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Measuring biomass changes due to woody encroachment and deforestation/degradation in a forest–savanna boundary region of central Africa using multi-temporal L-band radar backscatter

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ABSTRACT

Satellite L-band synthetic aperture radar backscatter data from 1996 and 2007 (from JERS-1 and ALOS PALSAR respectively), were used with field data collected in 2007 and a back-calibration method to produce biomass maps of a 15 000 km^2 forest–savanna ecotone region of central Cameroon. The relationship between the radar backscatter and aboveground biomass (AGB) was strong ($r^2 = 0.86$ for ALOS HV to biomass plots, $r^2 = 0.95$ relating ALOS-derived biomass for 40 suspected unchanged regions to JERS-1 HH). The root mean square error (RMSE) associated with AGB estimation varied from ~25% for AGB < 100 Mg ha^{-1} to ~40% for AGB > 100 Mg ha^{-1} for the ALOS HV data. Change detection showed a significant loss of AGB over high biomass forests, due to suspected deforestation and degradation, and significant biomass gains along the forest–savanna boundary, particularly in areas of low population density. Analysis of the errors involved showed that radar data can detect changes in broad AGB class in forest–savanna transition areas with an accuracy >95%. However, quantitative assessment of changes in AGB in Mg ha^{-1} at a pixel level will require radar images from sensors with similar characteristics collecting data from the same season over multiple years.

1. Introduction

The interface between tropical forest and savanna in west and central Africa is a wide, structurally and floristically diverse mosaic of vegetation types, with forest penetrating deeply into the savanna biome as gallery forests along river banks, and also as forest patches on plateaus and in between rivers (Dai et al., 2004; Hely et al., 2006; Menaut, 1983). The savannas in this region are not maintained by precipitation, there being enough rainfall to support full canopy closure except in the poorest or inundated soils. Instead they are maintained largely by anthropogenic disturbance such as fire and clearance for grazing, agriculture and timber (Bucini & Hanan, 2007; Sankaran et al., 2005). Changes in these disturbance regimes can therefore result in rapid changes in the woody cover of this region. Due to the large extent of the tropical forest–savanna ecotone in Africa (1.28 million km^2 is forest–savanna mosaic, compared with 2.36 million km^2 forest and 4.12 million km^2 woodland; Mayaux et al., 2004), any changes in the woody vegetation cover and the resulting feedbacks could have significant implications for biodiversity and the carbon cycle (Lewis, 2006). Such ecotones are also important as they are transitional habitats that appear to be areas of evolutionary dynamism, storing genetic diversity and acting as an important locus for the generation of new species (Smith et al., 1997, 2001).

Dynamics of woody vegetation in this ecotone are the result of the integration of a variety of different competing processes, each of largely unknown magnitude and spatial distribution. Forest is being cleared for agriculture, and woody savannas are often burnt to assist agriculture and cattle grazing (FAO, 2007; Zhang et al., 2006). Forest and woody savannas are also undergoing degradation, especially around settlements, for timber (legal logging concessions and illegal

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extraction), wood fuel and charcoal (Goetze et al., 2006; Mertens & Lambin, 2000). Changes in climate also have the potential to alter the area of forest and savanna, for example increases in dry season length will favor savanna, as would rising temperatures (Dai et al., 2004; Hely et al., 2006; Zeng & Neelin, 2000). In contrast, there are also processes that could cause forest to expand into savanna and savannas to increase in woodiness: reduced anthropogenic fire, caused by reduced human activity in an area; increased CO_2 concentration, which has the potential to increase tree growth in forests and therefore biomass (Lewis et al., 2004, 2009) by favoring the growth of trees with a C3 photosynthetic pathway, over grasses that have a C4 pathway[1] (Lloyd & Farquhar, 1996, 2008); and if rainfall increased, which would again favor trees over grasses (Hely et al., 2006).

It has been suggested that forest is expanding into savannas in central Africa because of urban-migration and a consequent reduction in fire frequency (Boulvert, 1990). Indeed, this forest encroachment has been found to be occurring in other tropical forest–savanna ecotones, including northern Australia (Bowman et al., 2001; Brook & Bowman, 2006; Hopkins et al., 1996), the Western Ghats of India (Puyravaud et al., 2003), and South America (Duarte et al., 2006; Durigan & Ratter, 2006; Marimon et al., 2006). However, little quantitative analysis followed Boulvert's initial observations in Africa: a literature search found only three studies reporting woody expansion in African tropical forest–savanna transitions, though there is much evidence of woody encroachment in semi-arid environments in Africa (Archer et al., 2001; Eamus & Palmer, 2007). In an ecotonal region of central Cameroon, optical remote sensing data and field measurements were used to show that over a period of 40 years (1950–1990), gallery forests encroached into the savanna landscape at a rate of 0.6 to 2 m a year (Happi, 1998). In eastern Cameroon, analysis of soil carbon isotopes ($^{13}C/^{12}C$, ^{14}C) along two transects showed both significant expansion of the forest, and that increased woody cover of the savanna has occurred over the past century (Guillet et al., 2001). In Budongo Forest Reserve, Uganda, a combination of field studies and vegetation index-based satellite change detection were used to demonstrate a 14% increase in woody vegetation (Nangendo, 2005). In combination, these studies provide some evidence that forest expansion is occurring, but none used a method that can be extrapolated to larger areas without a huge investment of resources: all involved extensive field studies or the manual interpretation of high-resolution remotely sensed images.

The use of space-borne radar backscatter data is becoming increasingly accepted as a useful method for measuring woody biomass over much larger areas in the tropics because of the capability of radar to penetrate through the forest canopy, and its capacity for all-weather acquisition (Lu, 2006; Ribeiro et al., 2008; Sano et al., 2005; Santos et al., 2002). Radar data are likely to be particularly applicable to forest–savanna boundary regions, as theory suggests there will be a substantial increase in backscatter as both the density and size of trees increase (Podest & Saatchi, 2002; Woodhouse, 2006), and biomass changes from savanna to forest are in the lower biomass ranges, where radar is most sensitive. As radar backscatter responds to the density, size, orientation, and water content of scattering elements on the surface (Rosenqvist et al., 2007), rather than just the color and density of leaves, it has the potential to be more sensitive to changes in the woodiness of savanna than spectral data. This is especially true because the radar signal will be much less sensitive to grasses than spectral data, especially when longer radar wavelengths are used. The spectral vegetation signal from trees can be very hard to distinguish from that of grasses unless hyperspatial data, capable of resolving individual trees (Lu, 2006), or multi-temporal data which enables the phenology of different landcover types to be separated (Loveland et al., 2000), are used.

The successful launch of the Advanced Land Observing Sattelite's Phased Array-type L-band Synthetic Aperture Radar (ALOS PALSAR) in 2006 has increased the potential to use radar to measure biomass, as this is the first long-wavelength (L-band, 23-cm wavelength) synthetic aperture radar (SAR) satellite sensor to have the capability of collecting cross-polarized (HV, horizontal-send, vertical receive) data in addition to horizontal-send, horizontal-receive (HH) data. This is an advantage for detecting biomass because for HV only scattering elements that change the polarization of the incoming electromagnetic radiation will be detected, so complex three-dimensional structures such as trees will produce a strong response, but soil moisture, which does not change the polarization of the incoming radiation, will not be detected.

Radar has been used only rarely to quantify biomass in forest–savanna transition regions, though when used it has been with considerable success (Lucas et al., 2000; Ribeiro et al., 2008; Sano et al., 2005; Santos et al., 2002). It has to our knowledge never previously been used for long-term biomass change detection in forest–savanna transition regions, despite the availability and potential of the data. Here, we compare satellite L-band radar data from 1996 and 2007 over a large ecotonal region of central Cameroon, both to assess changes in aboveground woody biomass in this region, and as a proof of concept for its application for large scale monitoring of changes in biomass from space.

2. Study area

The study area covers a 15 000 km^2 region in central Cameroon, centered around 6°4′18″ N, 12°53′18″ E, encompassing the Mbam Djerem National Park and the surrounding area to the north and east (Fig. 1). This region was chosen as it extends across a range of tropical vegetation types, from humid forests contiguous with the Congo Basin tropical forest belt in the south to savanna with narrow gallery forests in the north. It experiences an annual rainfall of 1720 mm, with a standard deviation of 213 mm (derived from Tropical Rainfall Measuring Mission (TRMM) 3B43 V6 data from January 1998 to December 2008). There is a pronounced dry season from December to March, with an average rainfall of 20 mm per month. The Mbam Djerem National park was established in the year 2000 as an expanded version of the longer-standing Pangare Djerem reserve with funds from Chad-Cameroon Pipeline Project, and is currently maintained by the Wildlife Conservation Society. It has a high species diversity, containing over 360 bird and 50 mammal species (Anonymous, 2007), and is regarded as having critical importance for the preservation of Central African biodiversity (Doumenge et al., 2003). The park itself has a very low human population density, with almost no permanent residents. Major anthropogenic disturbances in the park are fishing, bushmeat hunting in the southern forests, and grazing accompanied by burning in areas along the northern forest–savanna boundary. The regions surrounding the park are more populated, especially on the eastern side, with the two major towns being Tibati on the western side of Lake Mbakaou, and Ngaoundal in the northeast of the study area. The population of both towns has increased by approximately 85% in the past twenty years, from 15 522 and 11 382 respectively in 1987 to 28 981 and 21 239 in 2006 (CIESIN, 2004; PNUD, 1999).

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[1] C3 photosynthesis is the photosynthetic pathway that occurs in most plants including all trees. C4 photosynthesis is an alternative used by some grasses, including the majority found in this area, that gives increased efficiency of photosynthesis with respect to water 'use' (i.e. water loss through transpiration), and is therefore beneficial in drier and hotter environments (Taiz & Zeiger, 2006). However, the advantage which C4 plants have over C3 plants is reduced as the concentration of CO_2 in the atmosphere increases (energetically costly adaptations that increase the concentration of CO_2 in leaf cells becomes less advantageous; Lloyd & Farquhar, 2008). Thus increasing CO_2 concentrations could be responsible for woody encroachment by reducing the competitiveness of C4 grasses compared with C3 plants. However, increasing temperatures or a reduction in rainfall, that may occur concurrently with an increase in CO_2 concentration, could negate this effect by increasing the competitive advantage of C4 grasses over C3 trees.