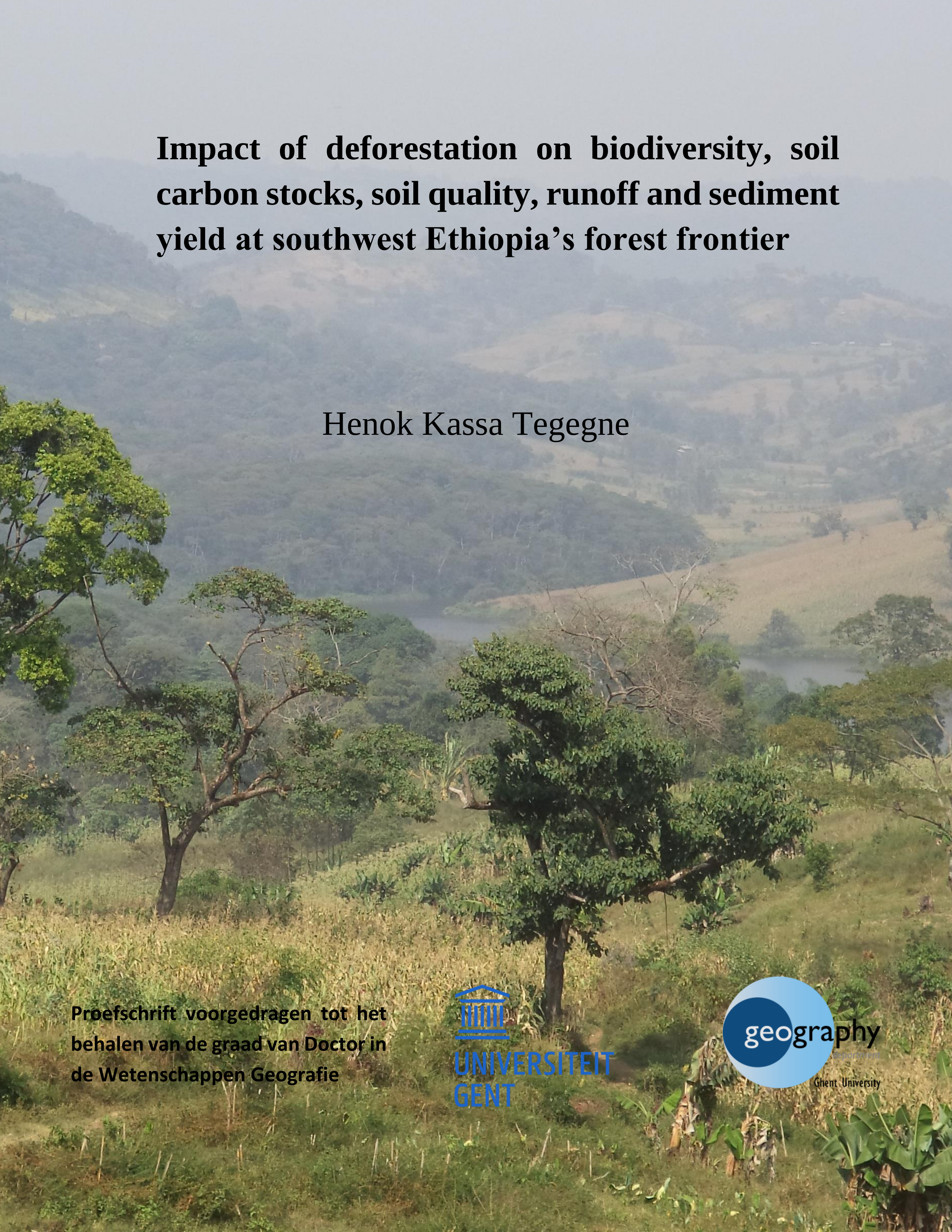

Impact of deforestation on biodiversity, soil carbon stocks, soil quality, runoff and sediment yield at southwest Ethiopia's forest frontier

Henok Kassa Tegegne

Proefschrift voorgedragen tot het behalen van de graad van Doctor in de Wetenschappen Geografie

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List of Acronyms

A	**Cross sectional flow area**
ADLI	Agricultural Development Led Industrialization
ANOVA	Analysis of Variance
BF	Base flow
Ce	Effective free flow' discharge coefficient
Ct	Carbon Stocks
d	Runoff depth
DEM	Digital Elevation Model
DM	Dakin middle
EEPCO	Ethiopia Electric Power Cooperation
FAO	Food and Agriculture Organization of the United Nations
FH	Faketen high
FL	Fanika low
FLAL	Fanika low agroforestry land use
FLCL	Fanika low cropland land use
FLFL	Fanika low forest land use
g	Gravity
GSE	Geological Survey of Ethiopia
hu	Flow height
L	Length
M	Gross mass of suspended sediment concentration
m a.s.l.	Meter above sea level
MACWE	Mizan-Aman City Water Supply Sanitation Enterprise
Mg	Mega gram
N	Number of rotation
OM	Oka middle
P	Rainfall
Q	Discharge
Qi	Runoff discharge for each10 min interval

Qs,d	Daily sediment export
R_s	Storm runoff
RC	Runoff coefficient
R	Runoff
SSY	Suspended sediment yield
SSC	Suspended sediment concentration
Var.	Variation
V	Flow velocity
W	Width
ZH	Zemika high
ZHAL	Zemika high agroforestry land use
ZHCL	Zemika high Cropland land use
ZHFL	Zemika high forest land use
ZM	Zemika middle
ZMAL	Zemika middle agroforestry
ZMCL	Zemika middle cropland land use
ZMFL	Zemika middle forest land use

List of Publications

International SCI-ranked journal articles as first author (with SCI impact factor IF)

Henok Kassa, Dondeyne, S., Poesen, J., Frankl, A., Nyssen, J., 2016. Transition from forest-based to cereal-based agricultural systems: a review of the drivers of land-use change and degradation in southwest Ethiopia. Land Degradation and Development, online early view. (IF: 8.145)

Henok Kassa, Dondeyne, S., Poesen, J., Frankl, A., Nyssen, J., 2016. Impact of deforestation on soil fertility, soil carbon and nitrogen stocks in Gacheb catchment, White Nile basin, Ethiopia. Agriculture, Ecosystems and Environment, in review. (IF 3.564)

Henok Kassa, Dondeyne, S., Poesen, J., Frankl, A., Nyssen, J., 2016. The agro-ecological implications of forest and agroforestry conversion towards cereal-based farming systems: the case of the Gacheb catchment in the White Nile Basin, Ethiopia. Agroecology and Sustainable Food Systems, in review. (IF 0.926)

Henok Kassa, Frankl, A., Dondeyne, S., Poesen, J., Nyssen, J. 2016. Sediment yield at southwest Ethiopia's forest frontier. Land Degradation and Development, in review. (IF: 8.145)

Conference presentations (as first author)

Henok Kassa, Dondeyne, S., Poesen, J., Frankl, A., Nyssen, J., 2015. Impact of deforestation on physico-chemical soil characteristics in the highlands of south-western Ethiopia. Paper presented at the 6th Belgian Geography Days, 13-14 November 2015, VUB, Brussels; book of abstracts p. 47.

Chapter 1

General Introduction

1.1 Problem statement

Land degradation in Ethiopia stems from the historical development of agriculture and human settlement in highland regions (Hurni, 1988; Nyssen et al., 2015). The human impact on the change in forest cover dates back 2000 to 3000 years in northern Ethiopia, which is a much longer period than in any other East African country (Nyssen et al., 2004; Lanckriet et al., 2016). The presence of this longstanding agricultural civilization that used the plough (Ehret, 1979; McCann, 1995) has led to the presence of extensive open fields, where good yields are sustained through fertilizer inputs (Kraaijvanger & Veldkamp, 2015).

In contrast, the southwestern Ethiopian montane rainforest (Fig. 1.1) where the local people have developed traditional management practices based on customary tenure rights and religious believes (Zewdie, 2007) has been much less studied, similarly to other agricultural systems on the margins of the Ethiopian highlands (Kuls, 1962; Tilahun, 2015). Semi-permanent cultivation systems (Ruthenberg, 1983) in and at the margin of tropical forests are under threat worldwide (e.g. De Jong et al., 2001; Fleskens & Jorritsma, 2010) and such is also the case in southwest Ethiopia (Engdawork & Bork, 2016). There, current land management dynamics that have resulted in deforestation are related to cropland expansion under the form of open farmlands, settlement and investment in commercial agriculture (Mekuria, 2005; Dereje, 2007; Bedru, 2007; Belay, 2010).

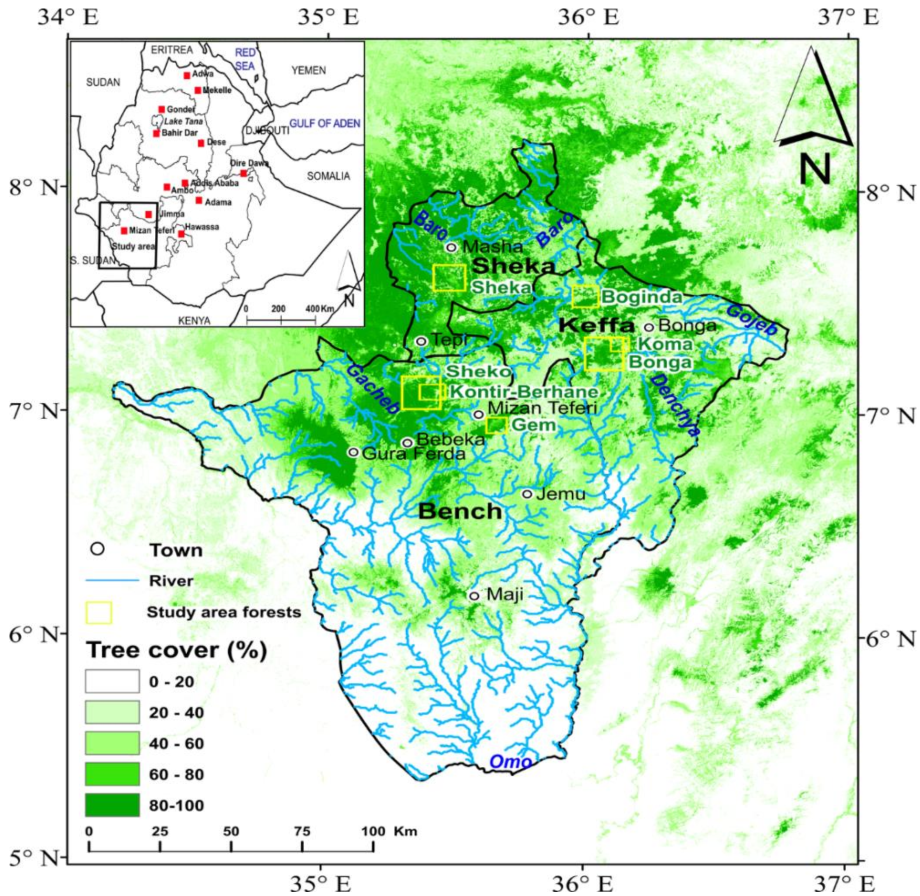

Figure 1.1. The montane forest in southwest Ethiopia with tree cover in 2000 (after Hansen et al., 2013)

1.2 The environmental degradation in southwestern Ethiopia

The southwestern part of Ethiopia highlands was completely covered by montane rainforest at the beginning of 19th century (Chaffey, 1979; Reusing 1998, 2000). In this respect, the closed evergreen broadleaf forest covers 38% of the area in between 1971 and 1975 (Chaffey, 1979). The evergreen broadleaf forest of southwestern Ethiopia is complex in structure and composition, where the upper canopy trees like *Aningeria adolfi-friedericii* (Engl.), *Croton macrostachyus* (Hochst.) ex Delile, *Celtis africana* N.L.Burm, *Albizia gummifera* (J.F.Gmel.) C.A.Sm, *Schefflera abyssinica* (Hochst. ex A.Rich) were associated with middle stratum trees like *Millettia ferruginea* (Hochst) Baker, *Hagenia abyssinica* (Willd.), *Polyscias fulva* (Hiern). The understory layer consist of small trees, shrubs and herbs like *Cyathea manniana* (Hook.), *Vernonia amygdalina* (Delile), *Grewia ferruginea* (Hochst.), *Justicia schimperiana* T.Anderson, *Coffea arabica* (L.) and patch of herbs (Friis, 1986; Feyera, 2006; Schmitt, 2006).

The forest management in southwestern Ethiopia is based on the local customary forest tenure system and religious concepts (Dereje & Tadesse, 2012; Zewedie, 2007). For instance, the access to cultural forest is restricted through resource and habitat taboos (Fig. 1.2) through the *guudo* (cultural forest used as a worship place) and *deddo* (a large tree under which prayers or religious ceremonies are conducted). This customary forest tenure system, which has been functioning for more than a century, is still recognized by the local communities. However, the past and present governments has not been given full recognition by any statutory law (Dereje & Tadesse, 2012; Zewedie, 2007).

The traditional agroforestry is one of practice of the local community in the southwestern Ethiopia by modification of the forest or planting selected agroforestry tress for home garden agroforestry practice. In the first case, some matured woody species in the forest are coppiced and reduced in density, to favour regeneration and productivity of the understory plants, mainly coffee and other plant species. The traditional agroforestry systems of southwestern Ethiopia consists of complex plant structure and composition, which is composed of *Coffea arabica* L., as a cash crop integrated with food crops such as false banana (*Ensete ventricosum* Welw. Cheesman), banana (*Musa sapientum* L.) and taro (*Colocasia esculenta* L. Schott) and spices like korarima (*Aframomum corrorima* Braun). Moreover, various fruit trees such as mango (*Mangifera indica* L.), avocado (*Persea americana* Mill.), papaya (*Carica papaya* L.) and orange (*Citrus sinensis* L. Osbeck) are also integrated in the farming system. Furthermore, native trees like *Albizia gummifera* J.F.Gmel. C.A.Sm., *Cordia africana* Lam., *Millettia ferruginea* Hochst. Baker, *Polyscias fulva* Hiern. Harms, are kept for shade, fodder, firewood, medicinal value and soil fertility maintenance (Bishaw & Abdu, 2003).

Figure 1.2. The upper part of this catchment in Daken (7° 2' 35''N, 35° 38' 55''E) is occupied by a cultural forest and henceforth protected from encroachment, what leads to the sharp boundary between cropland and forest.

Table 1.1. Forests studied in southwest Ethiopia, listed from South to North

Forest name	Coordinates of forest centre	Administrative zone	Area of the forest (km²) *	Nearby towns	Main ethnic groups in and around the forest	Elevation (m a.s.l.)	References
Gem	6.96°N, 35.65°E	Bench Maji	80-200	Mizan-Teferi	Bench	1400 - 2800	Getachew (2010)
Kontir-Berhane (part of Sheko forest)	7.08°N, 35.40°E	Bench Maji	250	Sheko, Mizan-Teferi, Gezmeret	Sheko, Bench, Keffa, Majangir, Me'en Settlers: Amhara	950 - 1800	Feyera (2006)
Sheko	7.09°N, 35.37°E	Bench Maji	2200 - 3940	Tepi, Mizan-Teferi, Gezmeret	Sheko, Majangir, Keffa, Bench, Me'en Settlers: Amhara	700 - 2800	Dereje (2005); WCC-PFM (2011); Feyera (2006)
Bonga	7.27°N, 36.07°E	Keffa	1600 - 2500	Sheshinda, Wushwush, Gimbo	Keffa, Bench, Kulo, Charra, Manjo**, Oromo, Nao Settlers: Amhara, Oromo, Gawata	1000 - 3500	Tezera (2008); Schmitt (2006); Sisay (2008); Bender-Kaphengst *et al*. (2011)
Koma (part of Bonga forest)	7.30°N, 36.09°E	Keffa	12	Wushwush, Agama, Komba	Keffa, Manjo** Settlers: Kambata	1850 - 2250	Stellmacher (2005); Stellmacher & Mollinga (2009); Vandenabeele (2012); Ayana *et al*. (2015)
Boginda	7.50°N, 36.02°E	Keffa	600 - 1000	Bonga, Wushwush, Gewata	Keffa, Bench, Kulo, Charra, Manjo**, Nao Settlers: Amhara, Oromo	1500 - 3500	Mekuria (2005); Philippe (2003); Sisay (2008)
Sheka	7.60°N, 35.48°E	Sheka	1000 - 2400	Masha, Tepi, Gecha	Sheka, Keffa, Sheko, Bench, Majangir , Manjo** Settlers: Amhara, Oromo, Sidama	900 - 2700	Tadesse (2007); Zewdie (2007); Tadesse & Fite (2011)

* Reported areas vary among authors; lower value indicates natural forest, higher values include also villages, grazing land and cropland in clearings; ** Manjo is a lower social-ethnic caste within the main ethnic groups

In the past, agriculture production in southwestern Ethiopia practiced shifting cultivation, cattle rearing, hunting and wild honey collection. The local farmers use sticks and hoes for tilling their farmland. The sedentary lifestyle and agriculture that now dominates, began with the imposition of the Menelik II regime in the 1890s (Akalu, 1982; Legesse, 2000). The agriculture land is mainly dominated by cereal crops like maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L.), barley

(*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.) and "teff" (*Eragrostis tef* Zucc.); integrated with some pulse crops like field pea (*Pisum sativum* L.) and haricot bean (*Phaseolus vulgaris* L.) and root crops like yam (*Dioscorea rotundata* Poir.*)*, taro (*Colocasia esculenta* L.) and cassava (*Manihot esculenta* L.) (FARM Africa & SOS Sahel-PFM, 2004; Tezera, 2008; van Beijnen et al., 2004; Belay, 2010).

1.2.1. Drivers of land use change

Resettlement

The arrival of settlers from drought-prone areas of central or northern Ethiopia and from other parts of southern Ethiopia to the densely forested region of southwest Ethiopia influenced the local forest management, agroforestry practices and forest cover (Belay, 2010; Mekuria, 2005; Stellmacher, 2005). There are, however, no official statistics on how many people have resettled in southwest Ethiopia over the past decades. During the reign of Emperor Haile Selassie (1930–1974), many peasants were relocated from northern Ethiopia to the southern and southwestern regions (Kassa, 2004; Wood, 1977). It is estimated that 20,000 families were resettled in Keffa through 1974 (Clarke, 1986). The Derg regime (1974–1987) officially supported the resettlement of several thousands of people from the central highlands to southwest Ethiopia because of an epidemic disease outbreak that caused a massive decimation of domestic animals (Alemneh, 1990). Approximately 250,000 people were resettled in Keffa between 1985 and 1988 (Alemneh, 1990). Similarly, the current government has relocated several thousands of people from northern and other southern regions to southwest Ethiopia (Belay, 2010).

Settlers originate from food-insecure and famine-struck areas of the country. The new settlers were and are still selected based on the severity of the problem, free consent and willingness of resettlers to move from drought-prone densely populated areas of central and northern Ethiopia (Wood, 1982; Pankhurst, 1988; Kloos & Aynalem, 1989). During Derg regime, large numbers of people were forcefully resettled in a disorganized way (Pankhurst & Piguet, 2004; Mulat et al., 2006).

Land allocated to new settlers, for farmland and for residence, had been forests which local people used for harvesting NTFPs (Mekuria, 2005; Belay, 2010; Moti et al., 2011; Bedru, 2007). The settlers were also provided with permanent communal grazing lands in the area (Belay, 2010).

Though most of the resettlement in Southwest Ethiopia was undertaken without consultation of the local people, except for the recent EPRDF regime planned resettlement, the host communities generally do not oppose resettlement if there is unoccupied land available (Moti et al., 2011). The installation of infrastructure and distribution of agricultural inputs related to resettlement programmes also benefits host communities. Pankhurst & Piguet (2004) indicate that the opposition of the host community on the new settler starts not on their arrival, but the crux of the matter lies in the relations between hosts and migrants and their resource use, given the tendency for migration to exacerbate resource conflict.

Reusing (2000) indicated that the settlers have introduced a new farming system, which is not adapted to the area. For settlers from northern, central and other parts of the southern region, resettlement entailed a shift from an intensive agro-based livelihood to a forest-based system of which they had no experience and were not prepared to manage. Rather, an extensive cereal-based farming system was established at the expense of large tracks of forest in the region (Alemneh, 1990; Baah et al., 2000; Mekuria, 2005). Forests are burnt, trees are felled and even the largest of them are killed by debarking and, in case of protected trees, illegal underground cutting of their roots. This led to the rapid expansion of cropland. Further, indigenous people are dynamically changing their agricultural system mimicking the resettlers' cultures (Belay, 2010). The increase in population because of resettlement in the region increased the demand for land, fuel wood and construction wood, which further aggravated deforestation (Mekuria, 2005; Reusing, 2000; Belay, 2010). Furthermore, the 2 ha of land given to new settlers upon arrival are frequently expanded through different mechanisms, i.e. by illegal clearing of the forestland, by bribing local administrators or through the purchase of land from the local community. Furthermore, the intensive coffee management needs more labour and, as a result, a type of social coalition has formed between the labourers and the local coffee growers to maintain labour support during coffee management periods. Hence, most coffee growers assign a plot of land to labourers for sharecropping practice to keep the workforce in the area. These casual labourers put their maximum effort to utilise the land productively as terms of the agreement are for short periods. A sharecropper who works in such a manner after a certain period of time may purchase this land or other agricultural land and become registered as a landowner. This manner of settlers gaining ownership of land further causes land shortages in local communities, which consequently results in the logging of forestland for new cultivation (Dereje, 2007; Belay, 2010). According to Reusing (2000), settler demand for the expansion of grazing land to support intense livestock production has also aggravated forest degradation.

Commercial agriculture

Commercial agricultural projects have expanded rapidly in forested areas of southwest Ethiopia. Large areas of forestland have been set aside for tea, coffee, soapberry, rubber tree, black pepper and cereal crop production investment in the region, which has resulted in a rapid decrease of forested areas in the region (Tadesse, 2007; Tezera, 2008; Dereje, 2007). For example, tea and soapberry plantations require the complete clearance of forest, while for coffee plantations some forest trees are left for their shade. The 6000 ha Bebeka coffee plantation is the largest and oldest in the country. Large forest land (3000 ha) managed under the *kobbo* customary system has for instance been converted to a commercial tea plantation (Tadesse et al., 2002). A coverage of 100 km^2 of commercial farms was reported for Sheka zone (Tadesse, 2007) and 220 km^2 for Keffa zone (Tezera, 2008). Given the increasing number of international land deals in Ethiopia (Dereje et al., 2015), it is anticipated that larger areas of forest land has been allocated to commercial agriculture in recent years. Many plantations in forests were started without any environmental impact assessment (EIA). Currently, project EIAs prepared by investors are accepted by authorities (including the Environmental Protection Agency) based on trust and without verification (Tadesse, 2007). Moreover, as the government's interest now in Ethiopia is rapid development, EIAs are frequently seen as hurdles introduced to act against development activities. Such conception leads to an exploitative type of relation between investment and nature (Leykun, 2008; Tadesse, 2007).

Land clearing for commercial farming has also contributed to changing the local people's perception and respect of taboos, cultural forests and sacred sites. Furthermore, investor expansion of coffee and tea inside the farmers' land through the approach of an out-grower scheme has facilitated forest degradation in the region. To encourage such expansion, investors have provided training and thousands of tea seedlings to farmers (Tadesse, 2007; Sisay, 2008).

Land tenure and its socio-economic impacts

Emperor Menelik II (1889–1913) confiscated land from the Keffa nobility and distributed fertile land and forests to northern landlords and loyal servants of the emperor (Wood, 1985). These feudal landlords had the right to impose taxes and to require the labour of the local peasants. In return, the landlords had the obligation of paying coffee as a tribute to the emperor. This obligation, coupled with the emerging coffee trade business and free labour resulted in the expansion of semi-forested coffee and the transplantation of coffee seedlings in the forest and home gardens in the region (Schmitt, 2006). Tewoldeberhan (1990) states that much of the existing forest at the beginning of the 20th century was secondary growth that had developed since the late 19th century as a result of the forest being cleared for agriculture.

During the reign of Emperor Haile Selassie (1930–1974), land in southwest Ethiopia was owned either by the state, the church, and particularly the fertile land was in the hands of northern landlords, political elites and appointed local chiefs. Additionally, landlords who gave use rights to the peasants ruled most of the forest. Because less revenue could be obtained from the degraded north, the central government had given much attention to the expansion of exportable products such as coffee in southwest Ethiopia. The increase in demand of coffee by the Arab world and Europe encouraged the northern landlords, as well as foreign merchants and investors, to cultivate coffee plantations in southwest Ethiopia in 1933 (Schmitt, 2006). Keffa began to contribute large amounts of coffee in the late 1950s and became Ethiopia's largest contributor (27%) of exportable coffee in the 1960s (Fee, 1961; Krug & De Poerck, 1968). Country-wide, the increases in exportation and in domestic consumption of coffee have led to a strong increase of the coffee production, from about 3 million bags (in 1990) to nearly 8 million bags in 2012 (Mitiku et al., 2015). This increase in coffee demand encouraged the expansion of coffee farms through the clearing of virgin forests, which, coupled with peasant insecurity in land use rights, led to the degradation of the region's forests (Tewoldeberhan, 1990).

After the overthrow of the Imperial regime in 1974, the Derg regime announced a land reform programme abolishing the feudal system and nationalising all lands. Coffee plantation areas owned by foreigners and feudal landlords were confiscated by the government or redistributed amongst local peasants (Schmitt, 2006). Peasant associations distributed land to landless tenant farmers. This trend resulted in the expansion of cultivated land at the expense of forestland (Mekuria, 2005). In addition to land distribution, peasant associations encouraged coffee and cereal production by distributing improved coffee and cereal varieties, fertiliser, agrochemicals and by disseminating modern management and marketing practices among the farmers. This encouraged the rapid expansion of cereal crops, coffee plantations and semi-forest coffee in southwest Ethiopia (Philippe, 2003; Schmitt, 2006, Mekuria, 2005). Disrupting the customary forest tenure system, weakening the local belief system and implementing development programmes, such as villagisation without the consent and willingness of the community, contributed to forest degradation in southwest Ethiopia (Stellmacher, 2005; Wood, 1993). Farmers in Southwest Ethiopia live in scattered manner partly because their most vital land resources are scattered in space (Lorgen, 1999). Enforced villagisation (Yihenew, 2002) started in 1985 and had two objectives: removing people from the natural forest edges so as to reduce the pressure on the forests and providing basic social services to farmers at a centralized location (Baah et al., 2000). This contributed to land use change dynamics: villagisation caused land abandonment around forest edges and initiated reversal transitions. However, this was short-lived and later farmers returned to their original locations exerting further pressure on the natural forest (Mekuria, 2005).

After the overthrow of the Derg regime in 1991, the Ethiopia People's Revolutionary Democratic Front (EPRDF) confirmed that the right to ownership of rural and urban land, as well as natural resources, is exclusive to the state and that it cannot be subjected to sale or other means of exchange (Philippe, 2003; Stellmacher, 2005; Stellmacher & Mollinga, 2009). The governmental forest policy in Ethiopia primarily focused on 'rigid conservation', hence on the exclusion of human interference, rather than on the management of forest resources. This affects the practicability of the ancestral customary forest management system in the area. For example, the lack of legal recognition of the customary institution by the government created a perception of forest resources not being a common resource, therefore every member of the community would be utilising the forest resources illegally (Zewdie, 2007).

Additionally, after 1991, the distribution of large forest areas for commercial agriculture, resettlement and the exclusion of local customary forest management in the region intensified large clearings of forests for their resources (Belay, 2010; Zewdie, 2007). The distribution of improved varieties of cereal and coffee, fertilisers, chemicals and credit services from the government facilitated the conversion to cultivated land (Mekuria, 2005). According to Dereje (2007), the increase in the price of coffee and market incentives further encouraged farmers to expand coffee cultivation both in the forest and in their garden.

The uncertainty in land and forest ownership results from the feeling among farmers that land or forest could be given or redistributed to others because all land, including the natural resources, belongs to the state. This feeling of insecurity causes further exploitation of the forests (Belay, 2010). Zewdie (2007) indicated that after the shift of ownership of forestland to the state, deforestation of the cultural forests and other forests around settlements was aggravated by the expansion of large-scale commercial farms and illegal timber extraction in the Sheka zone. This in turn created less responsibility for forests on the part of the local community and developed a perception of forest resources being common resources. The social, economic and cultural marginalisation of the *Manjo* community has had an immense effect on forest degradation. The marginalisation by the Keffa and Sheka people, which began during the imperial regime, forced them to live and hunt in the forest. However, the Derg regime tried to integrate these people with the rest of the society through the villagisation programme. They were assigned a plot of land. However, due to a lack of access to disease-resistant seeds or seedlings or to fertile land and lack of livestock and agricultural experience, they were forced to frequently change settlements. This, coupled with a weak position in land tenure, resulted in a shift to subsistence living, such as frequently changing agricultural locations by clearing forestland and selling wood and charcoal to villages (Zewdie, 2007; Hartmann, 2004; Gore, 1994).

Assefa (2007) and Zewdie (2007) further state that the increased demand for charcoal and wood in towns and large villages for construction and household consumption, coupled with the economic problems of densely populated rural communities, has caused immense forest degradation in the region. Nevertheless, no research was conducted on rural and urban consumption of wood fuel (Assefa, 2007, Belay, 2010).

1.2.2 Land use changes

The southwestern part of the Ethiopian Highlands was once almost completely covered by montane rainforests at the beginning of 19th century (Chaffey, 1979; Reusing, 1998, 2000). In this regard, 38.4% of the southwestern region remained covered by closed forests between 1971 and 1975 (Chaffey, 1979). In a similar study, Mekuria (2005) showed that the Bonga catchment (Fig. 1.1) has undergone significant alteration and transformation in recent decades. The portion of large natural forest (35%) and wooded grassland (30%) in 1967 dropped to 7% natural forest and 6%

wooded grassland in 2001, whereas 19% of the cultivated and settlement land in 1967 increased to 75% in 2001. Similarly, Behailu (2010) and Belay (2010) reported on the conversion of natural forests, shrubs, marshes and woodland to cultivated, grazing and settlement land in the Bench Maji and Keffa zones.

According to Dereje (2007), the 4000 km^2 Sheko forest (Fig. 1.1, Table 1.1) has also undergone significant changes to the portion of forestland (71%) in 1973, dropping to 48% in 2005, whereas agriculture and settlement lands increased to 15%, state coffee plantations to 5%, bare land to 10%, and agroforestry to 22%. Another change was the traditional forest fallow land management that was replaced by agroforestry (Fig. 1.3).

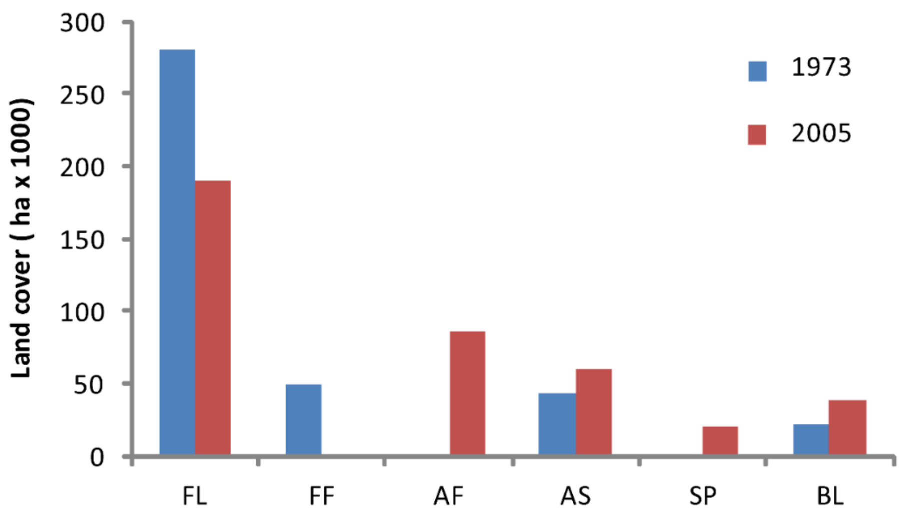

Figure 1.3. Land cover changes of Sheko forest between 1973 and 2005 (after Dereje, 2007). FL-forest land; FF-forest fallow land; AF-agroforestry; AS-agriculture and resettlement; BL-bare land; SP-state coffee plantation.

According to NTFP-PFM (2009), large clearings of coffee forestland were recorded between 1973 and 2009, with the forest coverage dropping from 74% to 59%, whereas agricultural land increased from 22% in 1973 to 36% in 2009 (Fig. 1.4). The portion of coffee and tea estates increased from 0% in 1973 to 1.6% coffee and 0.15% tea estates in 2009. Similarly, the portion of Sheka's dense closed forests (39%) and open forests (33%) in 1987 decreased to 31% and 25%, respectively, in 2001 (Bedru, 2007). However, the portion of agriculture (6%) and tea plantations (0%) in 1987 increased to 10% and 0.5%, respectively, in 2001 (Bedru, 2007).

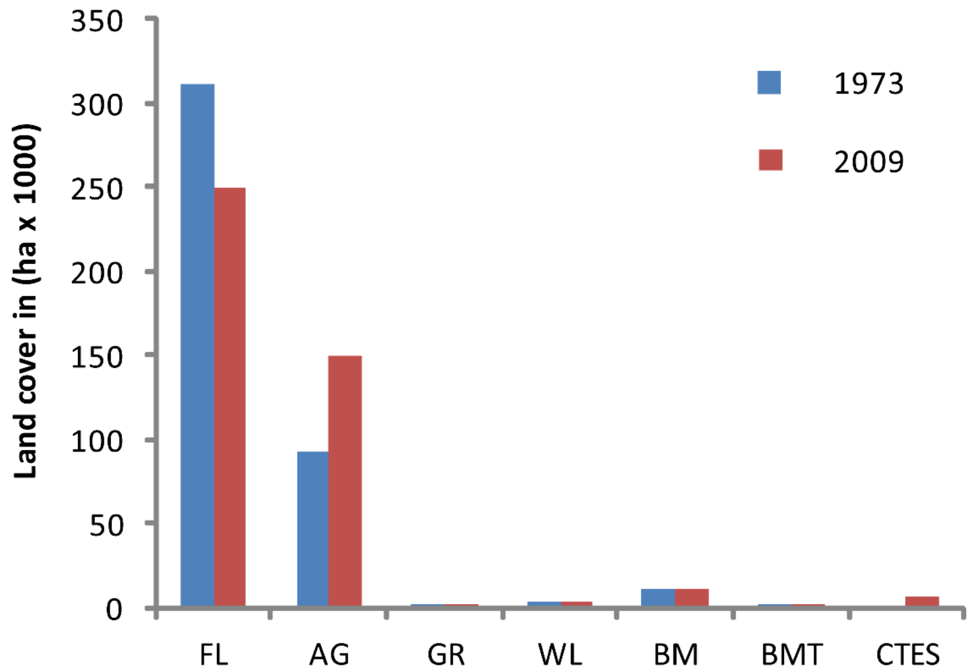

Figure 1.4. Land cover changes in and around the forests of Bench Maji, Sheka and Keffa zones in SW Ethiopia between 1973 and 2009 (after NTFP, 2009). FL-forest land; AG-agriculture land; BM-bamboo; BMT-bamboo and trees; CTES-coffee and tea estate; GR-grassland; WL-wetland.

1.2.3 Consequences of forest degradation

Impacts on biodiversity

In southwest Ethiopia, the conversion of natural forest to monoculture resulted in significant impacts on biodiversity richness (Tadesse, 2007). Monocultural tea and eucalyptus plantations instead of natural forest results in large losses of plant biodiversity, forest ecosystems and their services, and the many animal species that are dependent on forest ecosystems. Tea plantations and black pepper cultivation can cope with some exotic trees, however the soapberry *endod* (*Phytolacca dodecandra* L'Hér.) requires full land clearance for best results. Exotic tree plantations for coffee shade and as energy source for the tea processing industry have resulted in the destruction of forest ecosystems in the Sheka region. This has led to the loss of many species of birds, insects, mammals, bee colonies, and microorganisms that depend on the forest ecosystem (Tadesse, 2007). Similarly, wetlands for which indigenous cultivation systems had been developed

(Dixon, 2002), are excessively drained, which has led to strong decreases in species diversity (Kassahune et al., 2014).

Impact on soil loss and fertility

The soils in cereal-based farming show a change in properties compared to soils in a perennial-based farming system, which are generally higher in silt, clay, available P, available K, organic carbon, total nitrogen, and cation exchange capacity (CEC). Furthermore, most of the soil property values decline with increasing years of cultivation in the cereal-based farming system (Mekuria, 2005). In studies near Mizan Teferi (Getachew, 2010) and Bonga (Berhanu, 2011) (Fig.1.1), it was also shown that soil organic matter, total nitrogen, available phosphorus, and cation exchange capacity (CEC) were higher in forestland than cultivated land.

Very few studies on soil erosion rates have been conducted in Southwest Ethiopia. Getachew (2010) reported higher rates of soil loss (184 Mg ha^{-1} y^{-1}) in cropland compared to fallow land and forestland on the slopes of Gem mountain (Fig. 1.5). The soil loss rate increased over time as cultivation continued after forest clearing (Fig. 1.6). Moreover, the cultivated lands show a net soil loss with high sediment deposition on the lower and middle slopes in the early years after the start of cultivation, as well as increased sediment delivery to the rivers (Fig. 1.6). Rill and gully erosion are probably the dominant process that leads to the delivery of rock fragments from the hillslopes to the drainage network (Poesen, 1987). Mekuria et al. (2012) found a mean annual soil loss from cultivated fields of 15±3 Mg ha^{-1} y^{-1}, whereas Berhanu (2011) measured a soil loss of 14.7 Mg ha^{-1} y^{-1} in the upper part of a catchment cultivated by settlers in the Bonga area, 11 Mg ha^{-1} y^{-1} in the middle part and 7.6 Mg ha^{-1} y^{-1} in the lower part, which are higher soil loss rates than in a nearby catchment cultivated by natives.

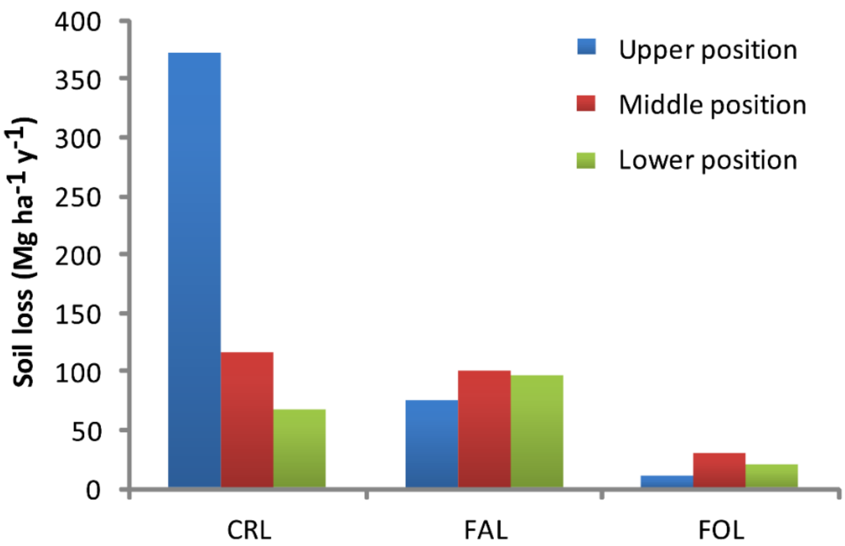

Figure 1.5. Rates of soil loss by water in cropped (CRL), fallow (FAL) and forest land (FOL) on upper, middle and lower slope positions in Bench Maji Zone (modified from Getachew, 2010).

Field observations show the presence of ancient debris flows and recent landslide scars, but its extent has not been studied. Possible linkages to deforestation are through (1) decreased shearing resistance of soils after disappearance of root cohesion (Ammann et al., 2009), and (2) river down cutting, which leads to increased sediment delivery to rivers (Fig. 1.7), as observed in the study area by Broothaerts et al. (2012).

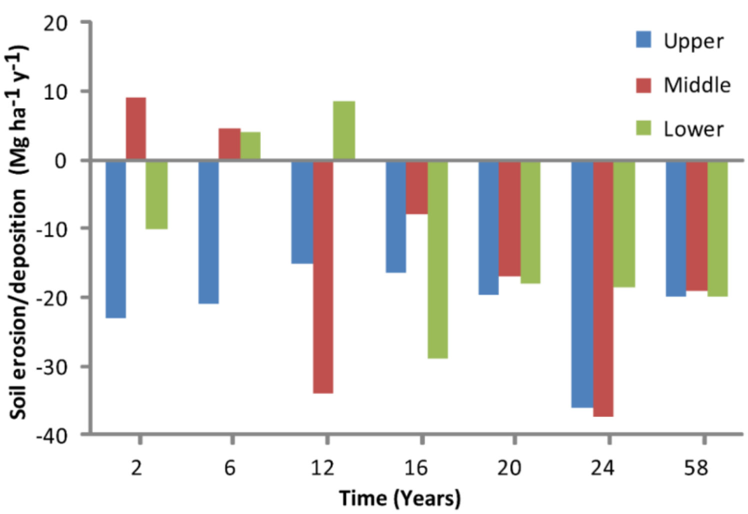

Figure 1.6. Soil erosion and deposition rates along the slope over time (in years since forest clearing) in a sub-catchment of Gimbo Wereda (Keffa Zone); positive values indicate deposition, negative values soil loss (after Mekuria et al., 2012).

Figure 1.7. Gravel bars in the Eseni river near Aman (6.9481°N, 35.5495°E). Local residents claim that the occurrence of gravel and sand in river beds is a new phenomenon that occurred after deforestation. The coarse material is commonly related to increased rill and gully erosion and peak flow discharge, but part of this material could also have been delivered by landslides entering the river.

Impact on the local communities' livelihood and culture

The livelihood of southwest Ethiopia's farmers largely relies on production of non-timber forest products such as honey, spices, medicinal plants, fodder, fuel wood and construction materials. Wetlands provided thatching materials, fodder, year-round water and medicinal plants (Kassahune et al., 2014). Problems related to the conversion of forests (and wetlands) to other land uses in line with agricultural investment and resettlement has resulted in altered livelihood strategies by the local community, which further exacerbates rural poverty and migration (Zewdie, 2007; Moti et al., 2011). Cereal crop production requires improved varieties and high inputs, which is less affordable for most farmers. This is a challenge compared to the forest NTFPS, which do not require much input (Mekuria, 2005). Finally, the large-scale clearing of cultural forests without the consent of the local community affects the cultural practices of the local community who consider the forests as sacred places (Zewdie, 2007).

1.2.4 Conservation efforts in southwest Ethiopia

Biodiversity conservation

The issue of *in-situ* wild coffee conservation has received attention since 1998 when the coffee improvement project of Ethiopia proposed the establishment of three *in-situ* conservation reserves in the southwestern forests (Demel et al., 1996). The Kontir-Berhane forest and the Buginda forest (Fig. 1.1, Table 1.1) were among the first priority areas for the *in-situ* conservation of wild coffee's genetic resources, but for a variety of reasons the project ceased in 2008. However, a new approach to forest management with the dual purpose of conservation and development through participatory management of the *in-situ* conservation of wild coffee was started in the Bench Maji and Keffa zones (WCC-PFM, 2011; FARM Africa & SOS Sahel-PFM, 2004). The introduction of participatory forest management (PFM) was designed to share government management of the forest to the local community as Co-management between the state and community. The forest areas were placed under the PFM programme to reduce environmental degradation, increase sustainable forest conservation, conserve the ecosystem and improve the welfare of the local community (Gobeze et al., 2009; Stellmacher & Mollinga, 2009).

However, through an in-depth ethnographic case study in the Agama forest (part of the Koma forest), Vandenabeele (2012) showed that the NGOs initiating the PFM face challenges because of missing to incorporate the local community's historical background and the socio-political context in the conceptual framework of the PFM. For instance, the community-based institutions (forest cooperatives) developed by the NGOs failed to achieve the desired goal of participatory forest management because local power relations were insufficiently considered. To be more precise, although government representatives signed an agreement to share resources and responsibilities with communities, "the long-standing uneven relationships between the government and local people hardly changed" (Ayana et al., 2015).

The Keffa and Sheka forests were registered as UNESCO Biosphere Reserves in 2010 and 2012, respectively. The biosphere reserve approach aims to conserve biodiversity and improve the livelihoods of the local community through innovative marketing of their products, environmentally friendly agriculture and ecotourism (Fig. 1.8). It also promotes education and research as well as interaction with global networks (Berghöfer et al., 2013; Tadesse & Fite, 2011).

Despite, the UNESCO designation of Keffa and Sheka Biosphere reserves is to enhance people's livelihoods and ensure environmental sustainability, which once designated, a site becomes a member of the World Network of Biosphere Reserves, wherein integrated research and monitoring as well as exchange and sharing of experience takes place. Yet, no much effort and fruits has been observed on cooperation, research and development programe on Keffa and Sheka Biosphere reserves. However, the Nature and Biodiversity Consrvation Union (NABU) project in Keffa is promoting ecotourism in Keffa Biosphere Reserve, increased the income of the local community by selling spices, cofee and fresh honey.   For example, ca. 10 000 tourists visited Keffa in 2008 of which 200 were foreigners (Tezera, 2008; Berghöfer et al., 2013). The Bebeka coffee plantation also organises touristic activities on its estate.

Figure 1.8. Promotion of ecotourism in Keffa

Farmer cooperatives (ca. 10 000 ha in Keffa) are supplying NTFPs such as high quality organic coffee, spice and honey for export to the international market (Berghöfer et al., 2013). Mitiku et al. (2015) showed that especially Rainforest Alliance certification improved the incomes of coffee producers.

Soil conservation

The majority of the cereal-based farming in the southwestern Ethiopian highlands is however accomplished without soil conservation measures (FARM Africa & SOS Sahel-PFM, 2004) and a nation-wide map shows that in the study area conservation structures are installed on less than 1% of the cropland, in contrast to 20-75% in central and northern Ethiopia (Hurni et al., 2015). Major reasons for absence of soil conservation on cropland in the study area are (a) a perceived absence of urgent need for conservation, given the recent deforestation and hence availability of still relatively deep soils (Yesuf et al., 2005), and (b) absence of "food-for-work" programmes or other financial or policy incentives for conservation activities (*sensu* Shiferaw & Holden, 1997), because overall the area is not considered as food insecure. However, Baye & Terefe (2009) indicated that introduced vetiver grass (*Vetiveria zizanioides* L) plays a crucial role in controlling runoff, soil erosion and in stabilising steep slopes inside coffee, rubber, fruit and cereal fields. Accordingly, the office of agriculture and other governmental institutions in the Bench Maji, Keffa and Sheka zones are reproducing and distributing vetiver grass, indigenous and nitrogen-fixing trees to agricultural land on steep slopes (pers. comm. Nardose Takele, 2013; own observations). Nevertheless, vetiver grass is not really taken up by the communities because of space occupied, its non-palatable nature, and decreased need for thatching given the wide introduction of metal sheets for roofing (based on interviews in villages of Bench-Maji zone).

1.3 Study area

We focussed on Bench Maji, one of the westernmost administrative zones of the Southern Nations, Nationalities and Peoples Region, the later being one of the nine regional states of the Federal Democratic Republic of Ethiopia. The Gacheb catchment (Fig 1.9) is one of the biggest catchments in Bench Maji Zone, which drains to the White Nile through the Baro-Akobo river system. The Gacheb catchment was selected mainly because of environmental problems, i.e the forest frontiers has been rapidly deforested for agriculture land expansion, flooding risk, sediment siltation and water turbidity. Further, the catchment is important sources of water supply for both drinking water treatment plant and hydropower plant (Fig 1.9; Fig 1.10).

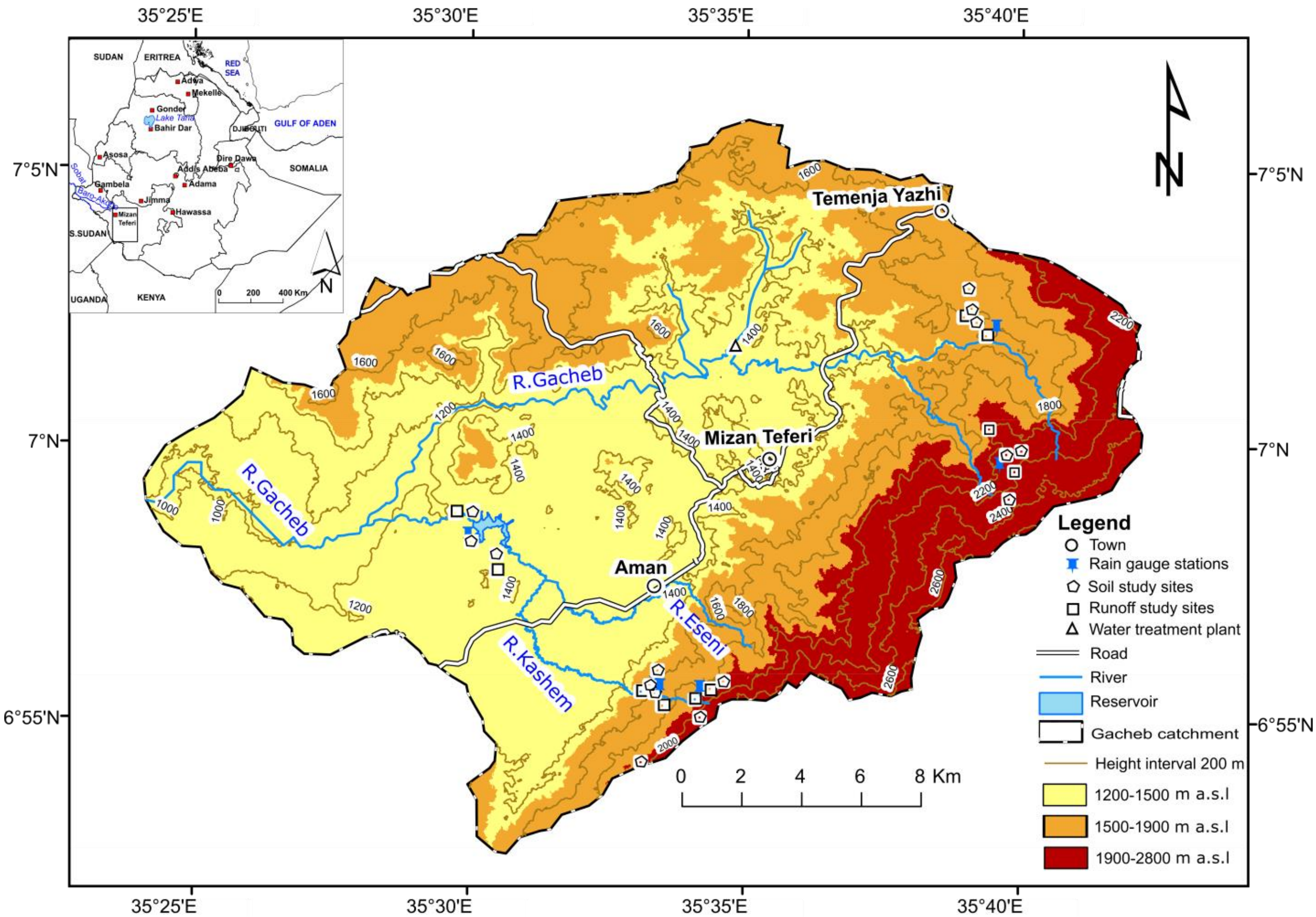

Figure 1.9. The study sites in the Gacheb catchment, southwest Ethiopia**.**

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Figure 1.10. Environmental problems at downstream sites in southwest Ethiopia: (a) agriculture land expansion near the river; (b) flooding and high suspended sediment in Dembi hydro-power reservoir; (c) high suspended sediment in the water source of a treatment plant; (d) frequent flooding and sediment clogging the Dembi hydropower machine.

Climate of southwest Ethiopia

Seasonal rainfall in Ethiopia is driven by the north-south movement of the Inter-Tropical Convergence Zone (ITCZ). After shifting northward, the ITCZ brings intense rainfall to southwest Ethiopia (Messerli & Rognon, 1980; Goebel & Odenyo, 1984). The annual rainfall pattern can be classified into two seasons: the dry season (December–February), and the rainy season (March–

November) with particularly strong rains in summer. The commonly used bimodal rainfall distribution of the central and northern Ethiopian highlands with spring rains (*belg*) and the summer main rainy season *kiremt* (Fazzini et al., 2015) is not applicable in southwest Ethiopia, neither when observing annual rain distribution (Fig. 1.11), nor in the terminology that is used in the local languages of southwest Ethiopia (Table 1.2). The average yearly rainfall in Aman near Mizan Teferi, the main town of Bench Maji zone (Fig. 1.11) is 2296 (±244) mm y^{-1}, 1707 (±216) mm y^{-1} in Bonga (Keffa zone), and 1603 (±404) mm y^{-1} in Tepi (Sheka zone) (NMA, 2013) (Fig. 1.11). The average air temperature ranges from 13 °C to 27 °C and varies according to elevation (IFPRI & CSA, 2006). Combined high rainfall, long growing season and temperature variation with elevation lead to a wide range of cropping possibilities.

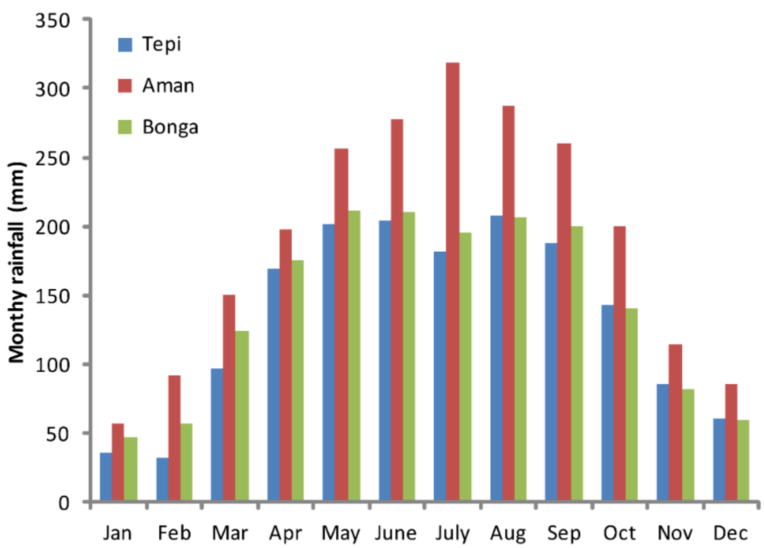


Figure 1.11. Average monthly rainfall at Tepi (1980-2012), Bonga (1960-2012) and Aman near Mizan Teferi (1954-2010) (Source: National Meteorological Agency).

Table 1.2. Terminology to designate the seasons in the languages of the main ethnic groups living around southwest Ethiopia's forests

Language[a]	Rainy season[b] (March – November)	Dry season (December – February)
Bench	Wole/ Dane enet	Ober enet
Keffa	Yoyo	Kawa
Sheka	Yoyo	Belo
Sheko	Ero benji	Siyatu benji

[a]All languages belong to the North Omotic language group; particularly Keffa and Sheka languages are closely related (Aklilu, 2003; Theil, 2012). [b]While agreeing that the second part of the rainy season is generally heavier, all key informants stressed that the terminology used designates the rainy season as a whole.

Lithology and soils

The southwestern Ethiopian highlands developed along the western margin of the Rift Valley as a result of uplifting over the past 18 million years (Beccaluva et al., 2011). The underlying basement rock is of Precambrian origin. These intensely folded and faulted basement rocks are mostly directly overlain by Tertiary volcanic rocks that dominate the geology of the area (Kazmin, 1972). Although undifferentiated on the maps, the Precambrian rocks comprise a variety of metasediments, metavolcanic and intrusive rocks (Westphal, 1975). Following the uplift, the region has been dissected by rivers, resulting in elevations ranging from 900 to 3500 ma.s.l. Southwest Ethiopia drains partly to the White Nile through the Akobo-Baro river system, and partly to the Omo-Turkana basin.

According to the harmonized soil map of Africa (Dewitte et al., 2013), the major reference soil groups of the southwestern highland plateaus are Nitisols, Vertisols, Leptosols, Regosols, Cambisols, Alisols and Acrisols. The dominant soil group in the Gacheb catchment are Leptosols, Nitisols, Alisols, Cambisols and Fluvisols. Nitisols are the dominant reference soil group in coffee-growing areas of southwest Ethiopia. Nitisols have a depth of more than 1.5 m, are clayey and red in colour. They primarily occupy slopes steeper than 5%. These soils are well-drained with good physical properties; they have high water-storage capacity, a deep rooting depth and stable soil aggregate structure. Nevertheless, rates of decomposition of organic matter and leaching of nutrients are extremely fast. Acidity ranges from medium to strong, and pH is generally less than 6 (Feyissa & Mebrate, 1994; Schmitt, 2006). On steep slopes, such as escarpments and on undulating topography, Cambisols and Regosols are most common. Vertisols are dark and heavy clay soils and are found in waterlogged plains and seasonal swamp areas in Keffa (Fig. 1.1). Acrisols are dark red to reddish brown soils, with a texture of clay to sandy clay. They are found in few areas of the Keffa zone (Tafesse, 1996). In Bench Maji Zone, Leptosols are dominant on crests, while Nitisols are dominant on the hill slopes (lower, middle and upper parts), to which Alisols and Cambisols are associated locally. Fluvisols are found in the flat valley bottoms where meandering rivers occur (Dewitte et al., 2013).

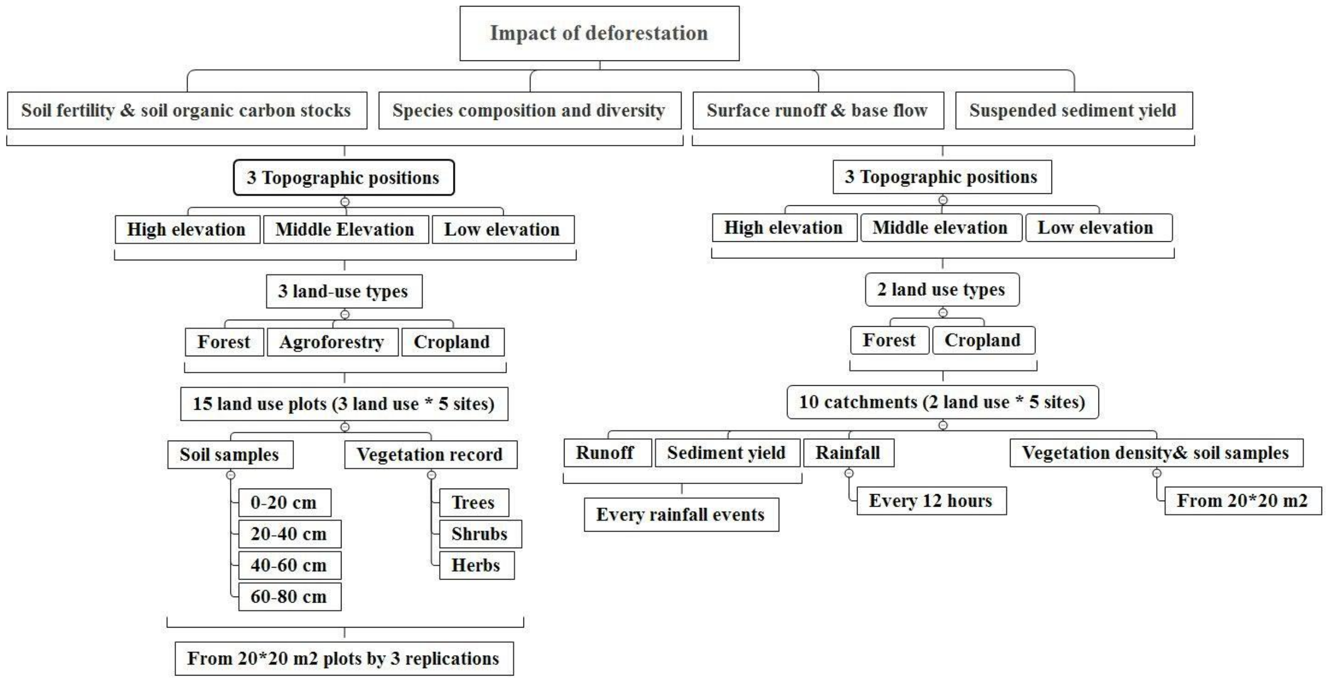
Biodiversity in the genetic home of coffee

Ethiopia is one of the top 25 biodiversity-rich countries in the world (WCMC, 1994). The majority of the species are found in the highland forests and particularly in the southwestern highlands. The forests of the southwestern highlands fall within the eastern montane hotspot of Ethiopia and are the genetic home of coffee (*Coffea arabica* L.) (Labouisse et al., 2008; Meyer, 1965; Vavilov, 1935). Among the seven major vegetation types in Ethiopia, four vegetation types occur in southwest Ethiopia, namely montane rainforest, transitional rainforest, dry peripheral semi-deciduous Guineo-Congolian forest and riverine forest (Friis, 1992).

The Bonga forest (Table 1.2) is one of the most species-rich forests in Ethiopia (Friis et al., 1982; Schmitt, 2006; Matheos, 2011; Sisay, 2008; Ensermu & Teshome, 2004; Kochito, 2008; Feyera, 2006). In addition to plant diversity richness, at least 17 endemic plant species were identified in these forests (Sisay, 2008; Schmitt, 2006). Similarly, the Maji, Sheka and Sheko forests (Table 1.2) are rich in plant species composition. Apart from richness, the Sheka forest holds 55 plant and 10 bird species endemic to Ethiopia (Tadesse, 2007; Feyera, 2006; Gemedo & Simon, 2007; MELCA Ethiopia, 2012).

According to Leykun (2008), three forests in Bonga hold 61 mammalian species, 210 bird species, 10 reptiles, 7 amphibian species and 6 fish species. The forests comprise 21% of all mammals and 23% of all bird species in Ethiopia, of which five species are endemic.

Figure 1.12. Schematic representation of the research organization



1.4 Thesis objectives and research questions

The main objective of this thesis is to evaluate the impact of deforestation on land degradation at southwest Ethiopia's Afromontane forest frontier.

This broad research aim can be further refined to more specific objectives:

- to contrast the soil fertility and organic carbon and nitrogen stocks in forest, agroforestry and cropland;

- to compare the species diversity in forest, agroforestry and cropland;
- to quantify the components of surface water balance in forest and cropland; and
- to quantify the suspended sediment yield from forest and cropland on daily basis.

The two key research questions of the thesis may arise as:

- To what extent does the transition from Afromontane forest to cereal based farming affect the environment?

- In which way could land management allow sustainable agricultural development and protection from land degradation ?

These important research questions were addressed by organizing the research on the impact of deforestation in to various chapters (Fig 1.12).

These core questions can be subdivided in a number of sub-questions addressed in the individual chapters:

- What do we know already about causes and impacts of the transition of Afromontane forest to cereal based farming? (Chapter 1)
- As compared to Afromontane forests, to what extent are the soil fertility, organic carbon and nitrogen stocks decreased in the main cropping systems (agroforestry and cropland)? (Chapter 2)
- To which extent did the species diversity decrease due to deforestation/land use change? (Chapter 3)
- Is the runoff response impacted by deforestation? (Chapter 4)
- Is the suspended sediment yield increased due to deforestation? And what is sediment yield from the forest itself? (Chapter 5)
- What is the overall implication of land management in the three main land use types (forest, agroforestry, cropland) on land degradation? (Chapter 6)

1.5 Definitions

Forest has more than 800 different definitions worldwide. According to the Food and Agriculture Organization (FAO), forest is tree covered land where the tree cover density is greater than 10%, 5 m tree height and 0.5 ha area coverage (FRA, 2015). Within the United Nations Framework Convention of Climate Change (UNFCC), the definition of forest is more flexible. The threshold value for a forests lies within a minimum range of 0.01-1.0 ha, 2-5 m tree height and 10-30 percent crown cover (UNEP et al., 2009).

In this work forest is understood as an area covered with large complex structure of trees, shrubs and herbs.

Alike the forest, “agroforestry” has received various definitions. According to FAO, agroforestry is a collective name for land use systems and technologies where woody perennials (trees, shrubs, palms, bamboos etc.) are deliberately used on the same land management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence (Nair, 1993). Agroforestry is an integration of composite agriculture production to the tree and shrub system.

Again, for cropland, many definitions exist. In this case “cropland” stands for land that is under an agricultural practice that has been introduced from central Ethiopia and that has been defined as a “permanent upland cultivation system” (Ruthenberg, 1983), or “grain-plough complex” (Westphal, 1975). Nearly all woody vegetation is removed, the land is shared among farmers along fixed boundaries, and cereal crops are dominantly grown using the oxen-drawn Ethiopian ard plough as main cultivation tool (McCann, 1995).

Forest frontier or "forest margin" is the spatial transition zone between tropical forests and converted land uses.

Cultural forest are large complex forest with similar or different tree density and composition conserved for religious, ceremonial and ecological purpose.

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Chapter 2

Impact of deforestation on soil fertility, soil organic carbon and nitrogen stocks in southwest Ethiopia

This chapter is modified from:

Henok Kassa, Dondeyne, S., Poesen, J., Frankl, A., Nyssen, J., 2016. Impact of deforestation on soil fertility, soil carbon and nitrogen stocks: the case of the Gacheb catchment in the White Nile Basin, Ethiopia. Agriculture, Ecosystems and Environment, submitted.

Abstract

The evergreen forests of southwest Ethiopia are important for soil fertility sustenance and climate change mitigation. However, the increasing human population and expansion of agriculture land have led to deforestation. We determine the effect of deforestation on soil fertility, soil carbon and nitrogen stocks and hypothesise that tropical forest and agroforestry have similar characteristics, in contrast to the deforested areas used as cropland. Hence, soil samples (n = 360) have been taken from natural forest, agroforestry and cropland at four depths (0-20 cm, 20-40 cm, 40-60 cm and 60-80 cm) in three altitudinal belts, high (2300-1800 m a.s.l.), middle (1800-1500 m a.s.l.) and low (1500-1200 m a.s.l.). The topsoil and subsoil physico-chemical characteristics bulk density, pH, organic carbon, total nitrogen, available phosphorus, exchangeable calcium, magnesium, cation exchange capacity and exchangeable base cations were significantly higher in both forest and agroforestry than in cropland, at all elevation zones. Soil organic carbon and nitrogen stocks in soil under forest are similar to those under agroforestry at all elevation zones (0-20 cm, 20-40 cm, 40-60 cm and 60-80 cm soil depths). However, soil organic carbon and nitrogen stocks in soil under both forest and agroforestry lands were significantly different from cropland on all elevation zones at all depths except 60-80 cm. The highest total soil organic carbon stocks were recorded in the forest (412 Mg ha^{-1} at the FH site and 320 Mg ha^{-1} at the FL site) and agroforestry (357 Mg ha^{-1} at the DM site, 397 Mg ha^{-1} at the ZH site and 363 Mg ha^{-1} at the ZM site). The total organic carbon loss due to the conversion of forest to cropland ranges from 3.3 Mg ha^{-1} y^{-1} at the FL site to 8.0 Mg ha^{-1} y^{-1} at the FH site. The soil organic carbon and nitrogen loss due to the conversion of forest to cropland is proportional to the loss from agroforestry to cropland. The total carbon dioxide emission due to the conversion of forest to cropland ranges from 12 Mg ha^{-1} y^{-1} at the FL site to 28 Mg ha^{-1} y^{-1} at the FH site. Agroforestry has the potential to maintain soil fertility, and stores higher soil organic carbon and nitrogen in proportion to the natural forest. Therefore, it can be suggested that agroforestry has a similar capacity as Afromontane forests to sustain soil fertility as well as to regulate greenhouse gas emissions.

Key words: Evergreen forest, Soil physico-chemical characteristics, Greenhouse gas

2.1 Introduction

The southwestern highlands of Ethiopia hold four potential natural vegetation zones (Afromontane rainforest, dry peripheral semi-deciduous Guineo-Congolian forest, transitional rainforest and riverine forest vegetation) (Friis et al., 1982; Tadesse, 2007). These forests provide different environmental contributions like soil fertility sustenance, soil erosion protection and climate change mitigation (Aticho, 2013; Getachew, 2010; Mekuria, 2005). However, the increasing human population and the growing need for expansion of agricultural land have led to deforestation. For instance, the region's coffee-based agroforestry and cereal cultivation have undergone a rapid expansion owing to the growing demand for food crops, coffee, spices and the fruit market, driven by the resettlement expansion, commercial investment, land tenure policy, socio-economic issues and the current Agriculture Development Led Industrialization (ADLI) economic policy of the country (Dereje, 2007; Mekuria, 2005).

The soil is the basis for agriculture, natural plant community and natural climate regulation, with 75% terrestrial organic carbon storage (Lal, 2004; Lemenih & Itanna, 2004). Vegetation has a lion's share in the sustenance of such ecosystem services of both surface and subsurface soil. However, the dense and fragmented forests in the upper reaches of the Gacheb catchment (ca. 450 km^2) have been converted to agroforestry and croplands (Dereje, 2007; Hansen et al., 2013). Land use changes demonstrate several undesirable consequences like decline in soil fertility, soil carbon and nitrogen stocks (Lemenih, 2004; Lemenih and Itanna, 2004; Tesfaye et al., 2016). For instance, radical losses in soil fertility, soil carbon and nitrogen stocks have been recorded in the first 20-25 years after deforestation in the southernregionofEthiopia (Lemenih et al., 2004; Mekuria, 2005; Tesfaye et al., 2016).

However, some studies show that the extent of soil quality,soil organic carbon and nitrogen stocksvaries with native vegetation, climate, soil type, management practice, land use history and time since conversion (Craswell and Lefroy 2001; Lemenih, 2004; Lemenih and Itanna, 2004). Moreover, studies show inconsistency regarding the role of coffee agroforestry on soil fertility maintenance, soil organic carbon and soil nitrogen stocks (Hombegowda et al., 2016; Kessler et al., 2012; Mohammed & Bekele, 2014; Souza et al., 2012). Furthermore, the soil fertility, soil organic carbon and nitrogen stocks' decline (owing to land use changes) was not restricted to the surface but comparative changes were proportionally high in the subsoil (Don et al., 2011;

Lemenih, 2004). For instance, more than 50% of the global organic carbon is stored in the subsoil (Amundson, 2001) and more than two-thirds of the soil nutrients are stored in subsoil and used for plant growth (Kautz et al., 2013).

Therefore, a regional scale evaluation of soil quality, soil organic carbon, nitrogen stocks and changes in trend concerning land use is very important for sustainable agriculture land management practice. Despite the study area's high annual rainfall, no effort has been made to assess the effect of land use changes on soil fertility, soil organic carbon and nitrogen stocks at deeper soil depths. The objectives of this study are: (i) to determine the impact of deforestation on soil fertility, (ii) to quantify the effect of deforestation on soil organic carbon and nitrogen stocks and (iii) to link deforestation induced loss of soil organic carbon to the climate change debate. The presented hypotheses include that the soil fertility, soil carbon and nitrogen stocks in agroforestry would be comparable to those of montane forests, while it would be less in croplands.

2.2 Materials and methods

2.2.1 Study area

The study area encompasses the upper Gacheb catchment, located in the headwaters of the White Nile in southwest Ethiopia. Altitudes range from 1000 to 2600 m a.s.l. (Fig. 2.1) and the lithology comprises Tertiary basalt traps and rhyolites (Mengesha et al., 1996; GSE 2005).The annual rainfall pattern is unimodal with a rainy season from mid-March to mid-November. Theaverage annual rainfall depth in Mizan Teferi (1440 m a.s.l.) is 1780 ± 270 mm y^{-1} and the annual reference evapotranspiration amounts to 1259±12 mm y^{-1} (Grieser et al., 2006); the average air temperature ranges from 13 to 27 °C (Tadesse et al., 2006). The harmonized soil map of Africa (Dewitte et al., 2013) indicates that Leptosols are dominant on crests, while Nitisols are dominant on the hill slopes (lower, middle and upper parts), to which Alisols and Cambisols areassociated locally.Fluvisols are found in the flat valley bottoms (where meandering rivers are located).

The forest vegetation of Gacheb catchment structurally consists of a mix of areas with upper canopy trees like *Aningeria adolfi-friederici* Engl., *Croton macrostachyus* Hochst. ExDelile, *Hagenia abyssinica* Willd., *Millettia ferruginea* Hochst. Baker, *Polyscias fulva* Hiern.Harms, *Albizia gummifera* J.F.GmelC.A.Sm., *Bridelia micrantha* Hochst.Baill. integrated with lower canopy trees like *Grewia ferruginea* Hochst. ex A.Rich, *Vernonia amygdalina* Delile. *Cyathea manniana* Hook and *Solanecio mannii* HookF.C. Jeffrey (Chapter 3).

The agroforestry land of Gacheb catchment is composed of *Coffea arabica* L., as a cash crop integrated with food crops such as false banana (*Ensete ventricosum* Welw. Cheesman), banana (*Musa sapientum* L.), taro (*Colocasia esculenta* L. Schott) and spices like korarima (*Aframomum corrorima*Braun). Moreover, various fruit trees such as mango (*Mangifera indica* L.), avocado (*Persea americana* Mill.), papaya (*Carica papaya* L.) and orange (*Citrus sinensis* L. Osbeck) are also part of the farming system. Furthermore, native treeslike *Albizia gummifera* J.F.Gmel. C.A.Sm., *Cordia africana* Lam., *Millettia ferruginea* Hochst. Baker, *Polyscias fulva* Hiern. Harms, are kept for shade, fodder, firewood, medicinal value and soil fertility maintenance. On the other hand, on the cropland cereal crops like maize (*Zea mays* L.) are integrated with root vegetables like taro and park trees (Chapter 3).

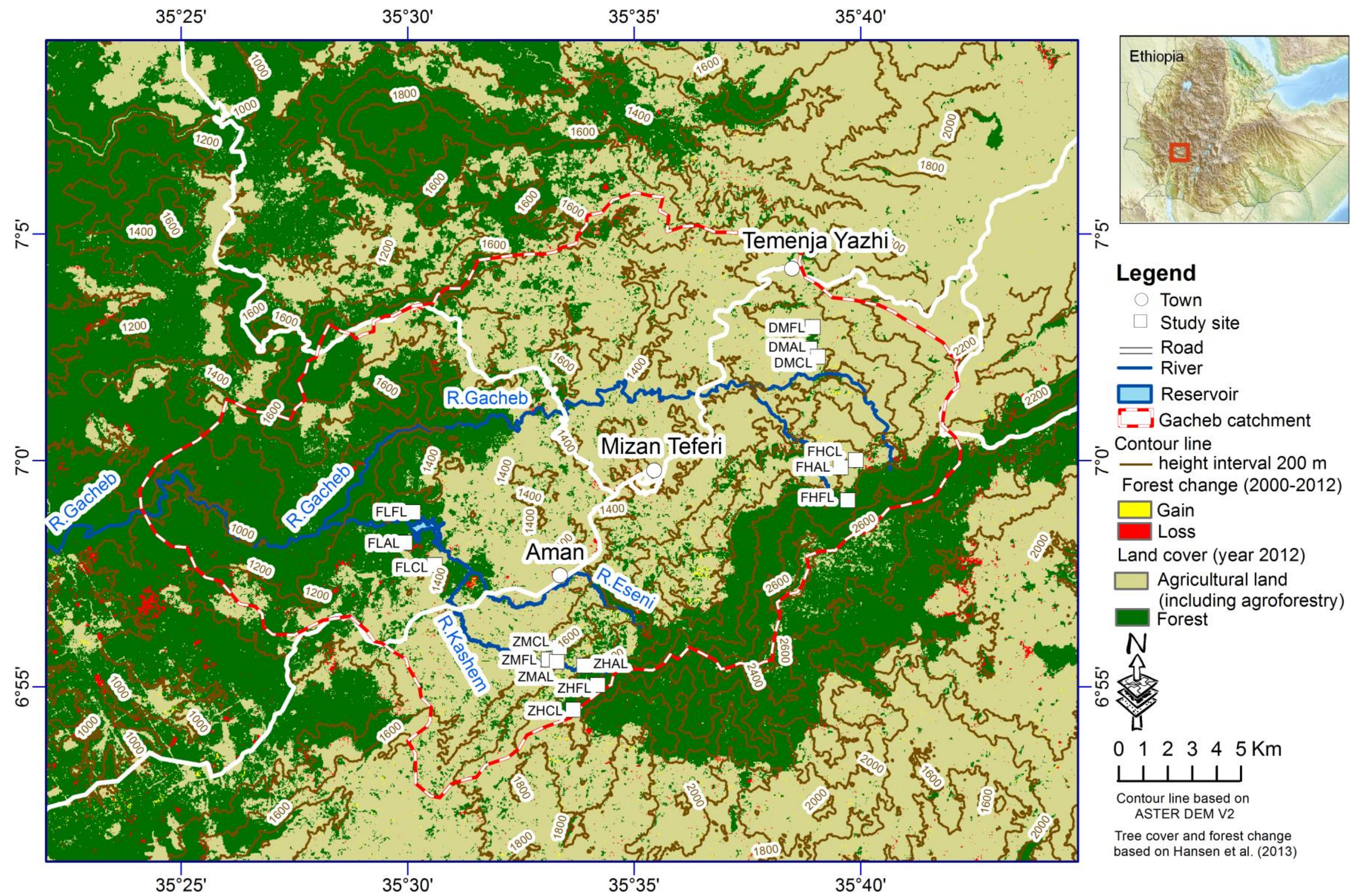

Figure 2.1. Land cover and location of the study area sites in the Gacheb catchment, southwestern Ethiopia.

2.2.2 Data collection and analysis

The soil samples were taken in April and May 2013. A preliminary field visit was made using topographic mapsso as to fully understand the land features and landscape for locating the study area's representative soil sampling points. Five study sites were randomly selected along three altitudinal transects and stratified according to the land-use type (forest, agroforestry, cropland) and three elevation zones (high, 2300-1800 m a.s.l., middle, 1800-1500 m a.s.l. and low, 1500-1200 m a.s.l.). Four depths have been selected for the following reasons: the soil depth (0-20 cm) is the average cropland plow layer in the study area, and the soil depths (20-40 , 40-60 and 60-80 cm) constitute the average depth to which nutrients and clay particles are leached to the subsoil in a high rainfall area and a layer where fine roots of trees have a role in nutrient addition and recycling. The plots - both under agroforestry and cropland - had been under forest up to 15 to 25 years earlier as reported by farmers and confirmed by satellite images. The land-use changes' history of the soil sampling plots was first gathered by interviewing the farmers and local agricultural institutions.

The soil samples were collected from 20 × 20 m^2 plots with three replicates at a 20 m interval. From each plot, soil samples were collected at 0-20 cm, 20-40 cm, 40-60 cm and 60 to 80 cm soil depths. A total of 360 soil samples have been taken from the three land-use types. Separate soil samples were gathered at the middle of each plot for soil bulk density determination. The soil samples consisted of bulked subsamples and were analyzed at the Addis Ababa National Soil Testing Centre and the Ghent University Sedimentology Laboratory. The standard analytical procedures have been followed so as to determine the soil texture (Sedigraph III plus Particle Size Analyzer), bulk density (using 100 cm^3 Kopecky rings), soil pH (1:2.5 H_2O), organic carbon contents (Walkley & Black, 1934), total nitrogen using the Kjeldahl method (Bremner & Mulvancy, 1982), available phosphorus (Olsen et al., 1954), exchangeable bases (Ca, Mg, K and Na) in the soils were estimated by the ammonium acetate (1M NH_4OAc at pH 7) extraction method. The extracted Ca and Mg were then defined utilizing an atomic absorption spectrophotometer. The exchangeable K and Na were measured using a flame photometer. The cation exchange capacity (CEC) was determined by the ammonium acetate method (Hesse, 1972). The base cation saturation (BS) has been calculated based on the standard formula:

$$BS\ (\%) = [(Na^{+} + K^{+} + Ca^{2+} + Mg^{2+}) / CEC] \times 100 \quad (2.1)$$

The soil carbon and nitrogen stocks were calculated based on the next formula (Chan, 2008a):

$$Ct = Kd \times \rho \times \%C \quad (2.2)$$

Where Ct= Carbon stock (g/cm^2), Kd= the depth of the soil sample thickness of the sampled soil layer (cm), ρ = the soil bulk density (g/cm^3), %C= the percentage soil organic carbon.

The total nitrogen was also computed with a similar formula. The sink/loss in soil C and N-because of deforestation- were estimated by subtracting the total soil C and N stocks under forest or agroforestry land to the corresponding depth under cropland. The computed loss values were then divided by the number of years since the conversion to obtain soil C and N losses per year. The carbon dioxide emission due to the conversion of both forest and agroforestry to cropland was calculated based on the relation between soil organic carbon and carbon dioxide reported by Chan (2008b); an increase in 1 Mg ha^{-1} in soil organic carbon represents a 3.67 Mg of carbon dioxide removal from the atmosphere.

The topsoil and subsoil'sphysico-chemical characteristics of the three land-use types have been analyzed by factor analysis (FA). The factor analysis was used in order to define the most significant topsoil and subsoil'sphysico-chemical characteristics in differentiation of the three land-use types. The physico-chemical characteristics with factor loading (>0.5) were considered. The differences in soil physico-chemical characteristics, soil carbon and nitrogen stocks between forest, agroforestry and cropland were tested by one way ANOVA using SPSS (software version 20). The means have been compared by the least significant difference (LSD).

2.3. Results

2.3.1 Contrasts between the three land-use types

The biplots of the topsoil show that the first factor axis (FA-1) corresponds to a gradient of plots from forest to cropland, whereby the plots under agroforestry are similar to those under forest. The soil physico-chemical characteristics N_t, pH, Mg^{2+}, Ca^{2+}, P and CEC are also higher under forest and agroforestry than under cropland. Most importantly, all cropland topsoil are sandy, but soil organic carbon are low in some and high in other cropland. The second factor axis (FA-2) is independent from the gradient, forest to cropland. This sets aside the three plots studied at low elevation (FL site) have lower soil organic carbon than the high (FH and ZH) and middle elevation (DM and ZM) sites. This correspons to a gradient from high soil organic carbon to low soil organic carbon (Fig.2.2a).

The biplot of the subsoil's first factor axis (FA-1) is independent from the gradient, forest to cropland. However, the plots at low elevation (FL site) are different from the high (FH and ZH) and middle elevation (DM and ZM sites) plots in the first factor axis (FA-1). This corresponds to a gradient from high soil organic carbon and low sand (FL site) to low soil organic carbon and high sand (FH, ZH, DM and ZM site). Soil physico-chemical charcterstics Mg^{2+}, Na^{+}, CEC and Ka^{+} are higher in FL site. The second factor of the biplots corresponds with a gradient of plots from forest to cropland. The plots under agroforestry are similar to the forest plots. Most importantly, a gradient from high soil organic carbon and high sand (Forest) to low soil organic carbon and low sand (cropland) (Fig 2.2b).

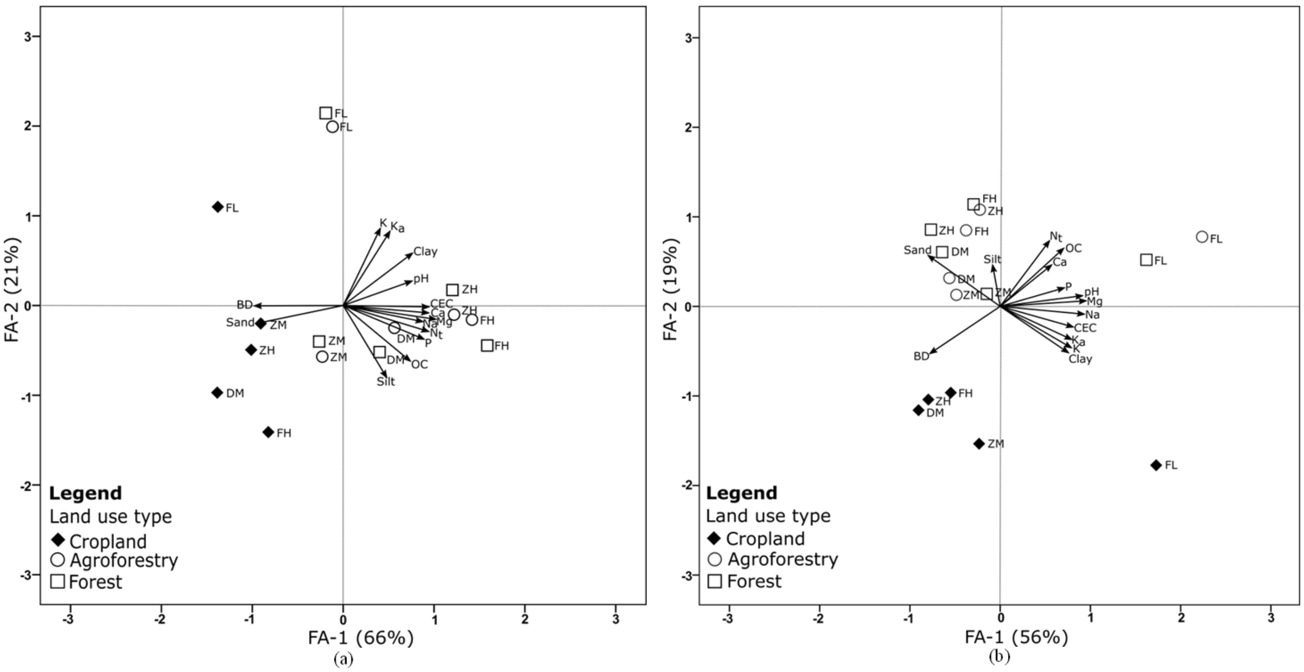

Figure 2.2. Biplots of (a) topsoil (0-20 cm) and (b) subsoil (40-60 cm) physico-chemical characteristics of 5 study sites**.** Land use types: cropland, agroforestry and forest. Study sites: FH= Faketen high, DM= Dakin middle, ZH= Zemika high, ZM= Zemika middle and FL= Fanika low. Soil physico-chemical characteristics: BD= bulk density, Soil texture (sand, silt and clay), OC= organic carbon, N_t= total nitrogen, CEC= cation exchange capacity, P= available phosphorous, K_a= available potassium, Mg= exchangeable magnesium, Ca= exchangeable calcium, K= exchangeable potassium, Na= exchangeable sodium. The arrow represents the direction of high weighting of soil physico-chemical characteristics in first factor (FA-1) and second factor (FA-2). The FA-1 and FA-2 of topsoil explains 87% of the variation between individuals. The FA-1 and FA-2 of subsoil explains 75% of the variation between individuals.

2.3.2 Soil physico-chemical characteristics

Soil texture and bulk density

The topsoil sand fraction of cropland is significantly different from that in forest and agroforestry ($P<0.00001$) at the FH, DM, ZH, ZM and FL sites. The highest sand contents were recorded in cropland at FH site (34%), DM (36%), ZH site (36%), ZM (36%) and FL site (27%). The topsoil silt and clay contents in the forest are significantly different from the cropland ($P<0.00001$) at all sites. The silt contents in forest and agroforestry were found to be similar at all sites, but clay content in the forest soil is different from the agroforestry at all sites except DM site. The highest silt contents were recorded in the forest (55% at the FH, DM and ZH site) and agroforestry (53% at the ZM site). Like silt, the highest clay contents were recorded in the forest (24% at DM site, 25% at the ZH, 26% at ZM site and 36% at the FL site) and agroforestry (23% at the FH and) (Fig 2.3). Similarly, the subsoil sand and silt content of the forest and agroforestry were similar on all sites, but cropland is different from both. On the contrary, the subsoil texture fraction (clay) in the forest, agroforestry and cropland proved to be similar at the FH, DM, ZH, ZM and FL sites (Fig 2.4).

The topsoil bulk density of cropland differs significantly from both that of the forest and agroforestry at all sites ($P<0.00001$). The topsoil bulk density of the forest is similar to agroforestry at all sites. The highest bulk density has been recorded in cropland at the FH site (1.0 g cm^{-3}), DM site (1.2 g cm^{-3}), ZH site (1.24 g cm^{-3}), ZM site (1.24 g cm^{-3}) and FL (1.21 g cm^{-3}) (Fig 2.3). Similarly, the subsoil bulk density of cropland varies significantly from both the forest and agroforestry at all sites ($P<0.001$). However, the forest and agroforestry are similar in the subsoil bulk density at all sites. The highest subsoil bulk density was recorded in cropland at the FH site (1.34 g cm^{-3}), DM site (1.30 g cm^{-3}), ZH site (1.37 g cm^{-3}), ZM site (1.32 g cm^{-3}) and FL site (1.30 g cm^{-3}) (Fig 2.4).

Soil pH and organic carbon

The topsoil pH in both forest and agroforestry was significantly different from that in cropland at all sites ($P<0.01$). Yet, the soil pH in agroforestry is similar to the forest's at all sites. The highest soil pH was recorded in the forest at the FH site (6.0), ZH site (5.7), ZM site (5.6) and FL site (6.4); and in agroforestry at DM site (5.7) (Fig 2.3). As the topsoil, the subsoil pH of both the forest as well as agroforestry is significantly different from cropland at all sites. However, the forest and agroforestry are similar at all sites except the ZM and FL site. The highest subsoil pH was recorded in the forest (5.4 at the FH site, 5.37 at the DM site, 5.1 at the ZH and 5.1 at the ZM site) and agroforestry (5.9 at the FL site) (Fig 2.4).

The topsoil organic carbon contents of the forest (as well as agroforestry) varied significantly from the cropland ($P<0.0001$) at all sites. However,the forest's organic carbon contents are similar to the agroforestry at all sites. The highest organic carbon was measured in the forest at the FH site (8.2%), DM site (6.8%), ZH site (7.9%), ZM site (6.5%) and FL site (5.0%) (Fig 2.3). The subsoil organic carbon contents regarding both forest and agroforestry are significantly different from cropland at all sites. Alike the topsoil, the forest and agroforestry are similar in organic carbon contents at all sites. The highest soil organic carbon was recorded in the forest at the FH site (4.0%), DM site (3.6%) and FL site (3.9%) and in agroforestry at ZH site (3.8%) and ZM site (3.6%) (Fig 2.4).

Total nitrogen, available phosphorus, exchangeable calcium and magnesium

The topsoil total nitrogen contents of both forest and agroforestry were significantly different from cropland at all sites ($P<0.001$). Yet, the forest and agroforestry were similar in nitrogen contents at all sites. The highest total nitrogen was recorded in the forest (1.1% at the FH site and 0.80% at the ZH site) and agroforestry (0.7% at the DM site, 0.7% at the ZM site and 0.79% at the FL site) (Fig 2.3). Likewise, the subsoil nitrogen contents of both the forest and agroforestry differed significantly from the cropland at all sites ($P<0.01$). Yet, the forest and agroforestry are similar at all sites. The highest soil total nitrogen contents were noticed in the forest at the FH site (0.43%), DM site (0.37%) and FL site (0.33%) and in agroforestry at the ZH site (0.42%), ZM site (0.32%) (Fig 2.4).

The topsoil available phosphorus contents (both agroforestry and forest) were found to be significantly different from the cropland ($P<0.0001$) at all sites. Similarly, the forest's topsoil available phosphorus contents are similar with agroforestry at all sites, except at the ZM and FL site. The highest available phosphorus was recorded in the forest (14 mg kg^{-1} at FH site) and agroforestry (11 mg kg^{-1} at DM, 12 mg kg^{-1} at ZH site, 11 mg kg^{-1} at ZM site and 12 mg kg^{-1} at FL site) (Fig 2.3). However, both forest and agroforestry are similar regarding the subsoil available phosphorus contents at all sites except for the FL site, but both are significantly different from the cropland at all sites except the similarity with the forest at the ZM site. The highest available phosphorus was measured in the forest (6 mg kg^{-1} at FH site, 4 mg kg^{-1} at DM site, 6 mg kg^{-1} at ZH site and 6 mg kg^{-1} at ZM site) and agroforestry (10 mg kg^{-1} at FL site) (Fig 3b).

The topsoil exchangeable calcium and magnesium contents of both the forest and agroforestry are significantly different from the cropland (P<0.0001) at all sites. Yet, there is no difference in the exchangeable calcium and magnesium contents between the forest and agroforestry at all sites, except the ZH site. The highest topsoil exchangeable calcium was recorded in the forest at the FH site (20 cmol (+) kg^{-1}), ZH site (18 cmol (+) kg^{-1}) and ZM site (14 cmol (+) kg^{-1}) and in agroforestry at the DM site (14 cmol (+) kg^{-1}) and FL site (16 cmol (+) kg^{-1}). The highest topsoil exchangeable magnesium contents have been recorded in the forest at the FH site (36 cmol (+) kg^{-1}), DM site (30 cmol (+) kg^{-1}), ZH site (30 cmol (+) kg^{-1}), ZM site (31 cmol (+) kg^{-1}) and FL site (30 cmol (+) kg^{-1}) (Fig 2.3). However, the subsoil exchangeable calcium contents of the three land-use types are similar at all sites (except the difference at the ZM and FL site). On the contrary, the subsoil exchangeable magnesium contents of both the forest and agroforestry vary significantly from the cropland at all sites (P<0.0001). The highest subsoil exchangeable calcium was recorded in the forest at the FH site (11 cmol (+) kg^{-1}), DM site (10 cmol (+) kg^{-1}), ZM site (11cmol (+) kg^{-1}) and in agroforestry at ZH site (11 cmol (+) kg^{-1}) and FL site (14 cmol (+) kg^{-1}). The highest subsoil exchangeable magnesium was recorded in the forest at the FH site (25 cmol kg^{-1}), DM site (26 cmol (+) kg^{-1}), ZH site (23 cmol (+) kg^{-1}), ZM site (19 (cmol (+) kg^{-1}) and FL site (30 cmol (+) kg^{-1}) (Fig 2.4).

Cation exchange capacity and base cation saturation

The topsoil cation exchange capacity and the exchangeable base cation of both forest and agroforestry are significantly different from the cropland at all sites (P<0.0001). Yet, the forest and agroforestry are similar regarding CEC and the exchangeable base cation at all sites except the difference in CEC at FH site. The highest cation exchange capacity was recorded in the forest at the FH site (94 cmol kg^{-1}), DM site (83 cmol kg^{-1}), ZH site (75 cmol kg^{-1}), ZM site (81 cmol kg^{-1}) and FL site (86 cmol kg^{-1}). The highest exchangeable base cation was recorded in the forest (57% at FH site, 66% at ZH site and 56% at ZM site and) and agroforestry (53% at DM site and 63% at FL site) (Fig 2.3). Like the topsoil, the subsoil cation exchange capacity and exchangeable base cation contents (under both forest and agroforestry) were found to be different from the cropland at all sites, except the ZM site. Nevertheless, the forest and agroforestry are similar at all sites, except for the difference in the exchangeable base cation saturation at the FL site. The highest subsoil CEC was recorded in the forest at the FH site (69 cmol kg^{-1}), DM site (69 cmol kg^{-1}), ZH site (64 cmol kg^{-1}), ZM site (56 cmol kg^{-1}) and FL site (72 cmol kg^{-1}) (Fig 2.4). The highest subsoil exchangeable base cation was recorded in the forest (54% at DM site and 55% at ZH site) and agroforestry (53% at FH site, 55% at ZM site and 66% at FL site) (Fig 2.4).

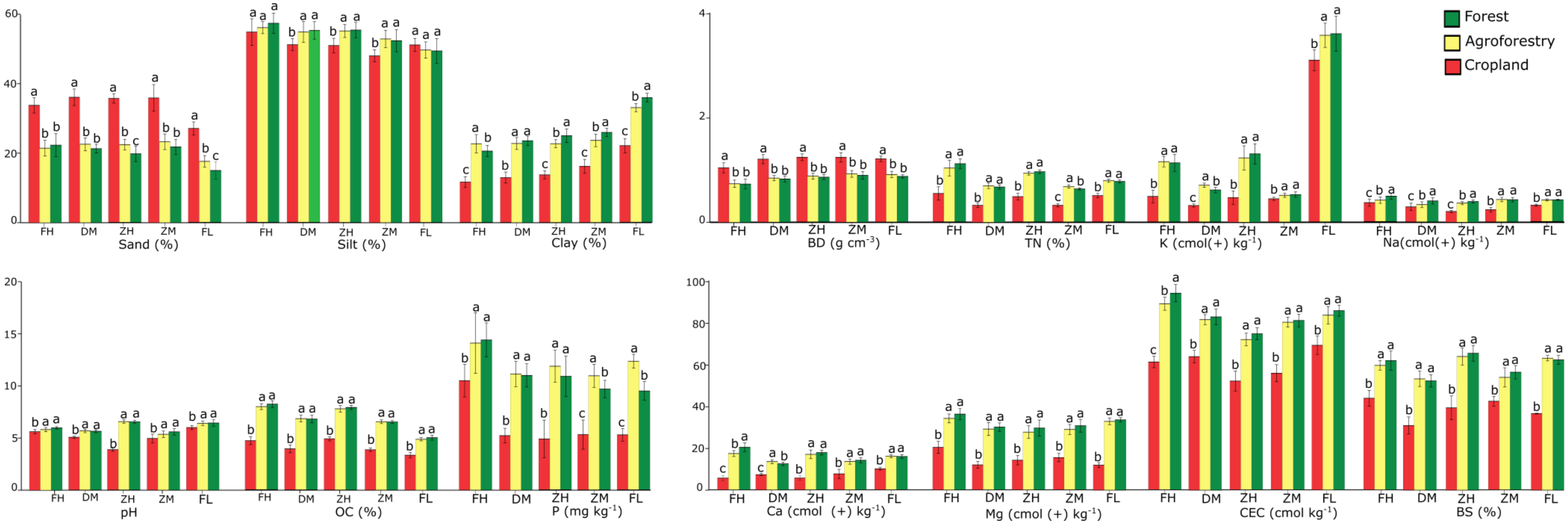

Figure 2.3. Physico-chemical characteristics of topsoil (0-20 cm) under forest, agroforestry and cropland. Study site: FH= Faketen high, DM=Dakin middle, ZH= Zemika high, Zemika middle, FL= Fanika low. Number of replicates (n=3). *Mean value of land used types soil physico-chemical characteristics with similar letter within the same site are not significantly different to each other at p<0.05.

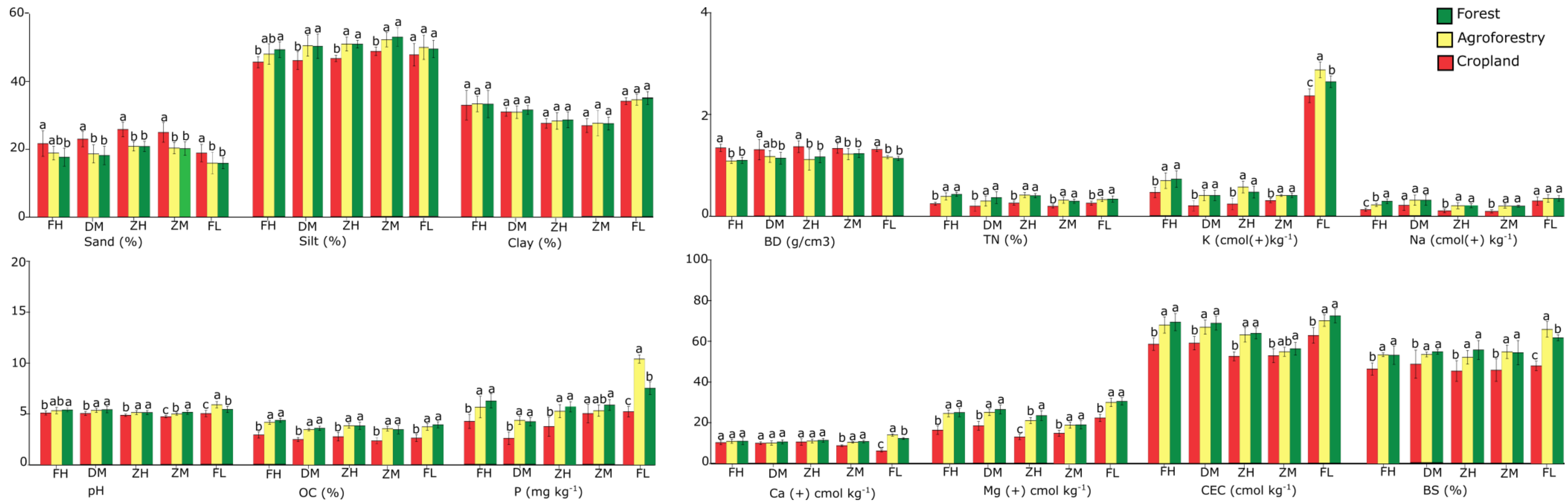

Figure 2.4. Physico-chemical characteristics of subsoil (40-60 cm) under forest, agroforestry and cropland.Study site: FH= Faketen high, DH=Dakin middle, ZH= Zemika high, Zemika middle, FL= Fanika low. Number of replicates (n=3) *Mean value of land used types soil physico-chemical characteristics with similar letter within the same site are not significantly different to each other at p<0.05.

2.3.3 Soil carbon and nitrogen stocks in the three land use types

Soil organic carbon stocks

The soil organic carbon stocks of both forest and agroforestry are similar in all sites at all soil depths (0-20, 20-40, 40-60 and 60-80 cm). However, both forest and agroforestry are significantly different from cropland in all sites at all depths except at 60-80 cm. The soil organic carbon stocks of forest and agroforestry are similar to cropland in all sites at 60-80 cm soil depth. The highest total soil organic carbon stocks were recorded in forest (412 Mg ha^{-1} at FH site and 320 Mg ha^{-1} at FL site) and agroforestry (357 Mg ha^{-1} at DM site, 397 Mg ha^{-1} at ZH site and 363 Mg ha^{-1} at ZM site) (Table 2.1).

Soil nitrogen stocks

Similarly, the soil nitrogen stocks in soil under both forest and agroforestry were similar in all sites at all soil depths (0-20, 20-40, 40-60 and 60-80 cm). Yet, the soil nitrogen stocks in both forest and agroforestry were found to be different from cropland in all sites at all soil depths except 60-80 cm. The soil nitrogen stocks in forest, agroforestry and cropland were similar in all sites at 60-80 cm soil depth. The highest total soil nitrogen stocks were recorded in forest (46 Mg ha^{-1} at FH site) and agroforestry (36 Mg ha^{-1} at DM site, 45 Mg ha^{-1} at ZH site, 37 Mg ha^{-1} at ZM site and 37 Mg ha^{-1}at FL site) (Table 2.1).

Table 2.1. Soil organic carbon and nitrogen stocks in cropland, agroforestry and forest land use types

			Soil organic carbon stocks (Mg ha^{-1})			Soil nitrogen stocks (Mg ha^{-1})		
Site	Elevation	Depth (cm)	Land use types			Land use types		
			CL	AG	FO	CL	AG	FO
FH	High	0-20	103±6.6b	149±8.3a	153±9.8a	12±1.3b	19±1.8a	21±1.3a
		20-40	78±1.3b	109±2.9a	109±1.0a	7±0.2b	10±0.3a	10±0.3a
		40-60	77±4.8b	98±3.4a	103±5.0a	7±0.4b	9±0.9a	10±0.7a
		60-80	50±3.4a	50±3.7a	52±2.4a	5±0.5a	5±0.8a	5±0.9a
		Total	308	406	417	31	43	46
DM	Middle	0-20	94±7.0b	135±6.6a	132±1.0a	8±0.3c	14±0.2a	13±0.3b
		20-40	74±3.4b	96±5.0a	95±1.6a	6±1.5b	9±0.4a	9±0.3a
		40-60	65±1.0b	84±2.0a	85±2.1a	5±0.2b	8±0.5a	8±0.2a
		60-80	36±2.3a	42±4.8a	40±2.3a	5±0.5a	5±0.5a	5±0.5a
		Total	269	357	352	24	36	35
ZH	High	0-20	121±4.4b	151±5.5a	151±1.5a	12±0.9b	16±0.2a	16±0.1a
		20-40	80±2.4b	99±4.6a	97±1.1a	9±1.2b	13±0.5a	12±1.4a
		40-60	75±5.8b	89±8.0ab	92±8.4a	7±0.4b	10±1.1a	10±0.4a
		60-80	54±3.4a	58±2.1a	54±5.5a	6±0.4a	6±0.5a	6±0.7a
		Total	330	397	394	34	45	44
ZM	Middle	0-20	96±3.2b	135±5.6a	130±5.8a	8±0.1c	14±0.1a	13±0.3b
		20-40	80±1.2b	102±3.9a	101±1.3a	7±0.4b	10±0.5a	10±0.2a
		40-60	63±6.0b	86±1.2a	85±7.9a	5±0.3b	8±1.0a	7±0.5a
		60-80	37±2.2a	40±2.8a	40±2.3a	5±0.5a	5±0.5a	5±0.6a
		Total	276	363	356	25	37	35
FL	Low	0-20	81±3.2b	104±2.1a	103±1.8a	12±0.4b	16±0.7a	15±0.3a
		20-40	72±3.5b	92±1.1a	92±0.8a	8±0.6b	9±0.1a	9±0.6a
		40-60	68±4.8b	85±3.2a	88±4.6a	7±0.6a	7±0.6a	8±0.7a
		60-80	37±1.8a	37±1.7a	37±2.6a	4±0.5a	4±0.6a	4±0.4a
		Total	258	319	320	30	37	36

Study site: FH= Faketen high, DM=Dakin middle, ZH= Zemika high, ZM=Zemika middle, FL= Fanika low. Land use types: CL=Cropland, AG=Agroforestry, FO= Forest. *Mean value of land used types soil carbon and nitrogen stocks with the same letter within the same site and depth are not significantly different to each other at $p < 0.05$.

Soil carbon and nitrogen loss

The estimated total soil carbon loss as the result of conversion of forest to cropland leads to a soil carbon loss of 8 Mg ha^{-1} y^{-1} at FH site, 4.2 Mg ha^{-1} y^{-1} at DM site, 4.3 Mg ha^{-1} y^{-1} at ZH site, 3.5 Mg ha^{-1} y^{-1} at ZM site and 3.3 Mg ha^{-1} y^{-1} at FL site. Similarly, conversion from agroforestry to cropland leads to a soil carbon loss of 7 Mg ha^{-1} y^{-1} at FH site, 4.4 Mg ha^{-1} y^{-1} at DM site, 4.5 Mg ha^{-1} y^{-1} at ZH site, 3.8 Mg ha^{-1} y^{-1} at ZM site and 3.2 Mg ha^{-1} y^{-1} soil carbon at FL site (Table 2.2).

The conversion of forest to cropland leads to an emission of 28 Mg ha^{-1} y^{-1} CO_2 at FH site, 15.2 Mg ha^{-1} y^{-1} CO_2 at DM site, 15.7 Mg ha^{-1} y^{-1} CO_2 at ZH site, 12.8 Mg ha^{-1} y^{-1} CO_2 at ZM site and 12 Mg ha^{-1} y^{-1} CO_2 at FL site. Similarly, converting agroforestry to cropland leads to an emission of 26 Mg ha^{-1} y^{-1} CO_2 at FH site, 23 Mg ha^{-1} y^{-1} CO_2 at DM site, 18 Mg ha^{-1} y^{-1} CO_2 at ZM site and 16 Mg ha^{-1} y^{-1} CO_2 at FL site (Table 2.2).

With regard to nitrogen loss, conversion of forest to cropland leads to a soil nitrogen loss of 1.1 Mg ha^{-1} y^{-1} at FH site, 0.6 Mg ha^{-1} y^{-1} at DM site, 0.7 Mg ha^{-1} y^{-1} at ZH, 0.4 Mg ha^{-1} year^{-1} at ZM site and 0.3 Mg ha^{-1} y^{-1} at FL site. Similarly, conversion of agroforestry to cropland leads to a soil nitrogen loss of 0.9 Mg ha^{-1} y^{-1} at FH site, 0.6 Mg ha^{-1} y^{-1} at ZH site, 0.7 Mg ha^{-1} y^{-1}, 0.5 Mg ha^{-1} y^{-1} at ZM site and 0.4 Mg ha^{-1} y^{-1} at FL site (Table 2.2).

Table 2.2. Soil carbon and nitrogen loss (Mg ha^{-1} y^{-1}) related to change in land use (conversion from forest and agroforestry to cropland)

			Forest			Agroforestry		
Sites	Elevat-ion	Soil depth (cm)	SOC loss (Mg ha^{-1} y^{-1})	N loss (Mg ha^{-1} y^{-1})	CO_2 loss (Mg ha^{-1} y^{-1})	SOC loss (Mg ha^{-1} y^{-1})	N loss (Mg ha^{-1} y^{-1})	CO_2 loss (Mg ha^{-1} y^{-1})
FH	FH	0-20	3.6	0.6	13	3.3	0.5	12
		20-40	2.2	0.2	8.1	2.2	0.2	8.1
		40-60	1.9	0.2	6.8	1.5	0.1	5.5
		60-80	0.1	0.0	0.3	0.0	0.0	0.0
		Total	**8**	**1.1**	**28**	**7**	**0.9**	**26**
DM	DM	0-20	1.9	0.3	7.0	2.1	0.3	7.5
		20-40	1.1	0.2	3.9	1.1	0.2	4.0
		40-60	1.0	0.2	3.7	1.0	0.2	3.5
		60-80	0.2	0.0	0.7	0.3	0.0	1.1
		Total	**4.2**	**0.6**	**15.2**	**4.4**	**0.6**	**16.1**
ZH	ZH	0-20	2.0	0.3	7.3	2.0	0.3	7.3
		20-40	1.1	0.2	4.2	1.3	0.3	4.6
		40-60	1.1	0.2	4.2	0.9	0.2	3.4
		60-80	0.0	0.0	0.0	0.3	0.0	1.0
		Total	**4.3**	**0.7**	**15.7**	**4.5**	**0.7**	**16.4**
ZM	ZM	0-20	1.5	0.2	5.4	1.7	0.3	6.2
		20-40	0.9	0.1	3.4	1.0	0.1	3.5
		40-60	1.0	0.1	3.5	1.0	0.1	3.7
		60-80	0.1	0.0	0.5	0.1	0.0	0.5
		Total	**3.5**	**0.4**	**12.8**	**3.8**	**0.5**	**13.9**
FL	FL	0-20	1.2	0.2	4.2	1.2	0.2	4.5

	20-40	1.1	0.1	3.9	1.1	0.1	3.9
	40-60	1.1	0.1	3.9	0.9	0.0	3.3
	60-80	0.0	0.0	0.0	0.0	0.0	0.0
	Total	**3.3**	**0.3**	**12.0**	**3.2**	**0.4**	**12.0**

Sites: FH= Faketen high, DM= Dakin middle, ZH= Zemika high, ZM= Zemika middle, FL= Fanika lower. Total soil carbon and nitrogen loss were the sum of loss from all soil depths (0-80 cm) within the land use type in each site.

2.4. Discussion

2.4.1 Factor analysis of soil characteristics

The biplot of the topsoil first factor axis (FA-1) reveals the similarity in soil characteristics between forest and agroforestry and the difference in soil characteristics of both forest and agroforestry with cropland. This study aligns with the findings of Biro et al. (2011), who reported the difference in soil characteristics between woodland and cultivated land in the first principal component axis (PC1). The topsoil's second factor axis (FA-2) reveals the distinction in soil organic carbon between the low elevation (FL) site and both the high (FH and ZH) and middle elevation (ZM and DM) sites. This is most likely because soil organic carbon content normally increases with altitude owing to slow soil organic matter decomposition. This findings is in line with the finding of Aguilera et al. (2013), who reported an increase in surface soil organic carbon with increasing altitude. Further, Wei et al. (2013) reported that low temperature at high altitude are useful in maintaining a low soil organic matter decomposition rate.

The biplot of the subsoil's first factor axis (FA-1) reveals that the low elevation subsoil organic carbon and sand content are difference from both the middle (ZM and DM) and higher elevation (FH and ZH) sites. Similarly Hobley & Wilson (2016) reported that the negative association of temperature with the depth depletion constants of soil organic carbon indicates that proportionally more subsurface soil organic carbon is retained in hotter than in cooler climates. Although this is potentially due to a low surface soil organic carbon in low altitude (warmer) compared with high altitude (cooler). The subsoil's second factor axis (FA-2) reveals the difference in soil organic carbon and sand content of the cropland from both the forest and agroforestry. The presence of high soil organic carbon and sand content in both forest and agroforestry is probably due to the contribution of fine root biomass of trees. and . This study is in line with Deng et al. (2016), who reported a greater presence of soil organic carbon in the subsoils (20-60 cm) of vegetated land (compared to cropland).

2.4.2 Soil physico-chemical characteristics

Soil texture and bulk density

The presence of high topsoil clay and silt fraction in forest and agroforestry may be due to the presence of various trees and shrubs canopy, litter and root protection of the surface soil from leaching and soil erosion. This study’s findings are consistent with Yeshaneh (2015), who indicated that the forest reduces the soil erosion risk by its crown, litter and root support. The resemblance in the subsoil’s soil texture (sand, silt and clay) between forest, agroforestry and cropland reveals the presence of a similar weathered parent material on each site and less land management intervention in the deep subsoil of cropland. These findings correspond with Yeshaneh (2015), who reported a small difference in the subsoil’s soil texture characteristics between the forest and cultivated land. The presence of high soil bulk density in the cropland may be due to soil compaction, mainly because of livestock grazing after the crop harvest, a continuous cultivation and a decline in organic matter. Livestock grazing can directly cause an increase in soil compaction and soil strength because of the pressure exerted on the soil via the livestock's hoof action (Hamza & Anderson, 2005; Don et al., 2011).

The presence of low subsoil bulk density in forest and agroforestry may be due to the existence of relative high subsoil organic carbon in the forest and agroforestry. The dead fine roots and mycorrhizal fungi constitute a primary supplement of the subsoil’s organic matter in forest and agroforestry; soil with a larger organic matter has a low bulk density because of the low particle density of the organic matter and soil aggregate formation. Tree roots contribute- to a larger extent - to a subsoil organic matter accumulation, up to the tree root senescence and root litter decomposition, which in turn decrease the subsoil bulk density (Sharma, 2011; Scheffer & Aerts, 2000).

Soil pH and organic carbon

The presence of lower topsoil pH in cropland can be related to the decrease in base forming cations (Ca^{2+}, K^{+}, Mg^{2+} and Na^{+}) through a continuous nutrient cation uptake by plants during repeated cultivation and leaching and soil erosion loss, as stated earlier on by Noble et al. (2000) and Adugna and Abegaz (2015). Additionally one can conclude that the existence of high subsoil pH in both forest and agroforestry may be related to the availability of high exchangeable bases cation (because of the organic matter decomposition and weathered parent material by the tree, shrub and mycorrhizal fungi function in the subsoil).This study is in accordance with the findings of Sharma (2011).

The occurrence of higher topsoil organic carbon in both forest and agroforestry can be due to the litter fall addition from trees and shrubs to the surface soil (Nsabimana et al., 2008; Worku et al., 2014; Fantaw et al., 2007). Furthermore, the forest and agroforestry possess a higher subsoil organic carbon; through dead fine tree and shrub roots and the mycorrhizal fungi contribution of organic matter in the subsoil(Lemma et al., 2006; Fantaw et al., 2007).

Total nitrogen, available phosphorus, exchangeable calcium and magnesium

The forest and agroforestry have higher topsoil nitrogen, available phosphorus, exchangeable calcium and magnesium. This is probably related to the high litter fall from various leguminous and non-leguminous trees, shrubs and herbs. The leguminous tree species (*Albizia gummifera* J.F.Gmel.C.A.Sm., *Millettia ferruginea* Hochst Baker, *Sesbania sesban* LMerr and *Leucaena leucocephala* Lam. de Wit) play a significant role in supplying organic matter, organic carbon and nitrogen to the soil. The inherent ability to fix the atmospheric nitrogen and the association with symbiotic bacteria and mycorrhizal fungi lead to organic carbon and nitrogen accumulation in the biomass of trees. The tree leafs contribute then significantly to the topsoil's levels of nitrogen, organic carbon, exchangeable calcium and magnesium. Furthermore, the cropland's loss of nitrogen, available phosphorus, exchangeable calcium and magnesium during the crop harvest, leaching and surface erosion can be the reason for the decline in those soil features. This study is consistent with the findings of Adugna & Abegaz (2015), Nsabimana et al. (2008) and Binkley & Giardina (1998).

Similarly, both forest and agroforestry show higher subsoil nitrogen, available phosphorus, exchangeable calcium and magnesium. This matches the availability and release of the organic matter supplement by dead fine tree roots and shrubs and mycorrhizal fungifunction in the subsoil. The mycorrhizal fungi associated to the roots of leguminous trees promote the subsoil's decomposition and organic matter breakdown. This enhances the availability of those soil nutrients in the subsoil. This study is in line with the findings of Sharma (2011) and Hodge et al. (2001), who stated that the arbuscular mycorrhizal symbiosis enhances the decomposition and increase of nitrogen capture from the organic matter in the soil. The cropland subsoil's similarity in exchangeable calcium contents with both forest and agroforestry may be due to the leaching of exchangeable calcium from the topsoil. These results are in line with Duguma et al. (2010) and Adugna & Abegaz (2015).

Cation exchange capacity and base cation saturation

The forest and agroforestry have a higher topsoil cation exchange capacity and exchangeable base cation. This may be due to the presence of high organic matter and clay contents in the topsoil of forest and agroforestry, from which the organic matter formed by trees and shrubs litter underwent a complete microbial breakdown and decomposition(and which release humic substances and exchangeable bases in their turn).This result matches the conclusions of Nsabimana et al. (2008) and Saikh et al. (1998). The presence of a higher subsoil cation exchange capacity and exchangeable basecations in the forest and agroforestry can be explained by the organic matter decomposition and the availability of weathered parent material. The various trees and shrub roots and mycorrhizal fungi have inherent ability to enhance the availability of organic matter, release of base cations and nutrients in the deep soil horizon. This result is consistent with the findings of Saikh et al.(1998), who reported an abrupt increase in the cation exchange capacity and exchangeable base cations on the organic matter (in rich evergreen forest of India).

2.4.3 Soil organic carbon and nitrogen stocks

The presence of high soil organic carbon and nitrogen stocks in the forest and agroforestry can be explained by a continuous leaf defoliation from trees and shrubs. Various leguminous tree species (*Albizia gummifera* J.F.Gmel.C.A.Sm., *Millettia ferruginea* Hochst Baker, *Sesbania sesban* LMerr and *Leucaena leucocephala* Lam. de Wit) could constitute the lion's share for the high organic soil and nitrogen stocks (in forest and agroforestry). The carbon and nitrogen fixed in the tissue of leguminous trees contribute a lot to to surface and subsurface soil in the form of detritus upon seasonal defoliation and senescence. These results correspond with the findings of Mohammed and Bekele (2014) and Lal (2001), who evidenced high soil carbon stocks in the native forest and (coffee-based) agroforestry compared to the arable land. Binkley and Giardina (1998) indicated that the tropical forest that holds leguminous trees, increases the nitrogen contents of the litter fall by 4-50 times compared to non-legumes.

Furthermore, the existence of low carbon stocks in the cropland may be due to the crop uptake, leaching and surface erosion losses. Inadequate land management, the crop residue removal and grazing after the harvest might have contributed to the low soil carbon storage in the cropland's topsoil and subsoil, in concordance with the findings of Don et al. (2011) and Lemenih (2004). The similarity in subsoil (60-80 cm) organic carbon stocks between the three land-use types may be due to the absence of human interaction with the subsoil. Further, the presence of the subsoil organic matter in the cropland, resulted most probably from gradual decomposition of the remnant roots of slashed forest trees and shrubs after conversion. This study is in line with Lemenih (2004), who concluded that the wood roots buried in the soil after slashing decompose gradually and continue to enrich the soil organic matter for some time after the forest clearance.Furthermore, the estimated topsoil organic carbon and nitrogen stocks in the forest and agroforestry fall within the range reported by Mohammed and Bekele (2014) (230 Mg ha^{-1} in forest; 151 Mg ha^{-1} in agroforestry and 65 Mg ha^{-1} on arable land) and Lemenih & Itanna (2004). The total soil organic carbon stocks (estimated to a depth of 80 cm)are withinthe range for the Afromontane forest in Tanzania (252 and 581 Mg ha^{-1}) (Munishi & Shear, 2004), lower than the range reported for the Afromontane forest in Bonga, located in the northern part of our study area (639.6 Mg ha^{-1}) (Aticho,2013) but beyond the rage estimated to a depth of 60 cm in a humid *Podocarpus falcatus* forest (235 Mg ha^{-1}) (Lemenih & Itanna, 2004), tropical soils in general (216 Mg ha^{-1}) (Lal,2004) and the global average (254 Mg ha^{-1}) (Batjes,1996).

Despite the fact that the estimated organic carbon loss could vary depending on the time of land use conversion, the organic carbon loss due to the conversion of forest to cropland as well as agroforestry to cropland were yet considered as a rapid decline. The topsoil organic carbon loss related to the conversion of both forest and agroforestryto cropland are in the same range to the carbon loss by converting the semi-arid Acacia woodland to cropland(2.4 Mg ha^{-1})(Lemenih and Itanna, 2004). The estimated carbon dioxide emission through the conversion to cropland is big enough to contribute to the atmospheric greenhouse gas effect.

2.5. Conclusions

The topsoil and subsoil fertility of agroforestry is comparable with that of the natural forest at the high, middle and low elevation zones. The soil fertility of the topsoil and subsoil under cropland were significantly lower compared to the forest and agroforestry at the high, middle and low elevation zones. The total soil organic carbon and nitrogen stocks were higher in the soils under both forest and agroforestry at the three elevation zones. The soil organic carbon and nitrogen storage potential of agroforestry is equivalent to the natural forest at all three elevation zones. Cropland has low soil organic carbon and nitrogen pools at all elevation zones. Conversion of both forest and agroforestry to cropland has promoted significant losses of carbon and nitrogen and emission of carbon dioxide to the atmosphere. Therefore, it is very important to strengthen the agroforestry as a main agricultural strategy in order to sustain the agriculture production and ecosystem services on steep mountainous terrain and in the heavy rainfall areas of southwest Ethiopia and probably in other similar areas. Additional efforts ought to be taken so as to maintain the soil fertility, carbon and nitrogen storage in cropland. However, further studies are needed to assess the nutrient, carbon and nitrogen stocks' levels in the vegetation canopy of the three land-use types.

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Chapter 3

The agro-ecological implications of forest and agroforestry conversion towards cereal-based farming systems: the case of the Gacheb catchment

This chapter is modified from:

Henok Kassa, Dondeyne, S., Poesen, J., Frankl, A., Nyssen, J., 2016. The agro-ecological implications of forest and agroforestry conversion towards cereal-based farming systems: the case of the Gacheb catchment in the White Nile Basin, Ethiopia. Agroecology and Sustainable Food Systems, submitted. (IF 0.926)

Abstract

The Afromontane forests of southwest Ethiopia are high in endemism and biodiversity. However, the increasing human population and expansion of agricultural land have led to deforestation. We evaluated the effects of land use change on species composition, species diversity and soil fertility. Woody and herbaceous plant species were recorded in natural forest, agroforestry and cropland at different altitudes, using 15 plots with three replicates. A total of 180 soil samples were taken. In total, 77 woody and herbaceous species have been recorded. The selective felling of trees and shrubs in the agroforestry system to favour coffee growth through enhanced light penetration also favours the grass and herb diversity. The Shannon species diversity of the forest is significantly different from both agroforestry and cropland. However, the agroforestry shannon species diversity is less than forest but greater than the cropland. The species richness of agroforestry is equivalent to that of the forest, but greater than the cropland. Therefore, this study suggests that the agroforestry practices are important for keeping biodiversity and soil fertility at levels similar to the natural forest.

Keywords: Afromontane forest, Agroforestry, Species composition, Soil fertility.

3.1 Introduction

The Afromontane forests of southwest Ethiopia are known for their high biodiversity due to their original sites providing *Coffea arabica* L. (e.g. Gebre-Egziabher, 1991; Feyera, 2006; Schmitt, 2006; Assefa et al., 2014). In-migration, population growth and expansion of plantation agriculture have led to significant deforestation (e.g. Getahun et al., 2013) but also to a conversion of the traditional agroforestry farming systems towards farming systems which are dominated by cereals, such as maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench), barley (*Hordeum vulgare*L.), wheat (*Triticum aestivum* L.), rice (*Oryza sativa* L.) and teff (*Eragrostis tef* Zucc.Trotter). Besides, large forest swaths are also being converted to commercial plantations of tea (*Camellia sinensis* L. O. Kuntze), coffee (*Coffea arabica* L.), soap berry (*Phytolacca dodecandra* L'Herit.) and rubber tree (*Hevea brasiliensis* Willd. ex A. Juss.) (Mekuria, 2005; Tadesse, 2007).

The agroforestry farming systems of southwest Ethiopia are structurally complex and harbour a large diversity of mainly indigenous species. Coffee, as a cash crop, is integrated with food crops (Wale 2010) such as false banana (*Ensete ventricosum* Welw. Cheesman), taro (*Colocasia esculenta* L.Schott) and cassava (*Manihot esculenta* Crantz.). Various spices are also integrated in the farming systems: korarima (*Aframomum corrorima* Braun. P.C.M.Jansen), ginger (*Zingiber officinale* Roscoe) and turmeric (*Curcuma longa* L.).Native trees include *Cordia africana* Lam., *Millettia ferruginea* Hochst. Baker., *Albizia gummifera* J.F.Gmel. C.A.Sm.and *Ficusvasta*Forssk.,which are being kept for shade, fodder, firewood, medicinal value and soil fertility maintenance (Bishaw & Abdelkadir, 2003; Anteneh, 2006). The cropland mainly consists of open field cultivation of cereal crops like maize (*Zea mays* L.) and sorghum (*Sorghum bicolor* L. Moench) (Mekuria, 2005).

In the upper Gacheb catchment (*ca.* 450 km²; Fig. 4.1), parts of dense montane forest have persisted. However, since the mid-20th century, large parts of this forest have been converted to agroforestry and cropland for cereal production, as shown in Figure 4.1 (Hansen et al., 2013; Dereje, 2007), resulting in a decline in biodiversity (Schmitt, 2006). The objective of this study was therefore (i) to evaluate the tree, shrub and herb species composition and diversity of forests, agroforestry and croplands and (ii) to assess the effects of land-use changes on the soil fertility and hence sustainability of the farming system. The hypothesis was that biodiversity in agroforestry would be less high than in the forest but larger than in the arable land. Likewise, it was expected that the soil fertility under agroforestry would be comparable to the one under forest, while it would be less in croplands.

3.2. Materials and methods

3.2.1 Study area and data collection

The study area is the upper Gacheb catchment, located in the headwaters of the White Nile in southwest Ethiopia. Altitudes range from 1000 to 2600 m a.s.l. (Fig. 3.1) and the outcropping lithology comprises Tertiary basalt traps and rhyolites (Mengesha et al., 1996; GSE, 2005). The annual rainfall pattern is unimodal with a rainy season from mid-March to mid-November. The average annual rainfall depth in Mizan Teferi (1440 m a.s.l.) is 1780 ± 270 mm y^{-1} and the annual reference evapotranspiration depth amounts to 1259±12 mm y^{-1} (Grieser et al., 2006); the average air temperature ranges from 13 to 27 °C (Tadesse et al., 2006). The harmonized soil map of Africa (Dewitte et al., 2013) indicates that Leptosols are dominant on crests, while Nitisols are dominant on the hill slopes (lower, middle and upper parts), to which Alisols and Cambisols areassociated locally. Fluvisols are found in the flat valley bottoms where meandering rivers occur. The dominant granulometric class of the study area is silt (51%), followed by clay (25%) and sand (24%).

In April and May 2013, vegetation records were made and soil samples were taken. Fifteen study sites have been selected along three altitudinal transects and stratified according to the land use type (forest, agroforestry, cropland) and three elevation zones (high, 2300-1800 m a.s.l.; middle, 1800-1500 m a.s.l., and low, 1500-1200 m a.s.l.). The plots that were under agroforestry and cropland had been under forest 15 to 25 years earlier, as reported by farmers and confirmed by satellite images. The main plots were 20 × 20 m^2 with 3 replications at 20 m interval. Trees with a diameter atbreast height > 2 cmand above 1.5 m height were counted inside the 20 × 20 m^2 plots, shrubs were counted in subplots of 5 × 5 m^2 at the four corners of the main plot, and herbaceous species inside 3 × 3 m^2 subplots at the four corners of the main plot. Species which are difficult to be identified in the field have been collected, pressed and taken to Mizan-Tepi University for further identification. The species richness (S), i.e. the number of different species represented in an ecological community, was obtained by simple tallying. The Shannon diversity index and species' evenness were calculated based on the equations by Magurran (1988):

$$H = \sum_{i=0}^{S} (Pi * \ln Pi) \tag{3.1}$$

where, H= the Shannon diversity index, P_i= fraction of the entire population made up of species i, S= numbers of encountered species. The evenness (E′) was calculated based on:

$$E' = H/H_{max} = H/\ln S \tag{3.2}$$

where, E′ represents evenness, H= Shannon diversity index, H_{max}= the maximum level of diversity possible within a given population, which equals lnS.

The topsoil (0-20 cm) soil characteristics soil texture (sand, silt and clay), bulk density, pH, organic carbon, nitrogen, available phosphorous, exchangeable bases (sodium, potassium, magnesium and calcium) and CEC, which was analyzed and used on chapter 2 was used again for correlation analysis in this chapter, since the soil samples were collected from vegetation recorded plots of the three land use types. The spearman's correlation analysis was used to evaluate the correlation between the FA axis and the topsoil variables.

3.3.2 Data analysis

Floristic composition and species association of the 15 sites have been analyzed based on the frequency of occurrence of all species with a two-way indicator species analysis (TWINSPAN) and a factor analysis with PC-ORD (McCune and Melford 2011). We applied TWINSPAN with the following parameters: cut-off levels set at 0, 2, 5, 10 and 20; the minimum group size for division 5; the maximum number of indicators per division 5, the maximum number of species in the final table. The differences in Shannon species diversity, richness and evenness between the three vegetation groups had been tested by one-way ANOVA using SPSS. The topsoil physico-chemical soil characteristics' ordination was determined by factor analysis (FA) with PC-ORD. The relation between the vegetation composition and topsoil physico-chemical characteristics was examined by calculating the Spearman's rank correlation coefficient between the FA axis -derived from the vegetation data- and the soil physico-chemical characteristics. Whether there are differences in soil physico-chemical characteristics between the forest,agroforestry and cropland at different sites was tested by the one-way analysis of variance (ANOVA) using SPSS (software version 20).

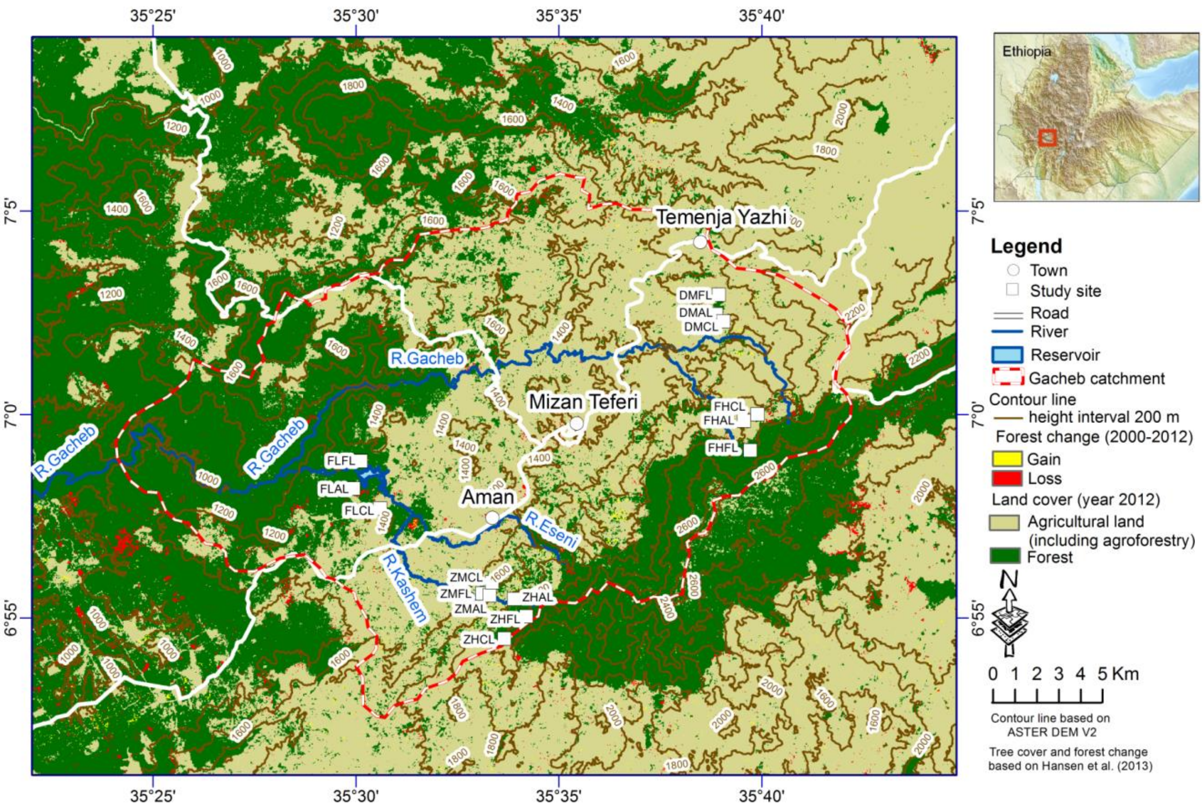

Figure 3.1. Land cover and location of the study sites in the Gacheb catchment, southwestern Ethiopia.Land cover and location of the study sites in the Gacheb catchment, southwestern Ethiopia.

3.3 Results

Vegetation characteristics

Overall, 77 plant species belonging to 40 families had been recorded in 45 studied plots. With TWINSPAN, the vegetation could be sorted, classified into evergreen forest, disturbed forest or/and agroforestry and arable land (Table A1-3). Out of the 77 species (trees, shrubs, herbs and grasses), the evergreen forest holds 58 species (75%), belonging to 28 families. However, the disturbed forest or/and agroforestry holds 51 species (66%) belonging to 29 families and arable land 19 species (25%) belonging to 16 families.

The identification of the common species on the basis of species frequency of occurrence on each land use of the vegetation group show that the evergreen forest holds 8 species which belongs to 7 families, the disturbed or/agroforestry holds 15 species which belongs to 12 families. Whereas the cropland holds 7 common species which belongs to 5 families (Table 3.1).

The endemic species identification on the basis of IUCN category show that the three vegetation groups in the Gacheb catchment holds endemic species. The evergreen forest holds 6 endemic species out of which three belong to the category of near threatened and vulnerable species under the IUCN species category, whereas the disturbed or/and agroforestry holds 2 endemic species which belongs to the vulnerable and least concern species category of IUCN. The arable holds one endemic species which belongs to least concern species category of IUCN (Table 3.2).

Table 3.1. Most common species in the three vegetation groups

Species	Vegetation groups: Evergreen forest	Disturbed or/and agroforestry	Arable	Family
Polyscias fulva Hiern	√	√	×	Araliaceae
Cordia africana Lam.	√	√	×	Boraginaceae
Croton macrostachyus Hochst. ex Delile	√	×	×	Euphorbiaceae
Albizia gummifera J.F.Gmel.C.A.Sm.	√	√	×	Leguminosae
Millettia ferruginea Hochst Baker	√	√	×	Leguminosae
Justicia schimperiana T.Anderson	√	×	×	Acanthaceae
Phytolacca dodecandra L'Herit	√	×	×	Phytolaccaceae
Carissa spinarum L	√	√	×	Apocynaceae
Mangifera indica L	×	√	×	Anacardiaceae
Rhamnus prinoides L'Hérit	×	√	×	Rhamnaceae
Coffea arabica L.	×	√	×	Rubiaceae
Ocimum lamiifolium Hochst.ex Benth	×	√	×	Lamiaceae
Ensete ventricosum Welw.Cheesman	×	√	×	Musaceae
Colocasia esculenta L. Schott	×	√	×	Araceae
Brassica oleracea L	×	√	×	Brassicaceae
Galinsoga parviflora Cav	×	√	√	Asteraceae
Bidens pilosa L.1753	×	√	√	Asteraceae
*Agerantum conyzoides*L.1753	×	√	×	Asteraceae
Zea mays L	×	×	√	Poaceae
Plectranthus barbatus Andrews	×	×	√	Lamiaceae
Veronica persica Poiret	×	×	√	Plantaginaceae
Bidens pachyloma Oliv. and Hiern Cufod	×	×	√	Compositae
Agerantum conyzoides L	×	×	√	Asteraceae
Summary	No of common species			
Evergreen	8			
Disturbed or/and agroforestry	15			
Arable	7			

The identification of the most common species on the bases of frequency of occurrence of the species on each land use types of each vegetation group. A species which occur in all 5 land use of each vegetation group are considered for identification of the most common species on each vegetation group.

Table 3.2. Endemic plant species on the three vegetation groups in Gacheb catchment. (IUCN categories; CR=Critically endengered; EN=Endengered; VU=Vulnerable NT=Near Threatned; LC=Least Concern; NE=Not Evaluated.

Endemic species	**Growth form**	**Family**	**IUCN category**	**Vegetation group**
Millettia ferruginea Hochst Baker	T	Leguminosae	LC	Evergreen forest & Disturbed/agroforestry
Solanecio gigas Vatke C.Jeffrey	S	Asteraceae	LC	Evergreen forest
Circium schimper Vatke C.Jeffrey ex Cuf.	H	Asteraceae	NE	Evergreen forest
Echinops kebericho Mesfin	H	Asteracea	VU	Evergreen forest & Disturbed/agroforestry
Inula confertiflora A. Rich.	H	Asteraceae	NT	Evergreen forest
Bidens pachyloma Oliv. & Hiern Cufod.	H	Asteraceae	LC	Arable
Hypericum quartinianum A. Rich.	S	Hypericaceae	VU	Evergreen forest
Summary	No of endemic species			
Evergreen forest	6			
Disturbed or/and agroforestry	2			
Arable	1			

Growth form: T= tree; S=shrub; H: herb

The Shannon species' diversity index for trees of the evergreen forest (2.3) is significantly different from disturbed forest or/and agroforestry (2.0) ($P<0.05$), as well as from the arable land (0.5) ($P<0.00001$). Similarly, the disturbed or/and agroforestry diversity index differs significantly from the trees on arable land. The Shannon's diversity index for shrubs in the evergreen forest (1.9) is significantly different from the disturbed forest or/and agroforestry (1.1) ($P<0.001$), as well as from arable land (0.7) ($P<0.00001$). Like the trees, the disturbed forest or/and agroforestry differs significantly in shrub species diversity from the arable land ($P<0.01$).The Shannon species' diversity index for herbs in the evergreen forest (2.2) is similar to the disturbed forest or/and agroforestry (2.0). However, the Shannon's index for herbs in both the evergreen and disturbed forest or/and agroforestry is significantly different from the arable land (1.8) ($P<0.005$).The total (trees, shrubs and herbs) Shannon diversity index of the evergreen forest (3.1) is significantly higher than the one of the disturbed forest or/and agroforestry (2.8) (P<0.01), as well as the one regarding the arable land (2.0) (P<0.00001). In contrast, the arboreal, herbal and total species' richness and evenness in the disturbed forest or/and agroforestry is similar to the evergreen forest's (Table 3.3).

Table 3.3. Vegetation indices of evergreen forest, disturbed forest or/and agroforestry and arable land

		Vegetation groups		
Growth form	Parameter	Evergreen forest	Disturbed or/and agroforestry	Arable
Trees	Shannon's diversity index	2.3±0.3a	2.0±0.2b	0.5±0.2c
	Species richness	13.8±3.6a	11.6±2.1a	2.4±0.9b
	Species evenness	0.9±0.05a	0.8±0.03ab	0.6±0.3b
Shrubs	Shannon's diversity index	1.9±0.2a	1.1±0.3b	0.7±0.2c
	Species richness	9.0±2.8a	6.2±1.3b	2.4±0.6c
	Species evenness	0.9±0.1a	0.6±0.1b	0.8±0.2ab
Herbs	Shannon's diversity index	2.2±0.2a	2.1±0.1a	1.8±0.1b
	Species richness	12.2±3.6a	10.4±2.0ab	8.0±0.7b
	Species evenness	0.9±0.1a	0.9±0.1a	0.9±0.1a
Overall	Shannon's diversity index	3.1±0.2a	2.8±0.1b	2.0±0.03c
Trees, shrubs & herbs	Species richness	35.0±9.4a	28.2±4.2a	13.4±0.9b
	Species evenness	0.9±0.04a	0.9±0.02a	0.8±0.02b

Mean values with different letters among the vegetation groups are significantly different from each other (p<0.05).

The ordination, based on the FA analysis based on frequency of occurrence of all species shows differences in species composition between the three land use types. The first FA axis (48% of the variance) corresponds to a gradient from the evergreen forest to the disturbed forest or/and agroforestry and a gradient from the evergreen forest to arable land. The second FA axis (34%) matches a gradient from the disturbed forest or/and agroforestry to arable land; and a gradient from the evergreen forest to arable land. However, the disturbed forest or/and agroforestry and evergreen forest were similar (Fig. 3.2). Further, the second FA shows that the forest in middle elevation (ZM and DM) are different from the forest in high and low (FH, ZH and FL) Fig. 3.2).

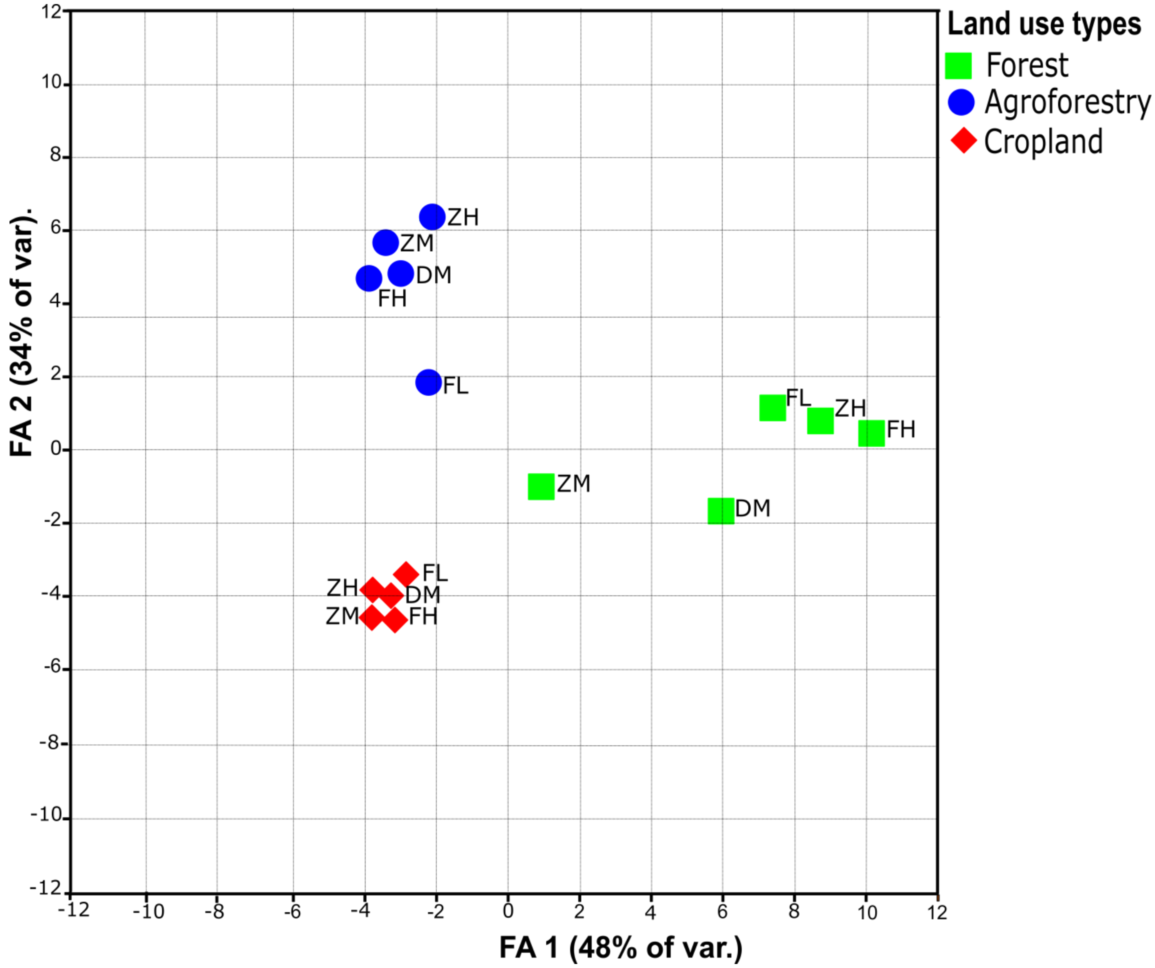

Figure 3.2 Biplot of the FA ordination of vegetation composition in three land use types at 5 topographic positions: FH= Faketen high, DM= Dakin middle, ZH= Zemika high, ZM= Zemika middle and FL= Fanika low. The first FA and second FA of the vegetation composition explain 82% of the variation between individual sites.

Topsoil characteristics in relation to vegetation

The Spearman's correlation coefficient was determined for the vegetation FA axis and soil variables (Table 3.3). The first FA axis of the vegetation, which corresponds to the gradient from forest to agroforestry and forest to cropland, is significantly correlated with the clay content (0.41), organic carbon (0.43), nitrogen (0.57), exchangeable sodium (0.56), potassium (0.46), calcium (0.52), magnesium (0.47), cation exchange capacity (0.51), bulk density (-0.53) and sand (-0.59) ($P<0.05$) (Table 3.3). The second FA axis, which corresponds to a gradient from agroforestry to cropland and forest to cropland, is significantly correlated with the clay (0.45) and bulk density (-0.39), organic carbon (-0.43), nitrogen (5.0), available phosphorus (0.43), exchangeable potassium

(0.38), exchangeable calcium (0.51). (Table 3.3). Overall, the first and second FA share the same significant correlation with clay, BD, OC, N, K and Ca. However, sand, Na, Mg and CEC are only significant in the first FA axis, whereas P is only significant in the second FA (Table 3.3).

Table 3.4. Spearman's correlation between FA axes of the vegetation and soil variables

Spearman's correlation		
	FA 1	FA 2
Sand	-0.59**	-0.36
Silt	0.34	0.24
Clay	0.41*	0.45*
BD	-0.53**	-0.39*
pH	0.38	0.36
OC	0.43*	0.43*
N	0.57**	0.50**
P	0.32	0.43*
Na	0.56**	0.24
K	0.46*	0.38*
Ca	0.52**	0.51**
Mg	0.47*	0.26
CEC	0.51**	0.37

** Correlation is significant at the 0.01 level (2-tailed).; * Correlation is significant at the 0.05 level (2-tailed).

3.4 Discussion

Vegetation patterns

The vegetation composition of woody and herbaceous plants reveals the presence of indigenous, modified and planted vegetation at the study sites. The evergreen forest group is state-managed natural and plantation forest, which matches the Afromontane rainforests and the transitional rainforest of southwest Ethiopia (Friis, 1992). The disturbed forest or/and agroforestry vegetation group is farmer-owned modified and planted vegetation, which corresponds to the semi-forest coffee, forest coffee (Schmitt, 2006) and home garden agroforestry (Badege & Abdelkadir, 2003). The arable land vegetation group is farmer-owned planted vegetation, which corresponds to the recently introduced cereal-based farming system (Mekuria, 2005).

The common species in disturbed or/and agroforestry group is 30% higher than the evergreen forest and 36% higher than the arable. The is due to the presence of commonly adopted crops (coffee, fruits, shade trees and food crops (enset, taro and cabbage)) in the agroforestry. Similarly, Cruz-Angón et al (2008) reported high numerical dominance of common species in agroforestry compared to natural forest. Yet, both evergreen and disturbed or/and agroforestry groups have 33% similarity in common species. This reveals the role disturbed or/and agroforestry group in conservation of indigenous species in agroforestry. Similarly, Vallejo-Ramos et al. (2016) reported the conservation of indigenous species in agroforestry.

The presence of relative higher endemic species in evergreen forest reveals the importance of the evergreen forest in conservation of endemic species. Similarly, Schmitt (2006) and Feyera (2005) reported the presence of endemic species in the Afromontane forest of southwest Ethiopia. The disturbed or/and agroforestry have relative medium endemic species, which implies that the disturbed or/and agroforestry play an important role in conservation of endemic species. In contrast, Laurance et al. (2006) and Garcia-Fernandez et al. (2003) reported high loss and poor endemic species in agroforestry. The presence of low endemic species in arable group may be attributed to management intervention.

The difference in tree species Shannon's diversity index between forest and disturbed forest or/and agroforestry reveals the occurrence of management interventions for coffee productivity: farmers selectively fell trees to enhance light exposure for the coffee plants, in line with findings by Schmitt (2006) and Steffan-Dewenter et al. (2007).

The occurrence of relatively lower values for shrub species Shannon diversity index, richness and evenness under the disturbed forest or/and agroforestry (as compared to the evergreen forest), as also observed by Schmitt (2006), may be related to the coffee dominance and the removal of competing shrubs. In contrast, the herb species Shannon diversity index and richness under the disturbed forest or/and agroforestry is similar to the evergreen forest's. This can be due to the fact that the removal of herbs, which is less frequent than the removal of shrubs, is offset by the enhanced light exposure and the nutrient contents of these soils. Steffan-Dewenter et al. (2007) found an even greater herb species diversity and richness under agroforestry than under the natural forest in a nearby study area.

The arable land has lower tree, shrub and herb species Shannon diversity index and richness, which is related to the dominance of maize cropping and affined management interventions. This study coincides with the findings of Tadesse (2007), who discussed the dominance of this single cereal crop and the monocultural cultivation in the study area.

Interactions between vegetation and topsoil characteristics of the land use

The influence of vegetation and its litter on topsoil characteristics as already observed by authors such as Ruggiero et al. (2002), Aweto (2013) or Runyan et al. (2012), is evidenced here by the strong correlation between the first and second FA axes and these topsoil characteristics. Furthermore, forest and agroforestry are distinct in vegetation composition, as reflected by the first FA axis of vegetation and by Shannon's index (i.e. tree and shrub life forms) (Fig. 3.2). Nevertheless, forest and agroforestry are exhibiting an equivalent topsoil fertility, since clay, OC, N, K and Ca were both significantly high in both forest and agroforestry, but still Na, Mg and CEC were high forest; and P is high in agroforestry. This implies that the tree species composition in agroforestry plays a significant role in the soil fertility restoration and maintenance. Particularly the presence of large number of leguminous plants (*Albizia gummifera* J.F.Gmel.C.A.Sm., *Millettia ferruginea* Hochst Baker, *Sesbania sesban* L Merr and *Leucaena leucocephala* Lam. de Wit) in the agroforestry of the study area (Table A1-3), has enhanced the nutrient cycling and litter decomposition, as also highlighted by Sharma (2011).

3.5 Conclusion

The presence of relative high tree, shrub and herb species Shannon's diversity indices (and richness in the disturbed forest or/and agroforestry vegetation group) is a sign of potential indigenous vegetation restoration and conservation in the study area. This biodiversity in both the evergreen forest and the disturbed forest or/and agroforesty also determines good topsoil fertility. Remarkably, the topsoil fertility under disturbed forest or/and agroforesty is equivalent to the natural forest's (Fig 2.2a, Fig 2.3), while the species composition, diversity and richness (for trees, shrubs and herbs) and soil fertility -under cropland- are much lower. Most importantly, both forest and agroforestry are conserving endemic plant species under endangered category of IUCN. Therefore, in the upper Gacheb catchment -and most probably in the larger part of southwest Ethiopia- agroforestry plays a similar role in forest biodiversity sustenance, conservation and topsoil fertility maintenance, confirming the findings by Toledo & Moguel (2012) who demonstrated the multiple values and benefits of coffee-based agroforestry systems worldwide.

Inversely, cereal-based open field cropping shows a negative impact on the species composition and diversity, as well as on the soil fertility.

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Chapter 4

Runoff response in five paired catchments astride southwest Ethiopia's tropical forest frontier

This chapter is modified from:

Henok Kassa, Frankl, A., Dondeyne, S., Poesen, J., Nyssen, J., 2016. Runoff response in five paired catchments astride southwest Ethiopia's tropical forest frontier. Working paper.

Abstract

Tropical montane forests are source of most of the plant's fresh water and regulators of the global hydrological cycle. However, increasing human population and expansion of agricultural land have led to deforestation. We evaluated the impact of deforestation on surface runoff, base flow and run coefficients (RC) in five paired forest and cropland small catchments in Gacheb catchment. The runoff data were recorded in the main rainfall seasons (June – October) of 2013 and 2014 using nine San Dimas flumes and one V-notch weir installed in natural forest and cropland stratified in three altitudinal zones; high (2300-1800 m a.s.l.), middle (1800-1500 m a.s.l.) and low (1500-1200 m a.s.l.). The results show that the average seasonal runoff and RC of the cropland is 2 to 4 times greater than that of the forest. However, the average seasonal base flow from forest is 1.5 to 4 times greater than from cropland. The average monthly runoff depth from cropland (51 mm) is significantly higher than that from forest (22 mm). Similarly, the runoff coefficient of the cropland (18%) is significantly higher than the forest (8%). In contrast, the monthly average base flow depth in forest (6 mm) is significantly higher than that of cropland (2 mm). The runoff coefficient of both cropland (R=0.64) and forest (R=0.22) has association with catchment area, but the association in cropland is stronger than the forest. Therefore, forest land use plays an important role on surface runoff and base flow regulation at small scale catchments in Ethiopia's upper White Nile basin.

Keywords: Afromontane forest, Base flow, Runoff coefficient, Vegetation density, Soil characteristic

4.1 Introduction

Tropical montane forests are the most important source of planet's fresh water and regulator of the global hydrological cycling (Bruijnzeel, 2004). They also play an important role in capturing water and minimizing surface runoff (Bruijnzeel, 2004; Kramer et al., 1995). However, human induced deforestation is directly impairing the hydrological and ecological functions, thereby causing profound environmental degradation (Foley et al., 2007; Nyssen, et al., 2004).

At the beginning of 19th century, southwest Ethiopia was completely covered by afromontane forest. Between 1971 and 1975, 38.4% of the southwestern region remained covered by closed forests. However, several studies show a rapid decline in natural forest cover and a rapidexpansion of cropland in the region. For instance, Bonga forest declined by 28% and 24% in between 1976 to 2001,whereas cropland and settlement increased by 56%; Sheko forest declined by 23% in the period 1973 -2005; part of Bench, Keffa and Sheka forest declined by 15%, while cropland increased by 14% (Mekuria, 2005; Dereje, 2007; NTFP, 2009).

The upper Gacheb catchment (Fig. 4.1) is the main source of water for a water treatment plant and a hydro power plant. However, large part the Gacheb catchment afromontane forest have led to deforestation, mainly because of increase in population and large scale expansion of agriculture land. Several studies in the humid tropics reported that deforestation has a significant impact on reservoir water storage capacity of the plant (Yin & Li, 2001), increase flooding risk (Acreman et al., 2000) and increase in water turbidity (Chapman & Chapman, 2003; Dessie & Bredemeier, 2013), hydrological cycle, hydrological process, water availability, water variability, surface runoff, soil infiltration, transpiration, groundwater recharge, stream flow dynamics and water yield of the catchment (e.g. Bewket & Sterk, 2005; Hayhoe et al., 2011; Meher, 1991; Muñoz-Villers & McDonnell, 2013; Sahin & Hall, 1996; Savary et al., 2009). However, studies reported that the magnitude of surface runoff varies with climate, management practice and duration of cultivation after forest conversion (Recha et al., 2012; Muñoz-Villers & McDonnell, 2013).

Despite, the southwest Ethiopia forest frontier is one the deforestation hot spots in Ethiopia, yet, no study has been carried out to evaluate the impact of deforestation on surface runoff in southwest Ethiopia. In this regard, several runoff studies have been conducted in northern Ethiopia (e.g. Girmay et al., 2009; Hurni et al., 2005; Teka et al., 2013). Moreover, there was no quantitative study on surface runoff at small catchment level in Ethiopia. Therefore, it is important to improve our understanding on the impact of deforestation on surface runoff characteristics in the upper part of Gacheb catchment.

The objective of the study using five paired catchments astride the forest frontier in Gacheb catchment was therefore (i) to evaluate the impact of deforestation on surface runoff, base flow and runoff coefficient for small catchments under forest and cropland, which is deemed representative for the larger southwestern Ethiopian highlands.

4.2 Materials and Methods

4.2.1 Study area

The upper Gacheb catchmentstudy area, located in the headwaters of the White Nile in southwest Ethiopia. Altitudes range between 1000 and 2600 m a.s.l. (Fig. 4.1). The underlying basement Precambrian formations comprise a variety of metamorphosed sedimentary, volcanic and intrusive rocks. These Precambrian basement rocks are overlain by Mesozoic strata (marine origin)and Tertiary basalt traps (Westphal, 1975; Mengesha et al., 1996).

The annual rainfall pattern is unimodal with a rainy season from mid-March to mid-November. Average annual rainfall depth in Mizan Teferi (1440 m a.s.l.) is 1780 ± 270 mm y^{-1}, annual reference evapotranspiration depth is 1259 ± 12 mm y^{-1} (Grieser et al., 2006), and the average air temperature ranges from 13 to 27 °C (Tadesse et al., 2006). The harmonized soil map of Africa (Dewitte et al., 2013) indicates that Leptosols are dominant on crests, while Nitisols are dominant on the hill slopes (lower, middle and upper parts), to which Alisols and Cambisols are locally associated. Fluvisols are found in the flat valley bottoms where meandering rivers occur.

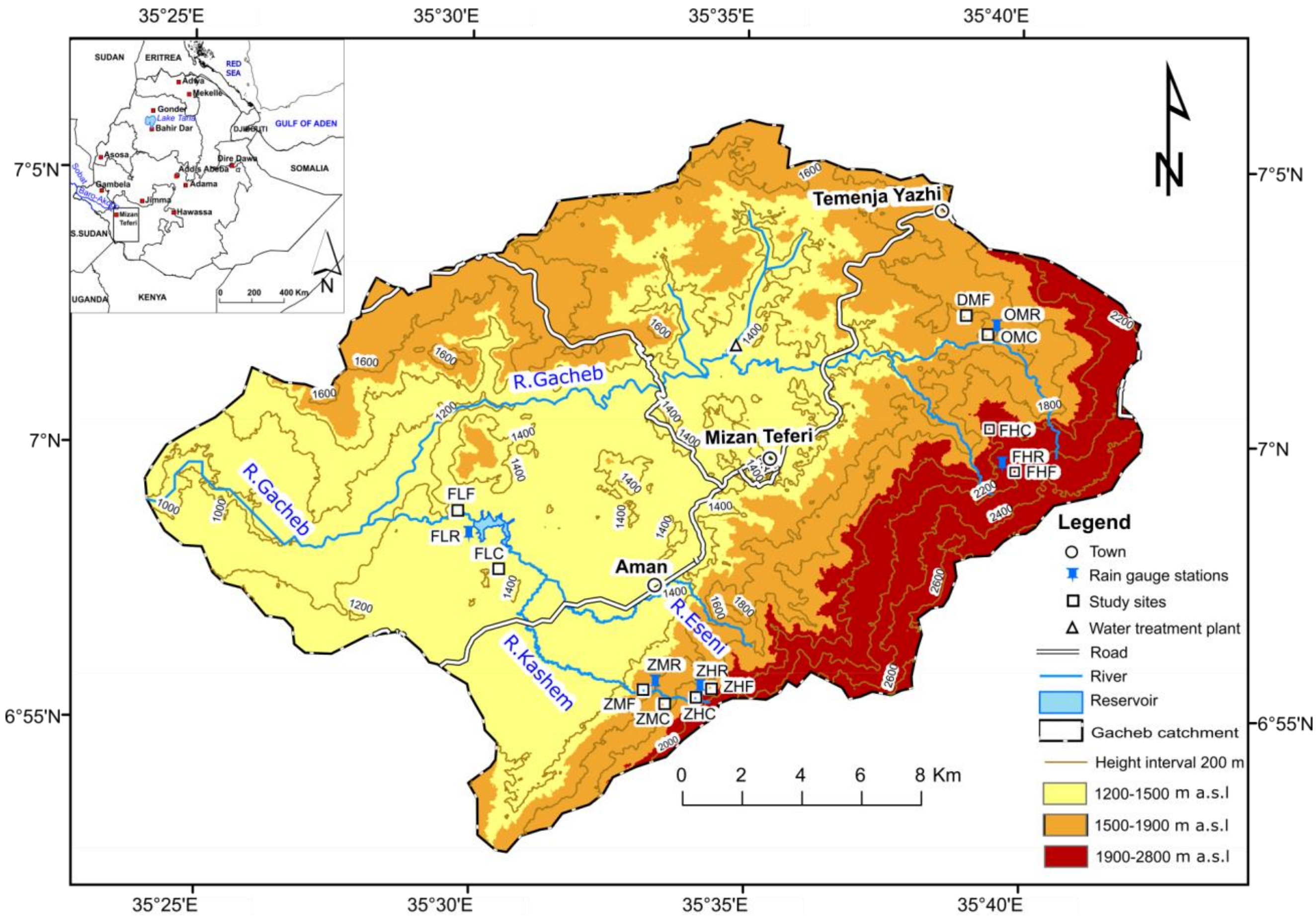

Figure 4.1. Location of the Gacheb catchment study area, southwest Ethiopia, with the study catchments and instrumentation

The Afromontane forest vegetation of Gacheb catchment is composed of *Aningeria adolfi-friederici* Engl., *Croton macrostachyus* Hochst. ex Delile, *Hagenia abyssinica* Willd., *Cordia africana Lam*., *Prunus africana* Hook.f.Kalkman, *Millettia ferruginea* Hochst. Baker, *Polyscias fulva* Hiern.Harms, *Albizia gummifera* J.F.Gmel C.A.Sm., *Bridelia micrantha* Hochst.Baill. at the upper stratum of the vegetation structure, integrated with *Grewia ferruginea* Hochst. exA.Rich, *Vernonia amygdalina* Delile. *Cyathe amanniana* and *Ricinus communis L*. at the lower stratum.

The agroforestry land of Gacheb catchment is composed of *Coffea arabica* L., as a cash crop integrated with food crops such as false banana (*Ensete ventricosum* Welw. Cheesman), banana (*Musa sapientum* L.) and taro (*Colocasia esculenta* L. Schott) and spices like korarima (*Aframomum corrorima* Braun). Moreover, various fruit trees such as mango (*Mangifera indica*

L.), avocado (*Persea americana* Mill.), papaya (*Carica papaya* L.) and orange (*Citrus sinensis* L. Osbeck) are also integrated in the farming system. Furthermore, native trees like *Albizia gummifera* J.F.Gmel. C.A.Sm., *Cordia africana* Lam. and *Millettia ferruginea* Hochst. Baker, are kept for shade, fodder, firewood, medicinal value and soil fertility maintenance.

In the croplands taro (*Colocasia esculenta*) is grown in moist places, while maize (*Zea mays*) is dominant. Beans are grown in as mixed crop with maize and single crop in the uplands, and sorghum may be added later on spots where the original crop failed and after harvesting of maize. Taking benefit of reliable rains at the onset of the rainy season, maize is sown in May, after 2-3 tillage operations with oxen-drawn Ethiopian *maresha ard* plough and 1-2 by hand tools that generally take place in April (Table 4.1). Given the high growth of maize, the cropped fields are not weeded after the crop is well established and a strong herb undergrowth develops on cropland, which after crop harvest is used as livestock feed in the cropland (Fig. 4.2B).

Table 4.1. Agricultural calendar in Gacheb catchment for major crops in the main growing season : maize (*), taro (¤), and beans (#).

Major activities[1]	J	F	M	A	M	J	J	A	S	O	N	D
Land preparation[2]				¤	*#							
Sowing or planting				¤	*#							
Weeding and cultivation[3]						*#¤	*#¤					
Harvesting									*#	*#	¤	¤

[1]In our study catchments, farmers do not use fertiliser, and maize monocropping is dominant (without crop rotation, without fallowing). Only in the upper FHC catchment, there is crop rotation with beans and barley.

4.2.2 Experimental setup and data collection

Runoff

Runoff data was collected at the outlet of paired catchments with forest and cropland (Fig. 4.1). Ten small catchments were selected along three altitudinal transects and stratified according to land use type (forest and cropland) and three elevation zones (high, 1900-2300 m a.s.l.; middle, 1500-1900 m a.s.l.; and low, 1200-1500 m a.s.l.). All forest and cropland catchments had a runoff monitoring station equipped with a calibrated flume at the outlet (Fig. 4.1; Table 4.1).

Runoff data was collected during the main rainy season of 2013 and 2014 (June 8 to October 30).Ten paired small catchments (5 in forest and 5 in cropland) were selected in the Gacheb catchment study area. The runoff stations consisted of nine San Dimas flumes and one V-notch weir, installed on the outlet of the drainage basins. The flumes were equipped with a graduated strip, to manually record the runoff depth. The flow depth was measured at ten minutes interval during every rainfall event. The dimension of the flumes installed in forest (1.5×0.5×0.5 m; Length×Width×Height) is different from the cropland (2.1×0.7×0.7 m; L×W×H), because the runoff depths from the forest are generally smaller than those from cropland (Table 4.2).

Flow discharge rating curves

In order to determine the discharge, a current meter was used to record the number of rotations within 30 second interval at various flow depths at all San Dimas flumes. The recorded rotation number at various flow depths was then converted to surface velocity with the standard formula:

$$V(\text{cm s}^{-1}) = 1.93+31.17\times N, \text{ if } N\leq 1.98;\ V(\text{cm s}^{-1}) = 0.19+32.05\times N, \text{ if } 1.98<N>10.27;$$
$$V\ (\text{cm s}^{-1}) = -14.09 + 33.44 \times N, \text{ if } N \geq 10.27 \qquad (4.\ 1)$$

where, V=surface velocity, 1.93, 31.17, 0.19, 32.05, -14.09 and 33.44= standard number for the current meter and N=Number of rotations.

The cross-sectional flow area was determined from the San Dimas flume width and the flow depth. Instantaneous runoff discharge for all velocity and corresponding flow depth measurements was then calculated as:

$Q = A * V$ (4.2) where,

Q= Instantaneous runoff discharge ($cm^3\ se^{-1}$), A= cross sectional flow area (cm^2) and V= surface velocity ($cm\ se^{-1}$)

However, the current meter calibration was suspected to lead to underestimations, because of partial submersion of the current meter during calibration of runoff events in all measurement stations. To validate this we compared our calibration with the standard discharge curve for modified San Dimas flume. It was found that the discharge curve for modified San Dimas flume developed by Bermel (1950) is in correspondence with our discharge rating curves. Hence, adapted discharge rating curves were developed for 500 mm (small San Dimas flume) and 700 mm size (large San Dimas flume) on the basis of Bermel's (1950) rating curve (Table 4.2).

Conversion to continuous discharge series

The continues discharge serious was calculated based on the modified equation for small and large San Dimas flumes, which was interpolated for installed San Dimas flumes (small=500 mm; large=700 mm) from Bermel (1950) flow depth-discharge rating curves measured over a wide range of flow depths on various modified San Dimas flumes. It is calculated with the equation (modified from Bermel (1950)):

$$Q = a\ d^b \qquad (4.1)$$

where Q = discharge, d = flow depth, a and b are fitting parameters.

At the lowest forest, when observing the channel, very small runoff discharge was expected and a V-notch weir was installed. The standardized rating curve for 90° V-notch weir was used to calculate the discharge. However, as the V-notch weir was installed in a level area, large volumes of water ponded behind it; hence a stage-water volume rating curve was developed based on the geometry of the pond. This volume was then added to the measured discharge in the V-notch weir (Table 4.2). These rating curves were used to convert the manually recorded continuous flow depth series to storm discharge records. The resulting continuous runoff discharge series were integrated on event and daily basis.

Figure 4.2. Cropland (top) and forest (bottom) catchments at the outlet of which San Dimas flumes were installed (October 2013)

Rainfall

Five rain gauges were installed, each of them representing two runoff monitoring stations (forest and cropland catchments) (Fig. 5.1). Half-daily (12 hr) rainfall was recorded every morning at 8:00 AM and evening 8:00 PM. The rainfall depth was calculated from the area of rain gauge opening and collected water volume.

Estimation of missing runoff discharge data

For some rain events, especially in the night, runoff discharge data could not be recorded. Hence, the missing discharge Q_d was estimated by a regression between the 12 hr observed rainfall and runoff per station (Table 4.3).

Base flow and runoff coefficients

The base flow was measured every morning and evening; as well as before and after every rain-related flood. The base flow recorded before the beginning of the rainfall events were used to calculate the base flow at that particular rainfall event on the station. The seasonal runoff coefficients were calculated by dividing the seasonal runoff by the seasonal rainfall per catchment. The seasonal runoff can, however, partly be attributed to base flow, while the other part consists of surface runoff.

Plant density

Plant density was recorded on plots within the forest and cropland catchments. The main plots were 20 × 20 m^2 replicated three times in each catchment. Tree species above 1.5 m height were counted inside the 20 × 20 m^2 main plot and shrubs were counted in subplots of 5 × 5 m^2 at the four corners of the main plot. The plant density of the trees, shrubs and herbs were calculated based on the equation by Mueller-Dombois & Ellenberg (1974):

$$\text{Density of species i} = \frac{\textbf{Number of the plants of species i}}{\textbf{Area of quadrants}} \qquad (4.\ 3)$$

Soil characteristics

Soil samples were collected from 20 × 20 m^2 plots under the forest and cropland, in each catchment where runoff was monitored. A total of 60 soil samples were taken from both forest and cropland. Separate soil samples were taken at the middle of each plot for soil bulk density determination. The standard analytical procedures were followed to determine soil bulk density (using 100 cm^3 Kopecky rings), soil texture (Sedigraph III plus particle size analyzer) and organic carbon content (Walkley & Black, 1934), which soil organic matter was obtained from the organic carbon (i.e SOM= SOC*1.72). The soil texture, bulk density, soil organic matter were selected to determine areas susceptible to surface runoff (Kadlec et al., 2012; Schmocker-Fackel et al., 2007).

Data analysis

The difference in monthly base flow, runoff, runoff coefficient, vegetation density and physico-chemical soil characteristics between forest and cropland was analyzed in one way ANOVA using SPSS (software version 20). Means were compared by least significant difference (LSD). The relationship between runoff coefficient and area of catchment was analyzed using correlation analysis.

Table 4.2. Characteristics of catchments monitored during the main rainy season of 2013 and 2014 (June 8-October 30)

Description	FHF	FHC	DMF	OMC	ZHF	ZHC	ZMF	ZMC	FLF	FLC
Location of stations	6°59' N 35°39' E	7°0' N 35°39' E	7°2' N 35°38' E	7°1' N 35°39' E	6°55' N 35°34' E	6°55' N 35°34' E	6°55' N 35°33' E	6°55' N 35°33' E	6°58' N 35°30' E	6°57' N 35°30' E
Area (ha)	11.5	7.0	7.9	5.2	5.9	4.2	3.7	4.0	4.1	3.6
Elevation (m a.s.l)	2135	1990	1632	1606	2022	1879	1544	1717	1261	1324
Rainfall (mm)	1405±92	1405±92	1218±88	1218±88	1535±31	1535±31	1360±23	1360±23	1126±14	1126±14
Slope (%)	42	29	23	33	35	18	20	23	14	14
Perimeter (m)	1399	1064	1050	990	952	954	730	1034	888	1032
Compactness	0.74	0.78	0.90	0.67	0.83	0.86	0.87	0.65	0.65	0.60
Tree density (m^{-2})	0.24 ±0.004	0.003 ±0.001	0.21 ±0.01	0.003 ±0.001	0.23 ±0.01	0.003 ±0.001	0.21 ±0.004	0.003 ±0.001	0.19 ±0.01	0.003 ±0.001
Shrub density (m^{-2})	2.6± 0.1	0.72±0.1	2.5 ±0.1	0.7±0.04	2.5 ±0.1	0.7 ±0.1	2.5 ±0.1	0.71 ±0.1	2.4 ±0.1	0.7 ±0.04
Location of rain gauge stations	6°59' N 35°39' E		7° 2' N 35°39' E		6°55' N 35°34' E		6°55' N 35°33' E		6°58' N 35°30' E	

FHF: Faketen high forest; FHC: Faketen high cropland; DMF: Dakin middle forest ; OMC: Oka middle cropland; ZHF: Zemika high forest; ZHC: Zemika high cropland; ZMF: Zemika middle forest; ZMC: Zemika middle cropland; FLF: Fanika low forest; FLC: Fanika low cropland.

4.3 Results

4.3.1 Rainfall

The average seasonal (146 days) rainfall depth was 1405 mm at FH site, 1223 mm at DM site, 1535 mm at ZH site, 1360 mm at ZM site and 1227 mm at FL site (Table 5.4). Average monthly precipitation during the rainy season was 281±95 (FH site), 244±73 (DM site), 307±110 (ZH site), 272±88 (ZM site) and 225±73 (FL site) (Table 4.5).

Table 4.3. Rating curves of standardized San Dimas flume and V-notch weir installed in forest and cropland catchments

Station	Catchment	Regression equation of flow discharge (Q, in cm^3 s^{-1}) vs. flow depth (d, in cm)	**Instrumentation and procedures**
FHF DMF ZHF ZMF	Forest Forest Forest Forest	$Q = 2352 * d^{1.366}$	All forest catchments except FLF are equipped with small San Dimas flumes (50 cm width and 50 cm height). Bermel's (1950) flow depth relationship with discharge for modified San Dimas flume was used as calibration curve equation.
FLF	Forest	$Q=2.3691Ce \tan(\theta/2)*\sqrt{2g}*hu^{2.5}$ $Q_v = 0.789*x$	This forest catchment was yielding very low runoff response, hence a V-notch weir was installed. Event runoff volume Q_d was calculated as the sum of ponded water behind the V-notch (Q_v) and possible free flow discharge through it ($\sum Q$). A regression equation was developed for standard V-notch weir with 90° opening (θ = 90°; Ce = discharge coefficient; hu = head), and depth – volume curve developed for the ponding water depth (x).
FHC OMC ZHC ZMC FLC	Cropland Cropland Cropland Cropland Cropland	$Q = 4729*d^{1.408}$	All cropland catchments are equipped with large San Dimas flumes (70 cm width and 70 cm height). Bermel's (1950) flow depth relationship discharge for modified San Dimas flume was used as calibration curve equation.

FHF=Faketen high forest; FHC=Faketen high cropland; DMF=Dakin middle forest; OMC=Oka middle cropland; ZHF= Zemika high forest; ZHC= Zemika high cropland; ZMF: Zemika middle forest; ZMC: Zemika middle cropland; FLC: Fanika low cropland; FLF: Fanika low forest.

3.3.2 Runoff

Seasonal runoff, base flow and runoff coefficient

In the study catchments at the tropical forest frontier of Gacheb, runoff coefficients vary between 12% in the Faketen high forest (FHF) sub-catchment in 2013 and 23% in the Faketen highland cropland (FHC) catchment in the same year (Table 4.4). Overall, the mean RC from cropland catchments (19% ±2%) is double than that from forest catchments (8% ±3%), whereas the mean base flow of the forest (29±14 mm) is 2 times higher than that from the cropland (13±7 mm) (Table 4.5). The RCs per land use class appear to be well grouped around their averages.

The contrast between forest and agricultural land is also evident in Fig. 4.3, where, as an example, the paired Oka and Dakin catchments are contrasted. This figure shows that the storm runoff in Oka is relatively higher than Dakin forest. However, the base flow in cropland is less than that from the forest throughout the season.

The seasonal runoff depth in cropland is higher than that for forest in all sites. The runoff depth in cropland was 314±45 mm at FHC site, 239±24 mm at DMC site, 290±58 mm at ZHC site, 211±38 mm at ZMC site and 212±35 mm at FLC site (Table 4.4). However, the seasonal base flow of the forest is higher than the cropland. The base flow in the forest was 42±6 mm at FHF site, 16±2 mm at DMF site, 39±9 mm at ZHF site and 18±4 mm at ZMF site. Alike the runoff, seasonal runoff coefficients of the cropland is higher than the forest. The runoff coefficients in cropland were 22±1 at FH site, 20±1 at DM site, 19±0 at ZH site, 16±1 at ZM site and 19±1 at FL site (Table 4.5).

Table 4.4. Regression equations for the relationship between observed 12 h rainfall depth (P, in mm) and storm runoff depth (Qd, in mm) in the paired catchments

Catchment	Land use	Year	Regression equation between half-daily rainfall (P) and runoff (Q_d)	Number of observation
FHF	Forest	2013	Q_d= 0.152P-0.68, R^2 = 0.94	n=117
		2014	Q_d= 0.152P-0.63, R^2 = 0.87	n=143
DMF	Forest	2013	Q_d= 0.062P -0.27, R^2 = 0.90	n=103
		2014	Q_d= 0.084P -0.55, R^2 = 0.89	n=71
ZHF	Forest	2013	Q_d= 0.141P-0.59, R^2 = 0.93	n=116
		2014	Q_d= 0.132P-0.57, R^2 = 0.94	n=131
ZMF	Forest	2013	Q_d= 0.117P -0.55, R^2 = 0.90	n=115
		2014	Q_d= 0.108P -0.49, R^2 = 0.92	n=113
FLF	Forest	2013	Q_d= 0.105P-0.45, R^2 = 0.87	n=78
		2014	Q_d= 0.111P-0.49, R^2 = 0.92	n=95
FHC	Cropland	2013	Q_d= 0.356P-1.48, R^2 = 0.96	n=128
		2014	Q_d= 0.343P -1.36, R^2 = 0.94	n=112
OMC	Cropland	2013	Q_d= 0.312P -1.30, R^2 = 0.92	n=89
		2014	Q_d= 0.368P -2.04, R^2 = 0.91	n=95
ZHC	Cropland	2013	Q_d= 0.302P-1.12, R^2 = 0.95	n=122
		2014	Q_d= 0.294P-1.30, R^2 = 0.94	n=110
ZMC	Cropland	2013	Q_d= 0.266P-1.13, R^2 = 0.94	n=112
		2014	Q_d= 0.243P-1.00, R^2 = 0.93	n=116
FLC	Cropland	2013	Q_d= 0.277P-1.14, R^2 = 0.91	n=82
		2014	Q_d = 0.30P-1.20, R^2 = 0.91	n=90

The half-daily rainfall and runoff relationship were developed to calculate the runoff for missed rainfall events. FHF=Faketen high forest; FHC=Faketen high cropland; DMF=Dakin middle forest; OMC=Oka middle cropland; ZHF= Zemika high forest; ZHC= Zemika high cropland; ZMF: Zemika middle forest; ZMC: Zemika middle cropland; FLC: Fanika low cropland; FLF: Fanika low forest.

Table 4.5. Seasonal depths of rainfall, runoff, base flow and runoff coefficients during the rainy seasons (June–October) of 2013 and 2014 for the 10 catchments in Gacheb catchment

Station	Year	Land use types	P (mm)	R_s (mm)	BF (mm)	R (mm)	RC (%)
FHF	2013	Forest	1470±118	132±13	46±4	178±17	12±2
FHF	2014	Forest	1340±78	103±9	38±2	140±12	11±1
Average			1405±92	118±21	42±6	159±27	12±1
FHC	2013	Cropland	1470±118	323±34	22±3	345±37	23±4
FHC	2014	Cropland	1340±78	258±23	24±3	282±26	21±4
Average			1405±92	291±46	23±1	314±45	22±1
DMF	2013	Forest	1280±79	47±5	17±1	64±6	5±1
DMF	2014	Forest	1155±72	42±4	15±1	57±5	5±1
Average			1218±88	45±4	16±2	61±5	5±0
OMC	2013	Cropland	1280±79	245±22	11±1	256±23	20±3
OMC	2014	Cropland	1155±72	211±17	11±1	222±18	19±2
Average			1218±88	228±24	11±0	239±24	20±1
ZHF	2013	Forest	1312±105	106±12	33±3	139±15	11±2
ZHF	2014	Forest	1757±105	143±12	45±4	189±15	11±2
Average			1535±315	125±26	39±8	164±35	11±0
ZHC	2013	Cropland	1312±105	241±29	8±1	249±30	19±4
ZHC	2014	Cropland	1757±105	321±27	10±1	331±28	19±4
Average			1535±315	281±57	9±1	290±58	19±0
ZMF	2013	Forest	1195±83	72±8	15±2	87±10	7±2
ZMF	2014	Forest	1524±89	99±8	21±1	119±9	8±1
Average			1360±233	86±19	18±4	103±23	8±1
ZMC	2013	Cropland	1195±83	175±20	9±1	184±20	15±4
ZMC	2014	Cropland	1524±89	231±40	7±1	238±20	16±2
Average			1360±233	203±39	8±1	211±38	16±1
FLF	2013	Forest	1023±82	66±6	0	66±6	6±1
FLF	2014	Forest	1230±64	79± 8	0	79±8	6±1
Average			1127±146	73±9	0	73±9	6±0
FLC	2013	Cropland	1023±82	176±20	11±2	187±20	18±4
FLC	2014	Cropland	1230±64	225±19	12±2	237±21	19±3
Average			1127±146	201±35	12±1	212±35	19±1

Summary	Forest	89±32	29±13	112±48	8±3
	Cropland	241±43	13±7	253±47	19±2

Seasonal rainfall (P), seasonal storm runoff (R_s), seasonal base flow (BF), seasonal catchment runoff (R) and seasonal runoff coefficient (RC). FHF=Faketen high forest; FHC=Faketen high cropland; DMF=Dakin middle forest; OMC=Oka middle cropland; ZHF= Zemika high forest; ZHC= Zemika high cropland; ZMF: Zemika middle forest; ZMC: Zemika middle cropland; FLF: Fanika low forest; FLC: Fanika low cropland.

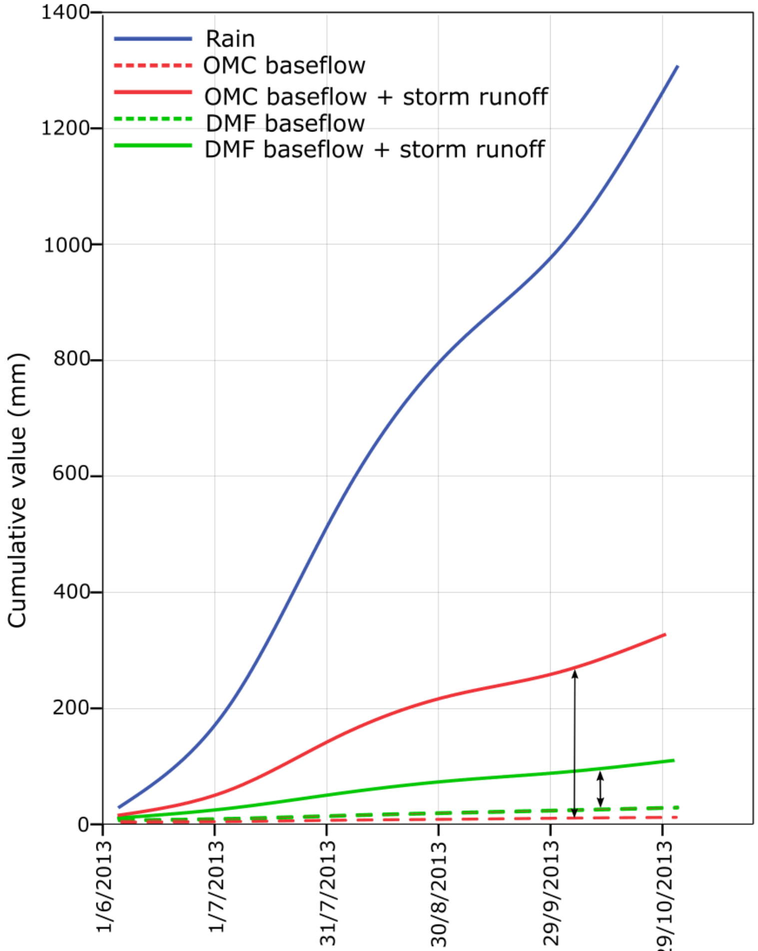

Figure 4.3. Cumulative rainfall, base flow and storm runoff depths from the paired Dakin forest catchment (DMF) (green lines) and Oka middle cultivated catchment (red lines)

Correlation between average monthly runoff coefficient and rainfall depth

The average monthly runoff coefficient of the cropland and forest has positive correlation with rainfall depth, but the relationship in the forest (R^2=0.66) is not as strong as the cropland (R^2=0.90) at FH site. Similarly, strong correlation between runoff coefficient and rainfall depth was recorded in cropland at DM (R^2=0.86), ZH (R^2=0.83), ZM (R^2=0.81) and FL (R^2=0.76) as compared to the corresponding forest sites (Fig. 4.4).

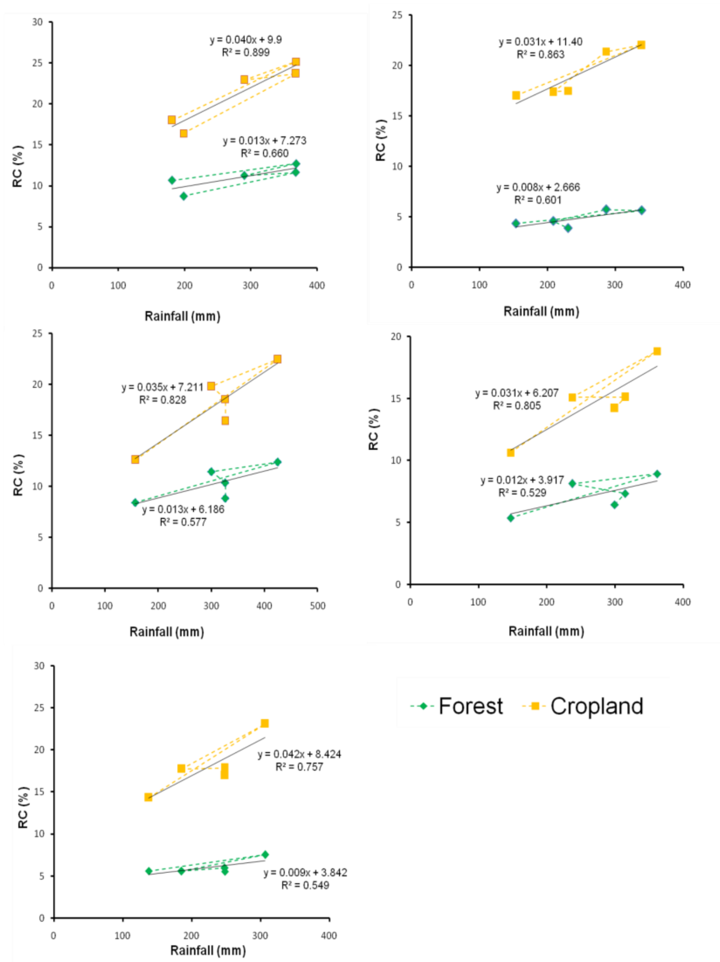

Figure 4.4. Average monthly (June to October) rainfall relationship with runoff coefficient in five paired catchments,with monthly evolution shown in red colour for cropland and blue colour for forested catchments: (a) FHF: Faketen high forest; FHC: Faketen high cropland; (b) DMF: Dakin middle forest; OMC: Oka middle cropland; (c) ZHF: Zemika high forest; ZHC: Zemika high cropland; (d) ZMF: Zemika middle forest; ZMC: Zemika middle cropland; (e) FLF: Fanika low forest; FLC: Fanika low cropland.

Average monthly runoff, base flow and runoff coefficient

The average monthly runoff depth from the cropland is significantly higher than that from forest ($P<0.01$) at all sites: cropland FHC (63±30 mm), DM (48±20 mm), ZH (58±28 mm), ZM (42±20mm) and FL (43±20 mm). However, the average monthly base flow from forest is significantly higher than from cropland ($P<0.05$) at all sites except FL. The highest base flow was recorded in a forest catchment at FH (8.3±3 mm), followed by DM (3±1 mm), ZH (8±4 mm), and ZM (4±1 mm). Alike the runoff, the average monthly runoff coefficient in cropland is significantly different from the forest ($P<0.0001$) at all sites. The highest runoff coefficients were recorded in cropland at FHC site (21±4%), DMC sites (19±2%), ZHC site (18±4), ZMC site (15±3%) and FLC site (18±3%) (Table 4.6).

Table 4.6. Average monthly rainfall (P), storm runoff (R), base flow (BF), runoff coefficient (RC) per season of the studied catchments. Data collected on 2013 and 2014 (June to October)

Site	**Station**	**Land use type**	**P (mm)**	**R(mm)**	**BF (mm)**	**RC (%)**
FH	FHF	Forest	281±95	32±14b	8.3±3a	11±2b
	FHC	Cropland	281±95	63±30a	4±3b	21±4a
DM	DMF	Forest	244±73	12±5b	3±1a	5±1b
	OMC	Cropland	244±73	48±20a	2±1a	19±2a
ZH	ZHF	Forest	307±110	33±15b	8±4a	10±2b
	ZHC	Cropland	307±110	58±28a	2±1b	18±4a
ZM	ZMF	Forest	272±88	21±9b	4±1a	7±1b
	ZMC	Cropland	272±88	42±20a	2±1b	15±3a
FL	FLF	Forest	225±73	14±7b	0±0b	6±1b
	FLC	Cropland	225±73	43±20a	2±2a	18±3a
Summary		Forest		22±10b	6±3a	8±3b
		Cropland		51±9a	2±1b	18±2a

Mean values with different letters among catchments at the same site are significantly different from each other ($P<0.05$). P: average monthly rainfall; R: average monthly runoff, BF: average monthly base flow (mm). RC: average monthly runoff coefficient. FHF=Faketen high forest; FHC=Faketen high cropland; DMF=Dakin middle forest; OMC=Oka middle cropland; ZHF= Zemika high forest; ZHC= Zemika high cropland; ZMF: Zemika middle forest ; ZMC: Zemika middle cropland; FLF: Fanika low forest; FLC: Fanika low cropland.

Figure 4.5. Base flow in the upper Kashem river in the second part of the rainy season. Photograph taken on 16 September 2012, nearby the ZMF monitored catchment under forest**.**

Vegetation density and soil physico-chemical characteristics

The forest and cropland shows a difference in vegetation density (tree and shrub) at all sites. The tree density in the forest is significantly different from the cropland ($P<0.0001$) at all sites. The highest tree density was recorded in the forest at FH (0.24 m^{-2}) and DM sites (0.21 m^{-2}). The shrub density under forest was also significantly higher than in cropland ($P<0.001$) at all sites (2.4 - 2.6 m^{-2}) (Table 4.7).

The soil bulk density, organic matter, clay and sand content of the forest is significantly different from the cropland at all sites. The highest soil bulk density was recorded in the cropland at all sites (1.3-1.4 g cm^{-3}). Alike the bulk density, the highest sand was recorded in the cropland at all sites

(24-33%). Expectedly, the highest organic matter (13 to 14 %), as well as clay (32 to 38%) was recorded under forest in all sites (Table 4.7).

Table 4.7. Vegetation density and topsoil characteristics of the paired catchments

Stations	**Land use types**	**Vegetation density**		**Soil characteristics**			
		Tree (m^{-2})	Shrub (m^{-2})	BD ($g\ cm^{-3}$)	OM (%)	Clay (%)	Sand(%)
FHF	Forest	0.24±0.004a	2.60±0.08a	1.1±0.02b	13.9±0.1a	32±0.9a	25±0.7b
FHC	Cropland	0.003±0.001b	0.72±0.10b	1.4±0.01a	9.3±0.2b	24±1.0b	33±1.4a
DMF	Forest	0.21±0.010a	2.5±0.06a	1.1±0.03b	13.9±0.3a	33±1.1a	22±1.5b
OMC	Cropland	0.003±0.001b	0.72±0.04b	1.4±0.03a	9.3±0.2b	26±1.0b	32±0.8a
ZHF	Forest	0.23±0.010a	2.5±0.1a	1.0±0.01b	13.9±0.3a	34±1.7a	23±0.5b
ZHC	Cropland	0.003±0.001b	0.71±0.1b	1.3±0.02a	9.5±0.2b	26±0.9b	32±1.0a
ZMF	Forest	0.21±0.004a	2.5±0.1a	1.1±0.1b	13.8±0.1a	33±1.1a	25±1.0b
ZMC	Cropland	0.003±0.001b	0.71±0.1b	1.3±0.1a	9.3±0.1b	23±0.8b	34±1.7a
FLF	Forest	0.19±0.006a	2.4±0.07a	1.1±0.03b	13.8±0.2a	38±1.5a	21±1.1b
FLC	Cropland	0.003±0.001b	0.72±0.04b	1.3±0.03a	9.1±0.3b	33±0.8b	33±1.1a

Mean values with different letters among the catchments on the same site are significantly different from each other ($P<0.05$). BD: Bulk density; OM: Organic matter; Clay; Sand. FHF: Faketen high forest; FHC: Faketen high cropland; DMF: Dakin middle forest; OMC: Oka middle cropland; ZHF: Zemika high forest; ZHC: Zemika high cropland; ZMF: Zemika middle forest ; ZMC: Zemika middle cropland; FLF: Fanika low forest; FLC: Fanika low cropland.

4.4 Discussion

Seasonal rainfall, runoff, base flow and runoff coefficient

The seasonal rainfall at the study sites (1227 – 1405 mm) is considered to be higher for humid area in Ethiopia and medium for humid tropical regions. The average monthly and seasonal rainfall of the study sites are within the range of 54 years average rainfall of Aman meteorological station (i.e average monthly rainfall: 269 mm; average seasonal rainfall: 1344 mm) (National meteorology agency). The seasonal cropland runoff is 39% higher than from the forest, which clearly manifests the presence of relatively high runoff in the cropland. The reported difference in percentage of total seasonal runoff between forest and cropland is in line with the findings of Mao & Cherkauer (2009) and Mishra et al. (2010), who reported 20-40% increases in total runoff in agricultural land compared to the forest. In general, the seasonal runoff from cropland seems low in view of the high seasonal rainfall, which is possibly due to high herb cover density (crops and weed) in the cropland during the growing season (Fig. 4.2a), which is in turn related to early and reliable onset of the rainy season. The cropland seasonal base flow is 38% less than from the forest; in cropland baseflow was observed to drastically decline and dry during the low rainfall season of the year. However, the base flow in the forest flows continuously throughout the year. The percentage of seasonal base flow difference between forest and cropland is within the range of Muñoz-Villers & McDonnell (2013), who reported a 35 to 75% decrease in base flow in non-forest land compared to forest in humid tropical region. On the contrary, Mishra et al. (2010) reported 4% increase in base flow following conversion to agricultural land. Like runoff, the seasonal runoff coefficient in cropland is 40% higher than under the forest. The increase in runoff coefficient from cropland is larger than the 20-30% reported by Pakoksung & Koontanakulvong (2000) in Thailand. Overall, the average seasonal runoff coefficient from forest (8%) seems large, which may be related to intensive livestock grazing in the forest catchments, where the majority of the local community around the forest herds their cattle. Especially during the growing season their land is occupied by crops and the communal grazing lands are not able to feed all cattle, horses and mules of the local community as reported by Zewedie, (2007), Reusing (2000) and Belay (2010), for the wider Afromontane forests of southwest Ethiopia. Additionally seasonal soil saturation with water may also enhance runoff from the forests.

Correlation between average monthly runoff coefficient and rainfall depth

The monthly runoff coefficients both for the forest and cropland catchments are positively correlated with rainfall depth, implying that the runoff coefficient increases with increasing rainfall depth. Yet, the correlation in cropland are significantly stronger than for forest, which is possibly associated with reduced rainfall interception in the cropland. This finding is consistent with Li et al. (2016) and Li et al. (2015), who reported the strong positive relationship between runoff coefficient and rainfall depth on agriculture land. In addition, the stronger temporal variation of the monthly runoff coefficient under cropland (Fig. 4.4) could be related to strong variability in phenology of maize and taro throughout the growing season.

Average monthly runoff, base flow and runoff coefficient

The cropland average monthly runoff is higher than forest. This may be due to soil compaction in cropland soils, the compaction possibly associated with the use of the cropland for grazing livestock and low organic carbon content. The livestock's hoof can exert downward pressure on the soil surface similar to that of heavy agriculture machineries, this directly compact the soil by breaking up the large soil pores, thus forming more small pores, increase soil bulk density and reduce soil infiltration rate (Soane & van Ouwerkerk, 1994). Further, the presence of low organic matter in the cropland tends to enhance compaction, which is associated with the decrease in soil aggregate formation and strength. Inversely, and as observed in the study area (Chapter 2), the high organic matter in the forest benefits the soil to have strong, large and stable aggregates that can resist compaction, which tend to increase the soil permeability and hence lower runoff from forests. This finding is consistent with the findings (Hoorman et al., 2011; Kavian et al., 2014). Furthermore, the presence of relatively low vegetation density (trees and shrubs) in cropland open a space for direct raindrop impact on the soil, hence this possibly have led to crust layer formation, sealed soil layer and greatly increase surface runoff (Mills & Fey, 2004).

The base flow at the outlet of cropland catchments is lower than the one from forests. This is possibly due to lower soil infiltration capacity in the cropland, which is associated with soil compaction and thus reduced recharge of subsurface water storages in the cropland. The higher base flow in the afromontane forest may be due to larger catchment water storage capacity associated with the presence of the dense permanent vegetation (Fig. 4.5). This finding is consistent with the findings of Price et al. (2011), who reported that compacted soil reduces ground water recharge and reduces base flow. Muñoz-Villers & McDonnell (2013) reported that forest catchments with deep soil profile tend to store more water, which leads to higher base flows for longer periods in the forest, besides the water uptake by the woody vegetation. Conversely, and in line with Markart et al. (2006) and Vlčková et al. (2009), we found high runoff coefficients in cropland, compared to forest.

Vegetation density and soil characteristics

The tree and shrub vegetation density of the forest is higher than the cropland. This may be associated with the occurrence of management intervention for monoculture farming of cereal crops in the cropland. This is in line with the study of Mekuria (2005) and Dereje (2007), who reported the dominance of single cereal crops on agricultural land. The soil organic matter and clay content in forest is higher than the cropland. This may be due to the litter fall from the tree and shrub, and thus increase the organic matter and protect the soil from erosion. This is in line with Fentaw et al. (2007) and Yeshane (2015), who reported the increase in soil organic matter and low soil loss under forest, because of tree litter fall and tree crown and root protection.

4.5 Conclusions

This study indicates that a conversion from forest to cropland affects runoff depth, base flow depth and runoff coefficient in the upper reaches of Gacheb catchment, and likewise in similar deforested areas of southwest Ethiopia. The seasonal surface runoff depth and runoff coefficient from cropland is 2 to 4 times greater than that from forest. Reversely, the monthly base flow in cropland is relatively lower than in forest, where tree and shrub vegetation density, soil organic matter, clay content are much higher than in cropland. The study suggests that forest can play a prominent role on regulating the base flow, runoff and runoff coefficient at small catchment scale in Gacheb catchment, and in the whole surrounding southwestern Ethiopian forest frontier zone.

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Chapter 5

Sediment yield at southwest Ethiopia’s forest frontier

This chapter is modified from:

Henok Kassa, Frankl, A, Dondeyne, S., Poesen, J., Nyssen, J., 2016. Sediment yield at southwest Ethiopia's forest frontier, Southwestern Ethiopia. Submitted. (IF 8.145)

Abstract

Deforestation is one of the major factors of soil erosion in equatorial regions, but to what extent does crop growth in deforested areas protect the land from erosion? We evaluated the effect of deforestation on suspended sediment yield at the scale of zero-order catchments by contrasting five paired small forest and cropland catchments at Ethiopia's southwestern forest frontier. Suspended sediment samples were collected from nine San Dimas flumes and one V-notch weir installed in catchments draining natural forest and cropland, at different altitudes. The suspended sediment data was collected from June 8 to October 30 of the years 2013 and 2014. The suspended sediment yield of both land-use types is strongly correlated with the corresponding discharge. The results show that the average seasonal suspended sediment yield from cropland (20 ± 7.6 Mg ha^{-1}) is five times higher than that from the paired forest (4.0± 1.9 Mg ha^{-1}). High sediment yield from forests is related to livestock grazing it, but forests still have an important role in the protection of the surface soil from erosion at southwest Ethiopia's forest frontier. Land management in southwestern Ethiopia's highlands will need a strong change in paradigm, in which the overall belief in the recently imported *mahrasha* ard plough is abandoned, oxen and other cattle decreased in number and kept at the homestead, the forest better protected from human and livestock interference, and the open farmlands turned into agroforestry. Such an approach is still possible as all required elements are available in the landscape.

Keywords: Deforestation; Soil loss; Afromontane forest; Tropics; Ethiopia.

5.1 Introduction

Deforestation is a global phenomenon, particularly severe in the tropical region (Steininger et al., 2001). There, it considerably increases the rate of soil loss, mainly by increasing the soil's vulnerability to erosion (e.g. removal of protective vegetation, degradation of soil structure) and by higher magnitudes of splash, sheet, rill and gully erosion (Lal, 1987). Deforestation has been a major factor leading to land degradation in Ethiopia (Nyssen, 2004). Currently, the closed afromontane forest of southwest Ethiopia (Fig. 1.1) is facing deforestation. For example, the share of the closed natural forest declined by 24-28% in Bonga forest; 23% in Sheko forest; 15% of Bench, Keffa and Sheka forest, while agriculture land abruptly increased by 56% in Bonga; 14% in Bench, Keffa and Sheka forest in between 1973 and 2005 (Dereje, 2007; Mekuria, 2005; NTFP-PFM, 2009).

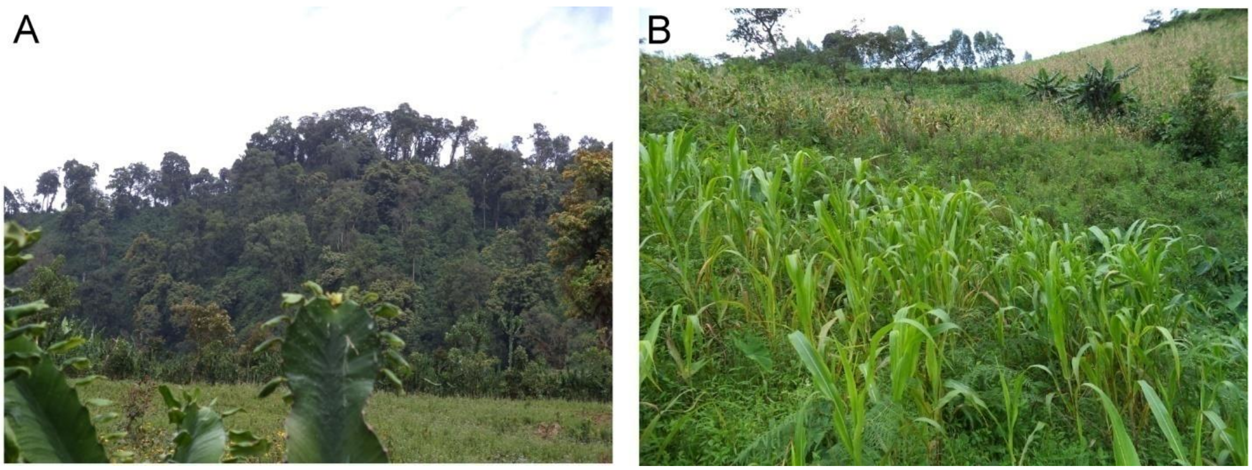

Figure 5.1. Gacheb sub-catchments: View of Faketen (FHF) forest in upper Gacheb basin on 21 October 2013 (A). View of the cropped Oka (OMC) catchment on 7 October 2013. Maize stalks and leafs are wilted, so it is harvesting time. In front some sorghum that was sown later to fill an area with poor crop growth. Since some decennia, the farmers typically manage their cropland as an open field with not much trees or shrubs (B).

This deforestation had several environmental and financial impacts on the region. Most notably, the Dembi hydroelectric power plant was decommissioned, due to the reduction of water storage capacity of the reservoir because of siltation (EEPCO, 2000). Furthermore, the water treatment plant has been forced to spend additional money and time for water treatment, mainly due to the presence of high concentrations of suspended sediment in the water (MACWE, 2014). Thus, the environmental degradation emanating from deforestation is not only the concern of farmers in the catchment, but also to downstream communities benefiting from the water resources. Management of the affected areas requires understanding the extent and magnitude of impact of deforestation, for which our knowledge remain poor for tropical mountain regions worldwide.

Even though previous studies have pointed to the impact of deforestation on soil loss in the study area, the intensity of soil loss may vary depending on land use and land management practice, duration of cultivation period, climate, runoff volume and topography (Girmay et al., 2009; Mekuria et al., 2012). However, no systematic studies have been done to quantify the impact of deforestation on sediment yield at the forest frontier in southern Ethiopia, taking into account also the variability in local catchment characteristics. Particular characteristics of southwest Ethiopia's forest frontier forest are that after deforestation, like in all tilled cropland the root mat is destroyed (de Baets et al., 2007; Ghidey & Alberts, 1997; Mamo & Bubenzer, 2001) but crops grow in dense stands (Fig. 5.1). Furthermore, soil loss in the Afromontane forest belt has been hardly studied, and there are particularly few filed measurements at the catchment scale, i.e. between erosion plots and whole river basins in Africa (Vanmaercke et al., 2014), and beyond (Vanmaercke et al., 2011).

To increase our understanding on the impact of deforestation at the scale of small catchments in tropical mountains, we quantified suspended sediment yield and export in ten zero-order catchments at three altitudinal ranges in Gacheb catchment of southwest Ethiopia. The objective of this study is to evaluate the effect of deforestation on suspended sediment yield between paired forest and cropland at small catchment scale in the White Nile basin of Ethiopia and to get an insight to what extent the dense crop cover does (not) compensate for the lost tree cover and corresponding soil strengthening by the root mat.

5.2 Materials and methods

5.2.1 Study area

The study area is the upper Gacheb catchment, located in the headwaters of the White Nile in southwestern Ethiopia. Altitudes range between 1000 and 2600 m a.s.l. (Fig. 5.2). The underlying basement Precambrian formations comprise a variety of metamorphosed sedimentary, volcanic and intrusive rocks. These Precambrian basement rocks are overlain by Mesozoic marine strata and Tertiary basalt traps (Westphal, 1975; Mengesha et al., 1996).

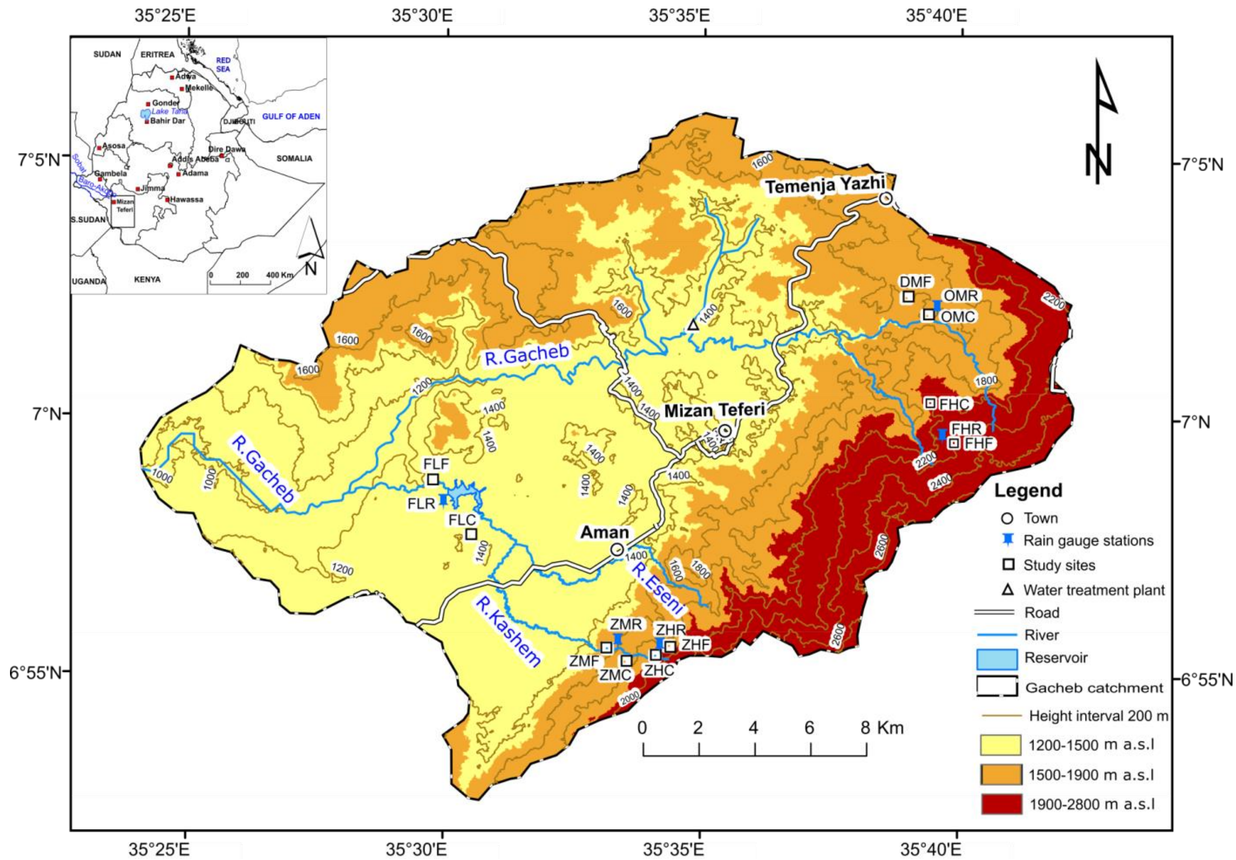

Figure 5.2. Location of the Gacheb catchment, southwestern Ethiopia, with the study catchments and instrumentation. In the codes, the first letter stands for the location (see Table 6.2), the second for elevation (Low, Middle, High) and the third for monitoring of Cropland, Forest or Rainfall.

The annual rainfall pattern is unimodal with a rainy season from mid-March to mid-November (Fig. 1.11). Average annual rainfall depth in Mizan Teferi (1440 m a.s.l.) is 1780 ± 270 mm y^{-1} and annual reference evapotranspiration depth is 1259 ± 12 mm y^{-1} (Grieser et al., 2006); the average air temperature ranges from 13 to 27 °C (Tadesse et al., 2006). The harmonized soil map of Africa (Dewitte et al., 2013) indicates that Leptosols are dominant on crests, while Nitisols are dominant on the hill slopes (lower, middle and upper parts), to which Alisols and Cambisols are locally associated. Fluvisols are found in the flat valley bottoms where meandering rivers occur. Topsoils in the studied catchments typically contain 8.0-8.1% OC under forest and 5.3-5.5% OC in cropland. Soil texture again is quite homogenouse per land-use type: clay-silt-sand proportion of 25-50-25% in cropland, and 35-50-15% in forest. Three main land-use types exist in this region: afromontane forest, agroforestry zones particularly around the villages and open field cropland.

The Afromontane forest vegetation of Gacheb catchment is composed of *Aningeria adolfi-friederici* Engl., *Croton macrostachyus* Hochst. ex Delile, *Hagenia abyssinica* Willd., *Cordia africana Lam*., *Prunus africana* Hook.f.Kalkman, *Millettia ferruginea* Hochst. Baker, *Polyscias fulva* Hiern.Harms, *Albizia gummifera* J.F.Gmel C.A.Sm., *Bridelia micrantha* Hochst.Baill. at the upper stratum of the vegetation structure, integrated with *Grewia ferruginea* Hochst. exA.Rich, *Vernonia amygdalina* Delile. *Cyathe amanniana* and *Ricinus communis L*. at the lower stratum.

The agroforestry land of Gacheb catchment is composed of *Coffea arabica* L., as a cash crop integrated with food crops such as false banana (*Ensete ventricosum* Welw. Cheesman), banana (*Musa sapientum* L.) and taro (*Colocasia esculenta* L. Schott) and spices like korarima (*Aframomum corrorima* Braun). Moreover, various fruit trees such as mango (*Mangifera indica* L.), avocado (*Persea americana* Mill.), papaya (*Carica papaya* L.) and orange (*Citrus sinensis* L. Osbeck) are also integrated in the farming system. Furthermore, native trees like *Albizia gummifera* J.F.Gmel. C.A.Sm., *Cordia africana* Lam. and *Millettia ferruginea* Hochst. Baker, are kept for shade, fodder, firewood, *medicinal value and soil fertility maintenance.*

In the croplands taro (*Colocasia esculenta*) is grown in moist places, while maize (*Zea mays*) is dominant. Beans are grown in as mixed crop with maize and single crop in the uplands, and sorghum may be added later on spots where the original crop failed and after harvesting of maize. Taking benefit of reliable rains at the onset of the rainy season, maize is sown in May, after 2-3 tillage operations with oxen-drawn Ethiopian *maresha ard* plough and 1-2 by hand tools that generally take place in April (Table 5.1). Given the high growth of maize, the cropped fields are not weeded after the crop is well established and a strong herb undergrowth develops on cropland, which after crop harvest is used as livestock feed in the cropland (Fig. 5.1B).

Table 5.1. Agricultural calendar in Gacheb catchment for major crops in the main growing season: maize (*), taro (¤), and beans (#).

Major activities[1]	J	F	M	A	M	J	J	A	S	O	N	D
Land preparation[2]				¤	*#							
Sowing or planting				¤	*#							
Weeding and cultivation[3]						*#¤	*#¤					
Harvesting									*#	*#	¤	¤

[1]In our study catchments, farmers do not use fertiliser, and maize monocropping is dominant (without crop rotation, without fallowing). Only in the upper FHC catchment, there is crop rotation with beans and barley.

[2]The land is tilled three times in all catchments with oxen-span and a plough of the ard type (2 times in DMC)

[3]Cultivation is done once, with hand tools (twice at FHC)

Table 5.2. Characteristics of sub-catchments monitored in the main rainy seasons of 2013 and 2014 (June 8-October 30)

Description	**FHF**	**FHC**	**DMF**	**OMC**	**ZHF**	**ZHC**	**ZMF**	**ZMC**	**FLF**	**FLC**
Location of stations	6°59' N 35°39' E	7°0' N 35°39' E	7°2' N 35°38' E	7°1' N 35°39' E	6°55' N 35°34' E	6°55' N 35°34' E	6°55' N 35°33' E	6°55' N 35°33' E	6°58' N 35°30' E	6°57' N 35°30' E
Area (ha)	11.5	7.0	7.9	5.2	5.9	4.2	3.7	4.0	4.1	3.6
Elevation(m a.s.l)	2135	1990	1632	1606	2022	1879	1544	1717	1261	1324
Rainfall (mm)	1405±92	1405±92	1218±88	1218±88	1535±31	1535±31	1360±23	1360±23	1126±14	1126±14
Slope (%)	42	29	23	33	35	18	20	23	14	14
Perimeter (m)	1399	1064	1050	990	952	954	730	1034	888	1032
Compactness	0.74	0.78	0.90	0.67	0.83	0.86	0.87	0.65	0.65	0.60
Tree density (m^{-2})	0.24 ±0.004	0.003 ±0.001	0.21 ±0.01	0.003 ±0.001	0.23 ±0.01	0.003 ±0.001	0.21 ±0.004	0.003 ±0.001	0.19 ±0.01	0.003 ±0.001
Shrub density (m^{-2})	2.6± 0.1	0.72 ±0.1	2.5 ±0.1	0.7±0.04	2.5 ±0.1	0.7 ±0.1	2.5 ±0.1	0.71 ±0.1	2.4 ±0.1	0.7 ±0.04
Location of rain gauge stations	6°59' N 35°39' E		7° 2' N 35°39' E		6°55' N 35°34' E		6°55' N 35°33' E		6°58' N 35°30' E	

FHF: Faketen high forest; FHC: Faketen high cropland; DMF: Dakin middle forest; OMC: Oka middle cropland; ZHF: Zemika high forest; ZHC: Zemika high cropland; ZMF: Zemika middle forest; ZMC: Zemika middle cropland; FLF: Fanika low forest; FLC: Fanika low cropland.

5.2.2 **Experimental setup and data collection**

5.2.2.1 Rainfall and runoff

Five rain gauges were installed, each of them representing two runoff monitoring stations (forest and cropland catchments) (Fig. 5.3, Table 5.2). Rainfall was manually recorded twice a day: in the morning at 8:00 AM and evening 8:00 PM.

Figure 5.3. Rain gauge located centrally between paired forest and cropland catchments (Zemika High); the data collector demonstrates how the upper part (funnel) can be lifted up to access the receiving container under it. Photograph taken on 17 October 2013

Runoff data was collected at the outlet of paired catchments with forest and cropland. Ten study sites were selected along altitudinal transects and stratified according to land use type (forest and cropland) and three elevation zones (high, 1900-2300 m a.s.l.; middle, 1500-1900 m a.s.l.; and low, 1200-1500 m a.s.l.). All forest and cropland catchments had a runoff monitoring station equipped with a standardized flume at the outlet (Table 5.2).

Runoff data was collected in main rainy season of 2013 and 2014 (June 8 to October 30). Ten paired sub-catchments (five fully under forest and five under cropland) were selected in Gacheb catchment. No catchments were found that are entirely under agroforestry. The runoff stations consisted of nine San Dimas flumes (Fig. 5.2; Fig 5.4) and one V-notch weir, installed on the outlet of the drainage basins. Compared to the rectangular cross-section of the San Dimas flumes, the V-shaped V-notch is more suitable for recording smaller flows. The flumes were equipped with a graduated strip, to manually record the runoff depth. The flow depth was measured at ten minutes interval during every rainfall event. The dimension of the flumes installed in forest (1.5×0.5×0.5 m; Length×Width×Height) is different from the cropland (2.1×0.7×0.7 m; L×W×H), because the runoff from the forest is generally lower than from cropland. In order to determine the discharge, a current meter was used to record the number of rotations within 30 second interval at various flow depths at all San Dimas flumes. The recorded rotation number at various flow depths was then converted to velocity with the standard formula:

$$V = 1.93+31.17\times N, \text{ if } N \leq 1.98;\ V = 0.19+32.05\times N, \text{ if } 1.98 < N > 10.27;\ V = -14.09 + 33.44 \times N, \text{ if } N \geq 10.27 \quad (5.1)$$

where, V= velocity in cm s^{-1}; 1.93, 31.17, 0.19, 32.05, -14.09 and 33.44 = calibrated values for the current meter; and N= Number of rotations.

The cross-sectional flow area was determined from the San Dimas flume width and the flow depth. Instantaneous runoff discharge for all velocity and corresponding flow depth measurements was then calculated as:

$$Q=A*V \quad (5.\ 2)$$

where, Q = Instantaneous runoff discharge ($cm^3\ se^{-1}$), A= cross sectional flow area (cm^2) and V = velocity (cm s^{-1}).

However, the current meter calibration was suspected to lead to underestimations, because of partial submersion of the current meter during calibration of runoff events in all measurement stations. To validate this we compared our calibration with the standard discharge curve for modified San Dimas flume. It was found that the discharge curve for modified San Dimas flume developed by Bermel (1950) is in correspondence with our discharge rating curves. Hence, adapted discharge rating curves were developed for 500 mm (small San Dimas flume) and 700 mm size (large San Dimas flume) on the basis of Bermel’s (1950) rating curve (Table 5.3).

Conversion to continuous discharge series

The continues discharge serious was calculated based on the modified equation for small and large San Dimas flumes, which was interpolated for installed San Dimas flumes (small=500 mm; large=700 mm) from Bermel (1950) flow depth-discharge rating curves measured over a wide range of flow depths on various modified San Dimas flumes. It is calculated with the equation (modified from Bermel (1950)):

$$Q = a\, d^b \tag{5.3}$$

where Q = discharge, d = flow depth, a and b are fitting parameters.

At the lowest forest, when observing the channel, very small runoff discharge was expected and a V-notch weir was installed. The standardized rating curve for 90° V-notch weir was used to calculate the discharge. However, as the V-notch weir was installed in a level area, large volumes of water ponded behind it; hence a stage-water volume rating curve was developed based on the geometry of the pond. This volume was then added to the measured discharge in the V-notch weir (Table 5.4). These rating curves were used to convert the manually recorded continuous flow depth series to storm discharge records. The resulting continuous runoff discharge series were integrated on event and daily basis. Rainfall-runoff relations were established so that the missed events (particularly during nights) could be estimated.

Figure 5.4. San Dimas flume installed at the outlet of the Dakin forest catchment (8 September 2013). At right the staff gauge that was read every 10 minutes during runoff events, and the plastic container to take grab samples or runoff water and sediment that was then transferred into a plastic bottle (A). Filtering installation in the labratory of Natural Resources Management Department at Mizan-Tepi University. The wooden boards have been perforated to fix funnels, in which Whatman filter paper was inserted. The bottles on top of the boards contain the sample, the bottles under it collect the filtered water so that the quality of filtering can be checked. After filtering, the filter paper is numbered, oven-dried and weighed. Two thousand fourteen samples were analysed in this way and used in the study (B).

5.2.2.2 Sediment yield measurements and export

During runoff events, suspended sediment samples were collected at different flow depths. Grab samples were collected and transferred into with 1 litre plastic bottles (Fig. 5.4). The samples were then filtered in a funnel using Whatman 42 filter paper (pore size of 2.5 μm). The filter paper with sediment was then oven-dried for 24 hours at 105 °C and weighed to determine the suspended sediment concentration (Fig. 5.4).

The suspended sediment concentration (SSC, in g l^{-1} or kg m^{-3}) was calculated as:

$$SSC = (M - 1.6186) / V \quad (5.\ 4)$$

where M is the gross mass of the dried filter with suspended sediments (g); 1.6186, the average mass (n = 10) of oven-dried empty filter paper (g); V, the volume of the water sample (l).

Based on a large set of SSC samples (999 in 2013, 1015 in 2014, or ca. 200 per catchment), suspended sediment to discharge rating curves were developed for all forest and cropland sub catchments (Asselman, 2000; Moliere et al., 2004; Vanmaercke et al., 2010).

Several studies show that the relationship between *Q* and *SSC* is often subject to a lot of scatter and variable at different temporal scales (Asselman, 2000; Moliere et al., 2004; Alexandrov et al., 2007). A preliminary check (Fig. 5.5; Table 5.3) showed that in our study catchments, relations were consistent throughout the rainy season. We have thus worked with seasonal rating curves per station. Daily sediment export was calculated for each forest and cropland station using:

$$Qs,d = \sum_{i=1}^{n} (Qi * SSCi * 600\ s) \quad (5.5)$$

Where Qs,d is the daily sediment export (t day^{-1}); *n* is the number of 10-min intervals per day; Qi is the runoff discharge for each 10-min interval ($m^3\ s^{-1}$), and SSC_i is the corresponding estimated SSC (kg m^{-3}) calculated with the discharge rating curves. Total sediment export for each forest and cropland sub catchment was calculated as the sum of all Qs,d values. Suspended sediment yield (SSY) is the total exported sediment per month or season (June to October) calculated against catchment area.

For about a quarter of the rainfall events, runoff could not be monitored and no SSC samples were taken, particularly for storms that occurred in the middle of the night. We have estimated the sediment yield of those events by establishing, per station and based on the monitored events, a regression analysis between event rainfall and sediment yield. Using the rainfall data of the missed runoff event, we could then calculate the estimated sediment yield of that event (Table 5.4).

Catchment boundaries were digitized using topographic maps of the study area, complemented with GPS recordings taken in the field. The area of all sub-catchments was then calculated using GIS software.

Plant density

Plant density, as a potential explanatory factor for differences in SSY, was recorded on plots within the forest and cropland catchments. The main plots were 20 × 20 m^2 replicated three times in each catchment. Tree species above 1.5 m height were counted inside the 20 × 20 m^2 main plot and shrubs were counted in subplots of 5 × 5 m^2 at the four corners of the main plot. The plant density of the trees and shrubs and herbs was calculated based on the equation by Mueller-Dombois & Ellenberg (1974):

$$\text{Density of species i} = \frac{\textbf{Number of the plants of species i}}{\textbf{Area of quadrants}} \qquad (5.\ 6)$$

Data analysis

The difference in monthly suspended sediment yield between forest and cropland was analyzed in one way ANOVA using SPSS (software version 20). Means were compared by least significant difference (LSD). The relationship between suspended sediment yield and area of catchment, seasonal rainfall and slope gradient was analyzed using correlation analysis.

5.3 Results

5.3.1 Suspended sediment concentration

The suspended sediment concentration (SSC) of our sites reached values up to 16 g l^{-1}; all sites showed a pattern of linearly increasing SSC with discharge (Fig. 5.5). Data are relatively well grouped around the regression lines and for all catchments the correlations between SSC and Q are strong (Table 5.3).

5.3.2 Sediment yield

The seasonal suspended sediment yield in cropland is higher than the forest in all sites. The suspended sediment yield in cropland ranges from 30 ± 5.5 Mg ha^{-1} in FH site to 14 ± 3.9 Mg ha^{-1} in FL site, whereas the forest suspended sediment yields are between 6.0 ± 1.3 Mg ha^{-1} at FH site and 2.0 ± 0.7 Mg ha^{-1} at FL site (Table 5.4).

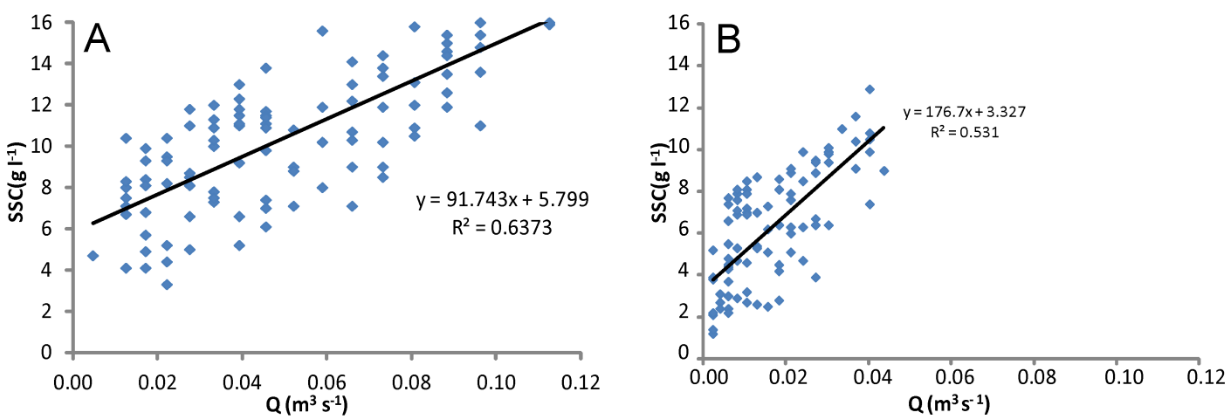

Figure 5.5. Suspended sediment concentration (SSC) as a function of discharge (Q) in two paired catchments af similar size in the mid-elevation belt. (left) OMC Oka cropland, n=116, 5.2 ha, outlet at 1606 m a.s.l.; (right) DMF Dakin forest, n=93, 7.9 ha, outlet at 1632 m a.s.l.

Table 5.3. Regression equations for the relationship between measured discharge (Q, in m³ s^{-1}) and suspended sediment concentration (SSC, g l^{-1}) in Gacheb catchment

Station	Catch-ment	Year	Regression Equation of SSC and Q	Regression equation of event P and SSY
FHF	Forest	2013	SSC=67.398Q +1.706 (R^2=0.52; n=117)	SSY=97362P-54032 (R^2=0.90)
		2014	SSC=13.967Q +2.534 (R^2=0.54; n=113)	SSY=83312P-36986 (R^2=0.81)
DMF	Forest	2013	SSC=17.675Q +3.327 (R^2=0.53; n=93)	SSY=24294P-11229 (R^2=0.84)
		2014	SSC=20.274Q +3.582 (R^2=0.56; n=89)	SSY=37773P-27201 (R^2=0.86)
ZHF	Forest	2013	SSC=12.640Q +3.239 (R^2=0.51; n=91)	SSY=40645P-18456 (R^2=0.91)
		2014	SSC=12.046Q +3.210 (R^2=0.50; n=95)	SSY=35056P-16243 (R^2=0.91)
ZMF	Forest	2013	SSC=17.049Q +3.399 (R^2=0.53; n=89)	SSY=23242P-11326 (R^2=0.87)
		2014	SSC=16.421Q +2.766 (R^2=0.58; n=94)	SSY=19028P-10296 (R^2=0.84)
FLF	Forest	2013	SSC=36.209Q +0.624 (R^2=0.51; n=91)	SSY=21095P-84346 (R^2=0.83)

		2014	SSC=34.432Q +1.589 (R^2=0.52; n=99)	SSY=12320P-54359 (R^2=0.89)
FHC	Cropland	2013	SSC=76.047Q +4.542 (R^2=0.67; n=114)	SSY=32182P-2E+06 (R^2=0.91)
		2014	SSC=77.485Q +6.510 (R^2=0.68; n=118)	
OMC	Cropland	2013	SSC=91.743Q +5.799 (R^2=0.64; n=116)	SSY=15333P-72667 (R^2=0.86)
		2014	SSC=70.491Q +6.229 (R^2=0.61; n=108)	
ZHC	Cropland	2013	SSC=77.278Q +5.057 (R^2=0.60; n=106)	SSY=12974P-56175 (R^2=0.93)
		2014	SSC=70.180Q +4.816 (R^2=0.60; n=110)	
ZMC	Cropland	2013	SSC=98.102Q +4.209 (R^2 =0.65; n=92)	SSY=11263x - 57532 (R^2=0.87)
		2014	SSC=71.207Q +4.849 (R^2 =0.64; n=97)	
FLC	Cropland	2013	SSC=95.235Q +2.513 (R^2 =0.62; n=90)	SSY=71590x - 37402 (R^2=0.86)
		2014	SSC=79.818Q +3.920 (R^2 =0.65; n=92)	

Gacheb catchment land use: FHF: Faketen high forest; FHC: Faketen high cropland; DMF: Dakin middle forest; OMC: Oka middle cropland; ZHF: Zemika high forest; ZHC: Zemika high cropland; ZMF: Zemika middle forest; ZMC: Zemika middle cropland; FLF: Fanika low forest; FLC: Fanika low cropland.

Table 5.4. Total seasonal rainfall and suspended sediment yield (period of June to October) from paired catchments at southwest Ethiopia's forest frontier

Station	**Land-use types**	**Year**	**P (mm)**	**SSY (Mg ha^{-1})**
FHF	Forest	2013	1470	6.6
FHF		2014	1340	4.8
Average			1405±92	6±1.3
FHC	Cropland	2013	1470	33
FHC		2014	1340	26
Average			1405±92	30±5.5
DMF	Forest	2013	1280	2.3
DMF		2014	1155	2.9
Average			1218±88	2.6±0.4
OMC	Cropland	2013	1280	19.1
OMC		2014	1155	18.7
Average			1218±88	19±0.2

ZHF	Forest	2013	1312	5.1
ZHF		2014	1757	6.7
Average			1535±315	6±1.1
ZHC	Cropland	2013	1312	21.1
ZHC		2014	1757	22.1
Average			1535±315	22±0.7
ZMF	Forest	2013	1195	3.9
ZMF		2014	1524	4.6
Average			1360±233	4±0.5
ZMC	Cropland	2013	1195	15.0
ZMC		2014	1524	20.7
Average			1360±233	18±4.0
FLF	Forest	2013	1023	1.1
FLF		2014	1230	2.1
Average			1127±146	2±0.7
FLC	Cropland	2014	1230	11.6
FLC		2014	1230	17.0
Average			1127±146	14±4
Summary	Forest			4±1.9
	Cropland			20±5.7

P: Rainfall; SSY: Area-specific seasonal suspended sediment yield. Catchment names like in Table 5.2

The average monthly SSY of the cropland is significantly different from the paired forest in all sites (Table 5.5). In general, the overall average monthly sediment yield of the cropland (3.5±2.4 Mg ha^{-1}) is significantly higher than that of the corresponding paird forest (0.9±0.5 Mg ha^{-1}). The average monthly suspended sediment yield of the cropland and forest (Table 5.5) shows very little hysteresis throughout the year (Fig. 5.6).

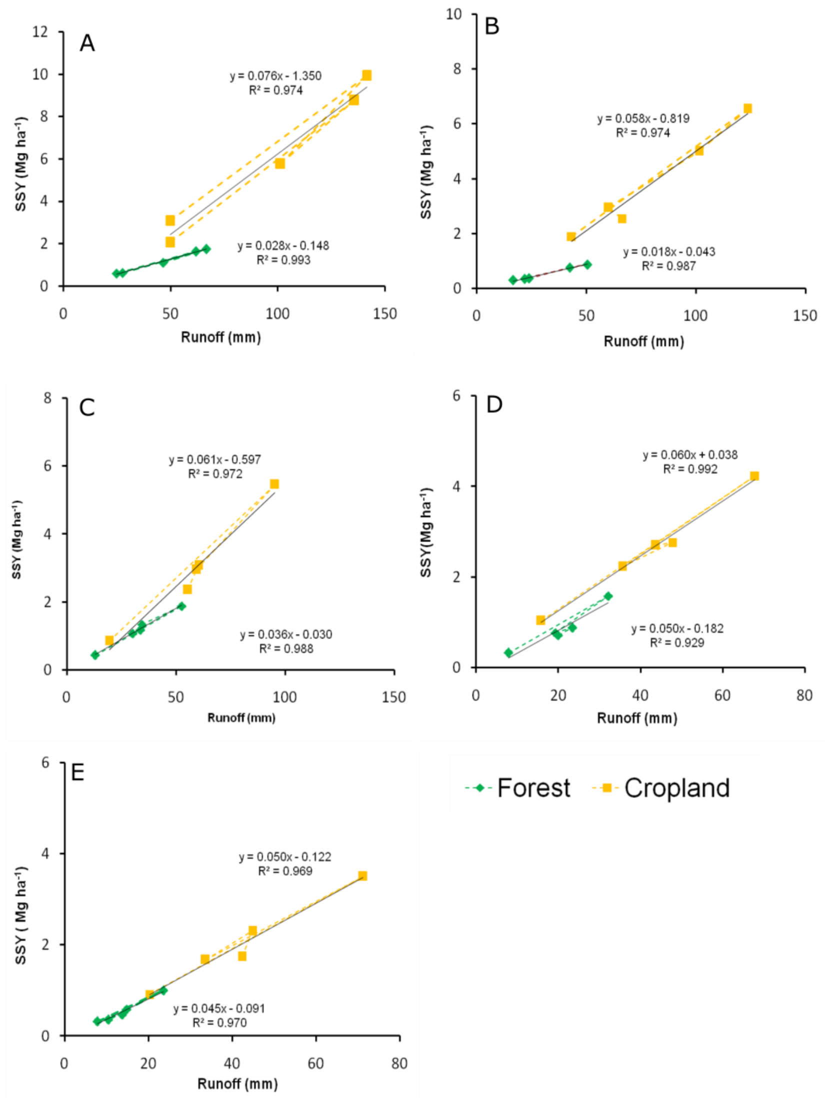

Figure 5.6. Average monthly (June to October) suspended sediment yield (From Table 6.5) relationship with runoff in five paired catchments. (A) FH site forest and cropland; (B) DM site forest and cropland; (C) ZH site forest and cropland; (D) ZM site forest and cropland; (E) FL site forest and cropland.

Explanatory factors for suspended sediment yield

Measured values for explanatory factors catchment area, slope gradient, seasonal rain and tree density, were analysed for the two sub-groups of catchments. It appears that the homogeneity in density of trees (0.19-0.24 m^{-2} in forest, 0.003 m^{-2} in cropland) and shrubs (2.4-2.6 m^{-2} in forest, 0.71-0.72 m^{-2} in cropland) in the studied catchments (Table 5.6) does not allow analysing their impact on sediment yield, other than the overall contrast between the two land-uses types. However, in cropland the SSY is strongly associated to catchment area (R^2=0.63), to average catchment slope gradient (R^2=0.50), to seasonal rainfall depth (R2=0.11); and similar strong association were found under forest: SSY with catchment area (R^2=0.19); with average catchment slope gradient (R^2=0.68), and with seasonal rainfall depth (R^2=0.93) (n=5) (Fig. 5.7).

Table 5.5. Monthly average area-specific suspended sediment yield (SSY, Mg ha^{-1}) in the monitored catchments (2013 and 2014)

Station	Site	Catchment	Year	June	July	August	September	October	Monthly average SSY (Mg ha^{-1})
FHF	FH	Forest	2013	0.7	1.9	1.0	2.3	0.7	1.1±0.6[b]
			2014	0.5	1.6	1.2	1.0	0.5	
		Average		0.6±0.2	1.7±0.2	1.1±0.1	1.6±0.9	0.6±0.1	
FHC	FH	Cropland	2013	3.2	10.5	5.9	11.6	2.3	5.9±3.5[a]
			2014	3.0	9.4	5.6	5.9	1.8	
		Average		3.1±0.1	9.9±0.8	5.8±0.2	8.8±4.0	2.1±0.4	
DMF	DM	Forest	2013	0.3	0.8	0.7	0.2	0.3	0.5±0.3[b]
			2014	0.3	0.9	0.8	0.5	0.4	
		Average		0.3±0.0	0.9±0.1	0.8±0.1	0.4±0.1	0.3±0.1	
OMC	DM	Cropland	2013	2.1	6.8	5.6	2.3	2.3	3.8±1.9[a]
			2014	1.7	6.3	4.4	3.5	2.8	
		Average		1.9±0.3	6.5±0.3	5.0±0.8	2.9±0.9	2.5±0.3	
ZHF	ZH	Forest	2013	0.4	1.9	1.1	1.1	0.6	1.2±0.5[b]
			2014	0.5	1.9	1.5	1.2	1.5	
		Average		0.4±0.1	1.9±0.0	1.3±0.3	1.2±0.0	1.1±0.7	
ZHC	ZH	Cropland	2013	0.7	6.0	2.8	3.1	1.8	2.9±1.6[a]
			2014	1.0	4.9	3.1	3.0	3.0	
		Average		0.8±0.2	5.5±0.7	2.9±0.3	3.1±0.1	2.4±0.9	
ZMF	ZM	Forest	2013	0.3	1.7	0.8	0.6	0.5	0.9±1.7[b]
			2014	0.4	1.5	0.7	1.1	0.9	

		Average		0.3±0.1	1.6±0.2	0.8±0.0	0.9±0.3	0.7±0.3	
ZMC	ZM	Cropland	2013	0.6	4.2	2.2	2.1	1.9	2.6±1.2[a]
			2014	1.5	4.3	2.2	3.5	3.5	
		Average		1±0.7	4.2±0.0	2.2±0.0	2.8±1.0	2.7±1.2	
FLF	FL	Forest	2013	0.3	1.2	0.3	0.8	0.6	0.5±0.3[b]
			2014	0.3	0.8	0.4	0.3	0.3	
		Average		0.3±0	1.0±0.3	0.4±0.1	0.6±0.4	0.5±0.2	
FLC	FL	Cropland	2013	0.6	2.7	1.0	2.6	1.3	2.0±1.1[a]
			2014	1.3	4.3	2.3	2.0	2.2	
		Average		0.9±0.5	3.5±1.1	1.7±0.9	2.3±0.5	1.7±0.6	
Summary		Forest							0.9±0.5[b]
		Cropland							3.5±2.4[a]

Mean values with different letters among the land use on the same site groups are significantly different from each other ($P<0.05$).
SSY: Suspended sediment yield.

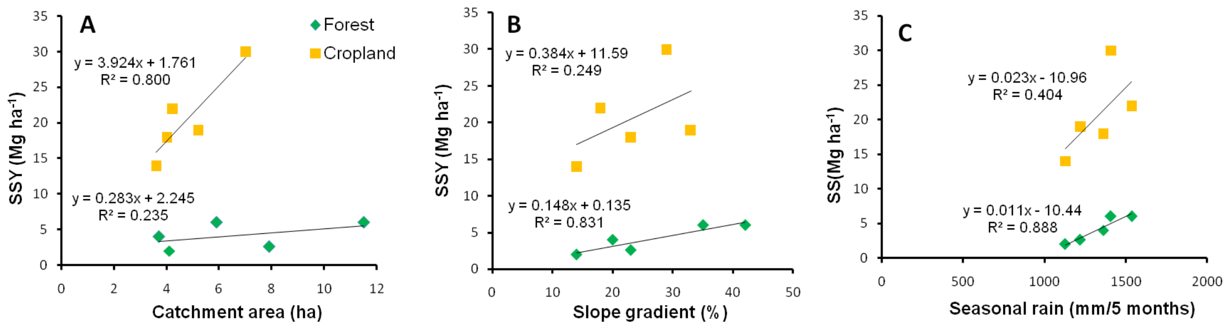

Figure 5.7. Total seasonal sediment yield (TSSY) in forested (n = 5) and cropland catchments (n = 5) astride the forest frontier in southwest Ethiopia, as a function of catchment area (A), average catchment slope gradient (B) and seasonal rainfall (C)

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Figure 5.8. Livestock grazing in ZHF forest

5.4 Discussion

Impact of land use on seasonal suspended sediment yield

Average seasonal suspended sediment yield from catchments under cropland (20 Mg ha^{-1}) is five times larger than that from similar catchments under forests (4 Mg ha^{-1}), what is explained by the relative high surface runoff and exposure of the soil to splash erosion. In reverse, the relatively high tree and shrub density in forests allows raindrop interception, and tree and shrub roots and litter increase the resistance of the surface soil to water erosion.

The average suspended sediment yiled in the forest (4 Mg ha^{-1}) is considerably less than in cropland but larger than the 0.5 Mg ha^{-1} suspended sediment yield from a caribbean forest (Cox et al., 2006), and much higher when compared with worldwide estimates of soil loss of 0-0.58 Mg $ha^{-1}y^{-1}$ (Sands, 2013), and 0.004 to 0.05 Mg ha^{-1} y^{-1} proposed for forests (Roose, 1988). The occurrence of high suspended sediment yield in the studied forest catchments, and also high suspended sediment concentration even at relatively low discharges (Fig. 5.5, right) is probably partly due to selective logging as evidenced by the presence of species typical of secondary vegetation (such as *Albizia gummifera* (J.F.Gmel.) C.A.Sm. *Hagenia abyssinica* (Willd), *Polyscias fulva* (Hiern).) or *Schefflera abyssinica* (Hochst. ex A.Rich)) and the pressure on the forest by grazing livestock, particularly in the crop growing period when stubble grazing is impossible. Livestock grazing basically results in decreased soil porosity and infiltration, which in turn increase surface runoff and soil loss. Soil disturbance by hoofs and horns of grazing livestock has been shown to significantly increase the suspended sediment yield in overland flow (McDowell et al., 2003).

When considering the monthly variation in SSY, we could not observe the expected higher sediment load for the same discharge in the early rainy season as contrasted to the late rainy season (Fig. 5.6). The absence of such hysteresis would indicate that conditions of production and transport of sediment yield stay more or less the same throughout the rainy season (Bača, 2008). This is most probably related to the overall humid environment that favours continuous vegetation growth, including off-season weeds, and soil humidity, hence little or no dust. Also the near-absence of crop rotation favours weed development (Liebman & Dyck, 1993).

The seasonal suspended sediment yield measured on the cropland catchments (20 Mg ha^{-1}) is larger than that of earlier partial studies from agricultural lands with similar slope, rainfall and management practices in neighbouring Keffa Zone (Fig. 1.1). For example, the soil loss in agriculture land was measured on runoff plots as 15 Mg ha^{-1} y^{-1} in Keffa Zone (Mekuria et al., 2012), 8-15 Mg $ha^{-1}y^{-1}$ at different slope positions on settlers' farms near Bonga in Keffa Zone (Berhanu, 2011). Just like our findings, the measured results strongly contrast with model results of 184 Mg ha^{-1} y^{-1} in Bench Maji Zone (Getachew, 2011). Our findings on cropland are also higher than the median of measured values in Africa for catchments of 2 ha (7.8 Mg ha^{-1} y^{-1}) or 8 ha (6.3 Mg ha^{-1} y^{-1}) (Vanmaercke et al., 2014). In Ethiopia, all measured SSY for catchments up to 1000 km^2 are in the range of 5-40 Mg ha^{-1} y^{-1} (Vanmaercke et al., 2010). Despite higher rainfall than all other measurement sites, our two-years measurement results on cropland are well within this range. Most plausible explanations are the fact that rains start slowly giving all chance to crops (and weeds) to get well established by the time that the June-September rains occur.

Impacts of rainfall depth and topography on sediment yield

Besides the overwhelming effect of land use type, the suspended sediment yield is also dependent on other catchment characteristics (Fig. 5.7). The increasing trends of SSY with catchment area, both in forest and in cropland could be related to the fact that soils are relatively saturated in the rainy season. In absence of soil and water conservation structures, alluvial plains or topographical flats, this leads to longer runoff length in the larger catchments, hence greater soil erosion, with little opportunity for deposition. Another reason for this positive relation is that in larger catchments (at this scale range) topographic thresholds are exceeded for e.g. (ephemeral) gully erosion and shallow landsliding. These processes become often more important when catchment size increases, as shown for instance by Verbist et al. (2010) in a tropical volcanic agroforestry landscape in Indonesia.

A steeper slope gradient leads to increase in SSY, despite the coarsening of soil particles on steeper slopes and higher rock fragment cover, as observed elsewhere in Ethiopia (Miserez, 2013; Lanckriet et al., 2012). Finally, we could also observe higher SSY in catchments with more seasonal rainfall (Fig. 5.7, right); as, per land use type, land cover is quite similar, more rain is expected to lead to more splash erosion, more runoff, and hence greater SSY. When comparing forest and cropland (Fig. 5.7), correlations are as strong, but the gradient is less, translating an overall buffering effect of the forest.

5.5 Conclusions

The study shows that changing southwest Ethiopia's Afromontane forest into open field cropland significantly affects the sediment concentration and seasonal suspended sediment which is around five times higher in cropland catchments as compared to the paired forest catchments. Suspended sediment yield is strongly correlated with runoff in both forest and cropland. Even under grazing pressure, the forest plays an important role in protecting the soil from loss. Yet, soil loss from cropland (20 Mg ha^{-1}/ rainy season) is lower than what could be expected after tropical deforestation, which we particularly relate to dense cover by crops and weeds particularly at the time of strongest rains. Unexpectedly high sediment yield from forests (4 Mg ha^{-1}/rainy season) is probably due to degradation and particularly livestock pressure on the forests. Under both land-uses types, soil loss increases with catchment area, average catchment slope gradient and seasonal rainfall.

It has been shown in the study area that promoting agroforestry instead of open field cropping is paramount to sustain the soil fertility, soil organic and nitrogen stocks, and species richness and diversity in the upper catchment. Moreover, even under significant human and livestock pressure, forests have a prominent role in buffering storm runoff and enhancing baseflow. Here we showed also that removing the tree cover leads to strong increases in suspended sediment yield. Nevertheless, not only the forest area is under pressure, but the quality of the forest itself is also endangered. In brief, land management in southwestern Ethiopia's highlands will need a strong change in paradigm, in which the overall belief in the recently imported plough is abandoned, oxen and other cattle decreased in number and kept at the homestead, the forest better protected from human and livestock interference, and the open farmlands turned into agroforestry. Such an approach is still possible as all required elements are available in the landscape.

5.6 References

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Chapter 6

General discussion and conclusions

6.1 General discussion

1. *What do we know already about causes and impacts of the transition of Afromontane forest to cereal based farming? (Chapter 1)*

Deforestation has received major attention, because it is resulting in environmental degradation in Ethiopia, and is the major factor challenging food security, livelihood and sustainable development (Bishaw & Abdelkadir, 2003; Nyssen, 2004). The impact is more for poor farmers of Ethiopia, especially farmers of southwest Ethiopia whose livelihood depends on collection of timber, wood, fruit, honey, spice and hunting from the forest (Anteneh, 2006). Despite the forest has been providing several importance to the local community livelihood, several human induced factors have led to deforestation, mainly related to expansion of agriculture land and settlement (Mekuria, 2005).

From the perspective of forest cover change, Reusing (2000), Mekuria (2005), Bedru (2007), Dereje (2007), and Belay (2010) are in agreement with the identified causes of Geist & Lambin (2002), Lambin et al. (2003) and Kabanza et al. (2013), who showed that forest cover changes are driven by a complex of underlying causes rather than by single factors such as ‘shifting cultivation’ or ‘increasing population’ pressure.

The forest degradation related to resettlement has been driven by the increase in population, government policy and economic factors. The introduction of a new unsustainable farming system, the increased demand for land, fuel wood and construction wood for a growing population, the illegal expansion of agriculture and grazing land and the policy choice to have settlers achieve food security at the expense of available natural resources provokes the degradation of dense natural forests in the settlement areas (Mekuria, 2005; Reusing, 2000; Behailu, 2010; Belay, 2010). Similarly, Geist & Lambin (2002) indicate that the immigration of settlers in less populated regions increased the deforestation in Africa and Latin America (Geist & Lambin, 2002). In contrast, Kabanza et al. (2013) showed that where population density was the highest in southeastern Tanzania, large areas of cropland and bush land were converted to cashew tree cultivation, which represents a case of “more people, more trees”.

In a country like Ethiopia, where agriculture is a mainstay for the livelihoods of the majority of the population, a natural or man-made failure in agriculture could have a tremendous effect on the food security of a population. Thus, resettlement is considered to be the easiest solution to curb the problem temporarily or permanently. However, as shown here, such resettlement programmes have a profound impact on the environment. In addition, population increase, market access, and government land policy enforceability further exacerbated the extent and degree of forest degradation.

Forest degradation related to the expansion of large-scale commercial agriculture has been driven by national and international market demand and government tenure policy. The rapid expansion of large-scale private cash crops (coffee, tea, *endod*, rubber tree, pepper and cereal), the expansion of the out-grower scheme approach, a large demand for tea, and illegal logging for the expansion of commercial farmland has resulted in the large-scale destruction of ecologically important forest resources. Furthermore, despite the environmental policy of Ethiopia (EPE) was issued in 1997 to provide guidance in the conservation and sustainable utilization of the country's natural resource, weak law enforcement in relation to the implementation of EIA and environmental audits are undertaken on private investment projects in the southwest Ethiopia. This is because the EIA has not given attention on the development project implementation, since project evaluation and decision making mechanism have focused only on short-term technical feasibility, economic benefit and increase in foreign currency (Tadesse, 2007; Bedru, 2007; Tezera, 2008; Dereje, 2007). Similarly, Dereje et al (2015) indicated that land has leased without Environmental impact assessment (EIA), this resulted large scale deforestation and woodland degradation. Further, Lambin et al. (2003) indicated that commercialisation and the increase in growth of the national and international market as well as market failure have driven deforestation in Indonesia, where the presence of ill-defined policy and weak institutional enforcement has resulted in an increase in extensive illegal logging. Furthermore, Barbier (1997) showed that economic factors and policies have a direct impact on the decision making of land managers. Forest degradation related to the expansion of large-scale commercial farms stems from crop selection, national and international markets, investors' perceptions about ecology and technological factors. Market- and profit-oriented agricultural investments always have short- or long-term impacts on the environment due to a higher priority assigned to profit maximisation than to ecological issues. Furthermore, poor environmental impact assessments and policy enforcement on investment projects have led to uncontrolled and unbalanced decisions concerning the environment. The government tenure policy has a significant impact on the sustainability of natural resources. Provision of ownership rights is of great importance on the behaviour of individuals towards resource utilisation and care. A feeling of insecurity about resources results in suspicion, less motivation to conserve and, consequently, leads to fear-motivated decision-making over resource utilisation, as also demonstrated by Kalema *et al*. (2015) in other parts of Equatorial Africa. In contrast, Liscow (2013) indicated that strong protection of property rights in Nicaragua encouraged agricultural investment and consequently led to accelerated deforestation. Yet, in their meta-analysis of the relationship between land tenure and tropical deforestation, Robinson et al. (2014) showed that, overall, greater land tenure security is associated with a slow rate of deforestation.

The unconsented villagisation programme caused local communities, that were dependent on forests for their livelihoods, to feel insecure, which further caused a shift in livelihoods, such as logging timber for sale to the village and further forest degradation when returning to their original location (Zewdie, 2007, Mekuria, 2005). Similarly, Kikula (1997) indicated that the villagisation programme in Tanzania has had long-term negative environmental impacts such as forest cover decrease and land degradation. Kabanza et al. (2013) also showed that villagisation resulted in a decline in forest cover in the Makonde plateau in southeastern Tanzania, even though the villagisation policy was enacted with the intention to reduce the impact on the forests and to provide collective social services. However, villagisation works only when the people consent to the programme; otherwise it has a strong impact on the environment by alternating the utilisation of resources in the new and in the previous place. Villagisation was perceived as temporary, which consequently led to the rapid and less sustainable utilisation of natural resources.

Governmental policy's direction towards promoting the large- and small-scale expansion of cash crops for national and international markets has resulted in forest degradation. The distribution of inorganic fertilisers, improved variety of coffee and cereals, pesticides, credit services for farmers and market facilities have resulted in the rapid expansion of crop and coffee land at the expense of forests (Mekuria, 2005; Belay, 2010). Similarly, Tuner (1999) indicated that the provision of better access to credit, improved crop varieties and markets can potentially encourage more deforestation rather than relieving pressure on the forest (Turner, 1999). Geist & Lambin (2002) also showed that economic factors are prominent underlying forces of tropical deforestation. High demand in national and international markets for commercialisation hastened deforestation. Land tenure and agricultural policy have been organised to promote cash crop expansion. The policy direction towards securing food demand at the local, regional and national level and a need to increase foreign income has resulted in forest degradation. A policy direction that promotes market-oriented production at the expense of forests could be catastrophic in the long run.

Though the intent of nationalising forest resources has been to better protect them, ignoring the cultural and socio-economic tie of local people with the forest exacerbated forest degradation. According to Zewdie (2007), the customary land tenure system played a pivotal role in the sustainable management of forests in the region. Typically, traditional leaders claim authority over land and natural resources by referring to their pivotal role in the relationship they maintain between local people and place by mediating between the material and the spiritual world (Dondeyne et al., 2012; Virtanen, 2005; Convery, 2006). The customary tenure system and culturally oriented ecological tie are important for the conservation of forest ecosystems as sites, such as springs, pools, rivers, forests, rocks and mountains are valued and respected because of their ancestral spiritual tie with the local community. So, despite the government attempts – indeed under the various political regimes – to undo the traditional customary tenure rules of access to land these still *de facto* function to some extent. Formal recognition of these institutions could be beneficial to the conservation and sustainable management of the forest resources.

2. *As compared to Afromontane forests, to what extent are the soil fertility, organic carbon and nitrogen stocks decreased in the main cropping systems (agroforestry and monocropping)? (Chapter 2)*

The topsoil clay content, bulk density, pH, soil organic carbon, nitrogen, phosphorous, cation exchange capacity and base cation saturation in agroforestry is equivalent to the forest (<3% difference) except an increase with (8%) in phosphorous in agroforestry, whereas the cropland show a decrease in clay, with (42%), pH (15%), soil organic carbon (39%), nitrogen (43%), available phosphorous (44%), cation exchange capacity (28%), base cation saturation (35%) and an increase in bulk density (40%), when compared to the forest. The clay content of the forest and agroforestry (25-30%) are within the marginal range of total clay content requirement for Nitisol (WRB, 2006). The percentage of soil organic carbon and nitrogen decrease from the cropland is in line with the decrease in percentage (30-50%) of those characteristics by Mulugeta (2005) and Rossi (2009). Similar decrease in available phosphorous, with (31-82%) Ngoze et al (2008), CEC

(25%) and base cation saturation (30-40%) Awoonor (2012) was reported in agriculture land. However, the available phosphorous in forest and agroforestry (6-11 mg kg^{-1}) are below the critical value (75-150 mg kg^{-1}), which reveals that the soils of the study area critically deficient in available phosphorous. Similar studies in studies in south west Ethiopia by Getachew (2010), Berhanu (2011), Mekuria, (2005), Mulugeta et al, (2005a and 2005b) showed a significant decrease in soil fertility after conversion of forest to agriculture land. Overall, the continues crop cultivation without management, as observed on the cropland in the study area have led to deterioration of soil quality. The severity of the problem in relation to crop cultivation in agriculture land evolved from malpractice, where cropland is cultivated continuously without supplementary inputs in one area till exhaustion and then moving on to the forest and/or some where the land appears in good condition. The soil organic carbon and nitrogen stocks in the agroforestry have not shown any decrease in percentage, when compared to the forest, whereas the cropland soil organic carbon decrease, with (21%) (Fig 6.1B) and nitrogen stocks (27%). Similar soil organic carbon stocks decrease was reported in agriculture land by Wei et al (2014) (41% decrease) and Done et al (2011) (25% decrease). The percentage of nitrogen stocks decrease in the cropland is in line with the range reported by Barros et al (2014) (17%). The major threat of soil organic carbon stocks decrease in the cropland associated with the increase in CO_2 emission to the atmosphere, which consequently have short and long term effect on the atmosphere, in particular it contributes to global warming and climate change impact. The emission of green house gases from agriculture has not been given attention, yet the agriculture is now become responsible for 7% of total emissions of green house gases in to the atmosphere (Parton et al., 2011). Therefore, apart from crop production it is very essential to view the reversible impact of expanding agriculture land, especially the impact related to green house gas emission.

3. *To what extent is the species diversity decreased due to deforestation/land use change? (Chapter 3)*

The overall plant species diversity of the agroforestry have shown a 12% decrease in plant species diversity, compared to the forest, whereas the cropland species diversity decrease by 36% (Fig 6.1A) The decrease in species diversity in cropland is in line with the report of 13-50% decrease in species diversity in agriculture land after conversion of tropical forest of Africa (Lovejoy, 1980;

Ehrlichh & Ehrlich, 1981); and below the range (40-70%) decrease in species diversity in cropland reported by Zhi-yun (1999). The plant species richness of the agroforestry decrease by 19%, whereas the cropland decrease by 62%. The decrease in species richness from the cropland is in agreement with Zhi-yun (1999), who reported 50-80% decrease in species richness in agriculture land, compared to forest. Similar studies around southwest Ethiopia by Tadesse (2007) and Moti et al. (2011) reported a significant biodiversity loss after forest conversion to monoculture. This finding is also in agreement with the findings of Thiollay (1997, 1999), Onderdonk & Chapman (1999), Hamer et al. (1996), and Vasconcelos (1999). Changes in forest cover, structure and composition have detrimental effects on the disturbance and survival of plant and animal diversity. Thiollay (1997, 1999), Schulze et al. (2000), Vasconcelos (1999), Hamer et al. (1996) and Onderdonk & Chapman (1999) found that changes in forest structure negatively affect the composition and diversity of microorganisms, insects, birds and primates. Habitat conversion or modification by humans to produce goods and services is the most substantial human alteration of ecosystems threatening biodiversity (Chapin et al., 2000). The conversion of forestland to monocultures has irreversible effects on biodiversity loss. Forests play an important role in creating positive ecological conditions for understory plants, animals, microorganisms, insects and birds. The disturbance and removal of the forest results in the disturbance of habitats, food and water sources of other organisms, which results in the migration and death of living organisms that depend on the forest. Worldwide, Runyan et al. (2012) showed that deforestation leads to a rapid decline of mycorrhizal fungi, Rhizobium sp. and soil microbial population. Overall, the presence of low difference in overall species diversity and richness between the forest and agroforestry is due the integration of various food and commercially important crops in the agroforestry system. The plant species richness and diversity were limited under cropland, in which few commercially important species dominate the land management unit. This practice severely threatens the diversity and led to a shift from the land of diversity and richness, which the area is known to dominance of monocropping or/and land of uniform species. This is evident in developing countries like Ethiopia, where natural resource utilization has been taken as a prior alternative for poverty reduction.

4. *Is the runoff response impacted by deforestation? (Chapter 4)*

The seasonal base flow of the cropland show a 57% decrease, when compared to the forest (Fig 6.1C). This is in agreement with the a decrease in base flow, with (50%) Ogden et al (2013) and 4% Alibuyog et al (2009) after conversion of tropical forest to agriculture land. On the other hand, the cropland seasonal runoff increase, with (126%), when compared to the reference forest (Fig 6.1D). Similar increase in surface runoff (100%) was reported by Dias et al (2015) after conversion of tropical forest to agriculture land. Similarly Lal (1990) reported a significant increase in runoff after conversion of tropical forest to annual cropping system. The decrease in base flow in the cropland appears as an evident for substantial negative effects of agriculture land use on water availability for irrigation and household and dried base flows on dry season of the year, as observed in all cropland catchment in the study area.

5. *Is the suspended sediment yield increased due to deforestation? And what is sediment yield from the forest itself? (Chapter 5)*

The seasonal suspended sediment yield of the cropland increase by 410%, when compared to the forest (Fig 6.1E). Similarly, Trimble & Mendel (1995) reported 200% increase in soil loss in the agriculture after conversion of tropical forest. Similar studies in south west Ethiopia by Berhanu (2011), Getachew (2010) and (Mekuria et al., 2012) reported significant increase in soil loss after conversion of afromontane forest to cultivated land. In addition, with time soil loss rates increase in line with declining soil structure and organic matter content, what will lead to irreversible degradation (Getachew, 2010; Runyan et al., 2012). Overall, the soil erosion result of the cropland reveals that the soil erosion of the cropland is sever, which is probably related to long term heavy rainfall, relatively low rainfall interception by the crop. Moreover, the seasonal suspended sediment yield in cropland (20 Mg ha^{-1})/season is beyond the critical threshold level for soil in Ethiopia (13 Mg ha^{-1} y^{-1}) and above the soil formation rate for warm humid agro-ecologies in Ethiopia (18 Mg ha^{-1} y^{-1}) (Hurni, 1983).

6. *What is the overall land management implication of the three main land uses (forest, agroforestry, cereal monoculture) on land degradation? (Chapter 6)*

The forest has an important role in stabilizing the soil quality, green house gas emission, biodiversity, surface runoff and soil loss, as it shows high value on soil physico-chemical characteristics, soil organic carbon and nitrogen stocks, plant species diversity; and scores less in surface runoff and soil loss. Alike the forest, the agroforestry has an important and equivalent role in sustaining soil fertlity, soil organic carbon and plant species diversity. As there were no homogenous catchments available under agroforestry we could not evaluate their impact at catchment scale on hydrology and sediment. Yet, our expertise in the field tends to indicate that similarly to other parameters, the effect of agroforestry on runoff and sediment yield is in between that of forest and open field cropland. The cropland now under crop cultivation are not in sustainable, as the soil quality, soil organic carbon stocks, plant biodiversity, and base flow are low; and high in surface runoff and soil loss. Moreover, the cropland land management in southwest Ethiopia's highlands appear to be poor, despite the high rainfall, mountain landscape and steep slopes could led to irreversible impact on land, as it can be seen on the cropland of the study area; low soil fertility, low plant diversity, low soil organic carbon and nitrogen stocks, low base flow; and high surface runoff and soil loss. Further, the impact is worst for poor farmers of south west Ethiopia, who do not have the capacity to purchase inputs like chemical fertilizer, no fallow period and have less crop residue remained in the soil for soil organic matter amendment, as the crop residue (maize stalk and weed) has been used by the grazing livestock's. As reported by Warren (2002), land degradation cannot be judged independent of its spatial, temporal, economic, environmental and cultural context. That is to say, while analysing land degradation in space and time, not only does the limitation of natural conditions have to be considered but also the roles of the socio-economic and cultural driving forces. Apart from the natural factors, ongoing changes on soicio-economic and cultural in southwest Ethiopia, which actually related to population increase, government policy and resettlement could lead to irreversible land degradation, in line with the report by Getachew (2010), Berhanu (2011) and Mekuria (2005) on southwest Ethiopia.

The presence of high species diversity and the increased and continual threat on the forest has encouraged conservation to reduce the risk of biodiversity loss, land degradation and socio-economic impacts. According to Baye & Terefe (2009), biological soil and water conservation techniques play an important role in controlling runoff and sediment transport. *In-situ* conservation of wild coffee in the forest with the intention to shift to co-management (involvement of local community and government) through participatory forest management contributed to the conservation of wild coffee and forests and generated income for the local community. Other conservation efforts, such as registration with UNESCO's biosphere reserves, have played an important role by strengthening biodiversity conservation, improving the local community's livelihood, and promoting environmentally friendly agriculture and eco-tourism. Because the cause for land use and land cover changes are diverse and are the result of different interacting factors, diverse strategies are needed to tackle the forest degradation problem other than simply giving more priority to strict conservation rules.

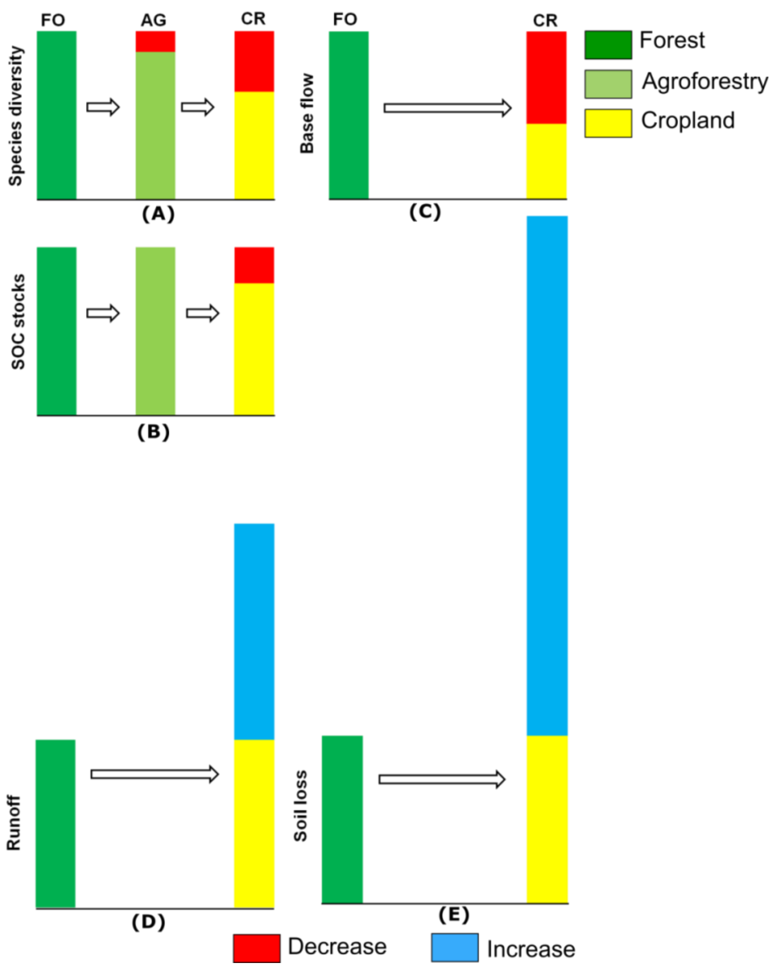

Figure 6.1. Conceptual model of the research results. Land use: FO: forest; AG: agroforestry; CR: cropland. species diversity (A); SOC stocks (B); base flow (C); runoff (D) and soil loss (E).

6.2 General conclusion

The agroforestry is paramount to sustain the soil fertility, soil organic and nitrogen stocks, and species richness and diversity in the upper catchment of Gacheb. Moreover, even under significant human and livestock's pressure, forest plays a prominent role in protection of surface runoff and suspended sediment yield. Nevertheless, not only the forest area is under pressure, but the quality of the forest itself is also endangered. In brief, land management in southwest Ethiopia's highlands will need a strong change in paradigm, in which the overall belief in the recently imported plough is abandoned, oxen and other cattle decreased in number and kept at the homestead, the forest better protected from human and livestock interference, and the open farmlands turned into agroforestry. Such an approach is still possible as all required elements are available in the landscape.

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Appendix A

Appendix A. The background history of studied cropland and agroforestry land use on chapter 2 and chapter 3.

Site	Land use	Current and Land use history	Land management
FH	Cropland	- Maize, taro and weeds are dominant crops in the cropland - The land was forest before 14 year	- No fallowing - Crop rotation: Maize, Bean and Barly - Plowing: Ox plow= 3 times, Hand tools= 2 times - No fertilizer application
	Agroforestry	Coffee mixed with various multipurpose trees (nitrogen fixing shade trees and fruit trees). Coffee is the dominant crop. Root and tuber crops (Taro and "Enset") are also mixed in the agroforestry.	- Litter fall from the tree are collected and incorporated to the soil - Weeding before coffee harvesting
DM	Cropland	- Maize, taro and weeds are dominant crops in the cropland - The land was forest before 20 year	- No fallowing - Crop rotation: Maize, Bean and Sorghum - Plowing: Ox plow= 3 times, Hand tools= 1 times - No fertilizer application
	Agroforestry	Coffee, fruit trees, root and tuber crops, multipurpose trees are appreciably present in the agroforestry. Coffee is a dominant crop but nitrogen fixing shade trees, fruits and food crops (root and tuber crops) are mixed and have complex structural composition.	- Litter fall from the tree are collected and incorporated to the soil - Weeding before coffee harvesting
ZH	Cropland	- Maize, taro and weeds are dominant crops in the cropland - The land was forest before 15year	- No fallowing - Crop rotation: Maize only - Plowing: Ox plow= 3 times, Hand tool= 0 - No fertilizer application
	Agroforestry	Coffee, shade tree, spices, fruit tree and food crops (root and tuber crops) are high and created complex structure in the agroforestry. Alike other agroforestry coffee is dominant crop but the presence of multipurpose trees, food crops and other cash crops are also dense.	- Litter fall from the tree are collected and incorporated to the soil - Weeding before coffee harvesting
ZM	Cropland	- Maize, taro and weeds are the dominant crops in the cropland. - The land was forest before 23 year	- No fallowing - Crop rotation: Maize and Sorghum

			- Plowing: Ox plow= 3 times, Hand tool= 1
	Agroforestry	Coffee mixed with various multipurpose trees (nitrogen fixing shade trees and fruit trees). Coffee is dominant crop but spices crops, fruit plants, root and tuber crops and nitrogen fixing shade trees are also high in the agroforestry.	- Litter fall from the tree are collected and incorporated to the soil - Weeding before coffee harvesting
FL	Cropland	- Maize and weeds are the dominant crops in the cropland -No taro crop in the cropland - The land was forest before 19 year	- No fallowing - Crop rotation: Maize, Bean and Sorghum - Plowing: Ox plow= 3 times, Hand tool= 1 times - No fertilizer application
	Agroforestry	Coffee mixed with various multipurpose trees (nitrogen fixing shade trees and fruit trees). Coffee is dominant crop. Fruit trees are sparsely distributed. Poor in presence of root and tuber crops.	- Litter fall from the tree are collected and incorporated to the soil - Weeding before coffee harvesting

Site: FH:Faketen high; DM: Dakin middle; ZH: Zemika high; ZM: Zemika middle; FL: Fanika low. *Detail of the the above land use types vegetation species frequency and composition are present on Appedix C table.

Appendix B

Appendix B (1). Topsoil (0-20 cm) physico-chemical characteristics of land use in Gacheb catchment

Land use types	Sand (%)	Silt (%)	Clay (%)	BD (g cm^{-1})	pH	OC (%)	N (%)	P (mg kg^{-1})	Na cmol (+) kg^{-1}	K cmol (+) kg^{-1}	Ca cmol (+)kg^{-1}	Mg cmol (+)kg^{-1}	CEC cmol kg^{-1}	BS (%)
FHC	34±1.1	55±1.9	12±0.8	1.0±0.05	5.6±0.1	4.7±0.2	0.5±0.1	11±0.8	0.4±0.03	0.5±0.1	5.6±1	2±1	61±1	44±2
FHA	21±1.1	56±0.9	23±1.3	0.7±0.04	5.8±0.1	8.0±0.1	1.0±0.1	14±1.5	0.4±0.03	1.2±0.1	17.4±1	34±1	89±2	60±1
FHF	22±1.6	57±1.4	21±0.8	0.7±0.05	6.0±0.1	8.2±0.2	1.1±0.1	14±0.8	0.5±0.03	1.1±0.1	20.4±1	36±1	94±2	62±2
DMC	36±1.2	51±0.9	13±0.8	1.2±0.04	5.1±0.1	3.9±0.2	0.3±0.02	5±0.4	0.3±0.04	0.3±0.02	7±0.3	12±1	64±2	31±2
DMA	23±0.9	55±1.5	23±0.9	0.8±0.03	5.7±0.1	6.8±0.2	0.7±0.03	11±0.6	0.3±0.03	0.7±0.02	14±0.5	29±2	82±1	53±2
DMF	21±0.6	55±1.3	24±0.7	0.8±0.03	5.6±0.1	6.8±0.2	0.7±0.02	11±0.6	0.4±0.03	0.6±0.03	13±0.4	30±1	83±2	52±2
ZHC	36±0.7	51±1.0	14±0.6	1.2±0.3	5.1±0.2	4.9±0.1	0.5±0.03	5±0.9	0.2±0.01	0.5±0.06	6±0.6	14±1	52±2	39±3
ZHA	22±0.8	55±0.9	23±0.6	0.9±0.3	5.6±0.1	7.8±0.2	0.9±0.02	12±0.8	0.4±0.02	1.2±0.12	17±1.0	28±2	72±2	64±2
ZHF	20±1.1	55±1.1	25±1.0	0.9±0.2	5.7±0.1	7.9±0.1	1.0±0.02	11±1.0	0.4±0.02	1.3±0.10	18±0.6	30±2	75±1	66±2
ZMC	36±1.9	48±0.9	16±1.0	1.2±0.05	4.9±0.2	3.9±0.1	0.3±0.02	5±0.7	0.2±0.02	0.4±0.02	8±1.1	15±1	56±2	42±1
ZMA	23±1.1	53±1.2	24±0.9	0.9±0.03	5.3±0.2	6.5±0.1	0.7±0.02	11±0.6	0.4±0.02	0.5±0.02	14±0.6	29±1	80±1	54±2
ZMF	22±1.1	52±1.6	26±0.6	0.9±0.04	5.6±0.2	6.5±0.1	0.6±0.01	10±0.4	0.4±0.02	0.5±0.02	14±0.6	31±2	81±2	56±2
FLC	27±0.9	51±0.9	22±1.0	1.2±0.03	6.0±0.1	3.4±0.1	0.5±0.02	5±0.3	0.3±0.01	3.1±0.1	10±0.3	12±1	69±2	37±0.1
FLA	18±0.8	50±1,2	33±0.6	0.9±0.03	6.4±0.1	4.9±0.1	0.8±0.02	12±0.3	0.4±0.01	3.6±0.1	16±0.3	33±1	84±2	63±0.6
FLF	15±1.3	49±1.8	35±0.6	0.9±0.02	6.4±0.2	5.0±0.1	0.8±0.02	10±0.5	0.4±0.01	3.6±0.2	16±0.5	34±1	86±1	62±1.1

Appendix B (2). Subsoil (40-60 cm) physico-chemical characteristics of the land uses in the Gacheb catchment

Land use types	**Sand (%)**	**Silt (%)**	**Clay (%)**	**BD (g cm^{-1})**	**pH**	**OC (%)**	**N (%)**	**P (mg kg^{-1})**	**Na cmol (+) kg^{-1}**	**K cmol (+) kg^{-1}**	**Ca cmol (+) kg^{-1}**	**Mg cmol (+) kg^{-1}**	**CEC cmol kg^{-1}**	**BS (%)**
FHC	22±1.9	46±0.8	33±2.2	1.3±0.04	5.1±0.1	2.9±0.2	0.2±0.02	4.2±0.3	0.1±0.02	0.5±0.05	10±0.5	16±1	59±2	47±2
FHA	19±1.0	48±1.5	33±1.2	1.1±0.03	5.3±0.2	4.1±0.1	0.4±0.03	5.6±0.5	0.2±0.02	0.7±0.08	11±0.5	25±1	68±2	53±1
FHF	18±1.3	49±1.2	33±2.0	1.1±0.03	5.4±0.1	4.3±0.1	0.4±0.02	6.2±0.3	0.3±0.02	0.7±0.08	11±0.9	25±1	69±2	53±2
DMC	23±1.1	46±1.3	31±0.6	1.3±0.10	5.0±0.1	2.5±0.1	0.2±0.05	2.5±0.3	0.2±0.05	0.2±0.05	10±0.3	18±1	59±2	48±4
DMA	19±1.3	50±1.5	31±0.9	1.2±0.06	5.3±0.1	3.5±0.1	0.3±0.05	4.3±0.2	0.3±0.05	0.4±0.05	10±0.5	25±1	67±2	53±1
DMF	18±1.4	50±1.8	32±0.7	1.1±0.06	5.4±0.2	3.6±0.1	0.4±0.06	4.2±0.2	0.3±0.05	0.4±0.05	10±0.5	26±1	69±2	54±1
ZHC	26±1.1	47±0.5	28±0.7	1.4±0.06	4.8±0.1	2.7±0.2	0.3±0.02	3.7±0.5	0.1±0.02	0.2±0.06	11±0.8	13±1	52±1	45±3
ZHA	21±0.7	51±1.0	28±1.2	1.1±0.10	5.1±0.1	3.8±0.1	0.4±0.03	5.2±0.3	0.2±0.03	0.6±0.06	11±0.5	21±1	63±2	52±2
ZHF	21±0.8	51±0.6	29±1.2	1.2±0.06	5.1±0.1	3.8±0.2	0.4±0.02	5.7±0.3	0.2±0.02	0.5±0.06	11±0.5	23±1	64±1	55±2
ZMC	25±1.4	49±0.6	27±1.0	1.3±0.05	4.7±0.1	2.4±0.2	0.2±0.02	5.0±0.5	0.1±0.02	0.3±0.02	9±0.2	15±1	53±2	46±3
ZMA	20±0.8	52±1.1	27±1.9	1.2±0.06	4.9±0.1	3.6±0.1	0.3±0.03	5.3±0.3	0.2±0.02	0.4±0.01	10±0.2	19±1	55±1	55±2
ZMF	20±1.0	53±1.4	27±1.0	1.2±0.04	5.1±0.1	3.5±0.2	0.3±0.03	5.8±0.3	0.2±0.01	0.4±0.02	11±0.3	19±1	56±2	54±3
FLC	19±1.3	48±1.6	34±0.5	1.3±0.02	5.0±0.2	2.6±0.2	0.3±0.02	5.2±0.3	0.3±0.04	2.4±0.07	6±0.3	22±1	63±2	48±1
FLA	16±1.6	50±1.8	34±0.8	1.2±0.02	5.8±0.2	3.7±0.2	0.3±0.02	10.4±0.2	0.4±0.04	2.9±0.08	14±0.3	30±1	70±1	66±2
FLF	16±0.8	49±1.3	35±0.9	1.1±0.02	5.4±0.2	3.9±0.2	0.3±0.03	7.5±0.3	0.4±0.03	2.6±0.06	12±0.3	30±1	72±2	62±1

Appendix C

Appendix C. Frequency of occurrence and species composition in evergreen forest, disturbed forest or/and agroforestry and arable land

Scientific name	Growth form	Evergreen forest					Disturbed forest or/and agroforestry					Arable land				
		ZHFO	ZMFO	FLFO	FHFO	DMFO	ZHAG	ZMAG	FLAG	FHAG	DMAG	ZHCU	ZMCU	FLCU	FHCU	DMCU
Polyscias fulva Hiern.	T	15	5	9	4	8	5	10	2	3	2	2	-	-	-	-
Schefflera abyssinica Hochst. ex A.Rich	T	15	-	-	3	-	2	-	-	-	-	-	-	-	-	-
Sapium ellipticum Hochst. Pax	T	6	-	2	3	6	-	-	-	-	-	-	-	-	-	-
Cordia africana Lam.	T	11	5	11	4	5	3	3	7	9	3	2	1	2	-	2
Cyathea manniana Hook.	T	25	-	-	22	-	-	-	-	-	-	-	-	-	-	-
Bridelia micrantha Hochst.Baill.	T	12	-	-	2	-	2	2	-	-	-	-	-	-	-	-
Croton macrostachyus Hochst.exDelile	T	3	4	14	3	5	3	-	2	-	2	-	-	-	1	-
Albizia gummifera J.F.Gmel.C.A.Sm.	T	8	7	9	4	8	3	21	25	19	23	-	-	-	-	-
Millettia ferruginea Hochst Baker	T	4	8	11	4	16	25	26	22	21	25	-	2	-	-	-

Scientific name	Growth form	Evergreen forest					Disturbed forest or/and agroforestry					Arable land				
		ZHFO	ZMFO	FLFO	FHFO	DMFO	ZHAG	ZMAG	FLAG	FHAG	DMAG	ZHCU	ZMCU	FLCU	FHCU	DMCU
Trichilia dregeana Sond.	T	5	-	-	2	-	-	-	-	2	2	-	-	-	-	-
Ficus sur Forssk.	T	4	2	6	4	-	-	-	2	2	-	-	-	-	-	-
Hagenia abyssinica Willd.	T	2	-	4	6	3	3	3	-	-	-	-	-	-	-	-
Prunus africana Hook.f.Kalkman	T	-	-	-	2	-	-	-	-	-	-	-	-	-	-	-
Aningeria adolfi-friedericii Engl.	T	11	-	-	5	3	2	-	-	-	-	-	-	-	-	-
Juniperus procera Hochst. exEndl.	T	-	42	-	-	-	-	-	-	-	-	-	-	-	-	-
Grevillea robusta A. Cunn	T	-	44	-	-	-	-	-	-	-	4	-	-	-	3	-
Spathodea campanulata P.Beauv	T	-	1	-	-	-	-	-	-	-	-	-	-	-	-	-
Ficus vasta Forssk	T	-	-	4	-	4	-	-	2	-	-	-	-	-	-	-
Dracaena steudneri Schweinf.ex Engl.	T	-	-	2	-	-	-	-	-	-	-	-	-	-	-	-
Sesbania sesban LMerr	T	-	-	3	-	-	3	4	-	3	2	-	-	1	-	-
Syzygium guineense Wall.	T	2	-	2	1	-	-	-	-	-	-	-	-	-	-	-
Celtis africana N.L.Burm	T	2	-	1	1	-	-	-	-	-	-	-	-	-	-	-

Scientific name	Growth form	Evergreen forest					Disturbed forest or/and agroforestry					Arable land				
		ZHFO	ZMFO	FLFO	FHFO	DMFO	ZHAG	ZMAG	FLAG	FHAG	DMAG	ZHCU	ZMCU	FLCU	FHCU	DMCU
Leucaena leucocephala Lam. de Wit	T	-	18	-	-	-	3	2	-	-	2	-	-	-	-	-
Milicia excelsa Welw.C.C.Berg	T	-	-	1	-	-	-	-	-	-	-	-	-	-	-	-
Ehretia cymosa Thonn.	T	2	-	-	1	-	-	-	-	-	-	-	-	-	-	-
Manilkara butugi L.Dubard	T	2	-	6	-	-	3	-	-	-	-	-	-	-	-	-
Mangifera indica L.	FT	-	-	-	-	-	21	4	2	5	22	-	-	-	-	-
Carica papaya L.	FT	-	-	-	-	-	3	3	-	3	-	-	-	-	-	-
Persea americana Mill.	FT	-	-	-	-	-	26	28	3	5	24	-	-	-	-	1
Citrus sinensis L.Osbeck	FT	-	-	-	-	-	-	5	2	-	-	-	-	-	-	-
Vernonia amygdalina Delile	S	20	-	8	12	11	3	3	-	-	-	-	-	-	-	-
Rhamnus prinoides L'Hérit.	S	-	-	-	-	-	6	6	3	3	5	5	-	-	-	-
Coffea arabica L.	S	-	-	-	-	-	54	42	40	39	46	-	-	-	-	-
Catha edulis Vahl Forssk. Ex.Endl	S	-	-	-	-	-	9	6	-	15	-	-	-	-	-	20
Grewia ferruginea Hochst.	S	5	-	-	3	6	-	-	-	-	-	-	-	-	-	-

Scientific name	Growth form	Evergreen forest					Disturbed forest or/and agroforestry					Arable land				
		ZHFO	ZMFO	FLFO	FHFO	DMFO	ZHAG	ZMAG	FLAG	FHAG	DMAG	ZHCU	ZMCU	FLCU	FHCU	DMCU
Delonix ragia Boi.ex Hook.Raf.	S	-	36	-	-	-	-	-	-	-	-	-	-	-	-	-
Ricinus communis L.	S	3	4	3	2	-	-	-	-	2	5	2	-	-	-	-
Solanecio gigas VatkeC. Jeffrey	S	12	-	-	16	2	-	-	-	-	-	-	-	-	-	-
Discopodium penninervium Hochst.	S	5	-	-	2	-	-	-	-	-	-	-	-	-	-	-
Heliotropium cinerascens A. DC.	S	-	-	-	-	-	-	-	-	-	-	-	6	-	-	-
Hypericum quartinianum A. Rich.	S	5	-	-	-	-	-	-	-	-	-	-	-	-	17	-
Isoglossa somalensis Lindau	S	-	2	-	-	-	-	-	-	-	-	-	-	-	-	-
Justicia schimperiana T.Anderson	S	3	2	5	2	3	-	5	-	-	-	-	2	5	-	-
Microglossa pyrifolia Lam. O. Ktze	S	3	-	2	-	-	-	-	-	-	-	-	-	-	-	-
Ocimum lamiifolium Hochst. exBenth.	S	3	6	-	2	-	-	-	4	3	2	-	-	-	-	-

Scientific name	Growth form	Evergreen forest					Disturbed forest or/and agroforestry							Arable land		
		ZHFO	ZMFO	FLFO	FHFO	DMFO	ZHAG	ZMAG	FLAG	FHAG	DMAG	ZHCU	ZMCU	FLCU	FHCU	DMCU
Phytolacca dodecandra L'Herit.	S	2	2	4	2	2	-	6	-	-	-	-	-	-	-	-
Premna schimperi Engl	S	2	-	3	2	-	-	-	2	-	-	-	-	2	4	-
Salvia lecucantha Cav.	S	3	6	-	3	3	-	-	-	-	-	-	-	-	-	-
Carissa spinarum L.	S	4	6	2	2	6	3	4	2	3	3	-	-	3	2	3
Ensete ventricosum Welw.Cheesman	H	-	-	-	-	-	6	8	3	10	2	-	-	-	-	-
Colocasia esculenta L. Schott	H	-	-	-	-	-	51	31	7	47	18	61	50	-	-	70
Zea mays L.	G	-	-	-	-	-	-	-	-	-	-	-	117	79	103	106
Musa sapientum L.	H	-	-	-	-	-	-	5	9	-	2	-	-	4	-	-
Ruta graveolens L.	H	-	-	-	-	-	3	6	7	-	4	-	-	-	-	-
Brassica oleracea L	H	-	-	-	-	-	2	12	6	5	2	-	-	-	-	-
Aframomum corrorima A.Braun Jansen	H	-	-	-	-	-	3	12	-	-	-	-	-	-	-	-
Acanthus eminens L.	H	2	4	4	2	3	-	-	-	-	-	-	-	-	-	-
Argemone mexicana L.	H	6	10	3	2	-	-	-	-	-	-	-	-	-	-	
Berkheya spekeana Oliv.	H	6	-	-	5	-	-	-	-	-	-	-	-	-	-	

Scientific name	Growth form	Evergreen forest					Disturbed forest or/and agroforestry					Arable land				
		ZHFO	ZMFO	FLFO	FHFO	DMFO	ZHAG	ZMAG	FLAG	FHAG	DMAG	ZHCU	ZMCU	FLCU	FHCU	DMCU
Cirsium schimperi Vatke C. Jeffrey exCuf	H	3	-	-	1	-	-	-	-	-	-	-	-	-	-	
Clematis hirsuta Guill&Perr.	H	4	-	12	6	4	-	-	3	-	-	-	-	-	-	-
Echinops kebericho Mesfin	H	3	-	-	4	2	-	-	-	-	-	-	-	-	-	-
Galinsoga parviflora Cav.	H	-	-	-	-	-	37	78	53	42	27	41	140	56	133	127
Leonatis ocymifolia Burm. f. lwarsson	H	5	-	6	-	-	-	-	-	-	-	-	-	-	-	-
Hypoestes forskaolii VahlRoem. & Schult.	H	3	-	21	9	-	3	-	-	-	-	-	-	-	-	-
Inula confertiflora A. Rich.	H	6	9	-	7	-	-	-	-	-	-	-	-	-	-	-
Isodon schimperi VatkeJ.K.Morton	H	2	-	12	8	-	1	-	7	21	6	-	-	-	-	-
Justicia striata Klotzsch Bullock	H	3	2	5	2	3	-	5	-	-	-	-	2	5	-	-
Lablab purpureus L. Sweet	H	2	6	9	6	4	3	-	-	-	-	-	-	26	15	8
Physalis peruviana L.	H	2	2	-	1	2	-	-	-	-	-	-	-	-	-	-
Plectranthus barbatu Andrews	H	25	9	26	15	2	-	-	-	-	-	22	37	8	15	35

Scientific name	Growth form	Evergreen forest					Disturbed forest or/and agroforestry					Arable land				
		ZHFO	ZMFO	FLFO	FHFO	DMFO	ZHAG	ZMAG	FLAG	FHAG	DMAG	ZHCU	ZMCU	FLCU	FHCU	DMCU
Bidens pilosa L. 1753	H	3	15	4	5	3	4	9	26	27	25	27	45	76	16	21
Solanum incanum L. 1753	H	-	9	-	-	2	-	-	-	-	-	-	4	-	-	-
Veronica persica Poiret	H	-	-	-	14	10	4	-	12	24	5	22	20	99	26	34
Bidens pachyloma Oliv. and Hiern Cufod.	H	-	-	-	-	-	-	-	-	-	-	12	32	12	26	13
Agerantum conyzoides L.1753	H	-	-	-	-	-	6	27	22	28	5	29	45	20	10	11
Ocimum basilicum L.	H	3	-	-	2	-	3	-	-	-	-	-	-	-	-	-

The three vegetation groups are based on species presence and absence data from 45 studied plots using TWINSPAN analysis: evergreen forest, disturbed forest or/and agroforestry and arable land. Growth forms: T: tree; FT: fruit tree; S: shrub;G: grass; H: herb.