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An above-ground biomass map of African savannahs and woodlands at 25 m resolution derived from ALOS PALSAR

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ABSTRACT

Savannahs and woodlands are among the most important biomes in Africa: they cover half of sub-Saharan Africa, provide vital ecosystem services to the rural communities, and play a major part in the carbon budget. Despite their importance and their fragility, they are much less studied than other ecosystems like rainforests. In particular, the distribution and amount of the above-ground woody biomass (AGB) is largely unknown. In this paper, we produce the first continental map of the AGB of African savannahs and woodlands at a resolution of 25 m. The map is built from the 2010 L-band PALSAR mosaic produced by JAXA, along the following steps: a) stratification into wet/dry season areas in order to account for seasonal effects, b) development of a direct model relating the PALSAR backscatter to AGB, with the help of *in situ* and ancillary data, c) Bayesian inversion of the direct model. A value of AGB and its uncertainty has been assigned to each pixel. This approach allows estimating AGB until 85 $Mg{\cdot}ha^{-1}$ approximately, while dense forests and non-vegetated areas are masked out using the ESA CCI Land Cover dataset. The resulting map is visually compared with existing AGB maps and is validated using a cross-validation approach and a comparison with AGB estimates obtained from LiDAR datasets, leading to an RMSD of 8 to 17 $Mg{\cdot}ha^{-1}$. Finally, carbon stocks for savannahs in Africa and in 50 countries are estimated and compared with estimates by FAO and from AGB maps available over Africa.

1. Introduction

The role of the African continent in the global carbon cycle has received increasing attention over the last decade (Bombelli et al., 2009; Ciais et al., 2009, 2011; Houghton and Hackler, 2006; Valentini et al., 2014; Williams et al., 2007). Although large uncertainties affect the continental estimation of the carbon budget, most recent studies agree that Africa is currently a small sink of carbon, with an average value of -0.61 ± 0.58 $Pg{\cdot}C{\cdot}yr^{-1}$ (Valentini et al., 2014). Africa is also a major source of interannual variability in the global atmospheric CO_2 concentration (Williams et al., 2007). The uncertainties and interannual variations associated to these estimates mostly involve savannahs and woodlands, whose contribution to the carbon budget is much more important in Africa than in the other tropical regions such as South America or Southeast Asia. Indeed, while the carbon density of savannahs and woodlands is lower than that of closed forests, they cover three times larger areas in Africa (Bartholomé and Belward, 2005), *e.g.* roughly 50% of the continent, and therefore represent a large carbon stock. Besides, with low – although increasing – fossil fuel emissions, the carbon balance of Africa is currently dominated by the uptake and release from terrestrial ecosystems, which is controlled by climate fluctuations and human-induced disturbances, both of which have stronger effects in savannahs and woodlands than in other ecosystems in Africa. For example fires, which play a significant role in the African carbon cycle with 1.03 ± 0.22 $Pg{\cdot}C{\cdot}yr^{-1}$ of carbon emissions, occur in savannahs and dry woodlands in 90% of the cases (Valentini et al., 2014). Deforestation rates in African savannah woodlands are found to be higher than in tropical rain forests, where massive deforestation has been avoided so far, in favour of selective logging (Brink and Eva, 2009; Ciais et al., 2011). Woody encroachment also appears to be a widespread source of change in the carbon stocks of these biomes (Mitchard and Flintrop, 2013). It is therefore important to accurately estimate and monitor the carbon stocks of African savannahs and woodlands in order to have a better knowledge of the African and global carbon budget.

Until recently, our knowledge of the global distribution and amount of woody carbon stocks was mostly based on field measurements of

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relatively small-size plots, which fail to adequately account for the spatial variability of their surrounding areas (Réjou-Méchain et al., 2014), and which are not uniformly distributed over the different forested biomes (Gibbs and Brown, 2007; Houghton et al., 2009). For instance, forest plantations are fairly well represented through commercial inventories but savannahs and woodlands, with no commercial value, have received much less attention. Also, they are not always considered as forests regarding the United Nations Framework Convention on Climate Change national forest definitions, and may therefore be disregarded in some monitoring activities. Besides, most carbon estimates are based on a handful of biome-average datasets where a single representative value of forest carbon per unit area is applied to broad forest categories or biomes (Achard et al., 2002, 2004; DeFries et al., 2002; Fearnside, 2000; Houghton et al., 2009; Ramankutty et al., 2007). Such approaches have led to large inconsistencies between studies. In the past few years, remote sensing approaches have offered considerable potential in support of woody carbon mapping as they provide long-term and repetitive observations over large areas. However, optical data, such as provided by the MODerate resolution Imaging Spectroradiometer (MODIS) or Landsat, are not sensitive to woody above ground biomass (AGB) beyond the canopy closure, and for savannahs and woodlands, are contaminated by the grass layer present in these open landscapes (Naidoo et al., 2016; Zeidler et al., 2012). Spaceborne LiDAR data (*e.g.* ICESat GLAS) are less suitable for open savannahs and woodlands and are limited by discontinuous coverage (Lefsky et al., 2005). Combinations of ICESat GLAS data with MODIS data have been developed to produce large-scale pan-tropical AGB maps. The approach consists in spatially extrapolating above ground woody carbon stocks obtained from *in situ* inventory plots and from ICESat GLAS transects, using MODIS only (Baccini et al., 2012) or using MODIS and Quick Scatterometer (QuikSCAT) data (Saatchi et al., 2011). While these two pan-tropical biomass maps, being the first of their kind with such a large coverage, have been widely used, they however suffer from a number of limitations: they have low spatial resolutions (0.5 to 1 km), no temporal repetition, and show large uncertainties (Mitchard et al., 2013a). In order to reduce the biases and improve the accuracy, independent reference plot datasets have been used to combine these two maps into an integrated map (Avitabile et al., 2016), but the limitations related to spatial and temporal resolutions remain. An update of the Baccini map has been recently produced at 30 m resolution, using Landsat data, and is available in the Global Forest Watch project (Baccini et al., 2015), but with reported large uncertainty at pixel level. For savannahs and woodlands in Africa, the uncertainty is expected to be very large, because of the above mentioned limitations of MODIS, Landsat, and ICEsat, worsened by the sparser GLAS coverage of such ecosystems used in the production of these datasets.

It has long been known that SAR data have high potential for AGB mapping and AGB stocks estimation, due to the relationships between the SAR backscatter and biomass (Le Toan et al., 1992). These relationships are affected by other parameters such as soil moisture (Harrell et al., 1997; Kasischke et al., 2011), topography (Castel et al., 2001), or the forest structure (Imhoff, 1995), which requires the adoption of specific strategies to mitigate the impacts of these environmental effects on the retrieval of AGB. Despite these limitations, SAR systems remain a promising tool for AGB estimation. Generally speaking, the backscatter in images acquired at short wavelengths like X-band or C-band show little dependence on biomass, although it has been shown that this weak sensitivity can be counterbalanced with the use of hyper-temporal observations, in particular in boreal forests (Santoro et al., 2011, 2013). Images acquired at long wavelengths like L-band or P-band are more strongly correlated with AGB. In the last decades, L-band spaceborne SAR data have become available, with the JERS-1 satellite active from 1992 to 1999 and ALOS PALSAR from 2006 to 2011, followed by PALSAR-2 onboard ALOS-2 launched in May 2014. SAOCOM (SAtélite Argentino de Observación COn Microondas) and NISAR (NASA/ISRO SAR Mission) L-band SAR systems are planned for launch in 2018 and 2020 respectively. Many theoretical and experimental studies showed that L-band SAR data are sensitive to forest AGB until a saturation level is reached and sensitivity is lost; however, a negative correlation between L-band backscatter and high AGB may occur when the forest is dense (Mermoz et al., 2015). The saturation is generally reported to occur between 70 and 150 $Mg{\cdot}ha^{-1}$ (Mermoz et al., 2014; Mitchard et al., 2009; Yu and Saatchi, 2016), depending on the experimental dataset and on the model used to relate the backscatter to AGB. L-band SAR data are therefore well suited to the estimation of savannah AGB, typically below 100 $Mg{\cdot}ha^{-1}$. For the denser woodlands, typically between 100 and 200 $Mg{\cdot}ha^{-1}$, and higher biomass values, P-band SAR systems have a better potential, but are not available so far in space because of frequency allocation limitations that were lifted only recently. The BIOMASS mission (Le Toan et al., 2011), planned for launch by the European Space Agency in 2021, will fill this gap and make it possible to exploit the synergy between L-band and P-band. Yearly PALSAR (2007–2010) and PALSAR-2 (2015-onwards) mosaics at 25 m have been built by the Japan Aerospace Exploration Agency (JAXA), and are freely available (http://www.eorc.jaxa.jp/ALOS/en/palsar_fnf/fnf_index.htm), which facilitates the use of large datasets for forest monitoring (Shimada et al., 2014). In the recent years, ALOS PALSAR data have therefore been used for AGB estimation in savannahs and woodlands for limited regions or countries in Africa and Australia (Carreiras et al., 2012, 2013; Lucas et al., 2010; Mermoz et al., 2014; Mitchard et al., 2009, 2011; Mitchard et al., 2013b; Naidoo et al., 2015; Ribeiro et al., 2008). However, these local studies have not been extended so far to continental scales, therefore the amount and distribution of the AGB in the whole African savannahs and woodlands remains to be better quantified (Bastin et al., 2017).

In this paper, we aim at filling this gap, by estimating woody AGB at a spatial resolution of 25 m over the entire savannah biome of Africa using ALOS PALSAR 2010 mosaics. The method comprises two steps. The first step consists in defining a direct model that relates the PALSAR backscatter to AGB, with the help of a selected set of field measurements. In the second step, a Bayesian inversion of this model is performed to produce the AGB gridded dataset. The paper is organised as follows: Section 2 gives general information on the savannahs of the African continent. Section 3 provides information on the data used in this study, both *in situ* plot data and SAR data. Section 4 presents the data analysis results and describes the development of the direct model as well as the Bayesian inversion scheme. Section 5 discusses the resulting estimates of savannah woody biomass in Africa and their associated uncertainties, and provides a validation assessment and a comparison with other large-scale AGB datasets available over Africa and national statistics.

2. Study area

2.1. Demography, climate and biomes

The African continent covers more than 30Mkm^2, which accounts for 20% of the Earth's land surface. The estimated population is nearly 1.2 billion people, mostly concentrated in savannah and woodland landscapes (Chidumayo and Gumbo, 2010), and increases nearly three times faster than in the rest of the world; demographers now project that Africa's inhabitants will triple or quadruple by the end of this century (Engelman, 2016). Africa comprises 54 member states of the United Nations, among which 28 are partner countries supported by the UN-REDD programme.

Africa lies mainly within the inter-tropical zone and is therefore a consistently hot continent. The different climate zones are therefore characterized primarily by their rainfall regimes. The number of dry months per year is shown in Fig. 1. It was produced using the mean monthly precipitations measured by the Tropical Rainfall Measuring Mission (TRMM) between 1998 and 2016 (3B43 products at a