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# Impact of deforestation on soil fertility, soil carbon and nitrogen stocks: the case of the Gacheb catchment in the White Nile Basin, Ethiopia.

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## 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 agricultural land have led to deforestation. We determine the effect of deforestation on soil fertility, soil carbon and nitrogen stocks and hypothesize that tropical forests and agroforestry have similar characteristics, in contrast to the deforested areas used as cropland. Hence, soil samples ($n = 360$) have been taken from the natural forest, agroforestry and croplands at four depths (0–20 cm, 20–40 cm, 40–60 cm and 60–80 cm) in three altitudinal belts. The topsoil and subsoil physico-chemical characteristics, pH, organic carbon, total nitrogen, available phosphorus, exchangeable calcium, magnesium, cation exchange capacity and exchangeable base cations were significantly higher in both the forest and agroforestry than in croplands, 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 were significantly different from cropland in 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 losses due to the conversion of forest to cropland are similar to the losses when converting 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.

## 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 communities and natural climate regulation, with 75% terrestrial organic carbon storage (Lal, 2004; Lemenih and 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

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use changes have several undesirable consequences like decline in soil fertility, soil carbon and nitrogen stocks (Lemenih, 2004; Lemenih and Itanna, 2004; Tesfaye et al., 2016; Henok et al., 2017). 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 southern region of Ethiopia (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 stocks varies 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 and 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).

Worldwide, research has been done to test the impact of deforestation on soil fertility and soil organic carbon stocks but the findings and suggested alternative land uses did not bring changes to the livelihood of the local community and did not reduce the pressure on the natural forest. Further, such experimental research did not include and verify locally adopted alternative land use types. Because of this, the earlier work did not come up with outcomes that could sustain the livelihood of the local community and the forest cover. For instance, majority of land use changes or deforestation related impact studies did not include agroforestry on their experimental research works, they mainly focus on comparison of forest with cropland, grazing, exclosures conservation agriculture and fallow land (Bhan and Behera, 2014; Getachew, 2011; Mekuria, 2005; Yimer et al., 2015).

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. Despite the study area's high annual rainfall, no effort has been made to assess the effect of deforestation 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 carbon and nitrogen stocks and (iii) to link deforestation induced loss of 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. Materials and Methods

### 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. 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. The average 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 are associated 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. ex Delile, *Hagenia abyssinica* Willd., *Millettia ferruginea* Hochst. Baker, *Polyscias fulva* Hiern. Harms, *Albizia gummifera* J.F.Gmel. C.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* Hook F.C. Jeffrey (own observations).

Deforestation takes place in which trees are completely or selectively removed to create farmland; as all forest soils are deemed to be very fertile, farmers try to encroach on forests nearby their existing plots, hoping not to be noticed, or punished by the authorities. This leads to two main other land use types: open field farmland and agroforestry. The agroforestry land of Gacheb catchment is composed of *Coffea arabica* L., as main 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 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. On the other hand, on the cropland, cereal crops like maize (*Zea mays* L.) are integrated with root vegetables like taro and park trees (own observations).

### 2.2. Data collection and analysis

The soil samples were taken in April and May 2013. A preliminary field visit was made using topographic maps so as to fully understand the land features and landscape for locating the study area's representative soil sampling points. Five study sites were selected along three 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 sampling 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 in a high rainfall area and fine roots of trees have a role in nutrient addition and recycling. During agroforestry site selection, we have carefully selected sites that are bit far from homesteads and free from animal and human manure dropping and application. 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 (Table 1).

The soil samples were collected from 20 × 20 $m^2$ plots with three replicates at a 20 m interval. 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 and Black, 1934), total nitrogen using the Kjeldahl method (Bremner and Mulvaney, 1982), available phosphorus (Olsen et al., 1954), exchangeable bases (Ca, Mg, K and Na) in the soils were estimated by the ammonium acetate (1 M $NH_4OAc$ 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

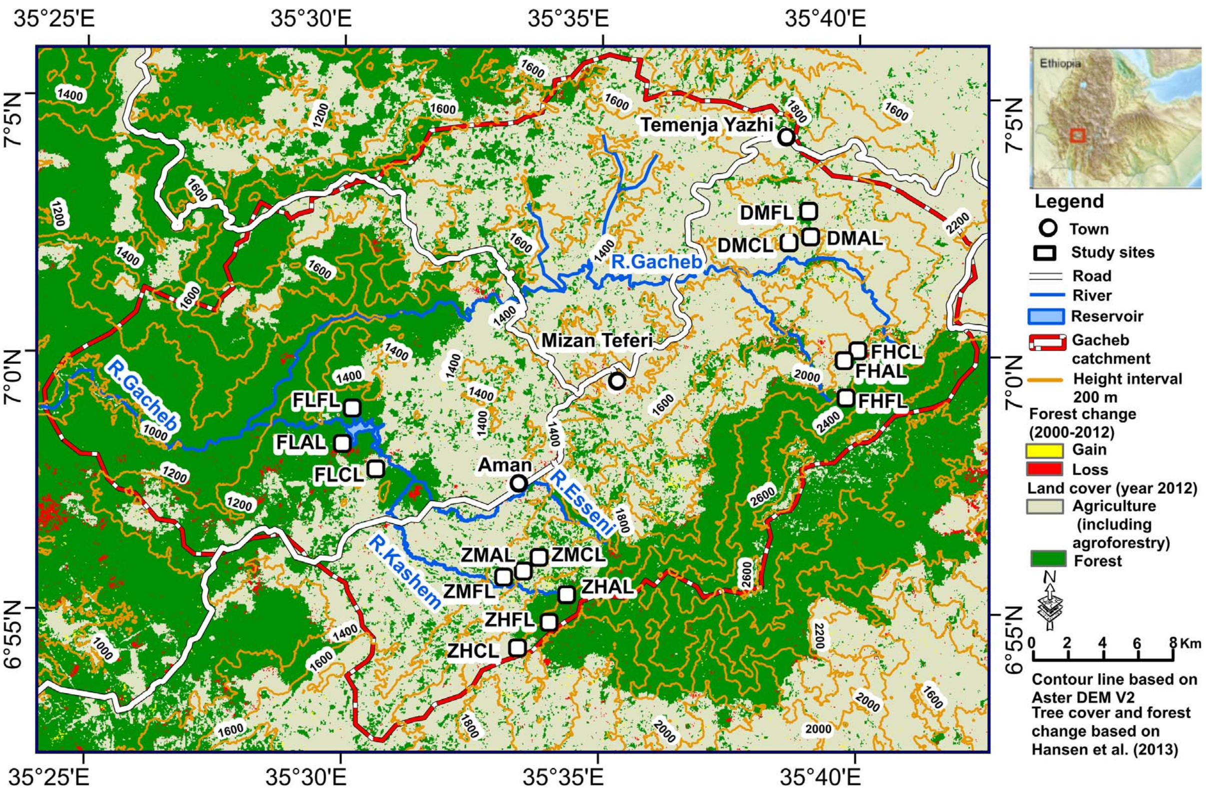

**Fig. 1.** Landcover and location of the study sites in the Gacheb catchment, southwestern Ethiopia.

**Table 1**
The background history of the studied cropland and agroforestry sites.

| Site | Land use | Current land use and land use history | Land management |
|---|---|---|---|
| FH | Cropland | - Maize, taro and weeds are dominant plants<br>- The land was forest before 14 years | - Crop rotation: maize, beans and barley<br>- Plowing: oxen 3 times, hand tools 2 times<br>- No fertilizer, no fallowing |
| | Agroforestry | - Coffee mixed with various 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 | - Tree litter incorporated to the soil<br>- Weeding before coffee harvesting<br>- No fertilizer |
| DM | Cropland | - Maize, taro and weeds are dominant plants<br>- The land was forest before 20 years | - Crop rotation: maize, beans and sorghum<br>- Plowing: oxen 3 times, hand tools once yearly<br>- No fertilizer, no fallowing |
| | Agroforestry | - Coffee is the dominant crop but nitrogen fixing shade trees, fruit trees and root and tuber crops are integrated | - Tree litter incorporated to the soil<br>- Weeding before coffee harvesting |
| ZH | Cropland | - Maize, taro and weeds are dominant plants<br>- The land was forest before 15 years | - No crop rotation: only maize<br>- Plowing: oxen 3 times, no hoeing<br>- No fertilizer, no fallowing |
| | Agroforestry | - Alike the other sites, agroforestry coffee is the dominant crop, but strong presence of shade and multipurpose trees, spices, fruit trees and food crops (root and tubers) | - Tree litter incorporated to the soil<br>- Weeding before coffee harvesting<br>- No fertilizer |
| ZM | Cropland | - Maize, taro and weeds are the dominant plants<br>- The land was forest before 23 years | - Crop rotation: maize and sorghum<br>- Plowing: oxen 3 times, hand tools once<br>- No fertilizer, no fallowing |
| | Agroforestry | - Coffee mixed with various nitrogen fixing shade trees and fruit trees. Coffee is the dominant crop but spices, fruit trees, root and tuber crops and nitrogen fixing shade trees are also well represented. | - Tree litter incorporated to the soil<br>- Weeding before coffee harvesting<br>- No fertilizer |
| FL | Cropland | - Maize and weeds are the dominant plants<br>- No taro<br>- The land was forest before 19 years | - Crop rotation: maize, beans and sorghum<br>− Plowing: oxen 3 times, hand tools once<br>− No fertilizer, no fallowing |
| | Agroforestry | -Coffee mixed with various nitrogen fixing shade trees and fruit trees. Coffee is dominant crop. Root crops are few in number | - Tree litter incorporated to the soil<br>- Weeding before coffee harvesting<br>- No fertilizer |

Study sites: FH: Faketen high; DM: Dakin middle; ZH: Zemika high; ZM: Zemika middle; FL: Fanika low.

by the ammonium acetate method (Hesse, 1972). The base cation saturation (BS) has been calculated based on the standard formula:

$$\mathrm{BS}\ (\%) = [(\mathrm{Na}^{+} + \mathrm{K}^{+} + \mathrm{Ca}^{2+} + \mathrm{Mg}^{2+})/\mathrm{CEC}] \times 100 \quad (1)$$

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

$$\mathrm{Ct} = \mathrm{Kd} \times \rho \times \%\mathrm{C} \quad (2)$$

Where Ct = Soil organic carbon stock (g $\mathrm{cm}^{-3}$), Kd = the depth of the soil sample thickness of the sampled soil layer (cm), ρ= the soil bulk density (g $\mathrm{cm}^{-3}$), %C = the percentage organic carbon.

The total nitrogen was also computed with a similar equation. The losses in soil organic carbon and nitogen −because of deforestation- were estimated by subtracting the total soil organic carbon and nitrogen stocks under forest from that of the corresponding depth under agroforestry or cropland. The computed loss values were then divided by the number of years since the conversion to obtain soil organic carbon and nitrogen 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 et al. (2008); an increase in 1 Mg $\mathrm{ha}^{-1}$ in soil carbon represents a 3.67 Mg of carbon dioxide removal from the atmosphere.

The topsoil and subsoil's physico-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's physico-chemical characteristics in differentiation of the three land-use types. The physico-chemical characteristics with factor loading (> 0.5) were considered. The difference in soil characteristics between the three land use types at (0–20 and 20–40 cm), and (40–60 and 60–80 cm) depth ranges were not showing much differences, hence, 0–20 cm and 40–60 cm soil depth ranges were used to compare the soil fertility of the land use types at five sites. 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.

## 3. Results

### 3.1. Contrasts between the three land-use types

The biplots of the topsoil show that the first factor axis (FA-1) of the biplots 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 $\mathrm{N_t}$, pH, $\mathrm{Mg}^{2+}$, $\mathrm{Ca}^{2+}$, P and CEC are also higher under forest and agroforestry than under cropland. Most importantly, all cropland topsoils are sandy and low in soil organic carbon except one of the cropland at high elevation. The second factor axis (FA-2) is independent from the gradient, forest to cropland. This sets aside the three plots at low elevation (FL site) which have lower soil organic carbon than the high (FH and ZH) and middle elevation (DM and ZM) sites. This corresponds to a gradient from low soil organic carbon to high soil organic carbon (Fig. 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 contents (FH, ZH, DM and ZM site). Soil physico-chemical charcterstics $\mathrm{Mg}^{2+}$, $\mathrm{Na}^{+}$, CEC and $\mathrm{K}^{+}$ 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 is present, from high soil organic carbon and high sand (forest) to low soil organic carbon and low sand (cropland) (Fig. 2b).

### 3.2. Soil physico-chemical characteristics

#### 3.2.1. Soil texture and bulk density

The topsoil sand fraction of cropland is significantly different from both forest and agroforestry ($P < 0.01$) 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 ($P < 0.01$) 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 (57% at the FH, 55% DM and ZH sites) 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) (Fig. 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 clay fraction in the forest, agroforestry and cropland proved to be similar at all sites (Fig. 4).

The topsoil bulk density of cropland differs significantly from both the forest and agroforestry at all sites ($P < 0.01$). 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 $\mathrm{cm}^{-3}$), DM site (1.2 g $\mathrm{cm}^{-3}$), ZH site (1.24 g $\mathrm{cm}^{-3}$), ZM site (1.24 g $\mathrm{cm}^{-3}$) and FL (1.21 g $\mathrm{cm}^{-3}$) (Fig. 3). Similarly, the subsoil bulk density of cropland varies significantly from both the forest and agroforestry at all sites ($P < 0.01$). 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 $\mathrm{cm}^{-3}$), DM site (1.30 g $\mathrm{cm}^{-3}$), ZH site (1.37 g $\mathrm{cm}^{-3}$), ZM site (1.32 g $\mathrm{cm}^{-3}$) and FL site (1.30 g $\mathrm{cm}^{-3}$) (Fig. 4).

#### 3.2.2. 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. 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, 5.4 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. 4).

The topsoil organic carbon contents of the forest (as well as agroforestry) varied significantly from the cropland ($P < 0.01$) at all sites. However, the forest's soil organic carbon contents are similar to the agroforestry at all sites. The highest soil 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. 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 subsoil 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. 4).

#### 3.2.3. 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 ($P < 0.01$). 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. 3). Likewise, the

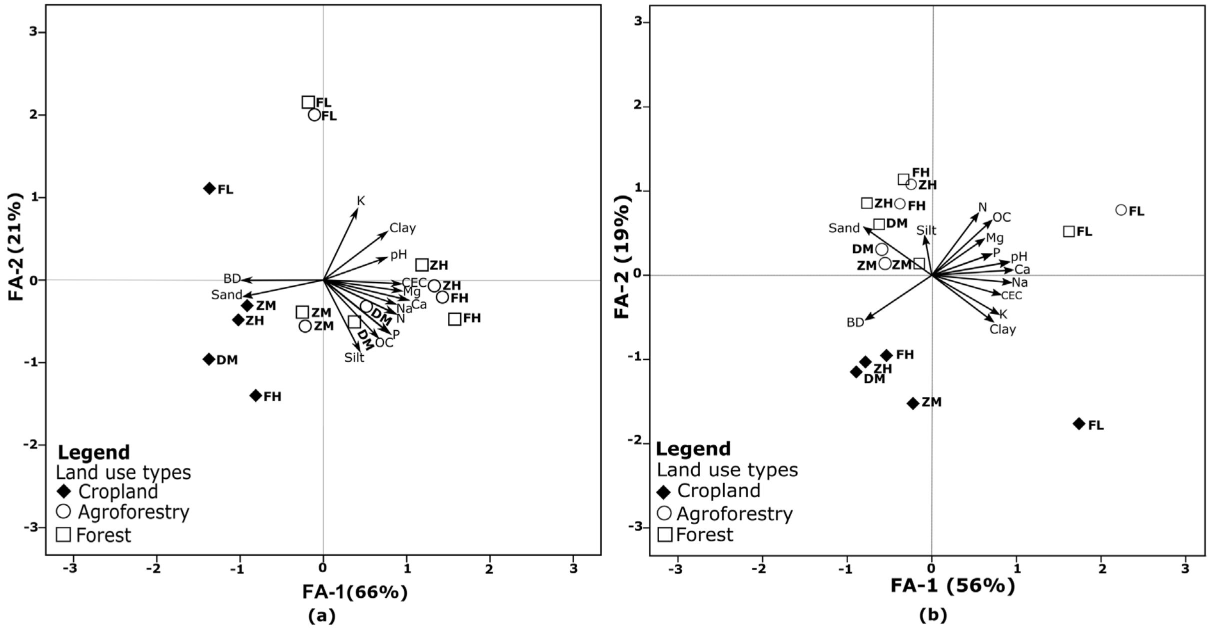

**Fig. 2.** Biplots of (a) topsoil (0–20 cm) and (b) subsoil (40–60 cm) physico-chemical characteristics of 5 study sites. Land-use types: cropland, agroforestry and forest. Study sites: FH = Faketen high, DM = Dakin middle, ZH = Zemika high, ZM = Zemika middle and FL = Fanika low. Soil physico-chemical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

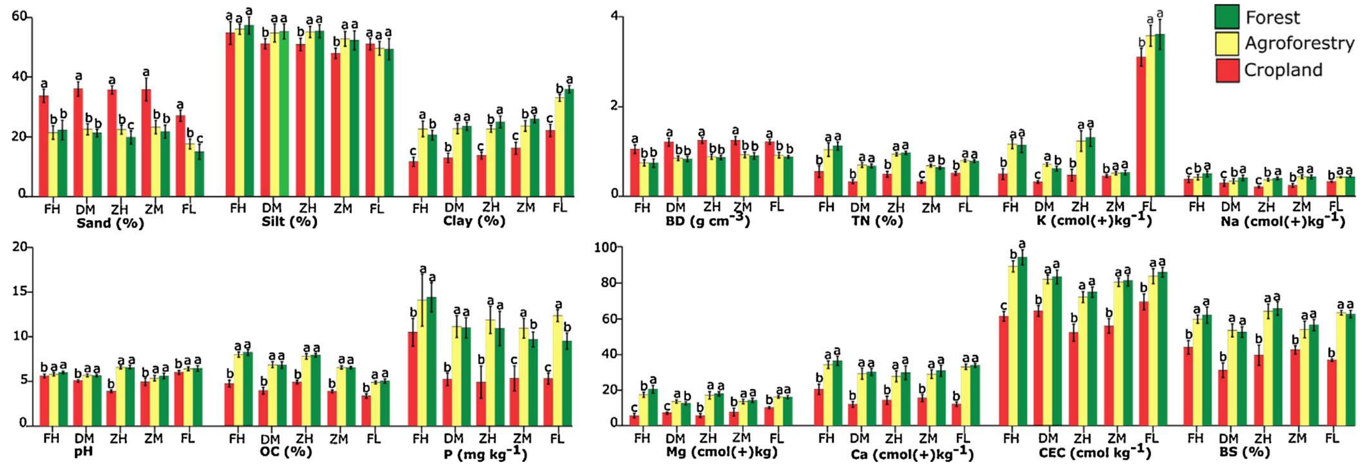

**Fig. 3.** Physico-chemical characteristics of topsoil (0–20 cm) under forest, agroforestry and cropland. Study sites: FH = Faketen high, DM = Dakin middle, ZH = Zemika high, ZM = Zemika middle, FL = Fanika low. Number of replicates (n = 3). *Mean value of land-use types soil physico-chemical characteristics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

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 subsoil 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. 4).

The topsoil available phosphorus contents (both under agroforestry and forest) were found to be significantly different from that of the cropland ($P < 0.01$) at all sites. Similarly, the forest's topsoil available phosphorus contents are different from the agroforestry at all sites, except at the FH site. The highest topsoil 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. 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 subsoil 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. 4).

The topsoil exchangeable magnesium and calcium contents of both the forest and agroforestry are significantly different from the cropland ($P < 0.01$) at all sites. Yet, there is no difference in the exchangeable magnesium and calcium contents between the forest and agroforestry at all sites, except the ZH site. The highest topsoil exchangeable magnesium 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 calcium 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. 3). However, the subsoil exchangeable magnesium contents of the three land-use types are similar at all sites (except the difference at the FL site). On the contrary, the subsoil exchangeable

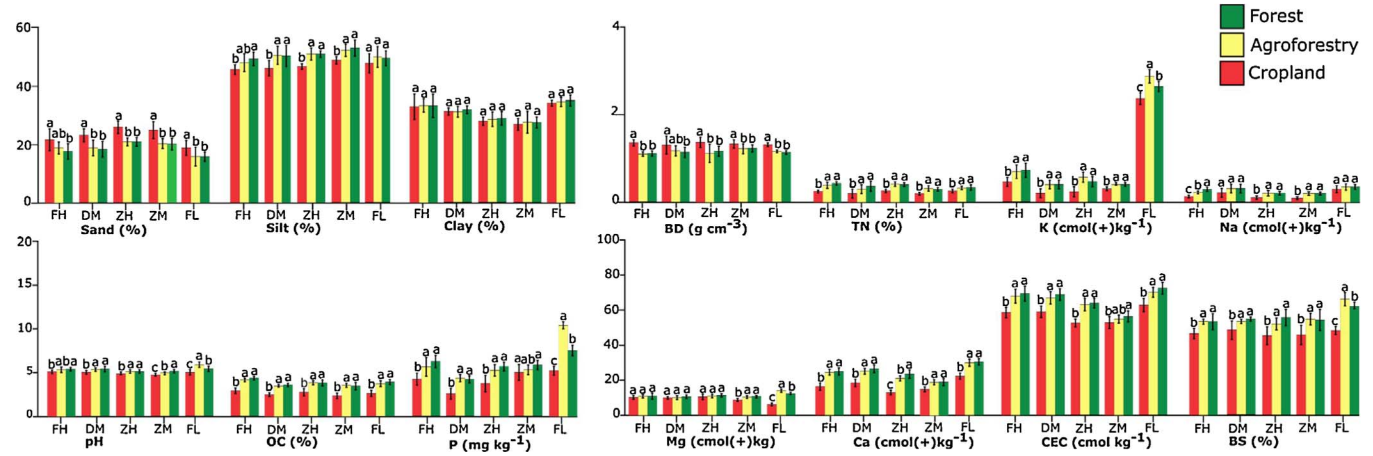

**Fig. 4.** Physico-chemical characteristics of subsoil (40–60 cm) under forest, agroforestry and cropland. Study sites: FH = Faketen high, DH = Dakin middle, ZH = Zemika high, Zemika middle, FL = Fanika low. Number of replicates (n = 3) *Mean value of land-use types soil physico-chemical characteristics with similar letter within the same site are not significantly different from each other at $p < 0.05$.

calcium contents of both the forest and agroforestry vary significantly from the cropland at all sites ($P < 0.001$). The highest subsoil exchangeable magnesium 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 calcium 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. 4).

### 3.2.4. 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 ($P < 0.01$).Yet, the forest and agroforestry are similar regarding CEC and exchangeable base cations at all sites. 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 (62% at FH site, 66% at ZH site and 56% at ZM site) and agroforestry 53% at DM site and 63% at FL site) (Fig. 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. 4).

## 3.3. Soil carbon and nitrogen stocks in the three land-use types

### 3.3.1. Soil organic carbon stocks

The soil organic carbon stocks of both forest and agroforestry are similar at all sites concerning all soil depths (0–20, 20–40, 40–60 and 60–80 cm). However, both the forest and agroforestry are significantly different from the cropland at all sites and at all depths (except 60–80 cm). The soil organic carbon stocks of the forest and agroforestry are similar to the cropland's for all sites at a 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).

### 3.3.2. Soil nitrogen stocks

Likewise the soil nitrogen stocks found in the soil of both forest and agroforestry were similar at all sites and all soil depths. Yet, the soil nitrogen stocks in both forest and agroforestry were different from the cropland at all sites and at all soil depths, except at 60–80 cm depth for which there was no difference between land-use types. 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).

### 3.3.3. Soil organic carbon and nitrogen loss

The estimated total soil organic carbon loss as the result of conversion of forest to cropland leads to a soil organic 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 organic 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 3).

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 3).

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).

## 4. Discussion

### 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. (2013), who reported the difference in soil characteristics between woodland and cultivated land in the first principal component axis (PCA1). The topsoil's second factor axis (FA-2) reveals the distinction in soil organic

**Table 2**
Soil carbon and nitrogen stocks in cropland, agroforestry and forest.

| | | | Soil organic carbon stocks (Mgha$^{-1}$) | | | Soil nitrogen stocks (Mgha$^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|
| 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 sites: 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-use types soil carbon and nitrogen stocks with the same letter within the same site and depth are not significantly different from each other at $p < 0.05$.

**Table 3**
Soil carbon and nitrogen loss and calculated potential carbon dioxide emission related to a 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 | High | 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 | Middle | 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 | High | 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 | Middle | 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 | Low | 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 |

Total soil carbon and nitrogen loss is the sum of loss from all soil depths (0–80 cm) within the land-use type in each site. Study sites: FH: Faketen high; DM: Dakin middle; ZH: Zemika high; ZM: Zemika middle; FL: Fanika low.

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 finding is in line with the findings of Aguilera et al. (2013), who reported an increase in surface soil organic carbon with increasing altitude, and the fact that low temperature at high altitude maintains a low soil organic matter decomposition rate (Wei et al., 2013).

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. 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).

### 4.2. Soil physico-chemical characteristics

#### 4.2.1. 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 interventionin 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 and 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 tothe tree root senescence and root litter decomposition,which in turn decrease the subsoil bulk density (Sharma, 2011; Scheffer and Aerts, 2000).

#### 4.2.2. 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 Abegaz and Adugna (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; Yimer et al., 2007). Furthermore, the forest and agroforestry possessa 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; Yimer et al., 2007).

#### 4.2.3. 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* L Merr 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 Abegaz and Adugna (2015), Nsabimana et al. (2008) and Binkley and Giardina (1998).

Similarly, both forest and agroforestry show higher subsoil nitrogen, available phosphorus, exchangeable calcium and magnesium, in relation to organic matter supplementing by dead fine roots and mycorrhizal fungi in the subsoil. The mycorrhizal fungi associated to the roots of leguminous trees also promote the weathering of parent material and organic matter breakdown. 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 magnesium contents with both forest and agroforestry may be due to the leaching of exchangeable magnesium from the topsoil. These results are in line with Duguma et al. (2010) and Abegaz and Adugna (2015). In general, the available phosphorus in forest and agroforestry (6–11 mg $kg^{-1}$) are below the critical value (75–150 mg $kg^{-1}$) (Howard et al., 1999), which reveals that the soils of the study area are critically deficient in available phosphorus.

#### 4.2.4. 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 base cations 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). In general, the CEC of the study area soils are high, this may be due to the lithology, which comprises of Tertiary basalt traps and rhyolites. Hence, the high CEC of the study areas soil may be due to contribution of weathered clay from basaltic and rhyolites rocks. Similarly, Godelitsas et al. (2010) reported that weathered clay from basaltic rocks are generally very high in cation exchange capacity (98 cmol kg$^{-1}$). Further, Nitisols with their high clay and organic matter contents, may have contributed to the high soil CEC (Verheye, 2009).

### 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* L Merr and *Leucaena leucocephala* Lam. de Wit) could constitute the lion's share for the high soil organic carbon 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; 15 Mg ha$^{-1}$ in agroforestry and 65 Mg ha$^{-1}$ on arable land) and Lemenih and Itanna (2004). The total soil organic carbon stocks (estimated to a depth of 80 cm) are within the range for the Afromontane forest in Tanzania (252 and 581 Mg ha$^{-1}$) (Munishi and 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 and 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.

## 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. However, the avaliable phosphorus content in forest, agroforestry and cropland is belowe the critical thershehold level for tropical soil. 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 soil organic 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 maintainthe 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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