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Determinants of aboveground carbon offset additionality in plantation forests in a moist tropical forest in western Kenya

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ABSTRACT

Few studies have attempted to identify factors that contribute to aboveground carbon offset additionality in forest restoration planting in the tropics. Moreover, those that have compared aboveground carbon offset potential of naturally regenerating secondary forests and plantation forests have yielded conflicting results regarding the ability of the latter to attain carbon offset additionality, thus limiting broad adoption of carbon-driven forest restoration interventions. We assessed woody species diversity, stem density, stem diameter and wood specific gravity of secondary and plantation forests in Kakamega Forest in western Kenya to identify determinants of aboveground carbon offset additionality in plantation forests. Secondary forests comprised old-growth, middle-aged and young vegetation stands. Plantation forests consisted of mixed indigenous, *Maesopsis eminii* indigenous monoculture and *Cupressus lusitanica*, *Pinus patula* and *Bischofia javanica* exotic monoculture stands. Assessment was carried in 135 sample plots in three forest blocks using stratified systematic sampling in nested plots. Analysis of variance indicated that there was no significant difference in woody species diversity between secondary and plantation forests due to natural forest succession in both forest types. Mixed indigenous plantation had more aboveground carbon stock than secondary forest stands of comparable stand age due to its greater proportion of tree species with high wood specific gravity and large tree diameter. Old-growth secondary forest had more aboveground carbon stock than monoculture forest plantations due to its relatively higher wood specific gravity. Middle-aged secondary forest had relatively lower aboveground carbon stock than plantation forests of comparable stand age because of its smaller tree diameter. The results suggest that stem diameter and wood specific gravity are the most important determinants of aboveground carbon offset additionality. Thus, forest managers and investors in carbon offset projects can achieve aboveground carbon offset additionality in forest restoration interventions by planting tree species with relatively higher wood specific gravity and manipulating them to attain large stem diameter through silvicultural management.

1. Introduction

Tropical forest ecosystems play a significant role in the global carbon balance. They account for only 37% of the estimated 1150 Gt of carbon that resides in forest ecosystems, but have the greatest impact on the terrestrial carbon balance (Malhi et al., 1999; Lewis et al., 2004; Lewis, 2006; Chaturvedi et al., 2011; Martin et al., 2013). This is because most of the carbon in tropical forests is stored in standing vegetation unlike the case of boreal and temperate forests where a greater proportion of the carbon is stored in the soil and in peat bogs (Malhi et al., 2002). Global wood utilization trends also indicate that wood supply in developing countries, most of which occupy the tropical zone, is driven primarily by the demand for fuel wood (Siry et al., 2005). Thus, most of the 5.6–8.6 billion tons of carbon, which is emitted annually into the atmosphere through deforestation and forest degradation (approximately 18% of present greenhouse gas emissions), originates from tropical forests (Glenday, 2006; Brickell, 2009; Keenan, 2009; Verburg et al., 2009; van der Werf et al., 2009; Orihuela-Belmonte et al., 2013). Despite such a huge contribution of deforestation and forest degradation to global greenhouse gas emissions, forest restoration efforts hold a great potential to significantly offset atmospheric carbon emissions (Brown et al., 2000; Laurance, 2007). However, large

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scale adoption of carbon-driven forest restoration strategies has been hampered by poor understanding of the aboveground carbon offset potential of passive and active forest restoration interventions (Lewis, 2006; Gibbs et al., 2007; Holl and Zahawi, 2014; Kinyanjui et al., 2014).

Comparisons of aboveground carbon offset potential of naturally regenerating secondary forests and plantation forests in tropical forest ecosystems have yielded conflicting findings regarding which of the two forest types has superior offset potential (Chaturvedi et al., 2011; Omeja et al., 2012; Bonner et al., 2013; Marin-Spiotta and Sharma, 2013). A number of studies have indicated that natural forest regeneration accumulates significantly more aboveground carbon stock than restoration planting (Glenday, 2006; Ch'ng et al., 2011), while other studies have reported that the latter sequesters significantly more aboveground carbon stock (Zheng et al., 2008; Baishya et al., 2009; Chaturvedi et al., 2011). Other studies have indicated that plantation forests are only marginally superior to secondary forests in aboveground carbon accumulation (Omeja et al., 2012; Bonner et al., 2013). However, ITTO and FAO (2009) and Kanowski and Catterall (2010) state that plantation forests also differ in aboveground carbon accumulation potential due to variation in tree species mix and stand structural attributes and are therefore not expected to give the same results. Since the findings of each of these studies are considered accurate, it is likely that there exist specific variables that determine the aboveground carbon accumulation potential in both naturally regenerating secondary forests and planted forests. For instance, Baishya et al. (2009) attributed superior aboveground carbon accumulation potential in plantation forests over secondary forests to good silvicultural management. It was unclear, however, whether the aboveground carbon accumulation potential of naturally regenerating secondary forest stands would also increase if they were subjected to similar silvicultural treatment. Given that carbon offset benefits can only be derived from forest restoration interventions with the capacity to achieve carbon offset additionality over the reference scenario (natural forest regeneration in this case) (Valatin, 2011; Omeja et al., 2011; Gillenwater, 2012), failure to clearly identify the determinants of aboveground carbon offset additionality has slowed the broad adoption of carbon-driven forest restoration planting. The situation is attributed to the fact that many actors in carbon offset schemes are apprehensive of engaging in restoration efforts whose aboveground carbon sequestration potential is inferior to natural forest regeneration. It is prudent, therefore, to provide a clear picture on the determinants of aboveground carbon offset additionality in order to inform forest managers and investors in carbon offset schemes of the best forest restoration approaches to employ.

In this paper, we assess the aboveground carbon offset potential of different secondary and plantation forest types using a chronosequence study in Kakamega Forest in western Kenya. The forest is an eastern relic of the African equatorial rainforest and one of the forest ecosystems that have been subjected to a great deal of degradation for close to a century (Lung and Schaab, 2006; Schaab et al., 2010). It has lost about 75% of its primary forest cover as a result of a series of disturbance events that occurred between 1930s and 1990s (Wass, 1995). Whereas most of the degraded forest sites regenerated naturally and ended up as secondary forests, some of the sites were placed under plantation forests of both indigenous and exotic tree species (Glenday, 2006; Otuoma et al., 2014). Other sites were subjected to repeat incidences of disturbance and degenerated into open fields that are presently used for grazing. The study analysed possible variation in woody species diversity, stand structural attributes and wood specific gravity in relation to aboveground carbon stock in order to identify variables that determine superiority in carbon offset potential between secondary and plantation forests in moist tropical forests. Secondary forest types comprised old-growth, middle-aged and young vegetation stands, while plantation forests consisted of mixed and monoculture indigenous and exotic stands. Findings of this study are expected to inform policy makers, forest managers and prospective investors in carbon credit schemes about tree species attributes and managerial aspects that forest restoration interventions should focus on in their endeavour to secure aboveground carbon offset additionality for future carbon offset projects.

2. Materials and methods

2.1. Study site

The study was carried out in Kakamega Forest between February 2013 and January 2015. The forest is located in western Kenya between latitudes 0°10′N & 0°21′N and longitudes 34°47′E & 34°58′E at an elevation of 1600 m above sea level (Fashing and Gathua, 2004; Farwig et al., 2008). The area has a hot and wet climate characterised by a mean temperature of 25 °C and an annual precipitation of 1500–2000 mm with a dry season between December and March (Glenday, 2006; Mitchell and Schaab, 2008). The forest has over 400 plant species (of which about 112 are tree species), over 300 bird species and about seven endemic primate species (Kokwaro, 1988; Otuoma et al., 2014).

The forest's vegetation comprises a disturbed primary forest, secondary forests in different stages of succession, mixed indigenous plantation forests, indigenous and exotic monoculture plantation forests, and both natural and man-made glades (Tsingalia and Kassily, 2009). Closed canopy old-growth natural forest stands are dominated by evergreen tree species such as *Funtumia africana* (Benth.) Stapf, *Strombosia scheffleri* Engl., *Trilepisium madagascariense* DC., *Antiaris toxicaria* Lesch., *Ficus exasperata* Vahl, *Croton megalocarpus* L. and *Celtis gomphophylla* Baker (Glenday, 2006; Lung, 2009). The forest supports an adjoining human population of about 280,000 people who are distributed in surrounding farmlands and urban centres (Otuoma et al., 2014). Some of the resources that they obtain from the forest include fuel wood, timber, construction poles, herbal medicine, fibre, pasture for livestock, indigenous fruits and traditional vegetable (Musila et al., 2010).

2.2. Study design

The study employed a nested experimental design (Kuehl, 2000; Onwuegbuzie and Leech, 2007). Assessment was carried out in three forest blocks, namely: Yala, Kibiri and Isecheno. Each of the forest blocks had nine different forest types, which were the treatments in the study. The nine forest types were disturbed primary forest (which was the control), old-growth secondary forest, middle-aged secondary forest, young secondary forest, mixed indigenous plantation, *Maesopsis eminii* Engl. indigenous monoculture plantation, and *Bischofia javanica* Blume, *Cupressus lusitanica* Mill. and *Pinus patula* Schlechtend. & Cham. exotic monoculture plantations. The treatments were treated as sub-blocks, which were nested within each of the three forest blocks.

Assessment was carried out in the nine sub-blocks using a variable area technique, which ensured that woody species of different stem sizes were assessed in sampling plots of different sizes to enhance the probability of obtaining tree data in equal proportions (NAFORMA, 2010; Nath et al., 2010). The sampling unit comprised a concentric sample plot of 30 m radius with stratified sub-plots of 15 m, 10 m, 5 m and 2 m radius from the center of the sample plot. The sub-plots were nested within the sample plot. There were five sample plots in each sub-block, which gave a total of 135 sample