Forest Ecology and Management 351 (2015) 36–46

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

The influence of stand variables and human use on biomass and carbon stocks of a transitional African forest: Implications for forest carbon projects

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ARTICLE INFO

Article history:
Received 5 February 2015
Received in revised form 24 April 2015
Accepted 29 April 2015
Available online 23 May 2015

Keywords:
Carbon stocks
Above ground biomass
Kenya
Transitional tropical forest
Human use of forests
Forest carbon project

ABSTRACT

The viability and effectiveness of forestry-based carbon projects depends on the accurate estimation of carbon stocks as well as understanding the variables that influence carbon stocks, including human activity. However, for much of Africa, accurate, ground-based measurements are few, forests have centuries of human use, and the variables that influence forest biomass and carbon stocks are not well understood. The objectives of this study were to use field-based sampling to estimate aboveground biomass (and associated carbon stocks), and explore AGB variation in relation to forest stand characteristics and human biomass removal in an African tropical forest that lies in a transitional ecological zone between lowland equatorial and moist montane forest. We quantified tree densities, estimated plot aboveground biomass (AGB) using pan-tropical allometric equations, and estimated human biomass removal in four regions of Kakamega Forest in western Kenya that varied in historical and current human use. Our carbon stock estimate (173.3 MgC ha^{-1}) was above large biome averages for moist tropical forests. Diameter of the largest tree, stem densities of large trees, and wood density were the most important variables influencing biomass, accounting for over 75% of the variation. While historical disturbance influenced biomass removal, we did not find that this disturbance or biomass removal significantly influenced AGB. The reason was that most biomass removal involves trees in small size classes, which are insignificant contributors to biomass. Our findings provide a field based estimate of carbon stocks for a transitional tropical forest. We also conclude that processes (both natural and anthropogenic) which influence the presence and health of species which can attain large size will have the greatest impact on biomass, while processes that influence stem densities of small trees will have no measurable effect. The application of these findings for forestry-based carbon projects would translate to the need for special attention being paid to activities which prevent or minimize loss of large dense trees (e.g. charcoal production, selective logging) if the carbon stock of a forest is to be maintained. On the other hand, activities which limit subsistence use in terms cutting small stems (e.g. energy efficient stoves), might not have measureable immediate effects on carbon stocks and the financial outcomes associated with the generation and sale of the carbon credits.

1. Introduction

Tropical forests represent less than 10% of total land area, yet contain over 40% of all carbon in terrestrial biomass (Lewis et al., 2009). These forests are not only an important store of carbon, but sequester carbon annually resulting in a net global sink of approximately 1.3 Pg C year^{-1} (Chave et al., 2008; Lewis et al., 2009). However, the degradation and deforestation of tropical forests contributes approximately 12% of the annual global emissions of anthropogenic greenhouse gases (van der Warf et al., 2009). In Africa, deforestation and degradation of forests accounts for up to 70% of national GHG emissions (UNFCCC, 2012).

The conservation and/or restoration of tropical forests can have profound effects on global atmospheric GHG's through increasing carbon storage and decreasing GHG emissions. Most tropical forests, however, are located in developing countries where there is a real challenge finding incentives to slow or stop forest loss (Santilli et al., 2005). The importance of including forestry related projects (e.g. afforestation, reforestation, and avoided deforestation

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http://dx.doi.org/10.1016/j.foreco.2015.04.032
0378-1127/

and degradation – REDD+) in climate policy are being reconsidered, primarily as a mechanism to provide financial incentives to halt forest loss in developing countries (http://www.un.org/climate-change/summit/action-areas/). However, full acceptance of forestry-based carbon projects by the international community will require addressing the obstacles that prevented their inclusion in the first commitment cycle of the Kyoto Protocol (Gullison et al., 2007), namely the lack of accurate measurements of carbon stocks, estimated from biomass, and the uncertainty of changes in emissions resulting from implemented activities.

The revenue generated from carbon projects is the difference between the changes in carbon stocks between the existing baseline condition and the project condition (with interventions) over a period of time. The viability and effectiveness of forestry-based carbon projects thus first rely upon the accurate estimate of standing biomass in forests (IPCC, 2006; Gibbs et al., 2007). While large-scale biome-averages for tropical forests (Baccini et al., 2008; Houghton et al., 2001; Ramankutty et al., 2007; Saatchi et al., 2011) are useful for obtaining global, continental, and perhaps national estimates of biomass in forests, they may under- or overestimate actual values needed for specific forests or forest complexes, especially when forests lie in transitional ecological zones or have unique land use histories (Gibbs et al., 2007). For example, based upon publications in the last 15 years from large-scale estimations of carbon stocks for tropical forests, Kakamega Forest (a tropical forest in western Kenya at elevations from 1460 and 1765 m a.s.l) has estimated carbon stocks (above and below ground) from 54 to 175 $Mg ha^{-1}$ (Gaston et al., 1998; Baccini et al., 2008; Saatchi et al., 2011). These biome averages are the only values that are available for most forests of Africa (but see Taylor et al., 2008). Although new ground-based studies are providing accurate biomass estimates of tropical forests in many countries (Slik et al., 2010; Hoshizaki et al., 2004; Chave et al., 2003; Fox et al., 2011), forests in African countries remain the least described. In addition, African forests and forest communities stand to benefit considerably from carbon projects: projects can provide revenue streams to local people for conservation and/or restoration activities, thus providing a mechanism to reduce forest loss and degradation.

The viability of forestry-based carbon projects also relies upon understanding the variables that influence biomass, and accurately quantifying the effect of human activities on carbon stocks and emissions. For example, the revenue generated from REDD + projects is dependent on implementing the correct activities under project conditions that will have the largest impact on reducing biomass removal. This decision rests upon accurately knowing how biomass varies spatially and temporally and how changing human activities will affect this future biomass as compared to a baseline. Human use of forest resources is ubiquitous in tropical forests (Asner et al., 2009) and the idea of pristine tropical forests is being amended with increasing evidence of long-term, historical use of forests (Ellis and Ramankutty, 2008; Van Germerden et al., 2003; Ssemmando et al., 2005). The primary drivers of current tropical forest degradation and deforestation are agriculture and logging, both of which are comparatively large-scale and intense activities and result in a net loss of forest area. On the other hand, there are many other human uses such as selective logging, charcoal production, and understory thinning from fuelwood collection which are considerably more challenging to detect with commonly using techniques such as remote sensing. In addition, these smaller scale activities may be just as widespread and similar in extent (Peres et al., 2005; Laporte et al., 2007), and influence carbon emissions more than deforestation alone (Gaston et al., 1998; Asner et al., 2010). In East Africa, for example, subsistence forest use has been shown to significantly alter forest structure and composition (Fashing et al., 2004; Olupot et al., 2009; Sassen and Sheil, 2013). Kenya provides a good example. Commercial logging was banned by presidential directive in most national forests in the mid 1980s (Mitchell, 2004), but removal of tree biomass still continues in the form of illegal pit-sawing of large trees, charcoal production, and removal of smaller trees for building and fuelwood (Wass, 1995; MoE, 2002; Mitchell, 2004; Bleher et al., 2006). The extent of fuelwood use, in particular, is very high. In 2010, for example, national forest biomass removal for fuelwood was estimated at 35.1 million tons, more than 50% higher than the annual growth of all sources of wood (MoE, 2002). This is largely the result of over three million people in Kenya living within 5 km of forest land using wood as the primary energy source (Wass, 1995; MoE, 2002). The effect of this biomass removal on total forest biomass per unit area has, however, not been adequately studied.

Human use of tropical forests is ubiquitous and occurs at multiple scales, from logging of large commercial trees to removal of small trees and branches for fuelwood. Forestry-based carbon projects are a financial mechanism to provide incentives to reduce and/or modify this use. The generation and sale of carbon credits are based on measurable reductions in biomass removal between historic (i.e. baseline) removals and future (i.e. project) removals. However, in order for forestry-based carbon projects to be financially viable for developing nations and indigenous peoples and useful in reducing forest loss and degradation, they must provide real and measurable changes in biomass. It is thus important to better understand the variation in forest biomass, the effects that human use has on this biomass, and the influence of biomass removal on carbon stocks. The objectives of this study were to (1) estimate above ground biomass (and associated carbon stocks) for an African tropical forest that lies in a transitional ecological zone between lowland equatorial and moist submontane, (2) understand AGB variation in relation to forest stand characteristics and human biomass removal, and (3) translate the findings for use in forestry-based carbon projects.

2. Materials and methods

2.1. Study area

This study took place in Kakamega Forest in western Kenya, an area encompassed by 0°08′N to 0°22′N and 34°46′E to 34°57′E. The forest lies on flat undulating terrain ranging in altitude from 1455 m a.s.l. along the Yala and Sioko Rivers to 2060 m a.s.l. at the top of a few scattered forest hills (Blackett, 1994). The climate is semi-tropical with temperatures averaging 19.3 °C (Kigomo, 1987) and ranging from a mean annual minimum of 10.6 °C to a mean annual maximum of 27.7 °C (Blackett, 1994), with a mean annual rainfall of approximately 2000 mm with one noticeable short, dry period (Haupt, 2000). Kakamega forest has been variously described as semi-montane, moist, semi-deciduous and as a transitional tropical rainforest (Tsingalia, 1988; Kokwaro, 1988; Wagner et al., 2008; Beentje and Ihlenfeldt, 1990). As an ecosystem, Kakamega Forest marks the easternmost extent of the Guineo–Congolian Biogeographical Region, and occupies a transitional position between the lowland equatorial forests of West Africa and the Congo Basin and the afromontane forests of the highlands west of the Rift Valley (Blackett, 1994). The forest complex is located in one of the world's most densely populated rural areas, with estimates ranging from 500 to 900 people per square kilometer (KNBS, 2009). The majority of the population are subsistence farmers who rely heavily upon the forest for resources to meet food, housing, and energy needs (Bleher et al., 2006), resulting in potentially significant impacts on forest biomass, structure, and function. The forest also has an extended and diverse human