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Quantifying the variability and allocation patterns of aboveground carbon stocks across plantation forest types, structural attributes and age in sub-tropical coastal region of KwaZulu Natal, South Africa using remote sensing

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A B S T R A C T

Quantifying the variability and allocation patterns of aboveground carbon stocks across plantation forests is central in deriving accurate and reliable knowledge and understanding of the extent to which these species contribute to the global carbon cycle and towards minimizing climate change effects. The principal objective of this study was to quantify the variability and allocation patterns of aboveground carbon stocks across *Pinus* and *Eucalyptus* plantation forests, tree-structural attributes (*i.e.* stems, barks, branches and leaves) and age groups, using models developed based on remotely sensed data. The results of this study demonstrate that aboveground carbon stocks significantly ($\alpha = 0.05$) vary across different plantation forest species types, structural attributes and age. *Pinus taeda* and *Eucalyptus grandis* species contained aboveground carbon stocks above 110 t C ha^{-1}, and Eucalyptus dunii had 20 t C ha^{-1}. Across plantation forest tree structural attributes, stems contained the highest aboveground carbon stocks, when compared to barks, branches and leaves. Aboveground carbon stock estimates also varied significantly ($\alpha = 0.05$) with stand age. Mature plantation forest species (*i.e.* between 7 and 20 years) contained the highest aboveground carbon stock estimates of approximately 120 t C ha^{-1}, when compared to younger species (*i.e.* between 3 and 6 years), which had approximately 20 t C ha^{-1}. The map of aboveground carbon stocks showed distinct spatial patterns across the entire study area. The findings of this study are important for understanding the contribution of different plantation forest species, structural attributes and age in the global carbon cycle and possible climate change moderation measures. Also, this study demonstrates that data on vital tree structural attributes, previously difficult to obtain, can now be easily derived from cheap and readily-available satellite data for inventorying carbon stocks variability.
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1. Introduction

Plantation forest ecosystems account for a dominant share of terrestrial carbon (IPCC, 2003). The sequestered carbon is stored both in the form of biomass (stems, barks, branches and leaves, foliage, roots, etc.) and in the form of organic carbon in the soil (Chen et al., 2015; Raich, Clark, Schwendenmann, & Wood, 2014; Wasige et al., 2014). Information on forest carbon storage and allocation patterns is therefore central for effective bioenergy production, detection of land-use change and assessment of carbon stocks for initiatives, such as REDD+: Reducing Emissions from Deforestation and Forest Degradation management practices, planning, and for understanding their contribution on the global carbon cycle (Carreiras, Vasconcelos, & Lucas, 2012; Chen et al., 2015; Chinembiri, Bronsveld, Rossiter, & Dube, 2013; Dube, Mutanga, Elhadi, & Ismail, 2014; IPCC., 2003; Laurin et al., 2014; UNFCCC., 1998a). Moreover, understanding the spatial patterns of these carbon reserves is also important as it significantly contributes to the Gross Domestic Product (GDP) of some countries especially those under the REDD+ project (Cerbu, Swallow, & Thompson, 2011; Gibbs, Brown, Niles, & Foley, 2007; Sandbrook, Nelson, Adams, & Agrawal, 2010). In South Africa, for instance the economic value of these commercial forests is equivalent to

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approximately 7.3% (ZAR 20.4 billion) of national annual revenues of which over 1.4 million people directly or indirectly depend on this industry for a living (Dube, Mutanga, Abdel-Rahman, Ismail, & Slotow, 2015; Nemani, Pierce, Running, & Band, 1993; Rock, Vogelmann, Williams, Vogelmann, & Hoshizaki, 1986).

So far, commercial forest resources cover approximately 3.1% (1.3 million ha) of the country's land surface (121.9 million ha) and form an essential base for timber, medicinal, pulp and paper products. Nearly 80% of these forest ecosystems are located in the south-eastern regions of the country, specifically in the Eastern Cape (11%), KwaZulu Natal (38.9%) and Mpumalanga (40%) provinces (FSA., 2010). When these plantation forests are equated to other forests within South Africa; the dominant hardwoods are *Eucalyptus* species, covering 39% and *Acacia mearnsii* with 17% of the total land area, whereas softwoods mainly *Pinus* forest species occupy the remaining 54% of the total land area (FSA., 2010). Also, the majority of these plantation forests are managed on a rotational basis (the rotation length can range from 6 to 25 years, depending on the nature of the end product). For instance, when plantation tree growth rates start to diminish, they are clear-felled and another crop of trees is planted (Christie & Scholes, 1995; Schönau & Boden, 1982). Despite the fact plantation forests eventually get felled, these forest ecosystems do account for the dominant share of terrestrial carbon stocks and the country's GDP (Dube et al., 2015; Roberts, Tesfamichael, Gebreslasie, van Aardt, & Ahmed, 2007).

Despite an increase in the areal extent of plantation forest species in the sub-Saharan Africa and South Africa in particular, their actual contribution to the global carbon cycle has not been fully quantified. This gap in knowledge can be attributed to the fact that most of these plantation forests are meant for commercial timber, pulp and paper production, hence most studies conducted in these forests are restricted mainly on volume or yield estimation (Christie & Scholes, 1995; Dube et al., 2015; Schönau & Boden, 1982). Also, most of these plantation forests are privately owned, hence not easily accessible for biomass related studies, by environmentalists, ecologists and the remote sensing communities. However, for a transition towards less global emissions and a reduction of atmospheric carbon, there is need to timely assess the role of these forests and the associated structural components, as well as age, in the global carbon cycle, especially in areas where their contribution as atmospheric carbon sinks is often ignored. A number of studies show that terrestrial ecosystems sequester large amounts of the atmospheric carbon, approximately 3 GtC per year (Patenaude et al., 2004; UNFCCC., 1998b; Wei et al., 2013), and normally account for approximately 80% of the earth's aboveground biomass (Dube & Mutanga, 2015a; Giardina & Ryan, 2002; Pan et al., 2011; Raich et al., 2014; UNFCCC., 1998b).

Information more specifically related to plantation forests biomass or carbon sequestration is therefore central for deriving forest carbon stocks and associated carbon fluxes. Given the importance of terrestrial ecosystems in the carbon cycle, there is a need for carbon quantification at local or regional scales, to facilitate a more accurate, timely and precise assessment of the regional carbon cycle, and inform carbon and bioenergy policies in order to ensure sustainable forest management practices. In African ecosystems for instance, literature shows that there is a great uncertainty in the current carbon balance and an unstable source with a carbon sink of about 0.3 Pg Cyr^{-1}, when compared to other parts of the world (Laurin et al., 2014; Wolf et al., 2011). To some extent, this assertion holds because in sub-Saharan Africa, especially South Africa, studies concerning the carbon storage and allocation pattern among most forest ecosystems, particularly plantation forest species are still scarce (Dube & Mutanga, 2015b). Also, despite the vivid interest for carbon accounting in the region, no study to the best of our knowledge has yet quantified the variability and allocation patterns of aboveground carbon stocks across different plantation forest species and different tree structural attributes.

Accurate and timely quantification of the variability and allocation patterns of aboveground carbon stocks across different plantation forest species, various tree structural attributes and age groups is thus, a critical step towards reducing the great uncertainty in the current carbon balance. So far, literature demonstrate that plant carbon allocation significantly varies between above-and-belowground components (Giardina & Ryan, 2002). For instance, the study by Giardina and Ryan (2002) shows that total belowground carbon allocation of a *Eucalyptus saligna* plantation decreases with stand age and this was facilitated by the nitrogen supply via regulating cytokinins and sucrose production (van der Werf et al., 2006). Chen et al. (2015) further showed the unequal carbon allocation in plants by demonstrating that the root carbon storage were only between 16 and 20% of total plant carbon storage and the proportion of different compartments to total plant carbon storage were largely influenced by tree traits. Now the main question that remains unanswered is which plantation forest species and structural components (*i.e.* stems, bark, branches and leaves) constitute the highest proportion of carbon storage. This gap in knowledge is further pointed out by Wei et al. (2013) who highlighted that aboveground biomass is bound to be linearly controlled by forest stand age and forest types amongst other characteristics. The validity of this assertion is further supported by the study by Pregitzer and Euskirchen (2004) who stated that forest carbon pools are largely affected by forest type, stand age and environmental factors. In that regard, for accurate and reliable quantification and understanding of plantation forest aboveground carbon stocks, all these variables have to be considered. The integration of numerous variables, particularly stand age characteristics, is critical as it provides information about the growing stages at which these species substantially contribute to the global carbon cycle as sinks. So far, the relationship between aboveground carbon storage and tree-age has not yet been fully established. For instance, some studies have reported a decrease in tree carbon storage with age and vice-versa (Chen et al., 2015; Wei et al., 2013).

Also, it is clear that accurate carbon accounting requires a strong understanding of the variability and allocation patterns in aboveground carbon stocks within and between different forest species, structural attributes, and across different age groups. Ecologists, environmentalists as well as the remote sensing community usually attempt to quantify forest aboveground biomass and carbon stocks using growth patterns, which minimizes bias and improves the estimation accuracy. Although great strides have been conducted on aboveground carbon stocks estimation, studies that have quantified variations and allocation patterns specifically across various tree species and tree structural attributes (i.e. roots, stem, bark, branches and leaves) and stand age, especially in managed plantation forests, are scarce (Chen et al., 2015; Wei et al., 2013). Moreover, those available have solely relied on the use of local measurements or field surveys, which is costly, time consuming and labour intensive, hence a great interest in obtaining reliable estimates over large areas from remote sensing data. Besides, model accuracies, as well as the spatial heterogeneity greatly increase the error of estimation obtained using field data and model simulation approaches. For instance literature shows that the use of field surveys or model simulations generally lead to substantial underestimation and misunderstanding of the actual carbon sequestered by terrestrial ecosystems (Baishya, Barik, & Upadhaya, 2009; Chen et al., 2015; Giardina & Ryan, 2002; Guo, Fang, Pan, & Birdsey, 2010; Raich et al., 2014; Yang & Guan, 2008; Zhang, Guan, & Song, 2012). On the other hand, literature demonstrates that remote sensing data provides a better alternative or data-source critical for quantifying and providing the timely and

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