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Original Research Article

Plantations of *Pinus* and *Eucalyptus* replacing degraded mountain miombo woodlands in Mozambique significantly increase carbon sequestration

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Total ecosystem carbon (C) stocks in tree biomass (aboveground and belowground), litter layer and soil (0–50 cm depth) were quantified in mountain miombo woodland and in 34-year-old first-rotation plantations of *Pinus taeda* and *Eucalyptus grandis*. The study was performed at three sites (Penhalonga, Rotanda and Inhamacari) in the western highlands of Manica province in Mozambique, bordering Zimbabwe. One 30 m × 30 m sampling plot was established for each forest type per site. Pre-tested allometric equations were used to determine total C stocks within aboveground tree biomass of each forest type and data from the literature on the relationship between aboveground and belowground biomass were used to estimate C stocks in belowground woody biomass (*i.e.* coarse roots). Measured soil and litter layer C data were taken from a previous study. Carbon stocks in mountain miombo woodland were used as a baseline to estimate C sequestration at the ecosystem scale, *i.e*. net ecosystem production (NEP) in the plantations, considering 34 years as stand age of the planted forests.

Total ecosystem C stocks in miombo woodlands (~116 Mg ha^{-1}) were significantly lower than in stands of *P. taeda* (363 Mg ha^{-1}) and *E. grandis* (~407 Mg ha^{-1}). Carbon sequestration rate at ecosystem scale (NEP) was 7.24 Mg ha^{-1} yr^{-1} in *P. taeda* stands and 8.54 Mg ha^{-1} yr^{-1} in *E. grandis* stands. NEP was dominated by the increment in biomass (~80%). This was also reflected in higher ratio between biomass C and soil organic C stocks in the plantations compared with miombo forest. The plantation species showed similar performance with respect to total C stocks and NEP. It was concluded that plantations of *P. taeda* or *E. grandis* have significant potential to increase C stocks and C sequestration rate in both soil and tree biomass on replacing degraded mountain miombo woodlands in the western highlands of Manica province.

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1. Introduction

Miombo is the most extensive of the native forest types in southern Africa and also the type most subjected to deforestation and forest degradation (Marzoli, 2007; Sitoe et al., 2012a; Nhantumbo and Mausse, 2015; CEAGRE and Winrock-International, 2016; Jew et al., 2016). Miombo woodland (hereafter referred to as 'miombo forest') is a colloquial term used to describe the largest tropical deciduous woodland and dry forest formation in Africa (Campbell et al., 1996; Frost, 1996; Kutsch et al., 2011; Chidumayo, 2013; Jew et al., 2016). In Manica province, the study area in the present analysis, as in Mozambique in general, miombo is the most important forest type in terms of surface area and ecological and economic values (Wild and Grandvaux Barbosa, 1967; Marzoli, 2007, Sitoe et al., 2012a).

For Mozambique and bordering regions, there is a strong need to counteract decades of deforestation and degradation (DFD) of native forests in order to increase the domestic supply of forest products, increase the capacity of forest ecosystems for carbon (C) storage and sequestration, and thereby reduce C emissions to the atmosphere. Historical data in the form of national statistics suggest that DFD will continue with increasing human population density, since the pressure on native forests is largely explained by population growth (Marzoli, 2007; Sitoe et al., 2012a). Proximate effects of DFD differ between countries and between regions within countries (Griscom et al., 2009, CEAGRE and Winrock-International, 2016). In any case, DFD has direct negative impacts on C stocks, net primary production (NPP) and biodiversity, and also contributes a considerable share of C emissions to the atmosphere (Griscom et al., 2009, CEAGRE and Winrock-International, 2016).

According to CEAGRE and Winrock-International (2016), between 2000 and 2012 about 138,000 ha of forest were destroyed in Mozambique (equivalent to 0.23% yr^{-1}), with the central region, which includes the province of Manica, accounting for 54% of total forest area lost. According to that study, deforestation and forest degradation in Mozambique are responsible for approximately 16 Mton of carbon dioxide (CO_2) being released per year to the atmosphere. This is equivalent to 4.4 million tons of C, of which nearly 80% came from miombo forests (CEAGRE and Winrock-International, 2016). Another study, also conducted in the central region of Mozambique, concluded that forest biomass and C stocks decreased at a rate of 3.1% per year between 2007 and 2010, again due to DFD (IIED, 2012).

A large proportion of DFD (>75%) is directly caused by agricultural practices and expansion (mainly shifting cultivation), wood fuel production (charcoal) and logging (especially illegal activities), often acting in combination (CEAGRE and Winrock-International, 2016). Some degraded miombo sites, including other wooded areas, will need active intervention to help in recovery of goods production (*e.g.* timber and fuel) and ecological functions (*e.g.* C storage, net ecosystem production, nutrient cycling and maintenance of wildlife habitats).

In the following, degraded forest, or "high-utilisation sites" according to terminology adopted by Jew et al. (2016), is defined as forest that has lost much of its original biomass or C stocks and net primary production (adapted from Lamb and Gilmour, 2003, IPCC, 2006, Thompson et al., 2013, Scott et al., 2015, Jew et al., 2016). This definition also denotes reduced forest cover, as long as the site can be considered 'forest' (Tavani et al., 2009; Sitoe et al., 2012b). Degraded forests can differ in many regards, for example in terms of the C storage capacity in aboveground tree biomass (Jew et al., 2016) and the capacity of the forest to recover unaided if further disturbance can be prevented (Lamb et al., 2005). On average, high-utilisation sites store approximately 15 Mg ha^{-1} of C stocks in aboveground tree biomass, which is a significantly lower level than at medium and low utilisation sites (about 31 Mg ha^{-1}) (Jew et al., 2016).

Several ways to counteract DFD in tropical forests are suggested in the literature (IUCN, 2004; Griscom et al., 2009; MINAG, 2009; FAO, 2010; UNEP, 2014; Sitoe and Guedes, 2015; CEAGRE and Winrock-International, 2016; MITADER, 2016). Within the forestry sector, establishing monoculture plantations with fast-growing non-native species is one of the ways to reverse DFD (Lamb, 2011). In most cases, commercial forest plantations aim to produce economically profitable wood products for the market, *e.g.* sawn wood and pulpwood (FAO, 2001; Chamshama et al., 2009; MINAG, 2009; Lamb, 2011). Biomass, including logging residues, from non-native species can also be used for energy purposes (firewood, charcoal, wood pellets) and biochar for soil amendment (Lamb, 1998; Canadell and Raupach, 2008; Sitoe, 2009; Porsö et al., 2016; Gustavsson et al., 2017; Xu et al., 2017).

Pinus taeda, P. patula, P. elliottii, Eucalyptus grandis, E. cloeziana and *E. camaldulensis* are examples of fast-growing non-native species often planted in reforestation/afforestation projects in Mozambique and neighbouring countries (FAO, 2001; Chamshama and Nwonwu, 2004; Chamshama et al., 2009; MINAG, 2009; Mujuru et al., 2014). Plantation of forest in Mozambique generally takes place on deforested land or at degraded miombo forest sites, including degraded agricultural land, thickets and marginal land (less fertile soils for growing food or land located on steep slopes) (MINAG, 2009; Maússe-Sitoe et al., 2016; MITADER, 2016).

Pinus and *Eucalyptus* plantations differ from miombo forest in several aspects. The forest plantations are managed for maximum growth and are often protected from fires, whereas miombo forest is typically subjected to frequent fires and many forms of use by local communities. The preference for *Pinus* and *Eucalyptus* species in reforestation and afforestation work is due to a number of aspects (Lugo and Brown, 1993, FAO, 2001, Dohrenbusch, 2012), including their high wood production rate and consequently high C sequestration rate in the tree biomass above the ground surface. For example, the rate of C sequestration in aboveground tree biomass of a mature plantation of species in the *Pinus* and *Eucalyptus* genera can range from 5.5 to 16 Mg ha^{-1} yr^{-1} (Lugo et al., 1988; IPCC, 2006). In contrast, in miombo forests the rate is generally less than 1 Mg ha^{-1} yr^{-1} (Williams et al., 2008; Lupala et al., 2014).

A large number of studies, reviewed by Cunningham et al. (2015) and Li et al. (2012), have shown that plantations of *Pinus* and *Eucalyptus* on abandoned farmland increase soil C stocks. However, despite the potential of these species to counteract