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Land cover impacts on aboveground and soil carbon stocks in Malagasy rainforest

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ABSTRACT

Deforestation and forest degradation can impact carbon dynamics and, subsequently, ecosystem functioning and climate change. In this study, we surveyed the influence of such land cover changes on four land cover/uses including closed canopy forest, tree fallow, shrub fallow, and degraded land among 120 study sites. We assessed these changes on total carbon stocks including both aboveground biomass (AGB) and soil organic carbon (SOC) including both topsoil, 0–30 cm, and deep soil, 30–100 cm. The four land cover/uses were located within four regions (Andasibe, Didy, Anjahamana, and Lakato) in the Eastern humid tropical forest of Madagascar. Our results show that total carbon stocks, AGB and soil, average 166 ± 57 Mg C ha^{-1} in which 82% is stored in 0–100 cm of soil surface horizon (55% stored in the topsoil and 27% in deep soil) suggesting the importance of soil pools in the sequestration of atmospheric carbon. The total carbon stocks were significantly higher in closed canopy compared to the other land covers. In lower altitude regions, the total carbon stock was lower ranging from 143.5 Mg C ha^{-1} to 163.7 Mg C ha^{-1}, relative to higher altitude areas where total C stock ranged from 170.6 Mg C ha^{-1} to 186.1 Mg C ha^{-1}. The relative importance of AGB and SOC were reversed in these study sites, with AGB/SOC ratios of 0.37 for Anjahamana, 0.17 for Lakato, 0.21 for Didy, and 0.17 for Andasibe. Climatic factor combined with soil properties could explain the SOC variations across the study regions. High SOC was related to lower precipitation, high clay content and high root development. These results provide an accurate assessment of carbon storage distribution in a tropical region and support the importance of forest conservation and effective land cover management in maintaining carbon storage in ecosystems as tools in climate change mitigation in tropical forests.

1. Introduction

Tropical ecosystems represent a major carbon (C) sink, sequestering large amounts of carbon dioxide (CO_2) from the atmosphere (Ngo et al., 2013). C sequestration and storage also play multifunctional roles in ecosystem services and provide environmental benefits through climate regulation (Brussaard, 2012; Millennium Ecosystem Assessment, 2005). C is initially stored in vegetation including aboveground biomass (AGB) through photosynthesis, and transferred to belowground including root and soil organic carbon pools, and in dead wood and litter pools (Thompson et al., 2012). Tropical forests have a high potential to sequester CO_2, accounting for more than 40% of total C stored in terrestrial biomass worldwide (Day et al., 2013). In fact, Saatchi et al. (2011) estimate that tropical and sub-tropical forests store around 247 Gt C in above and belowground biomass.

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However, these C stocks are affected by natural and human disturbances through land cover changes as a result of deforestation and forest degradation (Day et al., 2013; Guo and Gifford, 2002). Deforestation and forest degradation impact C stock regulation. During forest clearance, C accumulated in AGB is released as CO_2, increasing CO_2 levels in the atmosphere and contributing to global climate change (Day et al., 2013). Furthermore, changes in land cover from forest to non-forest systems result in increased soil loss which could be due to higher rates of flooding and erosion, further enhancing the large fraction of organic matter released as CO_2 (Richey et al., 2002; Thompson et al., 2012).

Studies on the estimation of C stock in tropical areas are scarce in number and the available information on C storage contains large variability, generally associated with the method of C assessment and limited size and number of sampling sites (including replication and sampled area) (Palm et al., 2000; Sierra et al., 2007). Faced with climate change, sustainable management of the terrestrial ecosystem is needed to conserve existing C stocks and enhance these stocks through the sequestration of atmospheric C. Consequently, there is a need to review the effects of land cover change on C storage.

The Intergovernmental Panel on Climate Change (IPCC) reported that deforestation and land cover change, resulting in CO_2 emissions, contribute as much as 24% of the annual CO_2 flux to the atmosphere (IPCC, 2014). Beginning in 2005, with the introduction of Reducing Emissions from Deforestation and Degradation (REDD) as a way for developing countries to reduce emissions, momentum has grown providing innovative ways to reduce greenhouse gas emissions and maintain and enhance C storage in developing countries through forest conservation and sustainable management of various ecosystems, termed REDD+ (Day et al., 2013; Syampungani et al., 2014). REDD+ requires an accurate estimation of C stock in forest and other land cover changes. Estimation of above and belowground C stocks across countries under different land covers accounts for 305 Mg C ha^{-1} for primary forest, 218 Mg C ha^{-1} for secondary forest, 136 Mg C ha^{-1} for tree fallow, 85 Mg C ha^{-1} for bush fallow, and 52 Mg C ha^{-1} for burned cropland (Woomer et al., 2000).

Natural forest in Madagascar has been severely deforested during the last half century owing to deforestation for timber production and due to land cover practices (Harper et al., 2007; Harvey et al., 2014; Styger et al., 2007). In eastern Madagascar, traditional farming practices of slash and burn, in which the forest is replaced for agriculture by cutting and burning the trees followed by agricultural cycles interspersed with fallow periods, lead to vegetation changes marked by transition of primary forest to grassland (Styger et al., 2007). The first fallow cycle after deforestation is associated with a tree fallow system where vegetation types are dominated by *Trema orientalis* and *Harunganamadagascariensis*. From the second to the fifth fallow cycle after deforestation, endemic shrubs, dominated by *Psidia atlissima* and exotic and invasive species dominated by *Rubus moluccanus* or *Lantana camara*, replace the previous tree fallow species resulting in shrub fallow landscapes. Beyond the sixth fallow cycle herbaceous fallows or grasslands dominate, marked by development of grass species and ferns, *Imperata cylindrica*, and *Aristida* sp. (Styger et al., 2009; Styger et al., 2007). These last systems represent the final stage of ecosystem degradation where lands are abandoned due to low crop productivity.This transition from primary forest to grassland can take between 20–40 years (Styger et al., 2007), and the transitions through these stages area associated with changes in canopy and understory tree density, plant species richness, and C stocks (Devi and Behera, 2003; Harrison, 2011). The influence of these land cover changes in Madagascar on carbon storage in aboveground and soil pools is poorly understood and an accurate quantification of AGB and SOC is required for the assessment of system vulnerability or potential and global C stocks. Increasing interest in measurement of AGB and SOC at 0–30 cm horizon, called topsoil was recently observed in Madagascar forest (Asner et al., 2012; Ramananantoandro et al., 2015; Razakamanarivo et al., 2012; Razakamanarivo et al., 2011; Vieilledent et al., 2012). Assessment of SOC up to 100 cm depth is essential to capture the full soil profile and needs to be examined accurately within different land covers as a large soil C fraction is sequestered in deep soil. Many previous studies have focused on the top soil, less on the deep soil.

This paper aimed to (i) quantify total C stock in aboveground and soil C pools including the top and deep soil C; (ii) determine the effect of traditional Malagasy land cover practices on AGB and SOC; and (iii) identify other environmental factors impacting C stocks.

2. Materials and methods

2.1. Study area

The Ankeniheny-Zahamena Corridor (CAZ) is located in eastern Madagascar. Containing important remnants of Madagascar's humid rainforest, including the majority of the rain forest of low and medium altitude, this area extends over 371,000 ha. The climate of the region is hot and humid tropical with an average annual rainfall of 2500 mm and a mean annual temperature between 18 and 24 °C. The area is characterized by two bioclimate zones, perhumid and humid (Cornet, 1974; Schatz, 2000). Perhumid, the wetter zone, dominates the eastern extent; humid, the drier zone, dominates the west. Soils in CAZ are dominated by ferrallitic soils (Ferralsols according to FAO classification). These high weathered soils are mainly characterized by their red colour due to the presence of iron oxides, the presence of low activity clay (kaolinite), and their low level of organic matter due to their rapid decomposition. In this area, some ferrallitic soils are characterized by a sequence of yellow and red soil horizons. Yellow horizons are often observed in primary and degraded forest. They result from the high weathering and leaching of soil minerals components including clay and iron due to the high precipitation (or rainfall) in the zone (Hervieu, 1967).

Four study regions were selected within the CAZ. The regions were selected to be indicative of CAZ based on a suite of biophysical and environmental variables including elevation, slope, bioclimate zone, climate dynamics, deforestation history etc. The initial selection of regions was further refined through an iterative process to capture (1) a region of rapid recent deforestation and potential impacts on ecosystem services from fallows on relatively un-degraded land (Lakato); (2) a region where reforestation activities have been implemented (Andasibe); (3) a low-lying, accessible, region in the perhumid bioclimate zone (Anjahamana); and (4) a region upstream of the 'rice bowl' of Madagascar. The characteristics of each region are captured in Table 1 and Fig. 1 below. Lakato is located in a high elevation section of CAZ and experiences a humid climate zone. With 1–2 dry season months, the soil in this area is old dominated by association of yellow and red ferrallitic soil. Lakato has a gradient of deforestation chronosequence, including both old as well as rapid recent deforestation, as highlighted above. Andasibe, situated in a high elevation section of CAZ in the south east, is located within the humid climate zone. It experiences 1–2 dry season months, is dominated by yellow or/and red ferrallitic soil, and has old deforestation. Further, reforestation activities have occurred in this region. Anjahamana, situated in a low elevation section of CAZ in the east, has a perhumid climate. This area experiences zero dry season months, and is dominated by an association of yellow and