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Deforestation and land use strongly effect soil organic carbon and nitrogen stock in Northwest Ethiopia

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ABSTRACT

Soil is the largest terrestrial organic carbon pool and can act as a source or sink for atmospheric CO_2. Although reliable soil carbon (SOC) stock measurements of major ecosystems are essential for predicting the influence of advancing climate change, comprehensive data on SOC stocks is still scarce for most ecosystems in subtropical areas. In this study, SOC and N stocks of different land use systems were investigated along a climatic gradient in Northwest Ethiopia. The land use systems ranged from dry subtropical Afromontane forest, as the baseline, to cropland as the most degraded system. In addition, we investigated the changes of SOC stocks after interventions to recover vegetation cover; these were eucalyptus plantations and an exclosure to prevent grazing. Total SOC varied between land use systems and ranged from 3.1 kg C m^{-2} in croplands to 23.9 kg C m^{-2} in natural forest, and average N stock ranged from 0.4 kg N m^{-2} in croplands to 2.1 kg N m^{-2} in natural forest. In forests, there were a clear vertical gradient in SOC and N stock down the soil profile, and 60% of the total SOC and N stocks were found in the upper 10 cm soil depth. Using the Sr/Ca and Ba/Ca ratios and the vertical distribution of the C/N ratio of the soil, the losses of SOC were shown to be due to loss of the of the upper soil layer. Afforestation of degraded croplands and grazing lands with eucalyptus increased SOC stocks to nearly 70% of the natural forest levels within 30 years. Exclosure, which removed grazing pressure and allowed regeneration of native vegetation, increased SOC in the top soil only.

1. Introduction

Soil is a key factor in the global carbon cycle and can act either as a source or as a sink to atmospheric CO_2. Worldwide, soils are estimated to hold 3150 Pg of carbon (C) which is more than four times the amount of carbon stored in terrestrial plant biomass (650 Pg C) or the atmosphere (750 Pg C) (Fan et al., 2016). The size of the pool of soil organic carbon (SOC) is determined by the input of plant-derived carbon, the potential to sequester carbon through physical and bio-chemical processes, and the loss of SOC through heterotrophic respiration, leaching, and erosion (De Deyn et al., 2008; Jobbágy and Jackson, 2000).

Reliable SOC stock measurements of major ecosystems are essential to parameterize models estimating net C stocks and changes in different biomes (Powers et al., 2011; Zimmermann et al., 2009). While current models are used to estimate global and regional soil carbon pools and for predicting the influence of advancing climate change on those pools (Jones et al., 2005), comprehensive data on SOC stocks is still scarce for some ecosystems at scales relevant to local management as well as national carbon inventories (Victoria et al., 2012). Because the impact of land use conversion (LUC) varies depending on the land use type and the abiotic factors present, regional and ecosystem level studies are important (Milne et al., 2007; Schrumpf et al., 2011; Schulp et al., 2008). In Ethiopia, extensive soil carbon surveys are especially scarce for the remnant natural forests of the NW Ethiopian highlands and the land use systems established on previously naturally forested area since 1950 (Zeleke and Hurni, 2001). Natural forests and woodlands cover <9.5% of the Amhara region and about 60% of the total area is used as cropland and grazing land (Bekele, 2011; Desta et al., 2000). *Eucalyptus globules* (Labill.) has been planted in the central highlands of Ethiopia since 1895 (Pohjonen and Pukkala, 1990). It is the dominant exotic species planted in the highland areas because of its fast growth (Pohjonen and Pukkala, 1990), non-palatability to livestock, multiple use and high economic return .

Soil carbon stocks are influenced by factors such as climate, geology and weathering history, and biotic variables such as species composition and density (Fernandez et al., 2013; Vesterdal et al., 2013). The most important human effect on the rate of changes in SOC stock is attributed to LUC (Don et al., 2011; Guo and Gifford, 2002; Houghton and Goodale, 2004), and LUC is a significant factor in global emissions of CO_2

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(IPCC, 2014). The contribution of LUC to anthropogenic CO_2 emissions have recently been estimated at 1.2 Pg yr^{-1}, or about 12–15% of total anthropogenic emissions (Deng et al., 2016). Many studies have shown that the conversion of natural vegetation to cropland often leads to a depletion of SOC stocks (Abu-hashim et al., 2016; Guo and Gifford, 2002; Poeplau et al., 2011). For example, Del Galdo et al. (2003) reported that cropland soils had a 48% lower SOC content in the top 10 cm compared to permanent grassland. The reduction of original SOC stock is more intense and faster in tropical ecosystems with loss of up to 60% in a few years compared to humid temperate ecosystems with loss of 30% in 60 years of cultivation (Victoria et al., 2012). Within the complex of LUC, two of the major environmental factors influencing SOC stocks are temperature and moisture that affect heterotrophic soil respiration and hence SOC stocks (Chen et al., 2013; Feng and Simpson, 2008; Wynn et al., 2006). In addition to affecting soil moisture in high rainfall areas, precipitation can also have physical effects on soils such as erosion (Guo and Gifford, 2002). Guo and Gifford (2002) hypothesized that after conversion of forest to croplands, especially in areas with high annual rainfall, topsoil erosion causes a major loss of carbon. Mean annual precipitation in the central highlands of Ethiopia is ca.1600 mm, but can reach up to 2000 mm within the three main rainy months (Awulachew et al., 2009). Due to such heavy seasonal rainfall combined with a topography of steep slopes, extensive topsoil erosion after heavy rainfall events is common in the Ethiopian highlands (Shiferaw and Holden, 1999).

To gain an insight into changes in soils, strontium (Sr) to calcium (Ca) and barium (Ba) to calcium ratios have been widely used as markers to reconstruct environmental history (Bullen and Bailey, 2005; Tabouret et al., 2010) and biogeochemical properties of the ecosystem (Capo et al., 1998; Kabata-Pendias, 2010). Biologically, Sr^{2+} is considered to be a non-essential element, however, it is strongly associated with and chemically very similar to Ca (Capo et al., 1998) with a similar ionic radius and charge (Bullen and Bailey, 2005). Strontium/Ca and Ba/Ca ratios can be a powerful tool in studies of chemical weathering and soil genesis. These ratios often combined with measurements of isotopic $^{87}Sr/^{86}Sr$ ratios have been used to trace the relative contributions of atmospheric dust input and mineral weathering to soil formation (Bullen and Bailey, 2005; Derry and Chadwick, 2007; Li et al., 2016). For example, Li et al. (2016) could show that atmospheric dust inputs from continental Asia are an important factor in soil development in Hainan Island of the coast of China. In study of European forest soils, Lequy et al. (2012) showed that up to 30% of nutrient inputs to the soil resulted from inputs of Aeolian dust.

In this study, we hypothesized that land-use change for forest to cropland results in a rapid loss of SOC stocks, and that reestablishment of vegetation cover on degraded lands results in a restoration of SOC. To test this hypothesis, we determined SOC stocks of different land-use types in ecosystems typical for Eastern Africa. In addition, we investigated the effectiveness of planting eucalyptus (afforestation) and excluding grazing on degraded ecosystems (exclosure) in restoring SOC stock levels. Total C and N stocks were estimated in five land use systems: natural forest, eucalyptus plantation, exclosure (a degraded area excluded from animal and human interventions for rehabilitation), cropland, and grazing land at elevations ranging from 800 to 2500 m a.s.l. (above sea level). In addition, Sr/Ca and Ba/Ca ratios were used as putative markers of soil loss.

2. Material and methods

2.1. Research sites

The study was conducted in the Amhara National Regional State (170,752 km^2) located in the North-central parts of Ethiopia. Elevations range from approximately 500 m a.s.l. near to the Sudanese boarder to 4620 m in the highlands. Thirty one percent of the Amhara region can be classified as lowlands (<1500 m) and 69% as highlands (Awulachew et al., 2009; Ayalew et al., 2012). The mean annual temperatures varies from 11 °C in the highlands (Betrie et al., 2011) to 27 °C in the lowlands (Ayalew et al., 2012). The average annual rainfall in lowland areas is around 700 mm (Bewket and Conway, 2007) whereas highlands often receive over 2000 mm of precipitation (Awulachew et al., 2009). While Ethiopia is located in the tropics, the climate of the study areas in the highlands are temperate with dry winters and warm summers, and are classified as Cwb according to the Köppen-Geiger climate classification system (Peel et al., 2007). The majority of the area has a unimodal rainfall characteristic with the main rainfall months between June and September whereas the dry months are from October to May with little rain in April and May. Climate data for the sites (Table 1) were obtained from previous studies (Abiyu, 2012; Assaye et al., 2013; Moges and Kindu, 2006; Wassie et al., 2009; Workneh and Glatzel, 2008).

The topography is typical of volcanic landscapes comprising volcanic rocks, deeply incised by streams resulting the current ragged and undulating landforms. The ragged topography combined with heavy rain events during the wet season (June–August) promotes soil erosion (Betrie et al., 2011; Bewket and Sterk, 2005; Shiferaw, 2011). The major soil types in the region are Alisols, Cambisols, Leptosols, Luvisols, Nitosols, and Vertisols according to World Reference Base for soil resources (Awulachew et al., 2009; Betrie et al., 2011; WRB, 2014).

Five research sites were selected in the North-Western part of Amhara to cover major climatic and edaphic conditions within the Amhara region (Table 1). The sites Katassi, Gelawdios, Tara Gedam, Ambober, and Mahibere-Selassie have an average distance of 120 km between each other. At each site, up to five land use types, namely natural forest, eucalyptus plantation, exclosure (rejuvenated woodland on former grazing land), cropland, and grazing land were identified adjacent to each other to give similar topography, edaphic, and climate conditions for comparison of land uses at each site. However, not all land use systems were available at each site. Geographical location, climate, soil, and vegetation characteristics of each site as well as the available land use systems are described in Table 1. Forests at Gelawdios, Katassi, and Tara Gedam are dry Afromontane remnant pristine forests composed of mostly an intimate mixture of indigenous tree species. These forests (except Katassi) are traditionally better protected by local institutions and mostly confined to sacred groves associated with churches and monasteries (Aerts et al., 2016). The dominant tree species for highland areas (Gelawdios, Katassi, and Tara Gedam) are *Albizia schimperiana*, *Apodytes dimidiata*, *Calpurnia aurea*, *Carissa edulis*, *Croton macrostachyus*, *Ekebergia capensis*, *Maytenus arbutifolia*, *Olea europaea*, *Prunus africana*, and *Schefflera abyssini*ca. The extensive lowland semiarid forest around Mahibere-Selassie monastery is a savannah woodland dominated by grasses with some scattered trees. This site, which represents the typical lowland forest type of this region, is subject to frequent man-made fires that burn off the grass cover but does not cause extensive damage to the trees. Characteristic tree species in the lowland are *Acacia polyacantha*, *Balanites aegyptica*, *Boswellia papyrifera*, *Diospyros abbyssinica*, *Ficus sycomorus*, *Pterocarpus lucens*, *Sterculea setigera*, *Oxytenanthra abyssinica, and Ziziphus spinachrist*. The *Eucalyptus globules* plantations at Katassi and Gelawdios were planted on grazing land around 1985, and were thus ca. 30 years old at the time of sampling. In Tara Gedam, *Eucalyptus camaldunesis* was planted on former cropland and it has been cut 3 times since planting. The date of planting is unknown but as in this part of Ethiopia, the coppicing intervals are between 5 and 10 years, the site must be between 20 and 40 years old and more likely 40 years old. Details of tree and basal area densities in the four natural forests and two eucalyptus stands can be found in Table 1. The exclosure at Ambober was established in 2007 on former grazing land (Abiyu, 2012). The exclosure system is commonly used to rehabilitate degraded land by protecting land areas from further animal grazing and human interference. In addition to preventing grazing, enrichment planting of seedlings of indigenous and some exotic tree species was carried out. Since inception, natural revegetation has returned