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Allometry and partitioning of above- and below-ground biomass in farmed eucalyptus species dominant in Western Kenyan agricultural landscapes

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ABSTRACT

Farmers in developing countries are one of the world's largest and most efficient producers of sequestered carbon. However, measuring, monitoring and verifying how much carbon trees in smallholder farms are removing from the atmosphere has remained a great challenge in developing nations. Devising a reliable way for measuring carbon associated with trees in agricultural landscapes is essential for helping smallholder farmers benefit from emerging carbon markets. This study aimed to develop biomass equations specific to dominant eucalyptus species found in agricultural landscapes in Western Kenya. Allometric relationships were developed by regressing diameter at breast height (DBH) alone or DBH in combination with height, wood density or crown area against the biomass of 48 trees destructively sampled from a 100 km^2 site. DBH alone was a significant predictor variable and estimated above-ground biomass (AGB) with over 95% accuracy. The stems, branches and leaves formed up to 74, 22 and 4% of AGB, respectively, while belowground biomass (BGB) of the harvested trees accounted for 21% of the total tree biomass, yielding an overall root-to-shoot ratio (RS) of 0.27, which varied across tree size. Total tree biomass held in live *Eucalyptus* trees was estimated to be 24.4 $\pm$ 0.01 Mg ha^{-1}, equivalent to 11.7 $\pm$ 0.01 Mg of carbon per hectare. The equations presented provide useful tools for estimating tree carbon stocks of *Eucalyptus* in agricultural landscapes for bio-energy and carbon accounting. These equations can be applied to *Eucalyptus* in most agricultural systems with similar agro-ecological settings where tree growth parameters would fall within ranges comparable to the sampled population.

1. Introduction

Fast growing species such as *Eucalyptus* have been introduced into many tropical countries to mitigate the dwindling supply of wood, especially for timber and biomass fuel [1]. In East Africa, eucalyptus species are common in farmed landscapes and the preferred species in managed plantations [2]. *Eucalyptus* is popular because of its fast-growing nature, multiple

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uses and importance as a ‘cash crop’ [1]. The higher proportion of *Eucalyptus* in agricultural landscapes is largely due to greater attention given to trees on farms, mainly because of their ability to couple economic gains with social services and environmental benefits. Despite the acknowledged importance of *Eucalyptus* trees, there is little knowledge about the amount of carbon that will be emitted to the atmosphere when areas dominated by these species are converted to other land uses.

In Kenya, the majority of timber and non-timber wood products are obtained from farm estates, presenting an opportunity for farmers to have access to additional income from their land [3]. To meet the high demand for tree products and services, considerable efforts have been focused on conserving and also increasing trees in the landscape. Two kinds of eucalyptus trees are favored on Kenyan farms: (1) naturalized eucalyptus introduced from Australia in the colonial era, and (2) eucalyptus hybrids introduced from South Africa. Eucalyptus plantations provide raw material for industries such as sawmilling, pulp and charcoal, while eucalyptus in agricultural landscapes supply timber, poles, building material and fuelwood, both for domestic and commercial purposes. Despite considerable efforts made to increase trees on farms, quantities of major biofuel trees continue decreasing in Kenya [2]. This decline has been attributed to competing demand for timber, food crop cultivation, human settlement and harvesting trees for fuelwood [1].

The role played by woody vegetation in the global carbon cycle has led to increased interest in estimating biomass held in all land uses, in addition to forests. Estimation of tree biomass in agricultural ecosystems can be crucial for the sustainable management of woody vegetation and also an essential component of monitoring carbon sequestration [4]. Periodic measurement of biomass accumulation can be used to establish the value of a given agroforestry practice. One can further determine the production potential or suitability of a certain species for a particular purpose, e.g. charcoal production. Measurement approaches can also be designed to predict harvest yield, thus helping to assess biomass loss or accumulation over time. By establishing the rate of biomass production, one can determine carbon sequestration potential of particular species. This allows the potential of trees in agricultural landscapes to offset anthropogenic carbon emissions to be established.

The Intergovernmental Panel on Climate Change, IPCC [5], provides methodologies for estimating tree carbon stocks. Without further data, IPCC default values are normally used, choosing a Tier 1 approach. This practice uses equations provided at global scale, stratified by eco-climatic zones such as those provided in Brown [6] or Chave et al. [7]. Kuyah et al. [8,9] showed that application of broadly derived forest-based equations to trees in agricultural landscapes yields biased estimates. Such bias can be minimized by applying Tier 2 or Tier 3 approaches, where country-specific models derived for local conditions are used. In this case, equations that adequately address unique project circumstances are either developed or chosen from the literature. Since tree species differ in architecture and wood gravity [10], and because the dimensional relationship of trees can be changed by silvicultural interventions, species-specific equations are necessary to produce reliable biomass estimates [11,12]. However, insufficient species-specific equations exist, particularly in sub-Saharan Africa where less than 1% of the tree species have country-specific equations [11]. Since it is not practical to fell trees to develop equations for each species, and because destructive sampling is generally not acceptable for rare species or in areas where the eventual objective is to conserve trees, biomass equations that cover trees with comparable shapes could be developed. This study aimed to (1) build biomass equations specific to dominant eucalyptus species found in Western Kenyan agricultural landscapes, (2) establish the suitability of mixed species equations developed for agricultural landscapes, and (3) determine the biomass distribution in the above- and below-ground fractions of *Eucalyptus*.

2. Methods

2.1. Description of the study area

The study was conducted on a 100 km^2 site on the Yala River basin covering part of Kakamega and Vihiga Counties in Western Kenya. The study site (latitude 0°7′51.57″N; longitude 34°49′13.01″E) covers an altitudinal gradient of 1430–1720 m above sea level. The regional climate around the Vihiga-Kakamega area is influenced by two rainy seasons: long rains from March to July and inconsistent short rains from August to November, allowing up to two cropping seasons per year. The mean annual precipitation is about 1950 mm, decreasing westwards, while temperatures range between 12 and 27 °C, with a mean annual temperature of 20.5 °C.

The landscape consists of mountainous highlands with numerous small streams and clusters of wetlands [13]. Acrisols, Ferralsols and Nitisols form the dominant soil types [14]. The soils are characterized by a good physical structure, but have low nutrient reserves due to prolonged weathering and intense agricultural use [15]. The soils are predominantly clay (46%) and silty clay (32%), although some clay loam (15%) and silt loam (5%) exist, while sand and loam together represent only 2% [13].

Agriculture is the economic mainstay in the area, with land-use systems varying from mainly subsistence smallholder farms to a few cash crop-oriented farms. Tea is the major cash crop, while maize, beans, banana and sweet potatoes are grown for subsistence. Woody vegetation forms part of the complex agricultural mosaic on smallholder farms, varying from individual free standing trees to pockets of stands that consist of indigenous and exotic forms managed in different ways [16]. Trees are grown around homesteads, in cropland and along farm boundaries, while woodlots occur mainly as small, mono-specific clusters of exotic trees, usually *Eucalyptus*.

2.2. Field measurement and biomass sampling

Trees used to build allometric equations were selected from 30 m × 30 m plots contained in the 100 km^2 block established within the Western Kenya integrated ecosystem management project [13] and described in Kuyah et al. [8]. The block is