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Soil δ^{15}N and nutrients under exotic tree plantations in the southwestern Ethiopian highlands

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Abstract

This study was undertaken to evaluate the effect of tree species on soil properties. Soil δ^{15}N, total N, C:N ratio, base cations and available P were analyzed under farmland, native forest and tree plantations established on abandoned farmland at Belete forest. Changes associated with land use were evaluated using a comparative approach. Forest clearing followed by continuous cultivation of annual crops resulted in a significant decline in total N, base cations and available P within 0–10 or 0–20 cm depth. Assuming a linear rate of loss, total N declined by 90.6 kg ha^{-1} year^{-1} or by 38% (6.8 Mg ha^{-1}) of the level in native forest during the 75 years of cultivation. The ^{15}N enrichment of soil and litter N in the farmland may indicate losses of N through leaching and harvest. The degree of change in soil properties under exotic trees after 20 years of afforestation of former farmland depended on tree species. Total N within 0–50 cm depth increased by 5.7 Mg ha^{-1} under *Cupressus lusitanica* and 2.0 Mg ha^{-1} under *Pinus patula*. The decrease in δ^{15}N value with afforestation was greater for *C. lusitanica* than for *P. patula*, indicating that N cycling under *C. lusitanica* progressed more towards 'native forest like' conditions. Under *C. lusitanica*, exchangeable Ca^{2+} increased significantly at 0–5 cm. Exchangeable K^{+} increased significantly within 0–30 cm depth under both *C. lusitanica* and *P. patula*. The increased C:N ratio under these tree species was attributed to recent organic matter (OM) addition. The soil under *Eucalyptus grandis*, established on former mixed land use (pasture plus farmland), had nearly similar δ^{15}N, TN, exchangeable Ca^{2+} and K^{+} to native forest. The residual effect of ^{15}N-depleted C_4 pasture grasses might explain the lack of difference in soil δ^{15}N profile below 10 cm depth between *E. grandis* and native forest. Greater OM inputs by *E. grandis* probably account for the greater C:N ratio relative to native forest soil.

Keywords: Afforestation; Land use change; δ^{15}N; Soil properties; Tree species

1. Introduction

In many parts of the tropics, large areas of soils have been degraded by conversion of forests to agriculture. In Ethiopia, native forest drastically declined in the 20th Century from 40% land cover to approximately 2.7% (Pohjonen and Pukkala, 1990), and it is still shrinking due to continued deforestation. Continuous unmanaged cultivation following deforestation has resulted in land degradation (FAO, 1986; Hurni, 1993). To counter such degradation, plantation of exotic species began in the late 1800s (Pohjonen and Pukkala, 1990). Afforestation and reforestation became official government policy in 1974 in response to increasing demand for poles, fuel and construction wood, and to counteract the negative effect of deforestation on the environment (Poschen-Eiche, 1987). Most of these plantations comprise exotic species of *Eucalyptus*, *Cupressus* and *Pinus*. The total plantation area in Ethiopia is estimated to be 216,000 ha and 2000 ha of new plantations are established every year (FAO, 2001).

Plantation forests provide economic, social and environmental benefits. Fast growing tree plantations provide wood for various purposes and play a significant role in rural economy in tropical regions (Parrotta, 1999). Afforestation and reforestation of degraded lands is often considered the soundest way of rehabilitation in the tropics (Parrotta et al., 1997), and have also been proposed in the Kyoto protocol as a strategy for mitigating the greenhouse effect. For plantations to be sustainable over rotations, an understanding of the effect of tree species on soil nutrients is essential.

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Trees are generally known to have many direct and indirect beneficial effects on soil (Fisher, 1995; Olsson, 2001). Direct effects include improved soil structure through root action, input of organic matter (OM), and increased nutrient availability through recycling. Indirect effects are changed climatic conditions, improved water and nutrient retention, decreased erosion and impact on other flora and fauna (Fisher, 1995; Olsson, 2001). However, the precise effects of different tree species on soil properties remain poorly understood (Binkley, 1995; Davis, 1998). The effect of trees should always be evaluated in relation to other land use alternatives and management, e.g. agriculture (Olsson, 2001). Although several studies have been undertaken in different parts of the world concerning the effects of plantation forest on soil, most of these studies focus on soil property changes under plantation forests compared to soils under the nearby native forest, other plantation species (mainly N_2-fixing tree species) or grasslands. Few studies from the tropics describe soil property changes following plantation of previous farmland (Binkley and Resh, 1999; Lemenih et al., 2004).

Natural ^{15}N abundance ($\delta^{15}N$) has been used for studying N cycle soil processes (Robinson, 2001). The $\delta^{15}N$ value varies in the biosphere as a result of isotopic fractionation in physical, chemical and biological processes (Högberg, 1997). Soil processes resulting in N loss exhibit isotopic effects leading to ^{15}N depletion in the products (e.g. NO_3^-, N_2O, NO, N_2, NH_3) that contribute to ^{15}N enrichment in the residual pools (organic N, NH_4^+, NO_3^-) in the soil and in the ecosystem (Högberg, 1997). The extent of isotopic fractionation depends on the types and importance of processes (Vervaet et al., 2002). The $\delta^{15}N$ of plant and soil systems reflects not only the fractionation of the soil N pool during N transformation, but also of different N sources (Handley and Scrimgeour, 1997; Robinson, 2001). Soil $\delta^{15}N$ can therefore be used as an indicator of changes in N dynamics and soil N sources among different ecosystems or following a change in land use (Piccolo et al., 1996). A better understanding of N dynamics is needed because of the close connection between N and carbon cycling in the biosphere (Ågren and Bosatta, 1996).

Studying the distribution of $\delta^{15}N$ and soil nutrients with soil depth and land use might yield insights into changes in the patterns and processes of nutrient cycling over time. The conversion of native forest to farmland and afforestation of previous farmland (or pasture plus farmland) with exotic trees at Belete, southwestern Ethiopia, provides the opportunity to examine the effects of plantation and deforestation on $\delta^{15}N$ and soil nutrients. The objectives of this study were (i) to compare and evaluate $\delta^{15}N$ distribution within the soil profile and between profiles under farmland, native forest, and plantations of *Cupressus lusitanica* (Miller), *Pinus patula* (Schiede and Deppe) and *Eucalyptus grandis* (Hill ex Maiden); (ii) to evaluate the effect of these exotic tree species on soil properties (N, C:N ratio, available P, exchangeable bases (K^+, Ca^{2+}, and Mg^{2+})); (iii) to evaluate the effect of deforestation followed by cultivation on these soil properties.

2. Methods

2.1. Site of the study

The study area, Belete forest and adjoining farmland, is located in the southwestern highlands of Ethiopia (7°33′N, 36°35′E). Mean annual temperature 1983–2003 was 19.4 °C and mean annual precipitation 1517 mm according to the closest meteorological station (Jimma, 38 km from the study site). The sampling sites, which lay within 2.5 km of each other, were located in the same agro-climatic zone, and situated between 2100 and 2340 m a.s.l. Geologically, the area is associated with Jimma Volcanics, with abundant rhyolites and trachybasalts (Tefera et al., 1999). The soils are provisionally classified as Humic Nitosols (FAO, 1998; JICA, 1998), with a clay loam texture and dark reddish-brown colour. Typical soil characteristics are described by Lemma et al. (in press).

The area with the current plantations of *C. lusitanica* and *P. patula* was deforested around 1928, at the same time as the area under the farmland, and was used for agriculture, mainly maize cropping, until it was set aside in 1981 and afforested in 1983 as a part of the government afforestation programme. The area under *E. grandis* was also deforested at about the same period, but it was used for pasture until conversion to agriculture in 1963, and finally afforested in 1983 in the national programme. Aerial photographs taken in 1975 and 1996 were used to locate plantation areas that were formerly used as arable land. Informal interviews with local elderly people living close by the study site were used to support this information and to verify the delineation. An extensive field survey was made to identify five suitable sites for the study: one under agriculture, one each under three plantation species mentioned above and one with native forest. Selection criteria were similarities in soil mineralogy (Lemma et al., in press), soil depth, slope form, minimum disturbance (e.g. roads and footpaths), size and accessibility. The present and past agricultural crop was mainly maize (*Zea mays* L.), and to a smaller extent teff (*Eragrostis tef*) and sorghum (*Sorghum bicolor* (L.) Moench). As in most parts of Ethiopia, farming was done by small family groups using traditional methods relying on rainfall and using neither lime nor fertilizer. The plough depth was typically 10–12 cm (Solomon et al., 2002).

2.2. Soil sampling

In April 2004, soil, litter and root samples were collected from four random squares (100 m^2 each) in each type of land use system, i.e. farmland, native forest and plantations of *C. lusitanica*, *P. patula*, and *E. grandis*. Within each plot, two randomly sited soil pits were dug. Since it was difficult to clearly separate the forest floor Oe and Oa layers from the mineral soil without too much disturbance, upper mineral soil samples (0–5 cm) included the Oe and Oa layers. In each pit, five soil samples were taken from the depths 0–5, 5–10, 10–20, 20–30, and 30–50 cm using a core sampler