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Soil carbon and nitrogen changes under a long period of sugarcane monoculture in the semi-arid East African Rift Valley, Ethiopia

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ABSTRACT

Sugarcane cultivation has been practiced over decades in a semi-arid area of the Ethiopian Rift Valley. This study evaluated the effect of sugarcane cultivation on soil C and N storages. We measured the differences in soil C and N along chronosequence fields. We estimated soil C and N losses associated with land conversion and the rate of changes over time. Results indicated that the soil C accumulation was lower under sugarcane field but slowly approached to never tilled (NT) condition. Land conversion resulted in soil C initial losses predicted to 37 Mg C ha^{-1} or 58%, which recovered with a net change of 0.35 Mg C ha^{-1} yr^{-1} or 0.29% yr^{-1}. Under the current management practices, the loss in soil C is projected to require a century to reach the sugarcane pre-establishment levels. Land conversion induced soil total nitrogen (TN) initial losses estimated to be 113 kg N ha^{-1}. However, the predicted net change in soil TN as a function of time appeared to be insignificant. Sugarcane as a direct replacement of native vegetation triggered losses in soil C levels. Yet, sugarcane cultivation as land use option established on marginal lands can have a great potential for soil carbon sequestration.

1. Introduction

Sugarcane is a promising source of sustainable energy contributing to climate change mitigation (Lal, 2008), in addition to other potential benefits such as ensuring food security and supporting the growth in global economy. Large-scale sugarcane agriculture in Ethiopia was first introduced in Awash Valley in the late 1950's (Halcrow, 1990). In recent decades, sugarcane monoculture has been expanded to wider areas of the country because of its contribution to national economy. In their assessment of the status of biofuels development in Ethiopia, Lawek and Shiferaw (2008) indicated that the trend in historical changes of the area under sugarcane monoculture in Ethiopia has increased by 134 percent between 1990 and 2008. Land conversion to sugarcane was mainly achieved by large-scale clearing of natural vegetation, plowing with farm machinery, and manual planting of cane (Kloos, 1982; Ayalew, 2001). Agricultural cultivation as a direct replacement of natural vegetation resulted in changes in the soil C storage (Rhoades et al., 2000; Osher et al., 2003; Ogle et al., 2005), yet little is known about the signs and magnitudes of these changes in sugarcane monoculture. Understanding of these changes has importance and last-longing implication for sustainable management of sugarcane at a local level, and mitigating climate change at the regional scale through soil C inventories.

Soil is the largest pool of organic carbon in terrestrial ecosystems where tropical soils contain more than 30% of the global soil C (Jobbagy and Jackson, 2000; Rhoades et al., 2000; Wang et al., 2009; Dintwe et al., 2014). It is believed that land use change to agricultural cultivation reduces C stored in soils and increases a net release of carbon into the atmosphere (West and Post, 2002; Warner et al., 2013). Many important efforts have been carried out to determine land use induced changes in soil C storage from local to global scales (Mann, 1986; Davidson and Ackerman, 1993; Houghton, 1999; Smith et al., 2000; Wu et al., 2003). The existing literature generally showed that conversion of natural land to croplands reduces soil C from 20 to 50% in tropics (Rhoades et al., 2000; Anderson-Teixera et al., 2009) compared to the soil C losses (averaging about 30%) in global temperate regions (Murty et al., 2002; Li and Zhao, 2001).

Soil C losses from agricultural practices were higher soon after the land conversion (Knops and Tilman, 2000; Rhoades et al., 2000; Murty et al., 2002), and diminished or probably stabilized with increasing the duration of cultivation (Anderson-Teixera et al.,

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2009). Despite this fact, land conversion to agriculture activities had a varying influence on the rate of soil C changes, depending on the types of native ecosystem undergoing the changes and the management options following them (West and Post, 2002; Ogle et al., 2005). For example, higher soil C losses were found in cultivated fields converted from forest clearing compared to the fields that replaced grass or pasture lands (Osher et al., 2003; Zinn et al., 2005; Anderson-Teixera et al., 2009). Despite the initial soil C differences among the pre-establishment land use or ecosystem types, accurate estimates of the historic loss are usually hampered by the lack of the required baseline data (Wu et al., 2003).

Comparison of two adjacent sites (uncultivated vs. cultivated sites) has been commonly used as a method of showing soil C change following land conversion to agriculture (Davidson and Ackerman, 1993; Dominy et al., 2001; Murty et al., 2002; Osher et al., 2003; Ogle et al., 2005). Paired plot comparison has considered control site as a baseline from which the reference is made for soil C change. Thus, the rate of change in soil C is primarily calculated as the difference in soil C between cultivated and control sites divided by the age of cultivation (Miller et al., 2004; Anderson-Teixera et al., 2009). However, this approach rarely accounted for the land conversion effect on soil C initial loss, which is usually higher and occurs upon conversion of natural land to agriculture (Osher et al., 2003; Anderson-Teixera et al., 2009). A chronosequence of cultivated fields that include multiple age data and undisturbed sites rather provides a better opportunity to see the relationship between soil C and time since cultivation. We used the advantage of fields that developed at different times to evaluate the soil C and total nitrogen (TN) changes over a long period of sugarcane monoculture. The objectives of this study were (1) to measure the differences in the soil C and TN between cultivated and never tilled (NT) fields; (2) to assess the land conversion effect on soil C and TN losses, and (3) to determine the rates of change in soil C and TN as a function of age. We hypothesized that soil C and TN storages are greater in never tilled (NT) soils than in the cultivated soils. We also hypothesized that the net change in soil C and TN accumulations significantly correlates with the age of cultivation.

2. The study area

We conducted the study at sugarcane plantation site in the floodplains of Awash River Basin within Metehara plain, Ethiopian part of the East African Rift Valley. The area is located between 8° 44′ 52″N to 8° 53′ 24″N latitude and 39° 49′ 03″E to 40° 01′15″E longitude. It covers an extensive area of the floodplains with an average elevation of approximately 950 m asl (Zeleke and Kibebew, 2009). Based on agro-climatic zonal classification, the area is described as semi-arid climatic zone (Daniel, 1977). Average annual precipitation recorded by meteorological station located on the plantation site is 531.7 mm (NMA, 2012). The temperature is generally high throughout the year wherein the mean maximum temperature of the three hottest months, and mean minimum temperature of the three coldest months are 34.6 °C and 13.8 °C, respectively. The soils of sugarcane plantation site are characterized as alluvial origin, which had deposited sediments transported from the central part of Ethiopian highlands (Goerner et al., 2008). Fluvisols cover much area of the plantation within floodplains, developed from sediments deposited from Pleistocene to recent times (FAO, 1984; Goerner et al., 2008). The Andisols and Cambisols also occupy significant area in the north and northeastern parts of the plantation (FAO, 1984; Abule et al., 2005).

The grass savannas, swamps and riparian forests on the floodplains constituted islands of lush vegetation, which was the only dependable dry-season grazing area before land conversion to the sugarcane plantation (Kloss, 1982). Currently, the plantation occupies more than 13,000 ha of land with eleven major sugarcane fields (Abadir, Awash, Chore, East, Kikan, Riverland, Ginfugela, North, South, Abadir Extension and Kenifa). The fields were developed at different times that varied in ages of cultivation ranging from 9 to 55 years (Ayalew, 2001). More than half of the plantation fields including Abadir, Awash, Chore, East, Kikan and Riverland were established during the emperor regime (before 1974). The Derg regime (1974–1991) established the fields such as the North, South and Ginfugela whereas Abadir Extension and Kenifa have been established after 1991in the current government.

2.1. Sugarcane land use and management practices

The cane plant has been grown as a ratoon and harvested the biomass (manually with pre-harvest burning). The ratoon gives yield continuously for an average eight years without replanting a new cane plant (Ambachew, 2005). Sugarcane cultivation has been undertaken using furrow irrigation system where the Awash River has been used as a main source of water. There have been six textural soil management classes that determined the irrigation volume and intervals (Zeleke and Kibebew, 2009). These are identified as class 1, 2, 3, 4, 5, and 6 with pF2 moisture contents of <35, 35–45, 45–55, 55–65, 65–75, and >75%, respectively. The plantation field has received N fertilizer as ammonium nitrate, which varied the rate among the soil management classes. Six major soil types such as heavy, clayey, loamy, sandy, and pumice soils have characterized the soils of the plantation. Clayey soils, which are identified by three major soil phases (clay, sandy clay, clay over loamy soils), occupy a large area than other soil types, covering more than 75% of the plantation field (Zeleke and Kibebew, 2009). We considered the clayey soils in this study since they were found in all sections of the plantation. The sugarcane field under the clayey soils was described as irrigation class 5 with pF2 moisture content of 65–75%, and irrigated with an average rate of 1400 m^3/ha within 22 day intervals. It received ammonium nitrate, averaging to 130 kg N h^{-1} yr^{-1} that represented nearly 26% of recommended mineral N fertilization (Ambachew, 2005).

3. Materials and methods

3.1. Soil data sampling procedures

We used a total of 138 geo-referenced soil profile data taken from the plantation fields. The Ethiopia National Soil Laboratory (ENSL) conducted soil survey and laboratory test from May 2008 to August 2009. We stratified the plantation fields into three as young, middle and old based on the average year of cultivation, i.e., 13, 30 and 48 years, respectively. We overlaid the soil profile points on the map of plantation soils to assess the spatial representation. After observing the distribution of points, six additional soil profile points (two from each chronosequence) were sampled to represent heterogeneity in the age variable. We randomly selected (6) points chronosequence in soil profile. Four of the sequence was from database and two were from the newly identified sites (Fig. 1). Each of the sample profile points was further indexed to the specific age under the cultivation. We also used separated five soil profiles that represented never tilled (NT) fields. The NT profiles were taken systematically from all sides of the plantation, but never disturbed with human interferences. Both the NT profiles and the sample profiles in chronsequences were under similar management condition to sugarcane pre-establishment. All sampled profiles in the chronosequences were taken from the same soil type that had similar parent material, soil management class and fertilizer application rate so that the risk of confounding factors and their