Forest Ecology and Management 313 (2014) 254–265

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Soil carbon and nitrogen sequestration over an age sequence of *Pinus patula* plantations in Zimbabwean Eastern Highlands

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A R T I C L E I N F O

Article history:
Received 6 October 2012
Received in revised form 6 November 2013
Accepted 19 November 2013
Available online 11 December 2013

Keywords:
Soil organic matter fractions
Forest floor
C:N ratios
Plantation forestry
Carbon

A B S T R A C T

Forests play a major role in regulating the rate of increase of global atmospheric carbon dioxide (CO_2) concentrations creating a need to investigate the ability of exotic plantations to sequester atmospheric CO_2. This study examined pine plantations located in the Eastern Highlands of Zimbabwe relative to carbon (C) and nitrogen (N) storage along an age series. Samples of stand characteristics, forest floor (L, F and H) and 0–10, 10–30 and 30–60 cm soil depth were randomly taken from replicated stands in *Pinus patula* Schiede & Deppe of 1, 10, 20, 25, and 30 years plus two natural forests. Sodium polytungstate (density 1.6 g cm^{-3}) was used to isolate organic matter into free light fraction (fLF), occluded light fraction (oLF) and mineral associated heavy fraction (MaHF). In both natural and planted forests, above ground tree biomass was the major ecosystem C pool followed by forest floor's humus (H) layer in addition to the 45%, 31% and 24% of SOC contributed by the 0–10, 10–30 and 30–60 cm soil depths respectively. Stand age caused significant differences in total organic C and N stocks. Carbon and N declined initially soon after establishment but recovered rapidly at 10 years, after which it declined following silvicultural operations (thinning and pruning) and recovered again by 25 years. Soil C and N stocks were highest in moist forest (18.3 kg C m^{-2} and 0.66 kg of N m^{-2}) and lowest in the miombo (8.5 kg m^{-2} of C and 0.22 kg of N m^{-2}). Average soil C among Pinus stands was 11.4 kg of C m^{-2}, being highest at 10 years (13.7 of C kg m^{-2}) and lowest at 1 year (9.9 kg of C m^{-2}). Some inputs of charcoal through bioturbation over the 25 year period contributed to stabilisation of soil organic carbon (SOC) and its depth distribution compared to the one year old stands. Nitrogen was highest at 10 years (0.85 kg of N m^{-2}) and least at 30 years (0.22 kg of N m^{-2}). Carbon and N in density fractions showed the 20 year old stand having similar proportions of fLF and oLF while the rest had significantly higher fLF than oLF. The contribution of fLF C, oLF C and MaHF C to SOC was 8–13%, 1–7% and 90–91% respectively. Carbon and N in all fractions decreased with depth. The mineral associated C was significantly affected by stand age whilst the fLF and oLF were not. Conversion of depleted miombo woodlands to pine plantations yield better C gains in the short and long run whilst moist forest provide both carbon and biodiversity. Our results highlight the importance of considering forestry age based C pools in estimating C sink potential over a rotation and the possibility of considering conservation of existing natural forests as part of future REDD + projects.

1. Introduction

Changes in soil organic matter (SOM) can result in significant contributions to emissions or uptake of greenhouse gases from forests and other land use systems. Forests govern C transfers directly through photosynthesis and respiration and indirectly by influencing the structure and size of plant-leaf development (Eliasson, 2007; Van Minnen, 2008). They represent an important C pool (Brown, 2002) that favour sequestration of C due to their increased woody biomass, extensive roots, and abundant litter (Sharrow and Ismail, 2004). The extensive rooting system of forest species influence soil microbial biomass thus control the cycle of C between the atmosphere and the soil (Brown, 2002). In general, tropical forests contain less C in soils than their biomass C, storing about 60% C aboveground and 40% belowground (Dixon et al., 1994). However, especially in these forests, roots go deeper and thus, root turnover may add to C sequestration in deeper horizons due to slow carbon turnover (Jobbagy and Jackson, 2000).

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http://dx.doi.org/10.1016/j.foreco.2013.11.024

The accumulation of soil C and N varies within different soil horizons and depths. Some forest sub soils hold about 45% of total SOC bound to the clay particles to form microaggregates. This complexion of SOC in the forest sub soils is essential for long-term stabilisation (von Lützow et al., 2006). The extent of this stabilisation is determined by organo-mineral interactions, micropores, type and nature of clay surfaces, and C location within the microaggregates.

Next to climate and soil type, the sequestration of C depends on forest species and management (Lal, 2003; Lamlom and Savidge, 2003) having a compromise between ecosystem C storage capacity and timber extraction. Long-term differences in SOC storage among three tree species have been studied by Seely et al. (2002) who concluded that all tree species are important C pools although they have different C storage capacities. Vesterdal et al. (2002) compared soils under Norway spruce (*Picea abies* L) and oak (*Quercus robur* L.) and showed them to sequester 0.9 kg m^{-2} of C and 0.2 kg m^{-2} of C respectively after 29 years and the SOC being mostly concentrated in the upper soil horizons. In Hawai, Kaye et al. (2000) reported storage of C by 17-year old *Eucalyptus* and *Albizia lebbeck* trees and reported that *Albizia* had 2 kg m^{-2} more soil C and 0.230 kg m^{-2} more soil N. The greatest potential for above ground biomass C storage in coniferous plantations (e.g. pines) is found in tree biomass (Peichl and Arain, 2006) with additional amounts from forest floor and mineral soil C (Taylor et al., 2007; Noh et al., 2010). Net rate of C uptake is greatest when forests are young, and slows with time. Old forests continue to sequester C at a decreased rate with decreased rate of respiration (Marris, 2008). When forests are cut, C is returned quickly to the atmosphere if the woody tissue is burned or converted to products that are short-lived (Ecological Society of America, 2000). Depending on harvesting practices, most of soil C remains in the soil and become part of the C stock of growing forest or a subsequent cycle in a plantation system. In addition to type of tree species, stand age is also critical in determining the amount of C in an ecosystem influencing the quality and quantity of C inputs released into an ecosystem (Matos et al., 2010; Penne et al., 2010). Some studies have shown that conversion of native forests to conifers can cause up to 15% losses of SOC depending on period following conversion while others estimated up to 20% SOC reductions over periods below 40 years (Guo and Gifford, 2002).

The general impacts of plantation forests have been outlined by region (Nilsson and Schopfhauser, 1995) and the IPCC (2003) suggested that the real C stock estimates might be much lower than indicated as some of the C has not been accounted for. Some studies have indicated relative increases in surface soil C stocks in plantations (Schwertmann et al., 1986) while other studies found limited capacity for soil C accumulation (Richter et al., 1999; Liao et al., 2012). In this study we will not only look at quantities of C but also at its stability. Next to quantity, type and degree of stabilization is also important for the assessment of C sequestration.

Most studies on soil C and N dynamics over stand age are mainly from other regions either from experimental stations reflecting site specific conditions e.g. (Covington, 1981; Rita et al., 2011) or model estimations on a local or regional scale e.g. (Peltoniemi et al., 2004). Forest systems of Zimbabwe include rainforest, indigenous woodlands, plantations and bushland/grasslands covering 0.1%, 65.9%, 0.4% and 1.5% of the land area respectively. Plantation forests consist of *Pinus* spp. (68%), *Eucalyptus* (20%) *Acacia mearnsii* (11%) and *Poplar* spp. (1%) (Forestry Commission Zimbabwe, 1996). The relatively extensive woodland cover makes it a potential C sink, but it is threatened by agricultural expansion and demand for wood.

The characterisation of C in the above ground biomass of forests is well advanced, but the below ground C dynamics is poorly understood causing a need for correlating the below ground biomass to the above ground biomass to predict C storage in forest soils (Brown, 2002). Determination of the flux of global C cycle needs substantial research which can link patterns and long term effects of C and N accumulation in the soil relative to forest age. The role of forests in the global C cycle has therefore initiated great interest in exploring the capacity of forest ecosystems to increase C uptake by means of afforestation and sustainable forest management through initiatives such as reduced emissions form forest degradation and deforestation (REDD+). There are few studies quantifying the potential for soil C accumulation and stabilisation under natural and exotic plantations in Zimbabwe and this creates a need for studies on the soil C sink potential of forest plantations. Reliable knowledge of the C and N dynamics in forest soils is therefore fundamental to understanding sustainable forest management practices and their role in climate change mitigation.

In this study we measured forest floor and soil C and N pools induced by plantation forestry at different stages during a rotation cycle. Our aim was to describe the distribution, accumulation, stability of forest floor and soil C and N pools and their temporal shifts over time. We hypothesise that (1) forest floor and soil C pools under plantation forestry are lower than natural forest, (2) more C is stored in the forest floor and soil pools with increasing stand age within a cycle and (3) soil C stabilisation increases with stand age.

2. Study site and methodology

The study was carried out within the Nyanga Pine Division of Wattle Company P/L in Eastern Zimbabwe at Mutarazi Estate situated at S19 01.032 E32 35.810, lying at the extreme South of the Nyanga District (Fig. 1). The altitude ranges between 1020 m and 1920 m above sea level. The terrain is characterised by relatively moderate slopes, and forms part of the Eastern escarpment of the Nyanga mountain range. It is drained mainly by the perennial Mutarazi river. The total plantation area is 3,806,990 ha of which 2548 ha was re-planted as at September 2010 (WATCO, 2010).

Mutarazi Estate falls into Natural Region (NR) I of the Zimbabwe agro ecological classification system (WATCO, 2010) with annual rainfall estimated at around 1500 mm and the seasonality follows the same general pattern as the rest of the country (bulk of rainfall being confined to the months of November to March). Small amounts of winter precipitation in the form of mist, fog and rainfall do occur on areas of high elevation. Average maximum temperature is 28 °C with a minimum of 0 °C. Lowest temperatures occur between May and August while the highest are from October to February. Relative humidity varies between mean 58% in September to a mean of 86% in January/February. The prevailing wind is easterly blowing dominantly during the months of November to May.

The soils are orthoferrallitic within the Kaolinitic order (Zimbabwean classification) which corresponds to Rhodic ferralsols in FAO classification (FAO, 2006). The soils are characterised by good depth, permeability and structural stability exhibiting a high degree of resistance to erosion. They have extremely poor chemical characteristics, with particularly high levels of acidity and low weathering rates (WATCO, 2010).

A wide variety of broadleaf, large tree species occur in natural forests including *Macaranga mellifera*, *Ilex mitis*, *Schrebera alata*, *Rapanea melanophloeos*, *Olea capensis* and *Schefflera umbellifera*. The understorey of these forests is usually dominated by extensive banks of ferns comprising mainly of *Asplenium* and *Cyathea* spp. Widespread stands of *Psychotria zombamontana* also occur. Forest fringes are dense dominated by species including *Hypericum revolutum*, *Pteridium*, *Rubus* and *Smilax anceps*. These forests are usually