.75 | 13 | 36.00 | 53 | 1 | 1,138 | –0.774 | 0.439 |
| | Aba Gerima | 36.04 | 5.19 | 14 | 35.50 | 48 | 2 | 372 | –6.070 | 0.000 |
| | Dibatie | 22.92 | 10.08 | 44 | 20.00 | 33 | 3 | 369 | –6.088 | 0.000 |
| Sand (%) | Guder | 45.00 | 10.01 | 22 | 45.00 | 58 | 1 | 884 | –2.529 | 0.011 |
| | Aba Gerima | 39.04 | 13.04 | 33 | 35.00 | 43 | 2 | 23 | –8.476 | 0.000 |
| | Dibatie | 17.00 | 6.94 | 41 | 16.00 | 26 | 3 | 135 | –7.697 | 0.000 |
| BD (g cm$^{-3}$) | Guder | 1.02 | 0.08 | 8 | 1.01 | 12 | 1 | 37 | –3.955 | 0.000 |
| | Aba Gerima | 1.25 | 0.27 | 22 | 1.16 | 25 | 2 | 39 | –3.892 | 0.000 |
| | Dibatie | 1.26 | 0.15 | 12 | 1.27 | 25 | 3 | 113 | –1.550 | 0.121 |
| pH | Guder | 5.46 | 0.30 | 5 | 5.53 | 38 | 1 | 616 | –4.372 | 0.000 |
| | Aba Gerima | 5.71 | 0.18 | 3 | 5.71 | 63 | 2 | 541 | –4.889 | 0.000 |
| | Dibatie | 5.79 | 0.30 | 5 | 5.75 | 65 | 3 | 1,068 | –1.255 | 0.209 |
| EC (dS m$^{-1}$) | Guder | 0.06 | 0.02 | 33 | 0.06 | 61 | 1 | 732 | –3.572 | 0.000 |
| | Aba Gerima | 0.05 | 0.02 | 40 | 0.05 | 40 | 2 | 1,107 | –0.986 | 0.324 |
| | Dibatie | 0.07 | 0.06 | 86 | 0.05 | 48 | 3 | 984 | –1.835 | 0.066 |
| CEC (cmol$_c$ kg$^{-1}$) | Guder | 26.74 | 4.60 | 17 | 25.60 | 28 | 1 | 140 | –7.654 | 0.000 |
| | Aba Gerima | 42.15 | 9.17 | 22 | 43.40 | 73 | 2 | 151 | –7.583 | 0.000 |
| | Dibatie | 37.21 | 4.95 | 13 | 38.00 | 63 | 3 | 702 | –3.780 | 0.000 |
| SOC (%) | Guder | 2.71 | 0.40 | 15 | 2.73 | 64 | 1 | 583 | –4.603 | 0.000 |
| | Aba Gerima | 2.14 | 0.65 | 30 | 2.22 | 37 | 2 | 870 | –2.628 | 0.009 |
| | Dibatie | 2.42 | 0.52 | 21 | 2.67 | 43 | 3 | 938 | –2.153 | 0.031 |
| TN (%) | Guder | 0.23 | 0.03 | 13 | 0.23 | 64 | 1 | 590 | –4.590 | 0.000 |
| | Aba Gerima | 0.18 | 0.06 | 33 | 0.19 | 37 | 2 | 885 | –2.775 | 0.006 |
| | Dibatie | 0.20 | 0.04 | 20 | 0.23 | 43 | 3 | 951 | –2.082 | 0.037 |
| P$_{av}$ (mg kg$^{-1}$) | Guder | 7.70 | 3.01 | 39 | 8.12 | 53 | 1 | 1,135 | –0.793 | 0.428 |
| | Aba Gerima | 8.21 | 6.69 | 81 | 5.66 | 48 | 2 | 511 | –5.103 | 0.000 |
| | Dibatie | 9.15 | 16.35 | 179 | 2.00 | 36 | 3 | 758 | –3.399 | 0.001 |
| K$_{av}$ (mg kg$^{-1}$) | Guder | 380.47 | 274.44 | 72 | 311.00 | 50 | 1 | 1,216 | –0.238 | 0.812 |
| | Aba Gerima | 336.87 | 150.25 | 45 | 311.25 | 51 | 2 | 1,014 | –1.627 | 0.104 |
| | Dibatie | 437.13 | 267.05 | 61 | 369.50 | 55 | 3 | 931 | –2.203 | 0.028 |

*n*, number of samples analyzed; SD, standard deviation; MR, mean rank; BD, bulk density; EC, electrical conductivity; CEC, cation exchange capacity; SOC, soil organic carbon; TN, total nitrogen; P$_{av}$, available phosphorus; K$_{av}$, available potassium. In the Pair column, the numbers 1–3 indicate the two sites compared in the Mann Whitney U test: 1, Guder vs Aba Gerima; 2, Guder vs Dibatie; and 3, Aba Gerima vs Dibatie. Differences in soil properties between the study sites were statistically significant when $|Z| > 1.96$ and $P < 0.05$ in the Mann-Whitney U test results.

### 4.3.2 Variation in soil properties within agro-ecological zones

Soil physico-chemical properties also showed clear variation within the three agro-ecological sites (Table 4.2). The coeffcients of variation (CV) for datasets of the 11 soil parameters range from 5% to 72% at Guder, from 3% to 81% at Aba Gerima, and from 5% to 179% at Dibatie. The lowest CV was obtained for pH at all sites, whereas the highest was for available phosphrous ($P_{av}$) at Aba Gerima and Dibatie, and for available potassium ($K_{av}$) at Guder. These CV values are generally within the range of values (4% to 163%) reported for these parameters in different parts of the world (Mapa and Kumaragamage, 1996; Stenger et al., 2002; Goenster-Jordan et al., 2018). The exceptionally high CV observed for $P_{av}$ at Dibatie is mainly because the level of this nutrient was markedly higher in the degraded bushland than in the other land use types at that site. This situation at Dibatie is discussed further in section 4.3.3.

Although the data from different land use types and management practices were pooled, the observed CV values of 3% to 5% for pH were much lower than those for the other soil properties (Table 4.2). This is largely attributable to lower spatial and temporal variation of inherent factors affecting soil pH at the study sites, mainly climate, mineralogy, and soil texture (Brady and Weil, 2014). This lower variation also be due to the fact that pH is measured on a logarithmic scale, and relatively small variations in pH values reflect much larger variations in hydrogen ion concentrations (Peech, 1965). Our results are consistent with the findings of Bewket and Stroosnijder (2003) and Hebb et al. (2017), who also reported small variation in the pH of soils from different land use types. On the other hand, the large variation (CV = 12%–179%) observed for other soil properties can be explained by the heterogeneous nature of the samples, which were collected from plots in different land use types and under different management practices (Table 4.1). This inference is supported by the findings of Stenger et al. (2002) and Goenster-Jordan et al. (2018), who reported significant heterogeneity in most topsoil properties, even at small spatial scales. Our results, therefore, suggest that proposals for soil management systems should be based on site-specific and fine-scale information about soil characteristics; recommendations based on average soil conditions might be ineffective in one area owing to the failure to consider soil constraints, whereas in another area, unnecessary inputs might have financial and environmental costs.

### 4.3.3 Effects of land use on soil properties

The ANOVA test results showed significant variations in soil parameter values among land use types in the three agro-ecological zones (Table 4.3). At each site, 7 of 11 soil parameters showed significant differences ($P < 0.05$ to $P < 0.001$) among the three land use types. This implies that soil properties in one land use type can differ markedly from those in other land use types in the same agro-ecological zone, thus, each land use type requires a different management system. Moreover, the soil parameters exhibiting statistically significant variation among land use types were different among the three agro-ecological zones: sand content, pH, CEC, SOC, TN, $P_{av,}$ and $K_{av}$ at Guder; silt content, BD, pH, CEC, SOC, TN, and $P_{av}$ at Aba Gerima; and clay, silt, and sand contents, pH, EC, $P_{av}$, and $K_{av}$ at Dibatie.

The post hoc multiple comparison test results (Table 4.4) revealed that mean SOC and TN values in cropland plots were far smaller than those in grazing land and degraded bushland plots at all three sites. The differences, however, were significant only between cropland and degraded bushland at Guder ($P < 0.01$) and Aba Gerima ($P < 0.001$), where they can most likely be attributed to the continuous practice of depletive farming systems over centuries. Other studies conducted in Ethiopia (Bewket and Stroosnijder, 2003;

Gelaw et al., 2014; Abegaz et al., 2016; Assefa et al., 2017; Negasa et al., 2017) have also observed that cultivated lands are characterized by low levels of SOC and TN owing to the removal of large amounts of organic matter through harvesting, and the rapid decomposition rates stimulated by frequent tillage operations. At all sites, SOC and TN values observed in cropland plots were far lower than the critical level, below which a potentially serious decline in soil quality occurs (Figure 4.2). This result, which is additional evidence that the amounts of carbon and nitrogen stored are lower in cultivated soils than in non-cultivated soils, can help land managers make rational decisions about actions that should be taken to maintain and improve the quality of soils used for crop production.

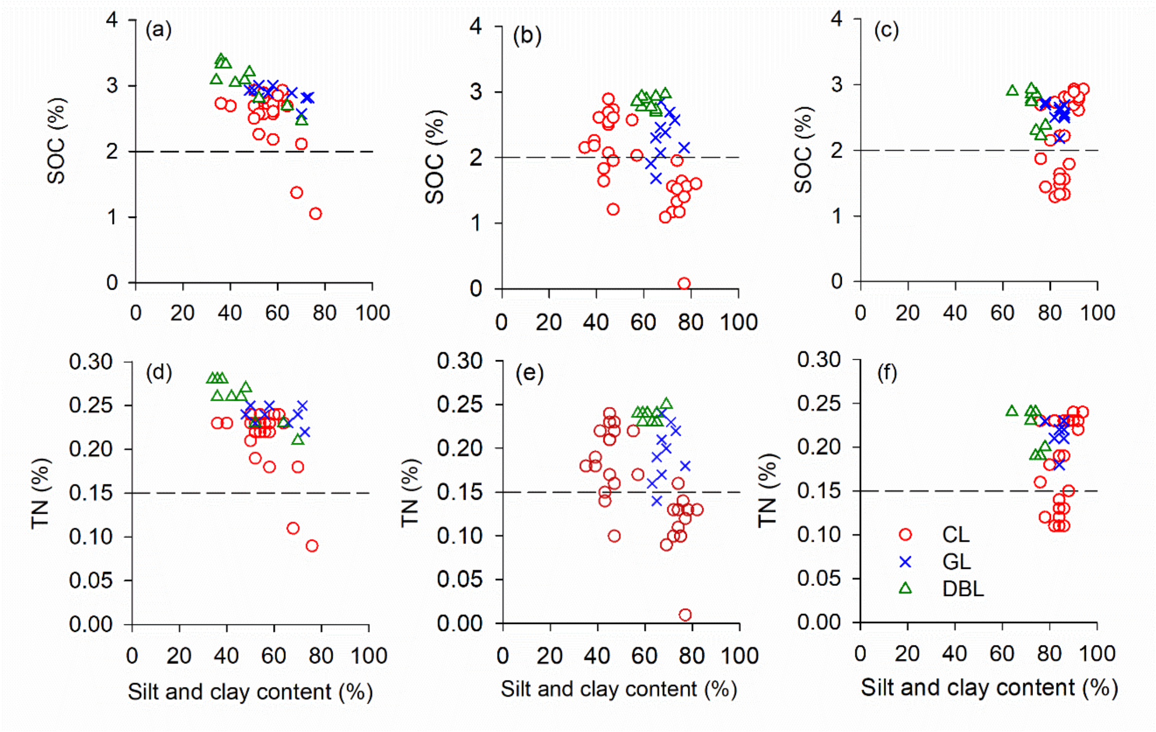

**Figure 4.2** Scatter plots of (a–c) SOC and (d–f) TN as a function of silt and clay contents of the surface soil in the three land use types, cropland (CL), grazing land (GL), and degraded bushland (DBL), at (a, d) Guder, (b, e) Aba Gerima, and (c, f) Dibatie.The dashed horizontal lines indicate the critical levels of SOC (2%), and TN (0.15%), below which a potentially serious decline in soil quality may occur (Waswa et al., 2013).

Soil pH varied significantly ($P < 0.01$) among land use types (Table 4.3); in all three agro-ecological zones, croplands tended to have lower pH (Table 4.4). This finding is in agreement with Negasa et al. (2017), who reported significantly lower pH values in cultivated lands than in other land use types in southern Ethiopia, but not with other study conducted in the highland of Ethiopia (Bewket and Stroosnijder, 2003) that observed generally similar pH values across four land use types (Forest, cultivated, Grazing, and

Eucalyptus plantation). The variation in pH (lower in cropland than in non-cropland plots) observed by the current study is attributable to the continuous cropping system used as well as to the long-term use of synthetic nitrogen fertilizers, which substantially decrease amounts of exchangeable base cations ($Ca^{2+}$ and $Mg^{2+}$) but increase the $H^+$ concentration (Schroder et al., 2011). It is worth noting, however, that average pH values, regardless of land use and agro-ecological zone, were generally within a favorable range (5.5 to 6.5) for the proper growth of most plants (Brady and Weil, 2014). Thus, at present, neither acidity nor alkalinity can be considered a major factor limiting the fertility and productivity of soils at the three agro-ecological sites.

At Dibatie, the amounts of $P_{av}$ and $K_{av}$ in bushland plots were significantly higher than those in croplands and grazing lands ($P < 0.001$, Table 4.4). This exceptional result is likely due to the presence of large Croton trees *(Croton macrostachyus)* in the sampled plots; because cattle used these trees for shade, high amounts of available nutrients might be returned to the soil of these plots in the form of dung and urine (Weeda, 1967). Moreover, the well-established understory vegetation in bushland plots (Figure 4.3) might play a major role in nutrient cycling, and the relatively higher aboveground dry matter yield of grass (Table 4.1), observed in 2016, may also explain the higher amounts of $P_{av}$

and $K_{av}$ in bushland plots at Dibatie. The lower levels of these nutrients in croplands and grazing lands is largely attributable to the removal of SOM through harvesting and grazing. This finding is in agreement with results reported by other studies (Gafur et al., 2003; Visser et al., 2005; Girmay et al., 2009; Kindiye, 2016) that available nutrients ($P_{av}$ and $K_{av}$) are lower in soils devoted to agriculture and livestock grazing than in those covered by undisturbed natural vegetation. At Guder and Aba Gerima, however, the amount of $P_{av}$ was significantly higher in croplands than in non-croplands; this result can be explained mainly by the application of diammonium phosphate, a concentrated fertilizer with high phosphorus content, to soils over several years of crop cultivation. This result is in agreement with Baligar et al. (2001), who reported that the overall efficiency of phosphate fertilizer is only 10%; most of the rest remains in the soil by complexing with less soluble and immobile components (Brady and Weil, 2014).

Overall, the results of the current study showed that soil parameter values that are critical to understanding the soil behavior and management are generally variable across land use types in all three agro-ecological zones (Table 4.3). Nevertheless, the number of parameters exhibiting significant variation across land uses was smaller than the number exhibiting variation across agro-ecological zones (Table 4.2). Thus, soil properties varied much less across land use types than across agro-ecological zones. The reason for this difference may be that those factors (climate, parent material, topography, and vegetation) affecting soil properties show less spatial variation in small sampling areas than when sampling is conducted over a wide geographic region (Brady and Weil, 2014; Goenster-Jordan et al., 2018). Therefore, planning and decision making for sustainable soil management practices need to be geographically fine-tuned to effectively achieve the desired objectives.

**Table 4.3** Mean values and ANOVA results for selected physico-chemical properties of the topsoil (0–20 cm) among three land use types at the three agro-ecological sites in the Upper Blue Nile basin.

| Site | Land use | Clay (%) | Silt (%) | Sand (%) | BD (g cm$^{-3}$) | pH | EC (ds m$^{-1}$) | CEC (cmol$_c$ kg$^{-1}$) | SOC (%) | TN (%) | P$_{av}$ (mg kg$^{-1}$) | K$_{av}$ (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Guder | CL | 19.13 | 37.13 | 43.73 | 1.03 | 5.29 | 0.06 | 25.55 | 2.54 | 0.22 | 9.13 | 490 |
| | GL | 22.20 | 37.40 | 40.40 | 1.06 | 5.71 | 0.07 | 26.08 | 2.86 | 0.24 | 6.54 | 324 |
| | DBL | 13.40 | 33.20 | 53.40 | 0.94 | 5.70 | 0.05 | 30.96 | 3.04 | 0.26 | 4.57 | 109 |
| ANOVA, F | | 2.24 | 3.10 | $5.76^{**}$ | 3.55 | $20.74^{***}$ | 2.29 | $6.51^{**}$ | $8.32^{**}$ | $7.97^{**}$ | $15.06^{***}$ | $10.31^{***}$ |
| Aba Gerima | CL | 24.27 | 33.73 | 42.00 | 1.15 | 5.61 | 0.05 | 39.31 | 1.86 | 0.16 | 12.17 | 337 |
| | GL | 26.60 | 41.80 | 31.60 | 1.55 | 5.75 | 0.04 | 47.28 | 2.31 | 0.19 | 2.25 | 396 |
| | DBL | 25.2 | 37.20 | 37.60 | 1.19 | 5.97 | 0.05 | 45.26 | 2.84 | 0.24 | 2.28 | 278 |
| ANOVA, F | | 0.83 | $14.52^{***}$ | 2.63 | $4.91^{*}$ | $39.64^{***}$ | 0.49 | $4.18^{*}$ | $13.47^{***}$ | $13.14^{***}$ | $27.33^{***}$ | 1.60 |
| Dibatie | CL | 69.40 | 16.93 | 13.67 | 1.31 | 5.61 | 0.05 | 36.99 | 2.28 | 0.19 | 1.80 | 312 |
| | GL | 60.00 | 23.40 | 16.60 | 1.23 | 5.88 | 0.05 | 35.48 | 2.57 | 0.22 | 1.74 | 422 |
| | DBL | 32.20 | 40.40 | 24.40 | 1.17 | 6.25 | 0.16 | 39.60 | 2.69 | 0.22 | 36.65 | 826 |
| ANOVA, F | | $115.66^{***}$ | $114.99^{***}$ | $38.11^{***}$ | 1.38 | $58.19^{***}$ | $31.83^{***}$ | 1.87 | 3.06 | 3.21 | $112.32^{***}$ | $30.86^{***}$ |

BD, bulk density; EC, electrical conductivity; CEC, cation exchange capacity; SOC, soil organic carbon; TN, total nitrogen; P$_{av}$, available phosphorus; K$_{av}$, available potassium. Abbreviations related to land use and the number of composite samples are defined in Table 4.1.

$^{***}$, $^{**}$, and $^{*}$ indicate that the ANOVA F-value is significant at $P < 0.001$, 0.01, and 0.05, respectively.

**Table 4.4** Mean differences in physico-chemical properties of the topsoil (0–20 cm) among the three land use types at the three agro-ecological sites in the Upper Blue Nile basin in the multiple comparison analysis results. I and J refer to the two land use types being compared in each row.

| Site | Variables | | Mean differences (I – J) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | (*I*) Land use | (J) Land use | Clay (%) | Silt (%) | Sand (%) | BD (g cm$^{-3}$) | pH | EC (ds m$^{-1}$) | CEC (cmol$_c$ kg$^{-1}$) | SOC (%) | TN (%) | $P_{av}$ (mg kg$^{-1}$) | $K_{av}$ (mg kg$^{-1}$) |
| Guder | CL | GL | –3.07 | –0.27 | 3.33 | –0.03 | $-0.41^{***}$ | –0.01 | –0.53 | –0.32 | –0.02 | $2.59^{*}$ | 165 |
| | | DBL | 5.73 | 3.93 | $-9.67^{*}$ | 0.10 | $-0.40^{***}$ | 0.00 | $-5.41^{**}$ | $-0.49^{**}$ | $-0.04^{**}$ | $4.56^{***}$ | $380^{***}$ |
| | GL | DBL | 8.80 | 4.20 | $-13.00^{*}$ | 0.12 | 0.01 | 0.02 | $-4.88^{*}$ | –0.17 | –0.02 | 1.97 | 215 |
| Aba-Gerima | CL | GL | –2.33 | $-8.07^{***}$ | 10.40 | $-0.40^{*}$ | $-0.13^{**}$ | 0.01 | $-7.97^{*}$ | –0.45 | –0.04 | $9.93^{***}$ | –59 |
| | | DBL | –0.93 | –3.47 | 4.40 | –0.04 | $-0.36^{***}$ | 0.001 | –6.25 | $-0.98^{***}$ | $0.08^{***}$ | $9.90^{***}$ | 59 |
| | GL | DBL | 1.40 | 4.60 | –6.00 | 0.36 | $0.22^{***}$ | –0.01 | 1.72 | –0.54 | –0.04 | –0.03 | 119 |
| Dibatie | CL | GL | $9.40^{**}$ | $-6.47^{**}$ | –2.93 | 0.08 | $-0.27^{***}$ | 0.00 | 1.51 | –0.29 | –0.03 | 0.07 | –110 |
| | | DBL | $37.20^{***}$ | $-23.47^{***}$ | $-13.73^{***}$ | 0.14 | $-0.64^{***}$ | $-0.10^{***}$ | –2.61 | –0.41 | –0.03 | $-36.79^{***}$ | $-514^{***}$ |
| | GL | DBL | $27.80^{***}$ | $-17.00^{***}$ | $10.80^{***}$ | 0.07 | $-0.37^{***}$ | $-0.11^{***}$ | –4.12 | –0.12 | –0.01 | $-36.85^{***}$ | $-404^{***}$ |

BD, bulk density; EC, electrical conductivity; CEC, cation exchange capacity; SOC, soil organic carbon; TN, total nitrogen; $P_{av}$, available phosphorus; $K_{av}$, available potassium. Abbreviations related to land use and the number of composite samples are defined in Table 4.1.

$^{***}$, $^{**}$ and $^{*}$ indicate that the mean difference is significant at $P < 0.001$, 0.01, and 0.05, respectively.

### 4.3.4 Effects of SLM practices on changes in soil properties

The impact of SLM practices on soil quality indicators can be assessed by comparing the actual values of soil parameters measured between the two sampling years (Table 4.5) and using the percentage changes relative to the values obtained in the initial year (Figure 4.4). Regardless of the site and land use type, average SOC, TN, $P_{av}$, and $K_{av}$ values in 2018 clearly surpassed those in 2015, whereas average BD was generally higher in 2015 than in 2018 (Table 4.5). These results are largely attributable to the development of good vegetation cover (Figure 4.3) owing to fencing and reduced tillage, because vegetation can increase the rate at which organic matter builds up and thereby enhance related soil attributes. These results, therefore, demonstrate that a desirable increase in carbon storage and related soil attributes, and a reduction in surface soil compaction (smaller BD), were achieved following the implementation of SLM practices. Further, they imply that SOM content and related soil properties can be changed in a relatively short period by implementing suitable SLM practices, whereas changes in other soil properties such as Silt and clay content, and pH were generally not as such detectable over the study period, probably because they are inherent properties of the soils at the study sites. This study further indicated that although undesirable decrease (negative relative change values) in some soil attributes (silt and clay content, pH, EC, and CEC) were observed in plots with SLM practices (Figure 4.4), most of the actual values were within, or in some cases even higher than, the optimal ranges suggested for good plant productivity (Table 4.5).

At all three sites, the improvement in SOC, TN, and related soil properties were generally higher in plots where SLM practices (*fanya juu*, soil bund reinforced with grass, exclosure, and exclosure with trenches) were implemented than in those where they were not (control plots), (Figure 4.4). This result implies that the sustainable land management interventions had a positive effect on the SOC pool and related soil properties, and it is consistent with the finding that implementation of regional or global policies directed toward the sustainable management of soil resources can improve carbon sequestration and soil quality (Lal, 2006). The percentage change values of SOC, TN, $P_{av}$, and $K_{av}$ observed in exclosure plots of non-croplands (both with and without trenches) were much higher than those in control plots (Figure 4.4). This result confirms that a ban on free grazing facilitates natural re-vegetation and improves the capacity of soils to resist degradation and nutrient depletion as well as their resilience to changes induced by disturbances such as erosion.

These results in exclosure plots are in accordance with the finding stated in chapter 3 i.e., exclosure is the best sustainable land management practice in runoff and soil loss reduction. Other studies elsewhere have also reported that exclosure is effective for vegetation restoration and soil erosion reduction and is key to the restoration of ecosystems in ecologically sensitive regions (Zhang et al., 2015; Zhou et al., 2016). In addition, studies conducted in the northern highlands of Ethiopia (Mekuria et al., 2007; Yayneshet et al., 2009) observed higher aboveground biomass, SOM, and TN contents in exclosures than in heavily grazed lands. It is important to note, however, that simple integrative approaches should be used to communicate with the immediate land users (local farmers) to ensure the proper implementation and sustainable use of SLM practices such as exclosure.

Our results showing remarkable positive changes in SOC, TN, $P_{av}$, and $K_{av}$, and both positive and negative changes in BD, pH, EC, and CEC, three years after the implementation of different land management practices, are in accordance with Arshad and Martin (2002), who reported that the measurable soil attributes that are primarily sensitive to management in a given agro-climatic region include soil depth, organic matter, respiration, aggregation, bulk density, infiltration, nutrient availability and retention capacity. Similarly, Murage et al. (2000) who conducted a diagnostic study in the central highlands of Kenya, suggested that total organic carbon is the most sensitive soil quality indicator, and it is subject to change even over a small spatial and temporal scales. Chantigny (2003) also reported that changes in dissolved and water-extractable fractions of organic matter following the implementation of management practices are generally of short duration, whereas changes in vegetation type and the amount of plant litter returned to the soil can have long-term effects on these forms of organic matter.

It is worth noting here that the variation (positive and negative changes) in some soil properties by this study could also partly be explained by the differences in the sampling times: during the wet period (August) for the initial year versus during the dry period (February) in the final year. For instance, a buildup of salts near the surface during the dry periods versus the leaching of these salts during the wet periods often produce seasonal variation in pH (Brady and Weil, 2014). This, therefore, implies that soil samples should be collected at the same time of the year when the changes in soil parameters are to be monitored over the number of years.

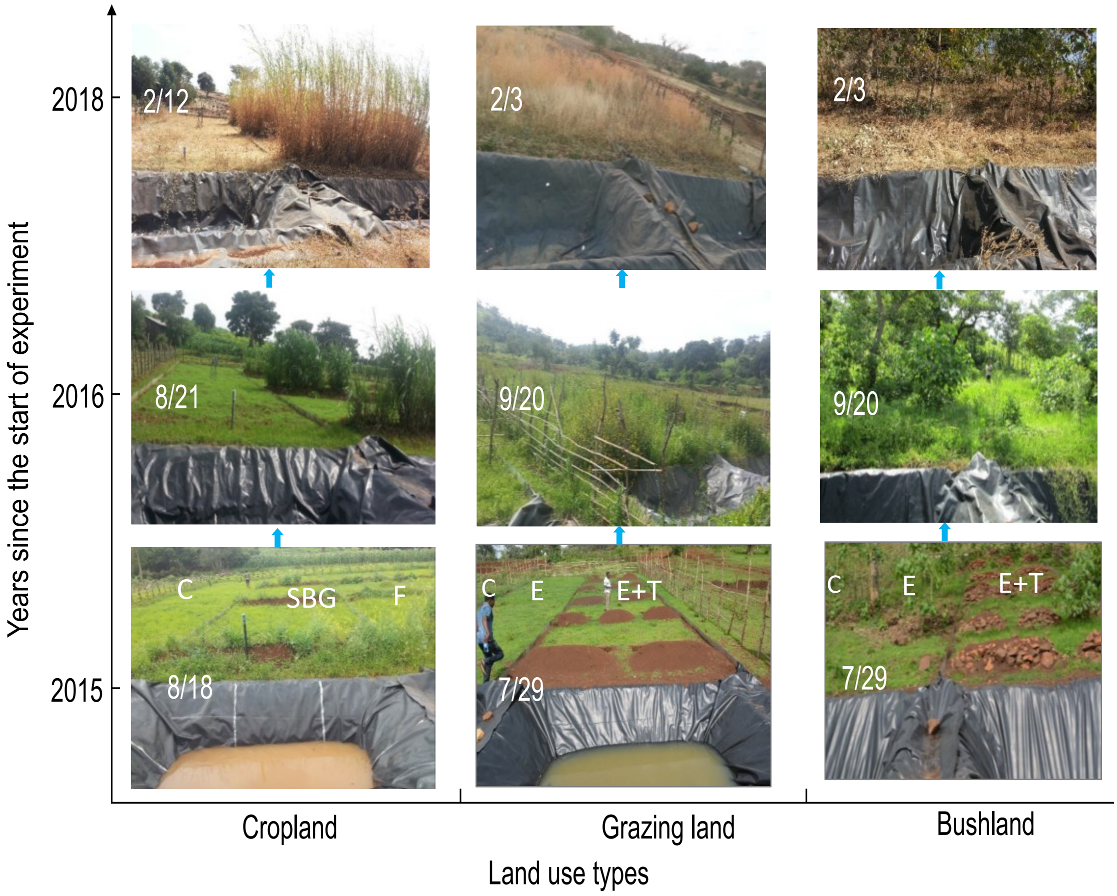

**Figure 4.3** Evolution of vegetation cover during the three monitoring years (2015, 2016, and 2018) in sampling plots in which different SLM practices were implemented: C, F, and SBG in cropland (left); C, E, and E+T in grazing land (middle) and degraded bushland (right). The photos of cropland were taken at Aba Gerima, and the photos of grazing lands and bushlands were taken at Dibatie. The photos are stamped with the dates (m/dd) that the photos were taken in each year. In this Figure, the C plots in grazing land and bushland are hidden to the left, see more detailed information in Figure 4.1, and abbreviations are defined in Table 4.1.

**Table 4.5** Physical and chemical properties of soils (average values with the standard deviation in parenthesis) in different land use types before (in 2015) and three years after implementation of different SLM practices (in 2018) at the three agro-ecologies in the Upper Blue Nile basin.

| Agro-Eclogy (site) | Land use | Years | SLM practices | *n* | Silt + clay (%) | BD (g cm$^{-3}$) | pH | EC (ds m$^{-1}$) | CEC (cmol$_c$ kg$^{-1}$) | SOC (%) | TN (%) | P$_{av}$ (mg kg$^{-1}$) | K$_{av}$ (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Guder | CL | 2015 | C | 2 | 71 (01) | 1.25 (0.06) | 5.03 (0.02) | 0.04 (0.00) | 39 (1.40) | 2.59 (0.26) | 0.22 (0.02) | 10.91(0.75) | 273 (43) |
| | | 2018 | C | 2 | 55 (04) | 1.01 (0.04) | 5.49 (0.13) | 0.05 (0.02) | 23 (2.00) | 2.61 (0.06) | 0.22 (0.00) | 8.50 (0.53) | 507 (330) |
| | | | F | 14 | 57 (04) | 0.99 (0.06) | 5.21 (0.25) | 0.06 (0.01) | 25 (2.65) | 2.85 (0.12) | 0.24 (0.01) | 9.25 (1.6) | 578 (197) |
| | | | SBG | 14 | 56 (11) | 1.08 (0.09) | 5.34 (0.29) | 0.06 (0.03) | 26 (3.50) | 2.94 (0.52) | 0.26 (0.05) | 9.10 (3.3) | 668 (202) |
| | GL | 2015 | C | 1 | 64 (00) | 1.11 (0.00) | 5.54 (0.00) | 0.06 (0.00) | 45 (0.00) | 2.22 (0.00) | 0.19 (0.00) | 6.87 (0.00) | 324 (000) |
| | | 2018 | C | 1 | 60 (00) | 0.99 (0.00) | 5.55 (0.00) | 0.07 (0.00) | 25 (0.00) | 2.98 (0.00) | 0.24 (0.00) | 7.15 (0.00) | 302 (000) |
| | | | E | 1 | 57 (00) | 1.08 (0.00) | 5.62 (0.00) | 0.11 (0.07) | 28 (0.00) | 3.00 (0.00) | 0.24 (0.00) | 8.45 (0.00) | 360(000) |
| | | | E+T | 8 | 61 (10) | 1.08 (0.02) | 5.75 (0.07) | 0.10 (0.01) | 26 (3.64) | 2.84 (0.13) | 0.25 (0.01) | 8.60 (3.41) | 353 (202) |
| | DBL | 2015 | C | 1 | 52 (00) | 1.14 (0.00) | 5.58 (0.00) | 0.07 (0.00) | 52 (0.00) | 2.46 (0.00) | 0.24 (0.00) | 3.65 (0.00) | 95 (000) |
| | | 2018 | C | 1 | 45 (00) | 0.90 (0.00) | 5.58 (0.00) | 0.04 (0.00) | 34(0.00) | 3.04 (0.00) | 0.25 (0.00) | 4.56 (0.00) | 129 (000) |
| | | | E | 1 | 41 (00) | 0.94 (0.00) | 5.63 (0.00) | 0.05 (0.00) | 38 (0.00) | 3.08 (0.00) | 0.27 (0.00) | 4.92 (0.00) | 198 (000) |
| | | | E+T | 8 | 43 (13) | 0.95 (0.10) | 5.71 (0.11) | 0.06 (0.01) | 39 (7.17) | 3.03 (0.34) | 0.29 (0.03) | 4.48 (0.74) | 224 (022) |
| Aba Gerima | CL | 2015 | C | 2 | 68 (12) | 1.25 (0.03) | 5.61 (0.01) | 0.05 (0.00) | 37 (8.50) | 0.59 (0.51) | 0.05 (0.04) | 2.57 (1.24) | 226 (150) |
| | | 2018 | C | 2 | 60 (00) | 1.20 (0.08) | 5.65 (0.11) | 0.04 (0.01) | 38 (12.00) | 2.38 (0.55) | 0.19 (0.05) | 11.15 (2.64) | 187 (098) |
| | | | F | 14 | 58 (16) | 1.15 (0.09) | 5.59 (0.08) | 0.06 (0.02) | 40 (9.00) | 1.77 (0.73) | 0.15 (0.06) | 11.90 (6.00) | 340 (156) |
| | | | SBG | 14 | 57 (16) | 1.13 (0.06) | 5.64 (0.14) | 0.06 (0.03) | 38 (11.00) | 1.88 (0.57) | 0.16 (0.05) | 12.59 (6.00) | 356 (196) |
| | GL | 2015 | C | 1 | 76 (00) | 1.31(0.00) | 5.88 (0.00) | 0.08 (0.00) | 44 (0.00) | 1.17(0.00) | 0.10 (0.00) | 2.08 (0.00) | 258 (000) |
| | | 2018 | C | 1 | 69 (00) | 1.32 (0.00) | 5.56 (0.00) | 0.07 (0.00) | 54 (0.00) | 2.38 (0.00) | 0.15 (0.00) | 2.15 (0.00) | 329 (000) |
| | | | E | 1 | 71 (00) | 1.29 (0.00) | 5.72 (0.00) | 0.05 (0.00) | 48 (0.00) | 2.55 (0.00) | 0.18 (0.00) | 2.08 (0.00) | 394 (000) |
| | | | E+T | 8 | 67 (03) | 1.10 (0.12) | 5.77 (0.10) | 0.04 (0.01) | 47 (8.25) | 2.62 (0.40) | 0.21 (0.04) | 2.71 (1.14) | 483 (131) |
| | DBL | 2015 | C | 1 | 71 (00) | 1.40 (0.00) | 6.08 (0.00) | 0.06 (0.00) | 41 (0.00) | 2.03(0.00) | 0.17 (0.00) | 0.62 (0.00) | 151 (000) |
| | | 2018 | C | 1 | 69 (00) | 1.29 (0.00) | 5.97 (0.00) | 0.06 (0.00) | 46 (0.00) | 2.83 (0.00) | 0.25 (0.00) | 2.13 (0.00) | 271 (000) |
| | | | E | 1 | 65 (00) | 1.32 (0.00) | 5.92 (0.00) | 0.05 (0.00) | 47 (0.00) | 2.96 (0.00) | 0.27 (0.00) | 2.43 (0.00) | 305 (000) |
| | | | E+T | 8 | 61 (03) | 1.22 (0.19) | 5.98 (0.09) | 0.05 (0.01) | 45 (3.89) | 2.93 (0.09) | 0.29 (0.01) | 2.43 (0.65) | 298 (059) |

Continued to next page

| Site | Land use | Years | SLM practices | n | Silt + Clay (%) | BD (g cm$^{-3}$) | pH | EC (ds m$^{-1}$ | CEC(cmol$_c$ kg$^{-1}$) | SOC (%) | TN (%) | $P_{av}$ (mg kg$^{-1}$) | $K_{av}$ (mg kg$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Dibatie | CL | 2015 | C | 2 | 85 (01) | 1.11 (0.00) | 5.84 (0.01) | 0.05 (0.00) | 42 (4.80) | 1.58 (0.21) | 0.13 (0.02) | 1.02 (0.68) | 96 (012) |
| | | 2018 | C | 2 | 84 (11) | 1.15 (0.05) | 5.65 (0.07) | 0.06 (0.03) | 42 (1.70) | 2.73 (0.06) | 0.23 (0.00) | 1.28 (0.54) | 248 (044) |
| | | | F | 14 | 87 (04) | 1.27 (0.08) | 5.63 (0.17) | 0.05 (0.03) | 36 (7.00) | 2.06 (0.69) | 0.17 (0.06) | 1.92 (1.46) | 318 (057) |
| | | | SBG | 14 | 87 (5) | 1.25 (0.17) | 5.68 (0.13) | 0.04 (0.01) | 37 (3.00) | 2.43 (0.51) | 0.20 (0.04) | 1.76 (1.10) | 322 (114) |
| | GL | 2015 | C | 1 | 84 (00) | 1.24 (0.00) | 5.84 (0.00) | 0.05 (0.00) | 36 (0.00) | 2.38 (0.00) | 0.20 (0.00) | 1.40 (0.00) | 51 (000) |
| | | 2018 | C | 1 | 84 (00) | 1.36 (0.00) | 5.83 (0.00) | 0.04 (0.00) | 28 (0.00) | 2.18 (0.00) | 0.18 (0.00) | 1.49(0.00) | 405 (000) |
| | | | E | 1 | 84 (00) | 1.33 (0.00) | 5.89 (0.00) | 0.04 (0.00) | 37 (0.00) | 2.61 (0.00) | 0.22 (0.00) | 1.51 (0.00) | 351 (000) |
| | | | E+T | 8 | 83 (04) | 1.11 (0.23) | 5.88 (0.07) | 0.06 (0.01) | 36 (4.00) | 2.61 (0.09) | 0.22 (0.01) | 1.54 (0.33) | 433 (061) |
| | DBL | 2015 | C | 1 | 72 (00) | 1.14 (0.00) | 6.10 (0.00) | 0.09 (0.00) | 51 (0.00) | 2.73 (0.00) | 0.24 (0.00) | 30.89 (0.00) | 207(000) |
| | | 2018 | C | 1 | 72 (00) | 1.31 (0.00) | 5.82 (0.00) | 0.09 (0.00) | 44 (0.00) | 2.67 (0.00) | 0.23 (0.00) | 33.19(0.00) | 523 (000) |
| | | | E | 1 | 72 (09) | 1.20 (0.00) | 6.00 (0.00) | 0.14 (0.00) | 41 (0.00) | 2.85 (0.00) | 0.25 (0.00) | 33.73(0.00) | 678 (000) |
| | | | E+T | 8 | 73 (04) | 1.07 (0.22) | 6.33 (0.14) | 0.15 (0.08) | 39 (4.00) | 2.75 (0.02) | 0.26 (0.02) | 36.00 (6.73) | 883(399) |
| Optimal ranges | | | – | – | – | 0.9–1.2[a] | 5.5–6.5[b] | 0.1–0.8[b] | 25–40[c] | 3–5[a] | 0.15–0.25[d] | 11–16[e] | 100–250[f] |

n, number of composite samples; C, control (conventional); F, *fanya juu*; SBG, soil bund reinforced with grass; E, exclosure; E + T, exclosure with trenches. Abbreviations related to soil parameters are defined in Table 4.4. Superscripts *a* to *f* denote the studies indicating the optimal levels of each soil parameter for plant productivity [[a]Reynolds et al. (2009), [b]Brady and Weil (2014), [c]Landon (2014), [d]Murphy (1968), [e]Jones (2002), [f]Oliver et al. (2013)].

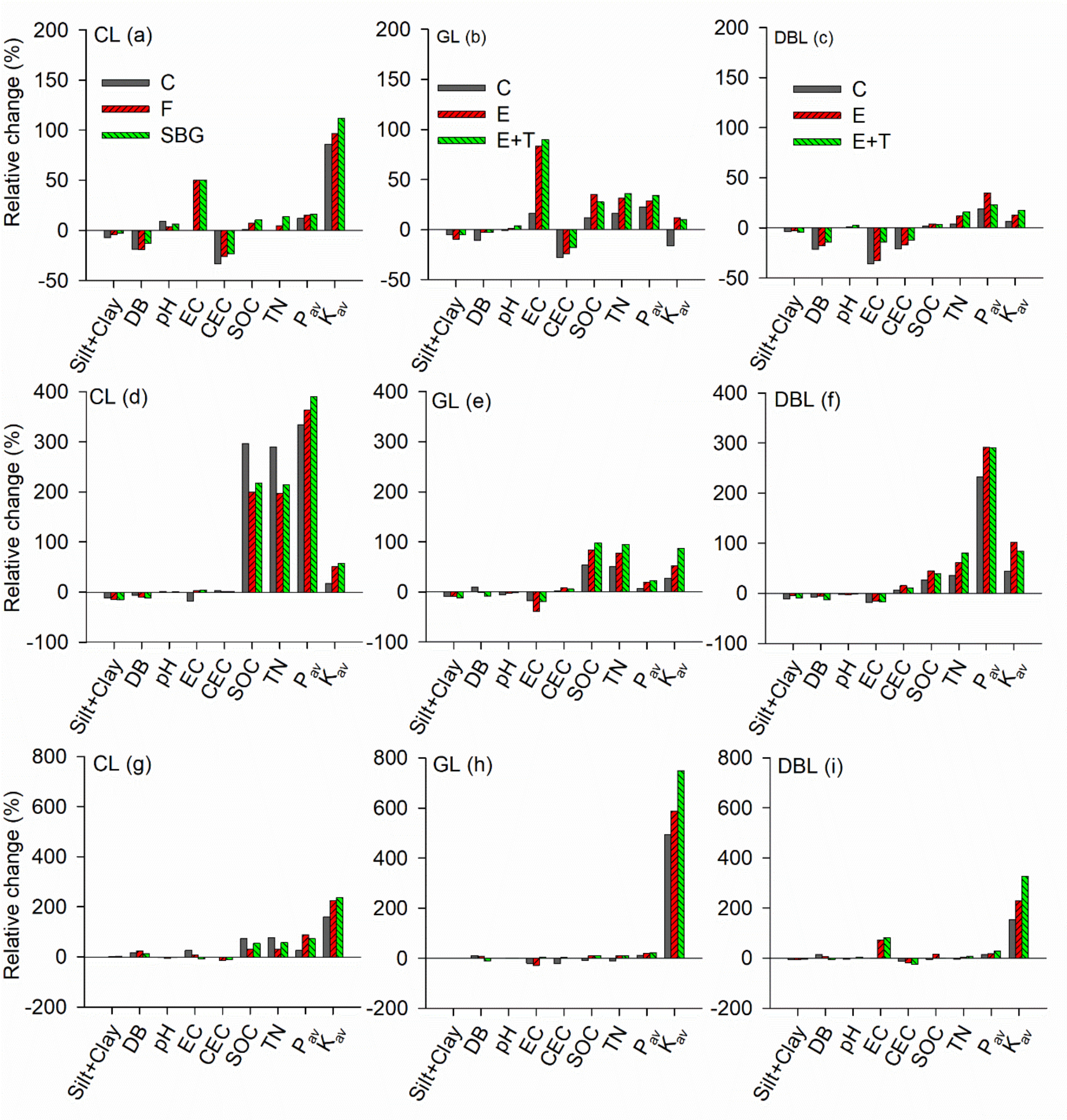

**Figure 4.4** Relative changes in soil quality indicator properties three years after the implementation of different land management practices in different land use types (CL, GL and DBL) at the Guder (a–c), Aba Gerima (d–f), and Dibatie (g–i**)** sites. The actual values are given in Table 4.5. The relative (percentage) change for each soil parameter was calculated from the ratio of the actual difference between two values (the value obtained in the 2018 minus the value obtained in the 2015) to the value obtained in the 2015 (reference value). C, control (conventional); F, *fanya juu*; SBG, soil bund reinforced with grass; E, exclosure; E + T, exclosure with trenches. Abbreviations related to soil properties are defined in Table 4.4.

### 4.3.5 Do soil properties vary between erosion and deposition zones in plots with SLM structures?

The impacts of SLM structures on soil quality gradients were evaluated by comparing soil parameter values between erosion and deposition zones of the sampled plots (Figure 4.1b, c, and f), (Table 4.6). Differences in box-and-whisker plots between erosion and deposition zones were observed in four soil parameters: clay content, $P_{av}$, and $K_{av}$ were generally higher in deposition zones than in erosion zones, whereas BD was generally higher in erosion zones (Figure 4.5). Possible reasons for this result include the following: (1) clay particles were selectively removed by surface runoff and deposited behind the SLM structures; (2) the available forms of nutrients ($P_{av}$ and $K_{av}$) were selectively enriched in the deposited sediment; (3) rain washed considerable amounts of $P_{av}$ and $K_{av}$ off the foliage of the protected vegetation, which grew well during the three year period (Figure 4.4), and the nutrients were eventually transported to the ditches by runoff; and (4) less depletion and an absence of disturbance by human activities in the deposition zones, mainly in cropland plots, because of prolonged waterlogging during the main rainy season.

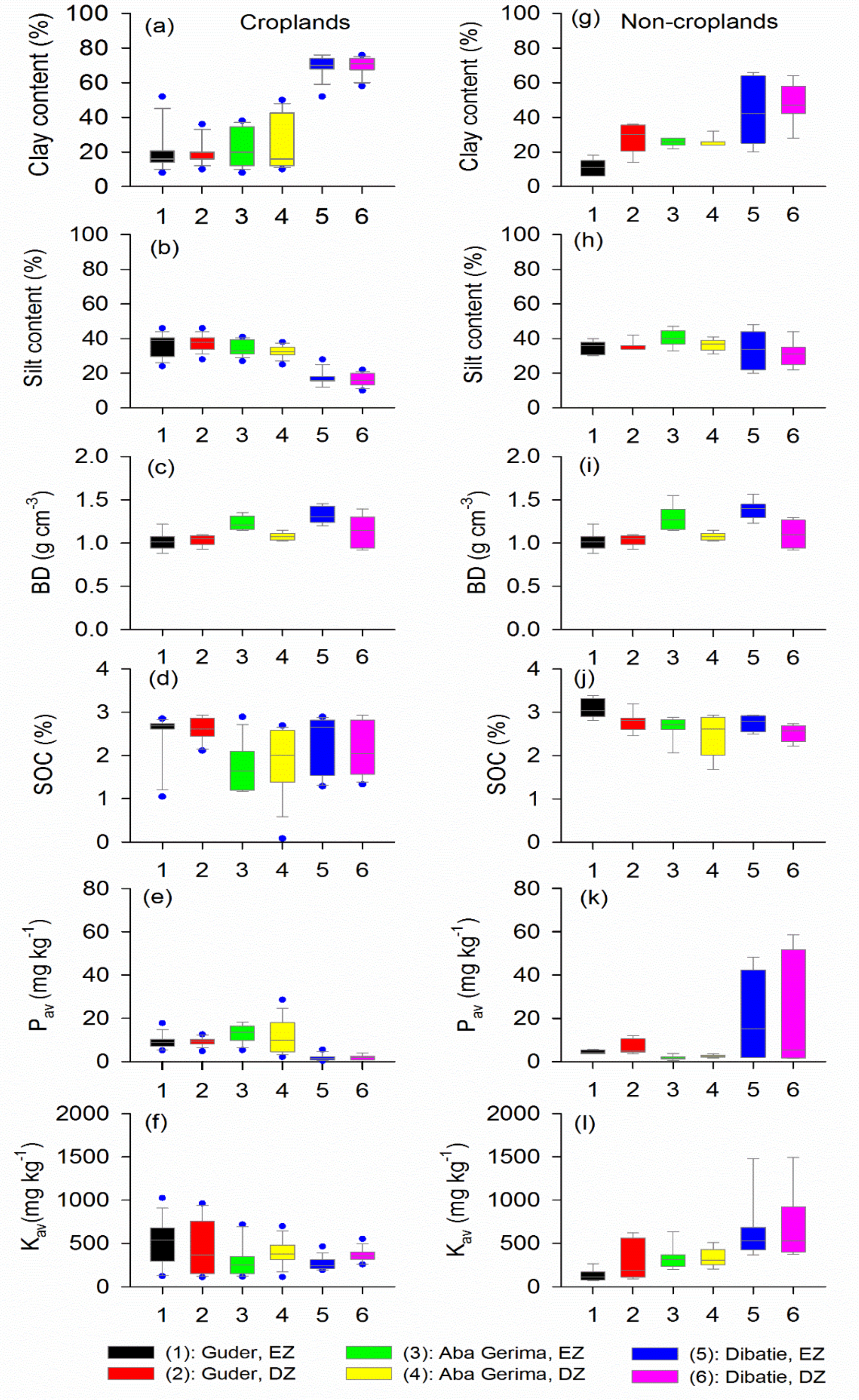

**Figure 4.5** Box-and-whisker plots showing variability in soil properties between

erosional and depositional zones:
Clay content (a), silt content (b), BD (c), soil organic carbon, SOC (d), $P_{av}$ (e), and $K_{av}$ (f) in soil samples collected from erosion zones (EZ), and deposition zones (DZ) along the slope in cropland plots with *fanya juu* and soil bunds reinforced with grass (a–f), and non-cropland plots with exclosure with trenches (g–l) at Guder, Aba Gerima, and Dibatie sites. Abbreviations are defined in Table 4; all data are shown in Table S1 of the supplementary material. Samples from the two non-croplands (grazing land and bushland) were aggregated for this analysis, but the separate analysis results for grazing land (GL) and bushland (DBL) plots are given in Table S1. The top and bottom of each box represent the upper and lower quartiles, respectively; the horizontal line within each box represent the median; whiskers represent variability outside the upper and lower quartiles, and the blue circles represent outliers.

Our finding of relatively higher clay content, $P_{av,}$ and $K_{av}$ in sediment deposition zones compared with erosion zones of plots (Table 4.6) shows that soil quality can vary within fields in which both erosion and sedimentation occur as a result of the selective transport of fine particles and available nutrients by erosion processes (Le Roux and Roos, 1983). Previous studies conducted in the highlands of Ethiopia have also observed higher contents of available nutrients in runoff-transported sediment samples. For instance, Haregeweyn et al. (2008) showed that the amount of $P_{av}$ and exchangeable potassium were significantly higher in reservoir sediment samples than in samples from the reservoir catchment. In a study conducted at Guder, (Kindiye, 2016) also reported that the mean concentrations of nutrients ($P_{av,}$ 19.24 to 59.39 mg $kg^{-1}$; $K_{av}$, 408.28 to 524.76 mg $kg^{-1}$) in sediment samples taken from trenches where runoff was collected from plots under similar SLM practices (trenches, soil bunds, and *fanya juu*) were much higher than those obtained in auger soil samples collected from within the plots ($P_{av,}$ 3.65 to 3.91 mg $kg^{-1}$; $K_{av}$, 273.00 to 360.00 mg $kg^{-1}$). Furthermore, in a similar study conducted in the central highlands of Ethiopia, (Adimassu et al., 2014) showed the mean concentration of $P_{av}$ was much higher in sediment samples (9.24 to 13.25 mg $kg^{-1}$) than in runoff samples (0.24 to 0.38 mg $L^{-1}$). Studies in the northern Ethiopia (Vancampenhout et al., 2006; Nyssen et al., 2007a) have also indicated that the maximum values of soil quality indicators (Pav, TN, and SOC) were found within 0 to 0.4 m on the upper side of stone bunds where sedimentation occurs.

**Table 4.6** Physical and chemical properties of soil samples (average values, and standard deviation in parenthesis) for erosion (EZ) and deposition (DZ) zones of plots with structural SLM practices in different land use types.

| Site | Land use | Sampling zones | Clay (%) | Silt (%) | pH | EC (ds $m^{-1}$) | CEC ($cmol_c$ $kg^{-1}$) | SOC (%) | TN (%) | $P_{av}$ (mg $kg^{-1}$) | $K_{av}$ (mg $kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Guder | CL | EZ | 19 (12) | 37 (7) | 5.34 (0.23) | 0.05 (0.02) | 26 (3.41) | 2.49 (0.55) | 0.21 (0.05) | 9.02 (3.12) | 458 (261) |
| | | DZ | 20 (7) | 37 (5) | 5.22 (0.30) | 0.06 (0.01) | 25 (2.53) | 2.60 (0.27) | 0.22 (0.02) | 9.33 (1.90) | 518 (310) |
| | GL | EZ | 15 (3) | 38 (2) | 5.72 (0.03) | 0.07 (0.01) | 26 (2.36) | 2.91 (0.08) | 0.24 (0.01) | 4.20 (0.94) | 177 (63) |
| | | DZ | 33 (4) | 37 (4) | 5.77 (0.09) | 0.06 (0.01) | 27 (4.96) | 2.77 (0.14) | 0.24 (0.01) | 9.00 (3.30) | 471 (182) |
| | DBL | EZ | 17(2) | 32 (3) | 5.67 (0.10) | 0.06 (0.01) | 33 (2.10) | 3.28 (0.14) | 0.27 (0.01) | 4.57 (0.90) | 80 (12) |
| | | DZ | 24 (9) | 35 (1) | 5.77 (0.11) | 0.06 (0.02) | 26 (9.54) | 2.79 (0.31) | 0.24 (0.03) | 4.40 (0.67) | 111 (17) |
| Aba Gerima | CL | EZ | 23 (11) | 35 (4) | 5.58 (0.08) | 0.04 (0.01) | 38 (11.80) | 1.77 (0.53) | 0.15 (0.04) | 13.04 (4.01) | 2961 (184) |
| | | DZ | 26 (15) | 32 (3) | 5.64 (0.15) | 0.06 (0.03) | 40 (7.63) | 1.88 (0.75) | 0.16 (0.06) | 11.46 (7.67) | 3991 (152) |
| | GL | EZ | 26 (3) | 45 (3) | 5.78 (0.04) | 0.04 (0.01) | 45 (6.60) | 2.47 (0.34) | 0.21 (0.03) | 2.04 (1.55) | 378 (150) |
| | | DZ | 26 (0) | 39 (2) | 5.75 (0.14) | 0.04 (0.01) | 49 (9.45) | 2.09 (0.36) | 0.18 (0.03) | 2.52 (0.65) | 398 (105) |
| | DBL | EZ | 26 (3) | 37 (3) | 5.99 (0.07) | 0.05 (0.01) | 45 (4.85) | 2.80 (0.10) | 0.23 (0.01) | 1.97 (0.42) | 262 (63) |
| | | DZ | 26 (4) | 34 (3) | 5.95 (0.12) | 0.05 (0.02) | 46 (2.25) | 2.86 (0.07) | 0.24 (0.00) | 2.62 (0.66) | 286 (54) |
| Dibatie | CL | EZ | 70 (6) | 17 (4) | 5.55 (0.20) | 0.05 (0.03) | 35 (7.04) | 2.30 (0.62) | 0.19 (0.05) | 1.78 (1.42) | 269 (74) |
| | | DZ | 72 (5) | 16 (4) | 5.66 (0.12) | 0.05 (0.01) | 38 (2.12) | 2.18 (0.64) | 0.18 (0.05) | 1.89 (1.16) | 365 (77) |
| | GL | EZ | 62 (5) | 22 (2) | 5.85 (0.06) | 0.05 (0.01) | 37 (1.48) | 2.59 (0.10) | 0.22 (0.01) | 2.00 (0.21) | 419 (74) |
| | | DZ | 57 (7) | 26 (4) | 5.92 (0.07) | 0.05 (0.01) | 35 (4.83) | 2.63 (0.09) | 0.22 (0.01) | 1.81 (0.43) | 447 (50) |
| | DBL | EZ | 26 (4) | 45 (2) | 6.25 (0.09) | 0.14 (0.03) | 41 (1.74) | 2.90 (0.04) | 0.24 (0.00) | 40.26 (8.52) | 822 (446) |
| | | DZ | 39 (7) | 36 (6) | 6.42 (0.16) | 0.18 (0.12) | 37 (4.92) | 2.41 (0.22) | 0.20 (0.02) | 39.33 (24.09) | 944 (403) |

The samples collected only from plots with structural SLM measures (*Fanya juu* and soil bund reinforced with grass for CL, and exclosure with trenches for GL and DBL) were considered for this analysis. For each sampling zones, n = 14 for CL, and n = 4 for GL and DBL. Abbreviations are defined in Table 4.1 and Table 4.2.

For most soil parameters (silt content, pH, EC, CEC, SOC, and TN), however, the variation in average values (Table 4.6) and box-and-whisker plots (Figure 4.5) between erosion and deposition zones of the plots were less than the variation between sites, and land use types. This result is not surprising and can best be explained by the short time period of the study, which was not long enough for soil erosion and other factors to bring about significant changes in soil properties. For instance, the lower seasonal runoff and soil loss rates observed in plots with SLM structures are mainly attributable to higher soil loss reduction efficiency in those plots (Table 4.1), in which vegetation became well established through the use of fencing and minimum tillage in cropland plots, and exclosures in non-cropland plots (Figure 4.3). This result can provide useful information that soil quality gradient can be minimized when SLM structures are integrated with vegetative measures to control soil erosion processes.

## 4.4 Conclusions

The results of this study demonstrate that physical and chemical properties of soils substantially varied across different agro-ecological zones, land use types, and land management practices in the Upper Blue Nile basin of Ethiopia. The laboratory analysis results for topsoil (0–20 cm) samples showed that SOC and TN were significantly higher in the highland agro-ecological zone than in the midland and lowland agro-ecological zones, largely because the higher aboveground dry-matter production coupled with higher rainfall and lower temperature conditions in the highlands favor the accumulation of SOM. In this study, the amounts of SOC and TN in cropland soils were lower than those in soils of grazing lands and bushlands; in fact, SOC and TN were sometimes much lower than the critical values below which a potentially serious decline in soil quality is expected to occur. This result may imply that in the Upper Blue Nile basin, carbon and nitrogen stocks have declined in soils under crop production, and is likely attributable to the continuous practice of unsustainable farming systems over centuries.

Of the soil parameters investigated in this study, those most subject to change by management (BD, SOC, TN, $P_{av}$, and $K_{av}$) generally showed a noticeable improvement three years after the implementation of the SLM practices; thus desirable changes in sensitive soil properties can be obtained in a short time period. The observed positive changes were greater in plots with soil bund reinforced by grass in fenced croplands, and with exclosure in non-croplands; therefore, exclosure is an effective land management strategy to restore natural vegetation and degraded soils in ecologically sensitive regions.

This study further revealed that most soil properties (pH, EC, CEC, $P_{av}$, and $K_{av}$) in plots with SLM practices were within, or in some cases even higher than, the optimal ranges suggested for good plant productivity. These results are largely attributable to the well-established vegetation cover, low soil loss rates, and organic matter build-up due to the use of exclosures in non-cropland plots, and fence and minimum tillage in cropland plots, over the three-year period. Thus, soil degradation can best be controlled by protecting vegetation against removal by free grazing and harvesting, and reducing the frequency and intensity of tillage operation. However, further investigation is necessary to examine the impacts of such practices on productivity and other soil quality properties such as soil microbial biomass, aggregation, respiration, and microbial and faunal diversity.

# Chapter 5

## General conclusions and recommendations

## 5.1 General conclusions

This study clearly demonstrated the substantial variability in runoff, soil loss, and soil properties as influenced by land use and management interventions in the Upper Blue Nile basin of Ethiopia. The variability in runoff, suspended sediment concentration, and sediment yield at watershed scales was attributed to the spatial and temporal variation in the important factors (magnitude and timing of peak rain events, land cover, and management practices). The study also figured out that the greater amount and variability of sediment yield (watershed scale soil loss rates) were caused by few but larger flow events.

This study, based on plot scale experiments, also revealed that magnitudes of runoff and SL (soil loss) widely varied across agro-ecologies, land use types, and management practices; the rates of both runoff and soil loss were generally higher from non-croplands in the midland agro-ecology (Aba Gerima) largely because of the occurrence of intense rain events, and heavy grazing which leads to continuous removal of protective cover and organic materials. Despite their effectiveness varied across site, land use type, and time, SLM practices (*Fanya juu,* soil bund*,* soil bund reinforced with grass, and exclosure with and without trenches) significantly reduced runoff and soil loss as compared to conventional practices, implying that it is worth investing in the use of SLM to control soil erosion. Soil bund reinforced with grass and exclosures were found to the best SLM practices to reduce both runoff and soil loss, most likely because of improvement in protective vegetative cover, and indicate that soil erosion and its consequences can best be controlled through enhancing vegetation growth and natural regeneration.

This study further demonstrated that physical and chemical properties of soils substantially varied across different agro-ecological zones, land use types, and management practices, like the variation in runoff and soil loss rates. This can also be attributed to the difference in factors (climate, soil parent material, and vegetation characteristics) that are principal determinants of soil formation and properties. For instance, the SOC and TN contents were significantly higher for soils in the highland agro-ecology than in the midland and lowland agro-ecologies, largely because of the higher rainfall and lower temperature conditions that favor the accumulation of SOM. In all agro-ecologies, the amounts of SOC and TN in cropland soils were significantly lower than those in soils of grazing lands and bushlands, and were in some cases much lower than the critical values below which a potentially serious decline in soil quality is expected to occur. This may imply that carbon and nitrogen stocks have declined in soils under crop production in the Upper Blue Nile basin, and is likely attributable to the continuous practice of unsustainable farming systems over centuries.

Soil properties those most subject to change by management (BD, SOC, TN, $P_{av}$, and $K_{av}$) showed a noticeable improvement three years after the implementation of SLM practices; the greater improvements were observed in fenced plots where protective vegetation cover was well developed (in plots with soil bund reinforced with grass and exclosures). This imply that, a ban on free grazing through the use of fence and exclosure is the best strategy to restore the natural vegetation and degraded soils in ecologically sensitive regions.

## 5.2 Recommendations

The watershed scale analysis of soil loss indicated that small number of peak flow events accounted for a larger percentage (53 to 93%) of the seasonal *SY,* and its variability. The results, hence, suggest that careful and site-specific sampling, combined with measurements of peak flow events, will be crucial to accurately assess the dynamics of sediment yield at watershed scales, and to support planning appropriate measures to control soil erosion. This study further revealed that soil loss rates measured at watershed scales were 3 to 1013 times higher than those measured at plot scales, indicating that processes not captured by plot-scale measurements (e.g., gully erosion, bank erosion, mass wasting) are dominant contributors of soil loss at watershed scales, and thus a great care must be taken when using plot scale results for spatial analysis of soil erosion and its consequences at watershed and regional scales.

All the SLM practices investigated by this study substantially reduced both runoff and soil loss; the relative effectiveness was, however, more important in the reduction of soil loss than of runoff, which can probably be attributed to the limited storage capacity to capture infiltration excess runoff water. Hence, additional strategies may be needed to manage excess runoff water so as to reduce its on-site and off-site consequences. For non-croplands, exclosures with and without trenches generally exhibited comparable effects on soil loss but exclosure with trenches reduced runoff much better than without trenches. This implies that exclosures alone might be suitable where soil loss is the main concern, whereas, exclosures and trenches may be needed where runoff and soil loss are both a concern.

The use of minimum tillage for croplands and exclosures for non-croplands were found to be the most effective SLM measures for reducing runoff and soil loss, and improving some soil quality properties. Further investigation is, however, necessary to examine the impacts of such practices on productivity and other soil quality properties such as soil microbial biomass, aggregation, respiration, and microbial and faunal diversity. Also, such practices must be examined and adopted in collaboration with land users for whom immediate needs must surpass concerns for the future.

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# Summary

Soil erosion is one of the most pressing environmental challenges in the highlands of Ethiopia where small-scale agriculture is the main source of livelihood for about 87% of country's population. Beyond soil and nutrient losses, accelerated soil erosion is causing rapid sedimentation problem that threatens the life of hydropower or irrigation reservoirs and canals in Ethiopia as well as in downstream countries such as Sudan and Egypt.

In the past few decades, huge financial and labor resources have been invested by both governmental and non-governmental organizations for the implementation of sustainable land management (SLM) practices to mitigate soil erosion in many regions of Ethiopia. The impacts of most SLM practices were better tested and well documented for the dryer areas of the northern highlands, while such relevant studies are limited for the wetter and actively eroding regions like the Upper Blue Nile basin. This is due partly to insufficient policy attention and difficulties inherent in collecting sufficient and reliable runoff, soil, and sediment data at wider spatial and temporal scales. This study was, therefore, aimed to improve our current understanding of the rates of soil loss at various spatial and temporal scales and identify SLM practices that can reduce runoff and soil loss and thereby enhance soil quality properties. The study was conducted in three

contrasting agro-ecologies [i.e., Dibatie (lowland), Aba Gerima (midland), and Guder (highland) watersheds] of the Upper Blue Nile basin of Ethiopia covering the period from 2014 to 2018 and combining field survey, monitoring, and experimentation techniques. The specific objectives were to (i) better understand the variability in soil loss (sediment yield) at watershed scales with and without SLM intervention; (ii) quantify the effects of land use and management practices on runoff and soil loss (SL), and identify SLM practice/s best control soil erosion; and (iii) understand the variation in key soil properties as influenced by land use and management practices. These objectives cover chapters 2–4 of this thesis which comprises five chapters summarized as follows:

Chapter 1 presents the introductory sections (background, problem statement, objectives, and the study area) based on the existing literatures, observed data, and facts. It provides condensed explanations of soil erosion and land degradation, and sustainable land management efforts and practices in Ethiopia. It then describes the aims of this study and the overall structure of the thesis.

Chapter 2 analyses the variability of sediment yield ($SY$) in the humid tropical highland, based on discharge and sediment data monitored at the outlets of adjacent paired watersheds with (Kasiry) and without (Akusity) intervention for SLM. The measurements were done during the rainy seasons of 2014 and 2015 using gauging stations equipped with automatic flow stage sensors, manual staff gauges and a depth-integrated sediment sampler. Empirical discharge–sediment curves were created for three different parts of each rainy season to calculate *SY*. The results of the Mann-Whitney U test reveal that the daily *SY*s were significantly ($Z > -1.96$ and $P < 0.05$) higher for the watershed without SLM (Akusity) than that with SLM (Kasiry) in the two seasons. Similarly, the cumulative seasonal *SYs* for Akusity (25.7 t $\text{ha}^{-1}$ in 2014 and 71.2 t $\text{ha}^{-1}$ in 2015) were much higher than those observed for Kasiry (7.6 t $\text{ha}^{-1}$ in 2014 and 27.2 t $\text{ha}^{-1}$ in 2015). For both watersheds, however, three peak flow events accounted for a larger percentage (53% to 93%) of the seasonal *SY,* and resulted in extreme variability in daily *SY* (CV = 582% and 685% for Akusity, and CV = 313% and 586% for Kasiry during the rainy seasons of 2014 and 2015, respectively). This indicates that peak flow events are major determinants of the amount and variability of *SYs*, and thus, careful measurement of such events is crucial to better understand the dynamics of *SY* in small watersheds of tropical highland environments.

Chapter 3 examines the effects of land use and SLM practices on runoff and SL in the three agro-ecologies of the Upper Blue Nile basin. The analyses is based on runoff and sediment data collected using runoff plots (30 m × 6 m) from three land use types (cropland, grazing land, and degraded bushland) in the highland, midland, and lowland agro-ecologies of the basin. Four treatments (control, soil bund, *Fanya juu,* and soil bund reinforced with grass) for croplands, and three treatments (control, exclosure with, and without trenches) for non-croplands (grazing land, and degraded bushland) were investigated during the rainy seasons of 2015 and 2016. The results show that runoff and SL varied greatly across agro-ecologies, land use types, and SLM practices. The highest rates of both seasonal runoff (898 mm in 2016) and SL (39.67 t ha$^{-1}$ in 2015) were observed from untreated grazing land in the midland agro-ecology, largely because of heavy grazing and intense rain events. In all agro-ecologies and land use types, both runoff and SL were significantly lower ($P < 0.05$) in plots with SLM than without, i.e., SLM practices effectively reduced runoff and SL with a relative effectiveness ranging from 11% to 68% for reducing runoff, and 38% to 94% for reducing SL, depending of land use and agro-ecology. Soil bund reinforced with grass in croplands and exclosure with trenches in non-croplands were found to be the most effective SLM practices for reducing both runoff and SL, indicating that combined structural and vegetative measures are the best way to control soil erosion and its consequences.

Chapter 4 investigates variations in soil properties among land use types and management practices. A total of 162 topsoil (0–20 cm) samples were collected and analyzed for key soil properties—texture, pH, electrical conductivity (EC), cation exchange capacity (CEC), total nitrogen (TN), soil organic carbon (SOC), available phosphorus ($P_{av}$), and available potassium ($K_{av}$). Also, 90 core samples were collected and analyzed for bulk density (BD) of topsoil. The results of one way ANOVA showed that Seven of the 11 soil properties significantly differed among the three land use types in all agro-ecologies ($P < 0.05$ to $P < 0.001$); pH, CEC, SOC, and TN values were lower in croplands than in grasslands and degraded bushlands. These imply that soil fertility under crop production has been greatly deteriorated by unsustainable cropping systems practiced over centuries. After the implementation of SLM practices, however, sensitive soil properties (BD, SOC, TN, $P_{av}$, and $K_{av}$) were markedly improved. This improvement is primarily attributed to the development of a well-established vegetation cover owing to minimum tillage and exclosures, indicating that soil degradation can best be controlled through enhancing vegetation growth and reducing soil disturbance by tillage.

Chapter 5 presents the general conclusions and recommendations based on the key findings from Chapters 2–4. Chapter 2 demonstrates that average sediment yield from the watershed with SLM intervention was 1.94 times lower than that from the watershed without; indicating that SLM interventions considerably reduced soil loss rates at watershed scales. It is also demonstrated in Chapter 3 and 4 as significantly lower runoff and SL rates, and greater values of soil quality parameters were observed in plots with SLM than without, regardless of agro-ecology and land use types. This, therefore, provides useful information that soil erosion and associated land degradation can best be controlled by implementing suitable SLM practices.

# 学位論文概要

土壌侵食は、小規模農業が国の人口の約87%にとって主な生計の源であるエチオピアの高地で最も差し迫っている環境問題のひとつである。土壌と栄養素の損失に加えて、急速な土壌侵食は甚大な堆積問題を引き起こしており、それはエチオピアならびにスーダンとエジプトなどの下流国における水力発電および灌漑用貯水池と運河の機能を脅かしている。

過去数十年の間に、エチオピアの多くの地域で土壌侵食を軽減するための持続可能な土地管理（SLM）の実施に向けて、政府機関・非政府機関の両者によって膨大な財源と労働力が投資されてきた。SLMの実施結果の影響は、北部高地のより乾燥した地域で主に検証されてきており、湿潤で侵食活動が活発な青ナイル川上流域では限られている。信頼性のある流出・堆積データが広域・長期に収集されていないことは、SLMに関する政策立案を困難にしている。したがって、本研究では、現在のさまざまな時空間スケールでの土壌損失率の理解を深め、流出量と土壌損失を減らし、それによって土壌特性を向上させることができるSLM手法を特定することを目的とした。調査は、2014年から2018年までの期間、エチオピアの青ナイル川上流域の3つの対照的な農業生態系、すなわちDibatie（低地）、Aba Gerima（中間地）、およびGuder（高地）流域で行われた。具体的には、①SLMの実施が流域スケールでの土壌損失（土砂生産量）の変動をよりよく理解すること、②土地利用および管理策が流出および土壌損失（SL）に及ぼす影響を定量化し、土壌侵食を最小化するSLMを特定すること、③土地利用や管理策が土壌特性に及ぼす影響の評価の3点に取り組んだ。これらの目的は、本論文の第2章から第4章に対応している。

第1章では、既存の文献、観察されたデータ、および事実に基づき本研究の背景、問題点、目的、および研究分野を示す。土壌侵食と土地劣化、およびエチオピアにおける持続可能な土地管理の取り組みについて解説する。つぎに本研究の目的と論文の全体的な構造について説明する。

第2章では、SLMの実施あり（Kasiry）および実施なし（Akusity）の隣接する

2つの流域の流出口で観測された流出量および堆積物データに基づいて、湿潤熱帯高地における堆積物生産量（SY）の変動を分析する。測定は、2014年と2015年の雨季に、自動フローステージセンサー、手動スタッフゲージ、および深度統合堆積物サンプラーを装備した測定ステーションを使用して行われた。SYを計算するために、各雨季の3つの異なる時期について経験的な流出量 - 堆積物曲線が作成された。Mann-Whitney U検定の結果、2つの季節において、SLMなし（Akusity）の流域で、日数SYが有意に（Z> -1.96およびP <0.05）高いことを明らかにした。同様に、Akusityでの累積季節SY（2014年は25.7 t ha-1、2015年は71.2 t ha-1）は、Kasiry（2014年は7.6 t ha-1、2015年は27.2 t ha-1）よりはるかに高かった。しかし、両流域では、3つのピークフローイベントが季節SYのより大きい割合（53%から93%）を占め、日々のSYの極端な変動性をもたらした（2014年と2015年の雨季においてAkusityではCV = 582%と685%、KasiryではCV = 313%と586%）。これは、ピークフローイベントがSYの量と変動性の主要な決定要因であることを示しているので、そのようなイベントを注意深く測定することが熱帯高地環境の小流域におけるSYの動態をよりよく理解するために重要である。

第3章では、青ナイル川上流域の3つの農業生態系における、土地利用とSLMが流出量とSLに与える影響について検討した。この分析は、流域の高地、中間地、低地の農業生態系における3つの土地利用タイプ（農地、放牧地、および劣化した低木地）からの流出プロット（30 m×6 m）を使用して収集された流出および堆積物データに基づいている。農地のための4つの処理（対照、ソイルバンド、ファニャジュ、および草で補強されたソイルバンド）、および非耕地（放牧地、および劣化した低木地）のための3つの処理（対照、耕地の有無）の結果は、流出量とSLが農業生態系、土地利用の種類、そしてSLMによって大きく異なることを示している。大規模な放牧と激しい雨のため、季節的な流出量（2016年は898 mm）とSL（2015年は39.67 t ha-1）の両方が、未処理の放牧地から観察された。すべての農業生態系と土地利用型において、流出とSLの両方がSLMのないプロットよりもプロットで有意に低かった（P <0.05）。SLMの効果としては、土地利用や農業生態学に応じて、流出量を11～68%削減し、SLを38～94%削減した。

耕作地では草で補強されたソイルバンド、非耕作地ではトレンチを導入した放牧柵が、流出とSLの両方を減らすための最も効果的なSLM手法であることが示された。

第4章では、土地利用型と管理策の間での土壌特性の変動を調査します。合計162の表土（0〜20 cm）サンプルを収集し、主要な土壌特性（土性、pH、電気伝導度（EC）、陽イオン交換容量（CEC）、全窒素（TN）、土壌有機炭素（SOC）、有効態リン（Pav）、および有効態カリウム（Kav））を分析した。また90個のコアサンプルを収集し、表土のかさ密度（BD）を分析した。一元配置分散分析の結果から、11の土壌特性のうち7つが3つの土地利用型の間ですべての農業生態学で有意に異なっていた（$P < 0.05$から$P < 0.001$）。pH、CEC、SOC、TNの値は、牧草地や荒廃した低木地よりも農地のほうが低かった。これらは、作物生産下の土壌肥沃度が何世紀にもわたって実践されている持続不可能な作付体系によって大きく悪化したことを意味している。しかし、SLMの実施後、敏感な土壌特性（BD、SOC、TN、Pav、Kav）は著しく改善された。この改善は主に、耕作と耕作が最小限であるために確立された植生被覆が発達したことに起因しており、植生の成長を促進し、耕作による土壌攪乱を減少させることによって土壌劣化を抑制できることを示している。

第5章では、第2章から第4章までの主な調査結果に基づいた一般的な結論と土壌保全に関する提案について説明する。第2章は、SLM実施による流域からの平均土砂生産量は、SLM実施なしの流域からのそれより1.94倍低いことを示している。 SLM実施が流域スケールでの土壌損失率をかなり減少させたことを示している。第3章と第4章では、農業生態学と土地利用型にかかわらず、流出量とSL率が有意に低いこと、そしてSLMがない場合よりも高い値の土壌特性が観察された。したがって、SLMを適切に実施することで、土壌侵食とそれに伴う土地の劣化を抑制することができるという有用な情報が提供された。

# List of Publications

1. Ebabu, K., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Aklog, D., Masunaga, T., Tsubo, M., Sultan, D., Fenta, A.A. and Yibeltal, M. (2018). Analyzing the variability of sediment yield: A case study from paired watersheds in the Upper Blue Nile basin, Ethiopia. Geomorphology 303: 446–455 (Published, DOI: 10.1016/j.geomorph.2017.12.020, this article covers Chapter 2 in the thesis).

2. Ebabu, K., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D.T., Aklog, D., Masunaga, T., Tsubo, M., Sultan, D., Fenta, A.A. and Yibeltal, M. (2019). Effects of land use and sustainable land management practices on runoff and soil loss in the Upper Blue Nile basin, Ethiopia. Science of the Total Environment 648: 1462–1475 (Published, DOI: 10.1016/j.scitotenv.2018.08.273, this article covers Chapter 3 in the thesis).