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Quantifying aboveground biomass in African environments: A review of the trade-offs between sensor estimation accuracy and costs

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Abstract: Increased global recognition of the role of forests in regulating the biosphere-atmospheric carbon cycle through carbon sequestration, has resulted in a wide range of scientific studies on estimation, mapping, monitoring and the prediction of Aboveground Biomass (AGB) on various scales in sub-Saharan Africa. In many parts of the developing world, specifically in sub-Saharan Africa, the accurate quantification of AGB, although still a challenge, is important for national carbon accounting, REDD+ project payments, sustainable forest management and strategic policy-making. In this review, an overview of remote sensing applications in AGB estimation in sub-Saharan Africa, including research challenges and basic information related to the trade-offs between sensor estimation accuracy and costs, is provided. It is assumed that this review is timely, due to a relative increase in the number of remotely sensed forests carbon studies in the recent years (specifically the period between 1998 and 2013). Remotely sensed data is particularly appealing, due to its robustness, instantaneity and repeated spatio-temporal coverage and hence the ability to successful estimate and map AGB. However, estimation accuracy and image acquisition cost vary with sensor resolution and type. It is assumed that this study will provide guidance in future national carbon accounting studies, which is one of the main objectives of the Kyoto Protocol and the REDD+ (Reducing Emissions from Deforestation and Forest Degradation) project, housed under the United Nations Framework Convention on Climate Change (UNFCCC), particularly for the developing world.

Key words: Accessibility, biomass, carbon stocks, forest plantation, predictive error, remote sensing, trade-offs.

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Introduction

Forest Aboveground Biomass (AGB) is a measure of tree or shrub cumulative Net Primary Productivity, NPP (Baral & Katzensteiner 2015; Devi *et al.* 2014; Wu *et al.* 2013). The mapping of forest AGB in terms of their status and development is becoming increasingly important, due to the growing need to improve the conservation of forests in the face of a changing climate. Forest ecosystems have been recognized by the Inter-Governmental Panel on Climate Change through the Kyoto Protocol, as capable of mitigating climate change problems (United Nations 2008). Therefore, the measurement and monitoring of AGB has become an important topic in international climate change negotiations. For instance, the 11th Conference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC) under the Kyoto Protocol initiated the Reducing Emissions from Deforestation and Forest Degradation (REDD+)

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project in developing countries (Agrawal *et al.* 2011). The main aim of the REDD+ project was to highlight the need for possible climate change mitigation measures through sound forest conservation actions in developing countries (Agrawal *et al.* 2011; Chinembiri *et al.* 2013). In sub-Saharan Africa thus far, few countries, have fully embraced the aims and objectives highlighted by the Kyoto Protocol, which advocate sustainable forest (i.e. both indigenous and emerging plantation forests namely, *Pinus, Eucalyptus* and *Acacia* spp.) management and assessing their contributions to biosphere-atmospheric carbon cycles, as potential carbon sinks. Studies conducted elsewhere in the world (e.g. South America) demonstrate that forest plantations occupy a significant spatial extent and are capable of storing meaningful amounts of atmospheric carbon content (le Maire *et al.* 2011).

The recognition of forests as a potential sink of atmospheric carbon content has resulted in many AGB quantification methods (i.e. direct and indirect methods) being developed (Chinembiri *et al.* 2013; Dube *et al.* 2016; Henry *et al.* 2011; Singh *et al.* 2011). Direct AGB estimation methods are broadly classified into (1) Tier-1: basic methods, based on generalized equations; (2) Tier-2: intermediate approaches, based on volume equations and wood gravity; and (3) Tier-3: complexity methods, based on biomass equations (Henry *et al.* 2011). However, the lack of suitable parameters is one of the major issues and challenges associated with direct methods of estimating and mapping AGB or carbon in places such as sub-Saharan Africa and southeast Asia. In sub-Saharan Africa, numerous studies have utilised traditional methods (i.e. direct methods) to estimate AGB (Dovey 2009; Henry *et al.* 2011; Schönau & Boden 1982). Most parameters for estimating biomass (i.e. allometric equations, wood density values, yield tables and biomass expansion factors) have, however, been derived from studies per-formed outside Africa, in countries, such as Costa Rica, Brazil and Mexico (Henry *et al.* 2011). Since most allometric equations were developed outside sub-Saharan Africa, the major challenge is finding ways to implement these parameters in Africa with limited uncertainities. Consequently, very few published sources exist for forest types in sub-Saharan Africa (Henry *et al.* 2011). In addition, besides the scarcity of suitable and key parameters, traditional methods are environmentally destructive and impractical for large-scale implementation. Moreover, these methods require intensive field work and large volumes of ancillary data for analysis, which are labor-intensive, costly and time-consuming (Henry *et al.* 2011). Moreover, when using traditional methods, site access in protected areas is poor, due to complex terrain and organizational restrictions (Jonckheere *et al.* 2005). By using remotely sensed data, these limitations may be addressed in a range of scales and remote sensing technology offers a suitable means for the independent verification of the forest carbon pool estimates (Muukkonen & Heiskanen 2005).

Remote sensing, unlike traditional approaches, provides spatial and temporal data that are useful in mapping AGB at different spatial scales in a more robust, quick and efficient manner (Boyd *et al.* 1999; Carreiras *et al.* 2012). It allows for repeated image acquisitions over the same locations, which are necessary for the detection of temporal changes in carbon stocks. In addition, remotely sensed data are stored in digital format so that they can be easily integrated with ancillary data in a Geographic Information System (GIS) for further analysis. In the light of these advantages, researchers have used optical sensors (Boyd *et al.* 1998, 1999; Foody & Boyd 2002) and active sensors (Carreiras *et al.* 2012; Colgan *et al.* 2013; Mitchard *et al.* 2009, 2011, 2012, 2013) to estimate AGB in sub-Saharan Africa, with varying degrees of accuracy. Therefore, the utility of remote sensing in estimating AGB necessitates a review of the extent to which the technology has been utilized within the African context. This information is important for sustainable forest management and the identification of readily available datasets for the accurate estimation of AGB on a regional scale. The current prevailing economic situation in most countries in sub-Saharan Africa requires cost-effective and accurate methods for quick, accurate and efficient AGB estimation, particularly on a national or regional scale (Dube *et al.* 2014). This article, therefore, seeks to (1) provide a critical evaluation of the literature on AGB estimation, using different remote sensing platforms, and (2) review the trade-offs between sensor estimation accuracy and costs.

In order to achieve the above objectives, a variety of keywords were used to gather relevant literature related to AGB from selected peer-reviewed journals. To the best of our knowledge, no study on AGB estimation, using remotely sensed data, was recorded prior to 1998 hence, only the literature obtained between the period from 1998 - 2013 was considered for this study. The keywords used included: “aboveground biomass", "aboveground carbon stocks", "forest carbon", "remote sensing biomass", "remote sensing forest carbon stocks", "lidar and biomass", "tree structural attributes", "SPOT and biomass", "stand level biomass or carbon mapping" and "pixel-based carbon estimation", "Aboveground biomass in Africa", "aboveground biomass sub-Saharan Africa", amongst others. The remote sensing journals searched included: Remote Sensing of Environment, ISPRS Journal of Photogrammetry and Remote Sensing, IEEE Transactions on Geoscience and Remote Sensing, Applied Earth Observation and Geoinformation, IEEE Geoscience and Remote Sensing Letters, Photogrammetric Engineering and Remote Sensing, IEEE Applied Earth Observations and Remote Sensing, International Journal of Remote Sensing, The Photogrammetric Record, Canadian Journal of Remote Sensing, GIScience and Remote Sensing, Remote Sensing Letters, Journal of Applied Remote Sensing, Sensors and Remote Sensing. Other selected journals searched included: International Journal of Geographical Information Science, Transactions in GIS, Computers and Geosciences, Journal of Spatial Science, International Journal of Digital Earth and Geocarto International, and Ecological Applications. Fig. 1 shows a visual textual summary of the frequently appearing single terms in this document, with higher frequency results in a larger font size, and vice versa.

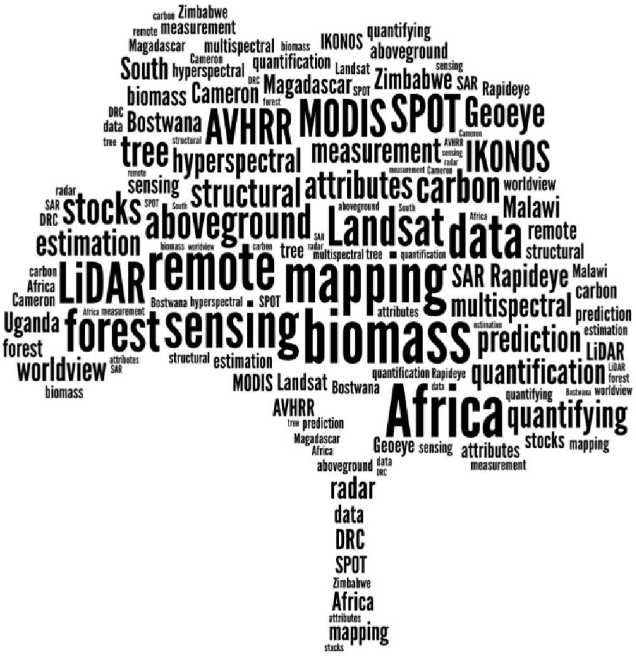

Fig. 1. A textual summary of this review.

Overview of aboveground biomass studies in sub-Saharan Africa

To the best of our knowledge, no study has reviewed the literature on the estimation of different forest AGBs in an African environment, using remote sensing. For instance, literature shows that only two studies reviewed forest AGB, based on traditional methods (Gibbs *et al.* 2007; Henry *et al.* 2011). However, literature gathered from selected major peer-reviewed remote sensing journals demonstrates a relative increase in AGB studies across the continent (Fig. 2). For this review, forty-nine (49) publications, with two-thirds of them published in the past decade (2003 - 2013), were gathered (Fig. 2). Overall, it was observed that more AGB studies using remote sensing datasets were published between 2004 and 2005 and between 2011 and 2013, when compared to the other years. This increasing trend of publications is expected to grow in the near future, making this a critical time to provide a detailed overview of the already available literature on AGB.

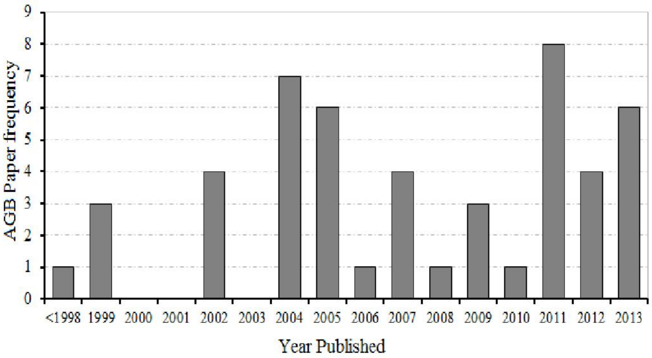

Fig. 2. Growth of remote sensing popularity in AGB mapping in sub-Saharan Africa between 1998 and 2013.

Based on the reviewed literature (Table 1), most AGB studies utilised coarse multispectral (31.25 %) and radar (22.92 %) datasets. Only one study by Thenkabail *et al.* (2004) utilised hyperspectral datasets. Table 1 shows that 70 % of the total AGB studies were conducted in West Africa, particularly in the Cameroon, Benin, and Ghana. Two-thirds of these studies were conducted in the Cameroon due to the presence of expansive, continuous and highly heterogenous plantations and moist, semi-evergreen regenerating and mature tropical forests (above 50 000 km^2), as well as the availability of direct foreign funding from the Terrestrial Iniative in Global Environmental Research (TIGER) programme of the Natural Environmental Research Council in the United Kingdom (UK) for mapping forest carbon within the country (Boyd *et al.* 1998, 1999).

The remaining 30 % were conducted in the central and southern African countries namely, Gabon, Democratic Republic of Congo, Uganda, Mozambique, Madagascar, Namibia, South Africa and Zimbabwe (Carreiras *et al.* 2012, 2013; Colgan *et al.* 2013; Cryus & Tanja 2004; Eckert 2012; Mitchard *et al.* 2012). Lidar was used to estimate AGB in countries like South Africa and Gabon (Colgan *et al.* 2013; Mitchard *et al.* 2011) and radar in the Cameroon, Guinea-Bissau, Mozambique and Uganda (Carreiras *et al.* 2012, 2013; Mitchard *et al.* 2012). Mulitispectral datasets have been applied in countries such as Zimbabwe (Cryus & Tanja 2004) and Cameroon (Boyd *et al.* 1998, 1999). All these studies focussed on estimating AGB from indigenous forests. None of them attempted to estimate AGB in commercial forest plantations, despite the vast tracts of land occupied by commercial forests in most of the sub-Saharan countries. It can also be noted that countries like Malawi, Angola, Kenya, Swaziland, Tanzania, Zambia, as well as those in the East, still lag behind in terms of forest AGB estimation. Having provided an overview of AGB studies in Africa, Fig. 3 provides a detailed spatial representation of AGB studies across sub-Saharan Africa. In general, it can be observed that these studies have been conducted in areas with high vegetation cover, as indicated by the high normalized difference vegetation index (NDVI) values, rather than in areas with low NDVI.

Active sensors

Aboveground biomass estimation using lidar and radar remote sensing sensors

Lidar is an active remote sensing technology that utilizes a laser, which transmits light pulse towards a target, and a receiver, to measure the backscattered or reflected light. This remote sensing dataset is regarded as one of the most robust and appropriate means of data collection and has the ability to characterize vertically distributed forest attributes (Wulder *et al.* 2012). Literature shows that the most important tree-structural attributes necessary for AGB estimation (i.e. tree height or forest structural information) can be easily extracted from lidar with great accuracy (Hyyppä *et al.* 2009; Montaghi *et al.* 2013; Wulder *et al.* 2012). For instance, work conducted in the developed world demostrates successful AGB estimation from lidar for a single tree, producing high r-square (R^2) and extremely low root mean square errors (Rowell *et al.* 2009).

The unique ability provided by the lidar dataset has seen few studies testing its strength in estimating AGB in sub-Saharan Africa (Mitchard *et al.* 2011, 2012). Work by Mitchard *et al.* (2011) is one of the pioneering studies in sub-Saharan Africa. In this study, authors mapped AGB in Gabon with a 25 % uncertainty error, using spaceborne lidar (ICES at GLAS footprints) and ground data. The use of generic tropical allometric equations and GLAS data to estimate tree height, however, increased the error term.

In addition, using spaceborne lidar, Colgan *et al.* (2012) successfully ($R^2 = 0.91$) investigated the influence of hill-slope topography and soil properties in estimating AGB in the Kruger National Park, South Africa. In a different study, Colgan *et al.* (2013) further assessed the accuracy of airborne lidar and field data in estimating AGB at a tree level in the savannas adjacent to the Kruger National Park. The results of their study showed that the use of the object-based model to identify and classify individual tree crowns, as well as to estimate AGB, significantly improved the estimation accuracy, compared to the use of existing airborne methods. Overall, lidar-based AGB studies demonstrate an enhanced capability of quantifying AGB at plot level (in sub-Saharan Africa), especially when compared to estimates derived using passive sensors, such as Landsat.

Similar to lidar, radar systems are active remote sensors (i.e. they independently generate their own source of energy during image acquisition process). These sensors are operational between approximately 1 cm and 10 m for VHF5 in the microwave portion of the electromagnetic spectrum (Patenaude *et al.* 2005). This unique characteristic permits radar systems to capture images without any obstruction, due to moderate precipitation to cloudy conditions (Koch 2010; Patenaude *et al.* 2005). In Africa, for instance, radar data is increasingly becoming popular in mapping AGB, specifically in tropical environments, with extreme weather conditions (Carreiras *et al.* 2012, 2013). Thus far, a review of the literature shows that a limited number of AGB research studies have been conducted across sub-Saharan Africa using radar datasets (Carreiras *et*

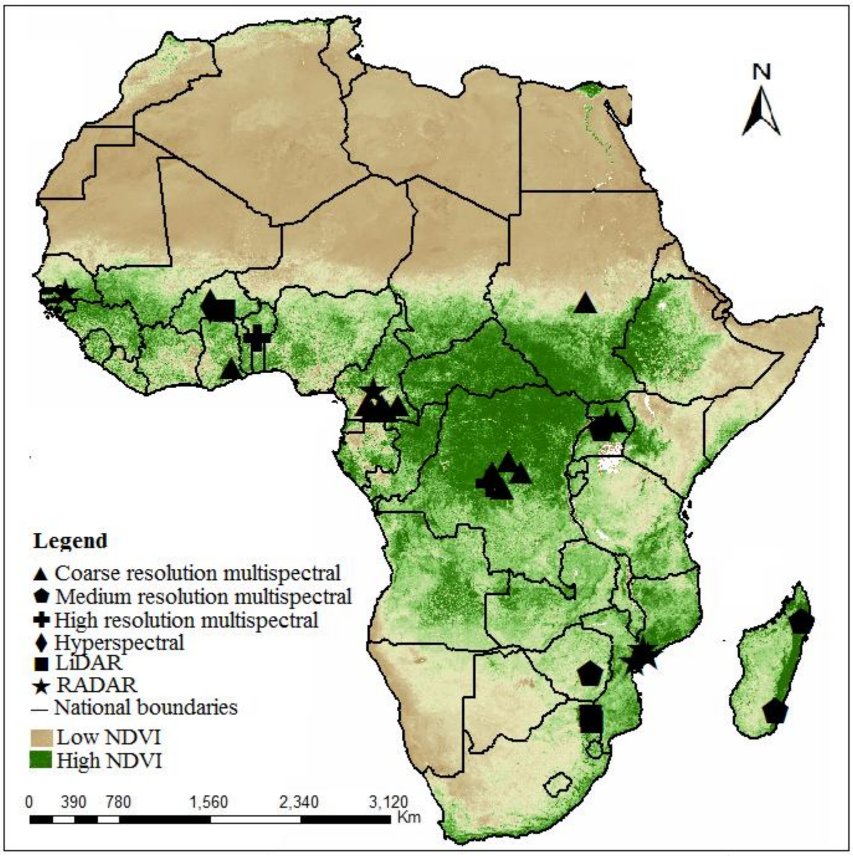

Fig. 3. Spatial distribution of AGB studies based on remotely sensed data in sub-Saharan Africa derived from the information garthered from selected peer-reviewed journals.

al. 2012, 2013; Mitchard *et al.* 2013). For example, based on Advanced Land Observing Satellite (ALOS), Phased Array L-band Synthetic Aperture Radar (PALSAR) and two regression algorithms (i.e. bagging stochastic gradient boosting (BagSGB) and semi-empirical models), Carreiras *et al.* (2012) successfully estimated AGB in Guinea-Bissau. This study yielded a very high correlation coefficient (R^2) value of 0.95 and a low root mean square error (RMSE) value of 26.62 Mg ha^{-1}. In addition, Mitchard *et al.* (2013), using ALOS PALSAR, detected AGB losses and gains in Miombo woodland ecosystems in Mozambique. In a different study, Mitchard *et al.* (2009) examined the relationship between field-measured AGB and cross-polarized radar backscatter values, with high prediction accuracies. However, higher saturation levels from ALOS PALSAR were noted and this was attributed to the structural features of African savannas (Mitchard *et al.* 2009). Similar observations were noted by Mitchard *et al.* (2011) who investigated the relationship between the radar backscatter (i.e. ALOS PALSAR HV) and AGB plots, with a high R^2-value of 0.86 and a RMSE varying between 25 - 40 %.

Although the above studies have successfully attempted to estimate AGB in different parts of sub-Saharan Africa, using lidar and radar datasets, their main limitation is that all of them were implemented at a local or small scale. AGB estimates are currently required at regional or global scale, because “wall-to-wall” estimates are more effective in providing a comprehensive understanding of the global carbon pool than local-scale. Unlike other parts of the world (i.e. the developed world), the application of these datasets on a regional or global scale remains one of the major challenges in sub-Saharan Africa. The main reasons for this limitation is the cost, the scarcity of data for operational applications and limited image pre-processing technical expertise, amongst others. Although AGB estimates from lidar, hyperspectral and radar datasets are more accurate and relaible, when compared to those derived using traditional multispectral datasets, such datasets may be restricted spatially to smaller areas. For this reason, there is a need for future studies in sub-Saharan Africa, to develop and identify appropriate sampling techniques that can help enhance the AGB estimation accuracy and at a minimal cost within the regions.

Aboveground biomass estimation using hyperspectral remote sensing sensors

Recent advances in sensor technology (i.e. the presence of unique and strategical-positioned bands) have enhanced AGB monitoring in regions with high forest canopy closure or high biomass. This enables the sensor to accurately characterize different forest-structural properties at optimal temporal and spatial scales. This has consequently resulted in the great appreciation and use of the datasets for AGB estimates, particularly outside sub-Saharan Africa, given that traditional multispecral sensors suffer from saturation problems.

Nonetheless, the utility of hyperspectral remote sensing platforms for estimating AGB in sub-Saharan Africa is still developing and its usage has gained limited acceptance for operational use, due to costs and restricted accessibility (Dube & Mutanga, 2015a; Dube & Mutanga 2015b; Dube & Mutanga 2015c; Dube *et al.* 2015; Mutanga *et al.* 2012; Thenkabail *et al.* 2004). Thus far, only one AGB study has been done using the hyperspectral remote sensing sensor (Thenkabail *et al.* 2004). The study found out that Hyperion narrowband data yielded good models that explained between 36 - 83 % more of the variability in rainforest biomass, when compared to Landsat products and Ikonos, which explained between 13 - 60 %. The study further concluded that the use of narrowband Hyperion data has a greater advantage and strength over broad-band Ikonos and ETM+ datasets in estimating AGB in the rainforest vegetation.

Passive sensors

Aboveground biomass estimation using old generational multispectral sensors

Coarse, medium and fine spatial resolution multispectral images have since become more popular and attractive for estimating AGB in resource-constrained sub-Saharan Africa (Boyd *et al.* 1998, 1999; Eckert 2012; Foody & Boyd 2002; Wu *et al.* 2013) and in other parts of the world (Manna *et al.* 2014). Coarse-to-medium multispectral data (i.e. MODIS, Landsat, ASTER and SPOT) are currently provided freely or are available at a low cost (Tables 1 & 2). Some of these sensors (i.e. Landsat products) provide images with a wide swath-width (above 185 km) and have a repeated global coverage, which is necessary for continuous AGB assessment. These unique characteristics have resulted in these sensor gaining more popularity for regional or global AGB mapping (Boyd *et al.* 1998, 1999; Foody & Boyd 2002). Currently, there are huge volumes of archived datasets (i.e. NOAA AVHRR, Landsat products and MODIS) with large spatial coverage and dating back to 1972, when the first Earth Resources Technology Satellite (ERTS-1) Landsat 1 was launched by the National Aeronautics and Space Administration (NASA 1999).

In sub-Saharan Africa thus far, numerous AGB studies have been conducted using the aforementioned sensors, with fairly reasonable accuracy (Boyd *et al.* 1998, 1999; Foody & Boyd 2002). Using the middle infrared (MIR) wavelengths (3.0 - 5.0 μm) of the National Oceanic and Atmospheric Administration-Advanced Very High Resolution Radiometer (NOAA-AVHRR), Boyd *et al.* (1998) successfully estimated tropical forests AGB in the Cameroon. This study demonstrated the potential of exploiting under-utilised electromagnetic portions between near infrared (NIR) and thermal infrared (TIR) wavelengths, when estimating AGB. The findings from the above study are also confirmed by Boyd *et al.* (1999), whose work demonstrated a strong relationship between total AGB, MIR reflectance and vegetation indices in the Cameroon. The two studies concluded that MIR spectral wavelengths are more sensitive to changes in forest properties than the visible and NIR reflectances. Wu *et al.* (2013), using canopy cover derived from the MODIS NDVI data (MOD13Q1) time-series, estimated AGB with a high coefficient of determination (R^2-value = 0.91). AGB estimation accuracies obtained by Wu *et al.* (2013) are comparable to those of Carreiras *et al.* (2012) and Mitchard *et al.* (2009), which are derived using lidar and radar datasets. Wu *et al.* (2013) concluded that the proposed approach was relevant for operational use in the tropical savannah woodlands and that it contributes to the low-cost and large-scale assessment and monitoring of forest carbon fluxes in sub-Saharan Africa.

Although the above AGB studies utilising multispectral data demonstrated reasonable estimation accuracies, their application at plot level or in densely forested areas imposes serious challenges. For instance, the application of medium-to-coarse spatial resolution multispectral sensors for AGB estimation in the tropics is neither feasible nor accurate, due to spectral saturation challenges associated with dense canopy closure (Thenkabail *et al.* 2004). The reflectance signal in the visible and NIR is mostly correlated with the green leaf area index (LAI) and canopy cover of the vegetation (Anderson *et al.* 2004). Furthermore, AGB generally becomes decoupled from LAI after a given stand age, as AGB continues to increase after canopy closure. The decoupling from LAI after a given stand age hinders accurate AGB estimation, when using multispectral sensors. The utility of all Landsat satellite products and MODIS for estimating AGB has thus, to a large extent, resulted in inaccurate results in the tropics, due to the presence of mixed pixels and the mismatch between pixel-size and field-plot area (Gibbs *et al.* 2007; Thenkabail *et al.* 2004). Given the poor financial situations in sub-Saharan Africa and the immediate need for AGB estimates on a regional scale, the use of cheap or readily available and suitable sensors with appropriate optimal spectral characteristics is necessary, if this objective is to be achieved.

For continuous and accurate large-scale AGB estimation, there is a need for the remote sensing research community and environmentalists to shift towards embracing the newly-launched, readily available and cheap multispectral sensors (i.e. 30-m Landsat-8 sensor, 5-m RapidEye, Sentinel-2, SPOT-6 and 2-m Worldview-2). This emerging group of new generation sensors, with refined radiometric, spatial, spectral and temporal properties, presents new opportunities for the detection and segmentation of forest structural attributes. Literature shows that these sensors provide more granular measurements of plant productivity, which is ideal for accurately estimating AGB in resource-limited environments (Dube *et al.* 2014; Eckert 2012; Mutanga *et al.* 2012).

Currently, the utility of these sensors has not been fully explored. For instance, only a single study estimated forest AGB, using Worldview-2 image in sub-Saharan Africa (Eckert 2012), as shown in Table 1. The results of the study indicated a higher correlation between image texture parameters and AGB when compared to spectral information. Mutanga *et al.* (2012), demonstrated the utility of three normalized difference vegetation indices (NDVIs) computed from the WorldView-2 red edge and NIR bands in the estimation and mapping of wetland vegetation AGB in South Africa. An average biomass of 3.44 kg m^{-2} and RMSE of prediction of 0.441 kg m^{-2} was obtained, which was much higher than the standard AGB saturation level reported in literature. This task was previously challenging, when using broad-band satellite imagery. The authors finally concluded that the indices calculated from the additional spectral bands of Worldview-2 performed better than the traditional multispectral indices, due to their enhanced sensitivity to vegetation properties namely, canopy AGB and chlorophyll content. This observation is confirmed by Kokaly & Clark (1999), who showed that vegetation indices calculated from the hyperspectral red-edge and NIR spectral bands minimize atmospheric and water absorption influence, as well as soil background, thereby enhancing estimation accuracy, a characteristic of some new generation sensors. Despite the promising performance from the new generation sensors, thus far, little is known on AGB estimation, using new generation sensors, such as RapidEye, Landsat-8, SPOT-6 and Sentinel-2. It is thus critical to explore the possibility of utilizing these sensors for AGB estimation, as well as investigating the potential of them being up-scaled to landscape level, to meet the objectives of the Kyoto Protocol and REDD+. Studies conducted outside sub-Saharan Africa have already shown improved forest AGB estimates from Worldview-2 imagery (Ozdemir & Karnieli 2011; Shamsoddini *et al.* 2013). Ozdemir & Karnieli (2011), using WorldView-2 texture metrics to derive different forest structural parameters in Israel, concluded that this dataset offers new opportunities for AGB estimation. Shamsoddini *et al.* (2013) mapped pine tree structural parameters from WorldView-2 data in New South Wales, with an estimation error of 30 %. The results demonstrated variability in the sensitivity of the two separate NIR bands over numerous tree structural parameters and this shows the utility of new bands and provides the opportunity to develop new indices for the better estimation of AGB.

Although the new generation sensors indicate a very promising opportunity for regional scale AGB estimation in resource-limited environments, they do have some limitations. The major limitations of the new generation sensors include (i) their inability to penetrate forest canopies in order to provide information on critical reflected solar energy; and (ii) the ineffectiveness to map AGB in tropical regions, where cloud cover is often a challenge. Like their predecessors, new generation multispectral sensors provide two-dimensional views of forest canopy surfaces. This ability only allows spectral properties from these sensors to relate more appropriately to the percentage canopy cover and LAI rather than directly to AGB. The lack of the most important shortwave infrared (SWIR) band (except for Landsat 8 and Sentinel-2 sensors), which has proved important for AGB estimation, especially in boreal forests (Lu 2006), also remains one of the major challenges. Many studies have demonstrated the relevance of SWIR in volume and AGB mapping. For example, work by Hyyppä *et al.* (2000) has demonstrated that the SWIR spectral range has the highest correlations of all the examined forest attributes. Muukkonen & Heiskanen (2005) also found the strongest correlation between forest AGB and the ASTER SWIR spectral band. It would therefore be important to ensure that the development of future generation sensors includes the SWIR band, since it is more critical in AGB estimation.

Trade-offs between availability, costs and the predictive accuracy

Research shows that active sensors, such as lidar and radar, provide high accuracy for estimating AGB, with an average R^2-value of ± 0.74 and ± 0.89, when compared to multispectral datasets. It can also be noted in Table 1 that only one study tested the utility of hyperspectral data in estimating AGB in sub-Saharan Africa. The limited number of studies using this sensor can be largely attributed to the cost, availability, as well as the Hughes phenomenon or "the curse of dimensionality" associated with this dataset. Although, lidar and radar data provide accurate and reliable AGB estimates, due to their cost and limited availability (Tables 1 & 2), the two data types have since gained more popularity for local scale-based applications (e.g. small scale: <10 000 ha) rather than wall-to-wall mapping (± 56 000 km^2) in sub-Saharan Africa (Carreiras *et al.* 2012; Colgan *et al.* 2013). The existing lidar and radar-based AGB studies in sub-Saharan Africa targeted mainly small-scale areas, despite the REDD+ project requiring regional or global scale estimates. The full application of these expensive and complex sensors in sub-Saharan still remains a challenge.

It is, therefore, important to establish sensors and methods that are cheap, fast and robust for application in developing countries, in order to be able to meet the requirements of the REDD+ project. However, not all African countries have the capacity to access funding and hence cannot use active sensors for estimating AGB. It is therefore essential that the systems for measuring and estimating AGB for REDD+ projects in sub-Saharan Africa are available at a low cost, with acceptable and reliable accuracy. As a result, the cheap, free and readily available multispectral datasets remain crucial for AGB estimation in sub-Saharan Africa. The moderately high average R^2-value (± 0.68) and slightly lower average predictive errors (± 32 %) in AGB results, as shown in Table 1, indicate the potential strength and possible avenues for improving regional estimates, using medium resolution sensors. Currently, most of these multispectral sensors (i.e. MODIS and Landsat products) are readily accessed from the NASA and USGS Earth Resources Observation and Science (EROS) Center archive (http://earthexplorer.usgs.gov/) dating back to 1972. In the future, the European Space Agency (ESA) will also make their images freely available, covering wide expanses of land area, which is important for regional or global AGB mapping. Further improvement is shown by fine spatial resolution multispectral sensors with higher predictive averages, almost comparable to those obtained using radar and lidar datasets (Table 1). The fine spatial resolution multispectral sensors are for instance, available at a fairly reasonable cost, especially when compared to lidar, hyperspecral and radar datasets (Table 2).

Previous studies conducted outside sub-Saharan Africa demonstrate a greater potential of employing multi-source (e.g. multispectral data with ancillary datasets) or multi-date datasets on multispectral platforms when estimating AGB (Baccini *et al.* 2004; Dube *et al.* 2015). Multi-date multispectral data performs well in discriminating AGB classes and allows the examination of the spatial and temporal contribution of forests to carbon sequestration (le Maire *et al.* 2011). In addition, the radiometric and temporal variations can contain new information about forest characteristics important for AGB estimation (le Maire *et al.* 2011; Powell *et al.* 2010). To the best of our knowledge, few investigations have been carried out using multi-date techniques for AGB estimation and most of these have been applied outside Africa. For instance, a recent study by le Maire *et al.* (2011) in Brazil showed that it is beneficial to use multi-temporal datasets in estimating AGB (R^2-value of 0.82) at global or regional scales. The study accurately demonstrated

Table 1. A summary of remotely sensed aboveground biomass average accuracies derived from studies done across sub-Saharan Africa.

Sensor type	No. AGB studies	% age studies	Avg. R^2	Avg. predictive error
Active:				
lidar (0.5 cm - 5 m)	8	15.67	0.89	14 %
radar (1 cm - 10 m)	11	22.92	0.74	25 %
Hyperspectral	1	2.08	0.83	-
Multispectral:				
FSR (< 5 m)	5	10.42	0.75	27 %
MSR (10 m - 60 m)	9	17.67	0.68	32 %
CSR (> 250 - 1000 m)	15	31.25	0.58	42 %
Total	49	100	-	-

**FSR = Fine spatial resolution; MSR = Medium spatial resolution and CSR = Coarse spatial resolution.

Table 2. Overview on trade-offs between aboveground biomass sensor predictive accuracy and costs.

Sensor resolution	Available satellite data	Utility for mapping	Acquisition cost
Very fine (between 0.5 cm - 10 cm)	Lidar, radar Hyperspectral	Pixel scale	Highly expensive
Fine (< 5 m)	Ikonos, Quickbird, RapidEye, Worldview-2	Validation at a localised scale	High
Medium (10 - 60 m)	SPOT Landsat	Small and large scale mapping of aboveground biomass	Low or free
Course (250 - 1000 m)	AVHRR MODIS	Large scale estimation and mapping of aboveground biomass	Free

*Multispectral optical sensors despite accuracy problems have been considerably utilised operationally in estimating and mapping aboveground boimass in Africa. Active sensors such as lidar and radar (i.e., ALOS PALSAR L-band cross-polarised (HV) radar data ALSOR PALSAR) are not yet used operationally for aboveground biomass estimation in an African Environment, except for small-scale use only.

the use of MODIS products (Vegetation Indices 16-Day L3 Global 250 m) and ancillary data in monitoring AGB over 15 000 ha of *Eucalyptus* plantations, using Stepwise linear or nonlinear (Random Forest) regression models. The integration of ancillary data, such as tree age, with multispectral data enhanced the AGB estimation and prediction accuracy. However, in Africa, multi-source datasets have not been fully embraced in AGB studies.

Future investigation

Although considerable progress has been made in sensor development and the application of remote sensing technology for AGB estimation, it still remains a challenge. Firstly, to the best of our knowledge, no work has been conducted based on remote sensing datasets to estimate and map forest plantations AGB in sub-Saharan Africa. Plantation forests, such as the *Pinus*, *Eucalyptus* and *Acacia* spp, occupy quite a significant portion of the land area and house a significant amount of unknown carbon, which plays a vital role on biosphere-atmospheric carbon fluxes. However, for accurate, unbiased and reliable national carbon accounting to meet the objectives of the Kyoto Protocol and the REDD+ project, the focus of future research must be directed towards estimating and mapping AGB across all terrestrial ecosystems in sub-Saharan Africa.

Meanwhile, to achieve the above objective, the challenge still exists to develop or identify effective, cheap, accurate and operational techniques to estimate and map AGB on a large-scale, capitalizing on the improved sensor characteristics and processing techniques. A new crop of studies focusing on the use of remote sensing in forest ecology or vegetation mapping demonstrates the adoption of new tree-based statistical ensemble methods (i.e. machine learning algorithms) namely, stochastic gradient boosting and random forests, as suitable for successful and improved estimation accuracies, when using the readily-accessible multispectral sensors (Carreiras *et al.* 2012; Mutanga *et al.* 2012) and when combined with ancillary data (Baccini *et al.* 2004; Dube *et al.* 2015; le Maire *et al.* 2011). Although active sensors provide optimal AGB estimates, possible variations and changes over time and space cannot be satisfied in the sub-Saharan Africa, due to available economic constraints and other related challenges mentioned earlier. Challenges posed by active sensors for successful application in sub-Saharan Africa are a clear indication that optical sensors remain the main possible solution for AGB quantification across the continent (Adelabu & Dube 2014; Dube *et al.* 2015; Powell *et al.* 2010). The major challenge that researchers have to resolve when dealing with multispectral sensors is improving their direct relationship with AGB, which is difficult to establish in areas characterized with wood volumes exceeding 100 m^3 ha^{-1}. There is, therefore, a need for future research, to move towards the integration of multispectral remotely sensed with ancillary datasets.

Another promising future research challenge would be to test the utility of new generation moderately fine spatial-resolution multispectral sensors (i.e. Landsat-8, RapidEye, Sentinel-2 and Worldview-2), which are moderately cheap and readily available. The WorldView-2 optical satellite sensor, launched in October 2009, provides panchromatic data at a geometric resolution of 0.5 m and multispectral data, divided into eight spectral bands, at a geometric resolution of 2 m. Furthermore, future research in sub-Saharan Africa should focus on testing the potential of new generation sensors as a substitute for active sensors because of their enhanced spatial resolution and the increased number of bands. Moreover, some of these sensors are comprised of an increased number of spectral bands, together with key and strategically-positioned vegetation wavelengths (i.e. the red edge bands: 690 - 730 nm). These strategically-positioned bands are not currently available on multispectral satellite sensors, except for hyperspectral sensors that are expensive to acquire and also require complex pre-processing methods. In addition, more research is needed to find the best variables (ancillary data) and predictive models that can be integrated with cheap, and sometimes free, multispectral datasets. Overall, the AGB estimation, using coarse spatial-resolution data, is still very limited because of the common occurrence of mixed pixels and the huge difference between the size of field measurements and image pixel size. This results in difficulties in the integration of ground-based sample data and remote sensing-derived variables. A synthetic analysis of multi-source data, with a combination of different modelling approaches, may be needed for accurate AGB estimations in a large area.

Conclusions

Literature demonstrates that there is a decline in the number of studies using conventional methods to estimate AGB, compared to remote sensing methods. Conventional methods, although accurate, are time-consuming, too costly and practically impossible to apply on a broader scale. Although active sensors, such as lidar and radar, provide higher and more reliable AGB estimates than coarse multispectral data, they are still not operational in the African environments, due to the cost of their acquisition. Given the poor economic situation of most sub-Saharan African countries, multispectral data still remain relevant for AGB quantification, regardless of saturation problems in densely closed canopies, the occurrence of mixed pixels and a huge mismatch between the size of field measurements and the image pixel size. Previous work outside sub-Saharan Africa shows that AGB estimates can be greatly improved by the use of multi-date multispectral datasets, the integration of remotely sensed data with ancillary data and spectral decomposition. Therefore, there is a need for further investigations into the applicability of the above approaches in quantifying AGB in sub-Saharan Africa, using new generation sensors. Additionally, there is a need to identify efficient and robust predictive models that can help improve AGB estimates from these datasets.

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