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Carbon stocks of mangroves within the Zambezi River Delta, Mozambique

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ABSTRACT

Mangroves are well-known for their numerous ecosystem services, including storing a globally significant C pool. There is increasing interest in the inclusion of mangroves in national climate change mitigation and adaptation plans in developing nations as they become involved with incentive programs for climate change mitigation. The quality and precision of data required by these programs necessitates the use of an inventory approach that allows for quantification, rather than general characterization, of C stocks. In this study, we quantified the ecosystem C stock of the Zambezi River Delta mangroves utilizing a rigorous, yet operationally feasible approach. We applied a stratified random sampling inventory design, based on five forest canopy height classes, derived from Ice, Cloud, and Land Elevation Satellite/Geoscience Laser Altimeter System (ICE Sat/GLAS) and the Shuttle Radar Topography Mission (SRTM) data, and a Spatial Decision Support System to allocate inventory plots. Carbon content in above- and below-ground biomass pools in addition to soils to a depth of 200 cm was measured. The average biomass C density for the height classes ranged from 99.2 Mg C ha^{-1} to 341.3 Mg C ha^{-1}. Soil C density was the largest measured C pool, containing 274.6 Mg C ha^{-1} to 314.1 Mg C ha^{-1} and accounting for 45–73% of the height class ecosystem C densities, which ranged from 373.8 Mg C ha^{-1} to 620.8 Mg C ha^{-1}. The ecosystem C density estimates for the five strata were weighted based on their spatial distribution across the landscape to yield a total C stock for the Zambezi River Delta mangroves of 1.4×10^7 Mg C. The error bounds from the 95% confidence interval are ±6% of our ecosystem C stock estimate, well within acceptable levels of uncertainty.

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1. Introduction

Mangroves are recognized for their numerous ecosystem services and functions that are critical to environmental health and human well-being. Although mangroves comprise only 0.7% of the world's tropical forest area (Giri et al., 2011), they have been shown to contain globally significant C pools, particularly in soils, storing up to three times more C per area than typical upland tropical forests (Donato et al., 2011; Kauffman et al., 2011). Studies from around the world have highlighted the capacity of mangroves to store C, revealing a wide range of ecosystem C stock estimations (Adame et al., 2013; Alongi, 2014; Jones et al., 2014; Rahman et al., 2014). The large amount of C processing that occurs in mangrove environments (Dittmar et al., 2006; Kristensen et al., 2008) is inextricably linked to the ecosystem services for which they are renowned, particularly sediment retention, fishery resources, and nutrient filtration (Alongi, 2002; Bouillon et al., 2008).

After fossil fuel combustion, deforestation and forest degradation constitute the second largest anthropogenic source of C dioxide to the atmosphere, comprising between 8% and 20% of total emissions (van der Werf et al., 2009; IPCC, 2013). International incentive programs for climate change mitigation are being considered as a viable option for reducing greenhouse-gas emissions from the land use sector. These programs include financial mechanisms regulated by compliance or voluntary C markets aimed to conserve or enhance ecosystem C stocks, thus reducing or avoiding emissions from land use and land cover change (Gullison et al., 2007). One mechanism that has been a focus of international climate policy is the UN's Reducing Emissions from Deforestation and Forest Degradation (REDD+) program, which proposes financial incentives to help developing countries reduce deforestation

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and degradation rates, build capacity for conservation and sustainable forest management, and enhance forest C stocks (UN-REDD, 2011). While the majority of the preparations have focused on terrestrial forests, the large C sequestration capacity of mangroves and high rates of mangrove deforestation worldwide have sparked considerable interest about including them in REDD+ programs.

Africa contains approximately 20% of the world's mangroves (Giri et al., 2011). Within Africa, Mozambique has the second largest area of mangrove cover after Nigeria (Fatoyinbo and Simard, 2013). Globally, Mozambique ranks 13th in mangrove coverage, equivalent to approximately 2.3% of the global mangrove forest area (Giri et al., 2011). While the functions of mangroves in Mozambique are analogous to those elsewhere (e.g., storm protection and fish nurseries), their associated goods and services are particularly valuable given the dependence of local communities on the forests and near-shore fisheries (Government of Mozambique, 2009).

The Zambezi River Delta mangrove extends for 180 km along the coast and approximately 50 km inland, accounting for almost 50% of the mangrove area in Mozambique and forming the second largest continuous mangrove habitat in Africa (Barbosa et al., 2001). The stature and importance of the Zambezi River Delta mangrove to the Mozambican people make it an area of interest for conservation and marketing of C sequestration potential and other ecosystem services.

Mangrove forests are often located in remote areas that are extremely difficult to access, making thorough investigations logistically challenging, as is the case with the Zambezi River Delta. Regardless of these inherent difficulties, the quality and precision of data required by programs like REDD+ necessitate the use of an inventory approach that allows for objective quantification, rather than general characterization, of the C stocks within the area of interest. The designed inventory provides the basis for quantifying C stocks, assessing uncertainties, and monitoring changes over time. The recent inventory of mangroves in Madagascar (Jones et al., 2014) is the only comprehensive C inventory performed to date in Africa, and one of just a few globally (Kauffman et al., 2011; Adame et al., 2013; Kauffman et al., 2014; Rahman et al., 2014). While approaches for forest inventory are well documented (e.g., Bechtold and Patterson, 2005), the challenge in mangroves is the design of an approach that provides a robust estimate of the C stock and is operationally efficient. Our objective was to quantify the mangrove C stock within the Zambezi River Delta that can serve as a baseline for measurement, reporting and verification (MRV).

2. Study area

The Zambezi River Delta (Fig. 1) comprises an area of approximately 12,000 km^2, extending 120 km downstream of the Zambezi and Shire Rivers confluence to the Indian Ocean. It also extends 200 km southwest–northeast along the coastline, from the Cuacua River, to the Zuni River Delta. The climate of the region is tropical, with a distinct dry winter season from April to October and a wet summer season from October to March (Barbosa et al., 2001; Hoguane, 2007). The mean annual precipitation ranges from 1000 mm at the most upstream regions of the delta to more than 1400 mm along the coast, with considerable inter-annual variation (Bento et al., 2007). Eighty-five percent of the rain falls from mid-November to late March (Tweddle, 2013). Mean monthly temperatures range from a minimum of 27 °C in June to a maximum of 37 °C in October (Tweddle, 2013).

The water levels in the Zambezi River Delta are reflective of the cumulative runoff patterns in the upstream sub-basins, with an estimated average water volume of 108×10^9 m^3 reaching the delta on an annual basis (Beilfuss and Santos, 2001). The tidal regime in the delta is semi-diurnal, with a spring tide maximum amplitude of 4.1 m (Beilfuss and Santos, 2001; Coleman, 2004). This tidal range is the largest in Mozambique and in the dry season tidal influence reaches 80 km upstream (Beilfuss and Santos, 2001).

The vegetation of the Zambezi River Delta is a mixture of woodlands, savanna, grasslands, mangroves, and coastal dunes within a mosaic of wetlands (Beilfuss et al., 2001). Small villages with accompanying subsistence agriculture plots are scattered throughout the extent of the delta. Mangrove communities occur on mud flats within the coastal estuary, occupying an area of approximately 30,267 ha, as delineated by Giri et al. (2011) (Fig. 1). These mud flats are composed of dark silt and clayey alluvium, rich in organic matter (Beilfuss et al., 2001). There are eight mangrove species present in the delta, representative of all species reported to occur in Mozambique: *Sonneratia alba* Smith, *Avicennia marina* (Forsskk.) Vierh., *Rhizophora mucronata* Lam., *Ceriops tagal* (Per.) C.B. Robinson, *Bruguiera gymnorrhiza* (L.) Lam., *Lumnitzera racemosa* Wild., *Heritiera littoralis* Alton, and *Xylocarpus granatum* Koenig. Mangrove associate species tend to occur in elevated areas with less tidal inundation (Vilankulos and Marquez, 2000) and include *Guettarda speciosa* L., *Hibiscus tiliaceous* L., and the large fern *Achrostichum aureum* L. (Barbosa et al., 2001; Beilfuss et al., 2001). Thickets of *Barringtonia racemosa* (L.) Spreng. also occur along the furthest upstream reaches of tidal influence within the estuary (Beilfuss et al., 2001).

The geomorphology of the delta is heavily affected by upstream activities and water flows, especially the operation of the Kariba and Cahora Bassa Dams. The dams have not only reduced fresh-water discharge to the delta, but also diminished sediment transport, resulting in coastal zone erosion and a reduction of sediment-maintained habitats, including mangroves (Davies et al., 2000). The degree to which these changes in flows and deposition directly affect the vegetative communities within the delta has not been well studied. Additionally, the delta is subject to frequent storms that cause geomorphic changes and can also directly damage mangrove stands (Beilfuss et al., 2001).

3. Methods

3.1. Inventory design

The inventory area included the entire 30,267 ha of mangrove forest, distributed along the north and south sides of the Zambezi River, as delineated by Giri et al. (2011). We used a stratified random sampling design, since stratification can improve the precision of the inventory (Cormack, 1988; Nusser et al., 1998). Mangrove canopy height, derived from Ice, Cloud, and Land Elevation Satellite/Geoscience Laser Altimeter System (ICE Sat/GLAS) and the Shuttle Radar Topography Mission (SRTM) data, is available for Africa (Fatoyinbo and Simard, 2013). We used the mangrove canopy height data as the basis for stratification, because forest height is functionally related to biomass estimation. Five canopy height classes were distinguished within the Zambezi River Delta using a Jenks natural breaks optimization: 2–6.9 m (HC1), 7–9.9 m (HC2), 10–12.9 m (HC3), 13–17.9 m (HC4), and 18–29 m (HC5). The number of plots per height stratum was determined by using a proportional allocation with respect to the total area in each stratum, based on the remote sensing mangrove coverage pixels.

The field work was conducted over two field seasons in September and October of 2012 and 2013. Our sampling approach used 7 m radius subplots (0.0154 ha) nested within a 0.52 ha square plot. The purpose of the subplots was to accommodate inherent spatial variation within the plot that was represented in

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