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Can afforestation with *Cupressus lusitanica* restore soil C and N stocks depleted by crop cultivation to levels observed under native systems?

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A B S T R A C T

This study quantified changes in soil organic carbon (SOC) and total nitrogen (STN) stocks from the conversion of natural forest to crop field followed by afforestation of these fields. Soil (0–100 cm), leaf and fine roots were collected in the natural forest, the adjacent to 50-year-old crop fields converted from the natural forest, and 5, 8, and 17-year-old *Cupressus lusitanica* plantation sites (hereafter P5, P8 and P17, respectively) established on the converted crop fields in Southern Ethiopia. Soil and leaf pH, soil texture, bulk density, fine root mass, and SOC and STN contents and stocks were determined. The results showed that soil pH was lower and clay fraction was higher in P17 site than natural forest. Leaf pH of *Cupressus lusitanica* in plantation sites was lower than those of trees in natural forest. Fine root mass was greater in the plantation sites than the crop field. Soil bulk density (0–40 cm) was higher in the crop fields than the natural forest but there was no significant difference between crop field and plantation sites. SOC and STN stocks (0–100 cm) were higher in the natural forest than the crop field and all plantation sites and there was no significant difference between the crop field and all plantation sites. Overall, SOC and STN stocks decreased by 22.9% and 40.3%, respectively, in conversion of natural forest to crop field. However, after 17 years of afforestation, the crop field showed no change of stocks. The results suggest that afforestation in agricultural lands may not guarantee, or take a long period, to restore SOC and STN to the original natural forest level.

1. Introduction

Land-use change is considered one of the most important global changes (e.g., Lambin and Meyfroidt, 2011; Schmitz et al., 2014). To meet food demand from increasing population, natural lands such as forests, savannahs and wetlands have been converted to agricultural lands. Globally, forest land has decreased from 4.28 to 3.99 billion hectare (ha) between the years 1990 and 2015 (Payn et al., 2015). Marginal and unproductive agricultural lands have been abandoned (e.g., MacDonald et al., 2000; Renwick et al., 2013) and afforestation has increased due to increased timber needs and concerns about the environment and carbon sequestration (e.g., Winjum and Schroeder, 1997; Payn et al., 2015). Globally, planted forests increased from 167.5 to 277.9 million ha between 1990, and 2015 (Payn et al., 2015). In 1990, Ethiopia had about 15.1 million ha of natural forest which was reduced to 12.5 million ha by 2015 (FAO, 2015). This was a loss of 2.6 million ha, an average annual loss of 105 000 ha (FAO, 2015). With the urge to conserve the natural forest Ethiopia embarked on large scale industrial plantation (Lemenih and Kassa, 2014). This establishment of large-scale forest plantations in Ethiopia can be traced back to the 1970s (Pohjonen, 1989). The total area of plantation establishment increased from 189, 000 ha in 1990 to 972,000 ha in 2010 (Lemenih and Kassa, 2014).

As a result of conversion of natural forest to agricultural land, there is substantial reduction in soil carbon (C) and nitrogen (N) (e.g., Six et al., 2000; Murty et al., 2002; Lal, 2005; McLauchlan, 2006). A meta-review of Murty et al. (2002) found the average losses of C and N to be 24% and 15%, respectively after conversion from a natural forest to a crop field. Another meta-analysis of Wei et al. (2014) found that SOC decreased by 44.5% following conversion from a natural forest to a crop field. Yimer et al. (2007) found that SOC decreased by 30.9% while soil N decreased by 32.1% in soils after 15 years of deforestation in the Bale Mountains of Ethiopia. The loss of SOC and SNT stocks could be driven by various factors including: a reduction in the amount of biomass reverted to the soil; change in soil moisture and temperature, which enhances the rate of decomposition of organic matter; high rate of decomposition of crop residues due to differences in C:N ratio and lignin content; tillage-induced disturbances; decrease in soil aggrega-

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tion and reduction in physical protection of the soil organic matter; and increase in soil erosion (Murty et al., 2002; Lal, 2005; McLauchlan, 2006; Axel et al., 2010).

Afforestation of agricultural land has been recognized as a valid measure to sequester soil C and N (e.g., Don et al., 2011; Li et al., 2012; Shi et al., 2013; Nave et al., 2013; Kim and Kirschbaum, 2015) since it provides organic matter to soils through litterfall and root turn over (e.g., Navarro et al., 2012; Hu et al., 2013). The direction and magnitude of changes in SOC and STN stocks after afforestation is usually influenced by several factors such as soil type, nutrient management, and soil physical and chemical properties (Paul et al., 2002; Laganiére et al., 2010 Yang et al., 2011; Li et al., 2012). Tree species also have influence on the accumulation of soil C and N stocks because of variability in C and N inputs (quantity and quality) and potential losses (Six et al., 2000; Laganiére et al., 2010).

There are numerous studies of soil C and N change through the conversion of natural forest to agricultural land and afforestation in agricultural lands. However, there is lack of understanding of how consequent changes from deforestation to afforestation affect SOC and STN stocks. With increasing concerns about the effects of deforestation on SOC and STN levels and the need for fuel and construction wood, former deforested areas are being replanted into plantations globally and especially in Ethiopia (Lal, 2004; Lemma et al., 2006; Hu et al., 2013). However, it remains unclear how the change from deforestation to afforestation affects SOC and STN stocks.

The aim of the study was to determine how SOC and STN stocks fluctuated after conversion from a natural forest to a crop field, and then following the establishment of *Cupressus lusitanica* plantation in the same crop field.

2. Materials and methods

2.1. Description of study site

The study was conducted in adjacently located natural forest, crop field and *Cupressus lusitania* plantation sites inside Wondo Genet College of Forestry and Natural Resources, Southern Ethiopia (38°37′-62′ E, 7° 6′-10′ N) (Table 1). The study site is surrounded by a green chain of mountains and wide altitudinal ranges with the highest peak being 2580 m a.s.l. at Mount Abaro and the lowest 1600 m a.s.l. A relatively level part of natural forest was clear cut in 1965–1966 to establish crop field. The remaining natural forest is dominated by three naturally growing species: *Acacia tortilis, Vernonia amygdalina,* and *Croton macrostachys*. Dominate natural forest understory plant species are *Justicia schimperiana T., Justicia procumbens, Anderson Setaria megaphylla T., Durand & Schinz* and *Ocimum lamiifolium Hochst*. The crop field was used to grow teff (*Eragratis teff*) rotated with Maize (*Zea mays*) during the first 10 year after conversion. Thereafter, it has been used as Maize (*Zea mays*) mono-cropping farmland. Diamonium phosphate (DAP, 50 kg ha^{-1}) and urea fertilizer (50 kg ha^{-1}) were applied to the maize crop during the rainy season (once a year, July through September). The crop field was prepared at the beginning of each planting season in May by tractor plowing to a depth of 30 to 40 cm and irrigated periodically during the dry season. Most of the crop residues was harvested or removed after harvest. The mean annual maize yield during the last ten years was 4 tons ha^{-1}.

Parts of the crop field were converted into *Cupressus lusitanica* plantation sites. The *Cupressus Lusitania* plantation areas consist of three different sites: trees planted in the year 1998 (17 years old; 2 ha in area, named P17), 2007 (8 years old;0.6 ha, named P8) and 2010 (5 years old; 5 ha, named P5). Initially, 1500 trees were planted per ha (2.5 m × 2.5 m spacing) but were later thinned to 1050 trees per ha (2.5 m × 5 m spacing). Thinning was performed every 2 or 3 years depending on the growth rate and density of the plantation. Only P5 was irrigated because the trees were planted in the dry season. The majority of the P5 trees have a diameter at breast height (DBH) of

Table 1
Summary of characteristics of the study site.

	Natural forest	Crop field	Five-year-old plantation (P5)	Eight-year-old plantation (P8)	Seventeen- year-old plantation (P17)
Location and elevation	38° 62′ 22“E, 7° 10′ 60“N, 1860 m a.s.l.	38° 37′ 18“E, 7° 6′ 9“N, 1860 m a.s.l.	38° 37′ 13“E, 7° 6′ 12“N 1860 m a.s.l.	38° 37′ 12“E, 7° 6′ 3“N, 1849 m a.s.l.	38° 37′ 11“E, 7° 6′ 3“N, 1848 m a.s.l.
Major vegetationspecies	*Vernonia amygdalina, Croton macrostachys* and *Acacia tortilis*	Maize (*Zea mays*)	*Cupressus lusitanica*	*Cupressus lusitanica*	*Cupressus lusitanica*
Land use change history	Undisturbed natural forest	Converted from the natural forest in 1965–1966 (50 year old)	Established in the crop field in 2010 (5 year old)	Established in the crop field in 2007 (8 year old)	Established in the crop field in 1998 (17 year old)
Land use management	Occasional grazing	Plowing with tractor (30–40 cm);irrigated periodically in the dry season	Grazing (weekly); thinning and pruning (every 3 years) and residues were removed.	Grazing (weekly); thinning and pruning (every 3 years) and residues were removed.	Grazing (weekly); thinning and pruning (every 3 years) and residues were removed.
Annual rain fall 1200 mm to 1244 mm					
Mean temperature 19.5 °C					
Soil type Mollic Andosol					