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Effects of 34-year-old *Pinus taeda* and *Eucalyptus grandis* plantations on soil carbon and nutrient status in former miombo forest soils

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ABSTRACT

There is a strong need in Mozambique to counteract decades of deforestation and forest degradation by planting new forests. Plantations of *Pinus/Eucalyptus* species and maintenance of mature miombo forests are activities supported by the REDD+ mechanism (Reducing Emissions from Deforestation and forest Degradation) in climate negotiations. This study examined the effects of first-rotation *P. taeda* L. (Loblolly pine) and *E. grandis* Hill ex Maiden plantations (ca. 34 years old) on soil carbon status compared with adjacent dry miombo forest. At three study sites located in the Western Highlands of Manica Province, Mozambique, study plots with *Pinus taeda, Eucalyptus grandis* and mixed-deciduous miombo species were delineated. The selection criteria were (i) forest stand of first-rotation plantation of *Pinus/Eucalyptus*, located adjacent to miombo forest, (ii) plantations established on soils similar to miombo forest soils, and (iii) former land use similar to that at current miombo sites. Stocks of soil organic carbon (SOC), total nitrogen (N) and extractable phosphorus (P) were quantified. Soil pH (H_2O), cation exchange capacity (CEC) and base saturation (BS) were measured in soil extracted with ammonium acetate.

Plantations of *P. taeda* and *E. grandis* increased total SOC stocks (0–50 cm) and N stocks in the top 10 cm. Assuming steady state in the miombo stands, the estimated net stock change in soil carbon was 1.41 Mg ha^{-1} yr^{-1} in *P. taeda* and 1.53 Mg ha^{-1} yr^{-1} in *E. grandis* stands. Estimated N accumulation rate was 32 kg ha^{-1} yr^{-1} in *P. taeda* and *E. grandis* stands. *P. taeda* had no significant effect on extractable P, soil pH and BS, but had significantly higher. CEC compared with miombo forest soil. *E. grandis* decreased P stocks, but increased soil pH and BS.

Overall, *P. taeda* and *E. grandis* plantation had a large impact on SOC in dry miombo forest and also affected soil acidity and soil nutrient status, except for total soil N stocks. These effects of tree plantation on soil reflected differences in management practices between miombo forest and plantations, with the latter being subjected to better protection against fires and illegal cutting.

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1. Introduction

Pinus and *Eucalyptus* plantations can have a marked impact on carbon (C) pools and nutrient status in tropical soils. However, the magnitude and nature of these effects may vary depending on the features of particular sites (Bahn et al., 2009; Chang et al., 2014; Jandl et al., 2007; Paul et al., 2002). A meta-analysis of afforestation by Li et al. (2012) concluded that soil C stocks increased after plantation of hardwood species such as *Eucalyptus*, but did not change with softwood species such as *Pinus*. The increase in soil C stocks by *Eucalyptus* spp. occurred in both the organic horizon and the mineral soil, whereas *Pinus* spp. increased soil C stocks in the organic horizon, but generally depleted C stocks in the mineral soil, resulting in insignificant overall change (Li et al., 2012). Lower soil C stocks in the mineral horizon under *Pinus* spp. plantations could be a consequence of lower below-ground litter production compared with *Eucalyptus* spp.

Li et al. (2012) also found that changes in stocks of soil C and nitrogen (N) are positively correlated and have a similar temporal pattern, but that changes in soil N are detected at later age stages than changes in soil C. In general, changes in soil C stocks are detected 30–40 years after plantation, whereas significant changes in soil N stocks appear from around 50 years after plantation. One main cause of the strong positive correlation between changes in soil C and soil N is the fairly fixed stoichiometric relationship between C and N in plant litter, a relationship that also includes phosphorus (P). As with N, the relationship between soil C and soil P suggests that an increase in soil organic C is associated with increased stocks of soil P, dominated by P in organic form. This is partly because as soil C stock increases, P fixation in minerals decreases (El-Baruni and Olsen, 1979). However, the correlation between C and P is generally weak ($r = 0.40$–0.57; Hou et al., 2014).

In highly weathered, leached and acidic soils, such as those in Mozambique, available soil P is typically low and is often the major growth-limiting factor, whereas N is not a limiting nutrient (Aggangan et al., 1996; Binkley, 1997; Högberg, 1986). In highly weathered soils, the availability of P also depends on soil pH level. Plant P availability is highest in the soil pH range 6–7, while P fixation is at its lowest (Devau et al., 2009). Uptake of P by tree species may cause a reduction in plant-available P, particularly if forest growth also results in lower soil pH. Lower soil pH and base saturation (BS) can be expected, as a result of higher accumulation of base cations by plants (Nilsson et al., 1982). In addition, increased stocks of soil C can be expected to increase the organic acidity, manifested in lower BS, lower pH and higher cation exchange capacity (CEC) of the soil (Berthrong et al., 2009).

Knowledge of how tree species affect ecosystem C and nutrient status is of particular importance in Mozambique, where there is a strong need to counteract decades of deforestation and forest degradation by planting new forest. New plantations and maintenance of mature woodlands are activities supported by the REDD+ mechanism in the United Nations Framework Convention on Climate Change (UNFCCC) and to sustain livelihoods. In Mozambique, forest plantations are desired by society and the national aim is to establish 1 million ha of forest plantations by 2022, i.e. a 10-fold increase in area compared with the current situation (see Coetzee and Alves, 2005; MINAG, 2009). Forest plantations in Mozambique consist mainly of *Pinus* and *Eucalyptus* spp., which are also common in neighbouring countries (e.g. South Africa and Zimbabwe; FAO, 2001). The plantations are mostly established on degraded miombo woodlands, thickets and degraded agricultural land. On average, degraded miombo sites, or high-utilisation sites, store approximately 15 Mg C ha^{-1} in above-ground biomass, which is significantly lower average C storage than at medium and low utilisation sites (e.g. 31 Mg C ha^{-1}) (Jew et al., 2016). However, expansion of forest plantations in Mozambique can also be achieved through direct conversion of non-degraded forests (Indufor, 2012; Nhantumbo and Salomão, 2010). Despite this large-scale land use change, lack of knowledge on how forest plantations affect soil organic carbon (SOC) and nutrient status in the long run limit the possibility to develop local guidelines on sustainable forestry.

Pinus/*Eucalyptus* plantations and native miombo forest differ in several aspects. The non-native species are easily managed, show rapid adaptability, high above-ground carbon sequestration rate and high production and productivity of wood (Dohrenbusch, 2011; FAO, 2001; Lugo and Brown, 1993). Most species in miombo forest have low growth rates (Ciais et al., 2011; Lupala et al., 2014; Sitoe, 1999) and natural regeneration can be relatively slow, due in part to lack of forest management practices (Jew et al., 2016; Kalaba et al., 2013; Williams et al., 2008). However, high production in plantations is generally associated with a high demand for soil nutrients, which may adversely affect soil properties (Berthrong et al., 2009; Jien et al., 2011; Knoepp et al., 2000; Liao et al., 2012; Zhang et al., 2012).

Dry miombo woodland (hereafter referred to as 'miombo forest') is defined as a sub-type of dry forest located in tropical climates, with summer rains bringing 500–1500 mm annually and a dry period of 5–8 months (Blackie et al., 2014; FAO, 2012). Miombo forest covers a large part (around 67%) of the inland of Mozambique (Sitoe et al., 2012), and is in fact the most extensive tropical seasonal woodland and dry forest formation in Africa (Frost, 1996). It is dominated by the genera *Brachystegia*, *Julbernardia* and *Isoberlina* (Fabaceae, subfamily Caesalpinioideae).

Miombo forest provides a wide range of goods and ecosystems services, thus playing an important role for the food security and livelihood of households, as well as climate change mitigation and adaptation. Despite its great importance, miombo forest is severely under threat (Bruschi et al., 2014; Cuambe and Marzoli, 2006; Jansen et al., 2008; Sawe et al., 2014; Sitoe et al., 2012). Increased population density is an important driver of deforestation and miombo degradation through increased wood extraction for energy (e.g. charcoal), clearance for subsistence agriculture and uncontrolled fires (see Backéus et al., 2006; Bruschi et al., 2014; Nhantumbo et al., 2001; Sawe et al., 2014; Sitoe et al., 2012).

The process of miombo degradation is generally taking place by selective logging, fires and clearance of small areas within forests (subsistence agriculture), resulting in a mosaic pattern of agriculture within the forest (Sitoe et al., 2012). Although dominant tree species in miombo forest are fire-resistant (Frost, 1996), fires cause serious damage to the ecosystem,