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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