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Large-scale estimation of change in aboveground biomass in miombo woodlands using airborne laser scanning and national forest inventory data

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A B S T R A C T

As a non-Annex 1 Party to the United Nations Framework Convention on Climate Change (UNFCCC), Tanzania has committed to submit the results of the measurement, reporting, and verification of greenhouse gas (GHG) emissions reductions and removals by sinks under the Biennial Update Reports of national GHG inventory and mitigation actions. Thus, implementation of a robust and cost-efficient carbon accounting system is one of the prerequisites for receiving financial benefits under the REDD+ mechanism. For estimation targeting large areas (i.e., country, region, and sub-regional), remote sensing techniques like airborne laser scanning (ALS) enable precise and timely estimation of biomass stocks and biomass changes. The main objective of the study was to compare alternative sampling strategies using ALS for estimating aboveground biomass (AGB) changes in miombo woodlands that would be suitable components of the National Forestry Resources Monitoring and Assessment (NAFORMA) program of Tanzania and of the Biennial Update Reports under UNFCCC. NAFORMA is the national forest inventory of Tanzania. The study area of 15,867 km^2 was located in the administrative district of Liwale, south-eastern Tanzania and dominated by miombo woodlands. A longitudinal survey was carried out during two temporally consistent field and ALS data acquisition campaigns in 2012 and 2014. The field data were collected on permanent plots of the NAFORMA program. ALS measurements were acquired along 32 parallel strips spaced 5 km apart and covering approximately 25% of the study area. Estimation methods (1) solely based on the ground inventory data provided by NAFORMA and (2) by incorporating field observations and auxiliary variables derived from ALS data were pursued for assessing AGB change as the difference between estimated AGB in 2012 and 2014, together with the uncertainties related to sampling variability. The AGB estimates varied from 58.48 to 59.55 Mg ha^{-1} in 2012 and between 58.20 and 59.29 Mg ha^{-1} in 2014. The sampling variability (in terms of standard errors) was between 1.37 and 4.79 Mg ha^{-1} in 2012, and 1.77 and 5.03 Mg ha^{-1} in 2014. The mean AGB change varied from 0.11 to 0.35 Mg ha^{-1} with standard errors of 0.31 to 0.85 Mg ha^{-1}. Compared to direct estimation based on field data only, the efficiency gain under ALS-assisted (design-based, model-assisted) estimation was 5–22%, and approximately 66% when using ALS data in a model-dependent estimation. The results provide statistically significant evidence of change in AGB over the 2-yr period spanned by the study only under model-dependent estimation at 50% confidence level, illustrating the great challenges of change estimation over such short time periods as requested for UNFCCC reporting.

1. Introduction

An emerging interest for large-scale biomass/carbon inventories in developing countries is driven by the efforts of the parties to the United Nations Framework Convention on Climate Change (UNFCCC) to reduce carbon emissions from tropical forests, more specifically known as the REDD+ program (Reducing Emissions from Deforestation and Forest Degradation in tropical countries) (UNFCCC, 2011). The carbon credits received by changing the land-use practices under the REDD+ mechanism are a potential source of income, however, the REDD+ benefits depend, among other factors, on the cost-efficiency of the carbon accounting systems for providing accurate and timely information on the forest carbon emissions (UNFCCC, 2010a). Thus, developing a robust measuring, reporting, and verification (MRV) system complying with

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the most recent guidance and guidelines of the Intergovernmental Panel on Climate Change would be a prerequisite for REDD+ implementation. As a developing country, Tanzania can receive financial benefits by implementing an efficient REDD+ MRV mechanism. Being a country with a low deforestation rate during the past 10 years (1.16%, FAO, 2010, Annex 3, Table 3), even a total uncertainty of carbon stock estimates <5% may cancel the carbon trading benefits (Köhl et al., 2011; Plugge et al., 2011).

According to the mitigation actions decided in the Cancun Agreements in the 16th session of the Conference of the Parties to UNFCCC, Tanzania, as a non-Annex 1 Party, should submit Biennial Update Reports of national GHG inventory and mitigation actions, as well as information on the MRV process to the UNFCCC secretariat (UNFCCC, 2010b). The National Forestry Resources Monitoring and Assessment (NAFORMA) program, which is the national forest inventory of Tanzania, is the first attempt to implement a cost-efficient survey of entire Tanzania with the aim to provide information supporting sustainable forest management practices, REDD+ MRV, and for other international reporting (Tomppo et al., 2010, 2014; Vesa et al., 2011).

Tanzania's forest land is dominated by woodlands which occupy 44.7 million ha, or 92% of the total forest land. Out of this miombo woodlands occupy a substantially large area as compared to other woodland types (MNRT, 2015). Miombo is also one of the dominant vegetation types in many Central and Eastern African countries, covering approximately 9% of the African land area (Frost, 1996; White, 1983). Timely and accurate monitoring of carbon stocks of miombo woodlands are thus essential for the country-level estimates.

Remotely sensed data can provide cost-effective information for improving the precision and timeliness of estimates based on the ground-based NAFORMA program. Auxiliary data produced by airborne laser scanning (ALS) have been demonstrated to boost the estimation precision of forest inventories (McRoberts et al., 2014a) by providing strong predictors of forest resource information (Næsset, 2014; Zolkos et al., 2013), the ALS-assisted estimation reaching higher precision due to stronger functional relationships compared to fusing of other types of remotely sensed data (Zolkos et al., 2013). This recommends ALS as a remote sensing technology of special interest for in particular AGB estimation under REDD+ (GOFC-GOLD, 2014), however, the high precision of full-coverage ("wall-to-wall") ALS-assisted surveys for very large areas (e.g., counties and states, countries, and sub-continents) may easily become economically infeasible (Næsset et al., 2009; Mitchard et al., 2012).

Alternatively, the ALS data can be collected as a sample consisting of individual flight lines covering only a small portion of the area of interest, with ground plots sub-sampled along these corridors. Such sampling strategies have been investigated by several authors in recent years (Parker and Evans, 2007; Andersen et al., 2009, 2011; Gregoire et al., 2011; Ståhl et al., 2011; Gobakken et al., 2012; Stephens et al., 2012; Næsset et al., 2013a; Saarela et al., 2015). Although the results of some of these studies seemingly indicate that the ALS-assisted estimation sometimes might be less precise compared to conventional field-based surveys, detailed analysis of some of the results (Næsset et al., 2013a) and extensive sampling simulations using artificial populations (Ene et al., 2012, 2013) revealed a substantial improvement in precision when incorporating ALS auxiliary information. Unfortunately, these improvements cannot always be quantified by the analytical variance estimators used to evaluate the estimation uncertainty in a given case. For certain populations, there is even evidence of rather limited improvements in precision when going from a sparse sample of ALS strips to a full census of auxiliary data (wall-to-wall ALS data) (Ene et al., 2016), suggesting that ALS strip sampling can be a very efficient alternative even compared to extensive and expensive ALS acquisitions.

The majority of studies on large-scale ALS-assisted inventories have been conducted in boreal and temperate forests (Andersen et al., 2011; Gregoire et al., 2011; Ståhl et al., 2011; Gobakken et al., 2012). For tropical forests, much effort has been spent on modelling the relationship between AGB and ALS data (Gonzalez et al., 2010; Mascaro et al., 2011a, 2011b; Meyer et al., 2013; Asner and Mascaro, 2014) with less focus on large-scale estimation. Furthermore, most of these investigations were focused on tropical forests of Central and South America (Asner et al., 2010, 2012a; Clark et al., 2011; Mascaro et al., 2011a, 2011b; Vincent et al., 2012) and Asia (Hou et al., 2011), while studies on tropical rainforests of West Africa (Vaglio Laurin et al., 2014), East and South-East Africa (Asner et al., 2012b, Hansen et al., 2015a, 2015b), including the miombo woodlands of East Africa (Saarela et al., 2014; Mauya et al., 2015a, 2015b; Næsset et al., 2016) are more sporadic.

Finally, even though there is now an emerging evidence of the usefulness of ALS data to enhance AGB estimates in various forest types around the world, there is still only a handful of studies that have addressed AGB change rather than current stock, and they are mostly related to boreal and temperate forests and restricted to areas with limited geographical extent where wall-to-wall acquisition of ALS data was indeed feasible (see McRoberts et al., 2014b for a literature review).

The main objective of the current study was to compare alternative strategies involving ALS-assisted sampling for AGB change estimation in miombo woodlands that would be suitable for the NAFORMA program over a 2-yr reporting period required by the Cancun Agreements. Estimation methods (1) solely based on the ground inventory data provided by the NAFORMA program and by (2) incorporating auxiliary variables derived from ALS data were pursued and compared for assessing the uncertainties related to sampling variability. Confidence intervals for change estimates for different levels of confidence were constructed to illustrate the great challenges of change estimation over such short time periods as requested for UNFCCC reporting. This study is the first opportunity to gain experience with large-scale estimation of change in AGB by exploiting the strengths of ALS strip data.

2. Material

2.1. Study area

The study area (Fig. 1) covering 15,867 km^2 is located in the administrative district of Liwale, south-eastern Tanzania (9°52′–9°58′ S, 38°19′–38°36′ E). Henceforth we will let LD ("Liwale District") denote our study area. The climate of Liwale is characterized by two rain periods a year; a short period from late November to January and a longer period from March to May. Annual precipitation is in the range 600–1000 mm. The main dry season is from July to October.

The miombo woodlands of Liwale are characterized by high tree species diversity associated with species such as *Brachystegia* sp., *Julbernadia* sp. and *Pterocarpus angolensis*. The land cover types within the miombo comprise areas classified as forest as well other cover types according to the definitions of NAFORMA.

Several settlements and villages are located within the study area. Human disturbances in the form of charcoal burning, harvesting for timber and poles, honey and game hunting, and fire incidences are common in all forests and woodlands. Illegal conducts in these forests usually happen due to the excuse of unclear boundaries. Harvesting is not allowed in all forests managed for protection of water catchment and biodiversity purposes although illegal cutting is often reported (Malimbwi et al., 2005).

The selected study area is characterized by agricultural activities where the average farm size is about 3 ha. Forest and agriculture products are the sources of livelihood for the people living adjacent to the forests. The use of the land, particularly the one close to the villages, is based on shifting cultivation and permanent fields of cashew trees together with food crops. The main cash crops include okra, tomatoes, and maize while the main food crops include maize, cassava, sorghum, rice, and various legumes.

LD was surveyed twice for the purpose of this study by collecting field inventory data and ALS measurements in 2012 and 2014.