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Annual dynamics of forest areas in South America during 2007–2010 at 50-m spatial resolution

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ABSTRACT

South America has the largest tropical rainforests and the richest biodiversity in the world. It is challenging to map tropical forests and their spatio-temporal changes because forests are facing fragmentation from human activities (e.g., logging, deforestation), drought, and fire, as well as persistent clouds. Here we present a robust approach to map forests in South America during 2007–2010 and analyze the consistency and uncertainty among eight major forest maps in South America. Greenness-relevant MOD13Q1 NDVI and structure/biomass-relevant ALOS PALSAR time series data recorded 2007 through 2010 were coupled to identify and map forests at 50-m spatial resolution. Both area and spatial comparison were conducted to analyze the consistency and uncertainty of these eight forest maps. Annual 50-m PALSAR/MODIS forest maps were generated during 2007–2010 and the total forest area in South America was about 8.63×10^6 km^2 in 2010. Large differences in total forest area (8.2×10^6 km^2–12.7×10^6 km^2) existed among these forest products, especially in the forest edges, semi-humid tropical, and subtropical regions. Forest products generated under a similar forest definition had similar or even larger variation than those generated with contrasting forest definitions. We also find out that one needs to consider leaf area index as an adjusting factor and use much higher threshold values in the Vegetation Continuous Field (VCF) datasets to estimate forest cover areas. Analyses of PALSAR/MODIS forest maps in 2008/2009 showed a relatively small rate of loss (3.2×10^4 km^2 year^{-1}) in net forest cover, similar to that of FAO FRA (3.3×10^4 km^2 year^{-1}), but much higher annual rates of forest loss and gain. The rate of forest loss (0.195×10^6 km^2 year^{-1}) was higher than that of Global Forest Watch (0.081×10^6 km^2 year^{-1}). PALSAR/MODIS forest maps showed that more deforestation occurred in the unfragmented forest areas. Caution should be used when using the different forest maps to analyze forest loss and make policies regarding forest ecosystem services and biodiversity conservation. The integration of PALSAR and MODIS images during 2007–2010 provides annual maps of forests in South America with improved accuracy and reduced uncertainty.

1. Introduction

Tropical forests are a huge reservoir of terrestrial carbon and estimated to hold 230–260 Pg C, or about 40–60% of the carbon contained in the world's terrestrial vegetation (Baccini et al., 2012; Pan et al., 2011; Saatchi et al., 2011; Zarin et al., 2016). Tropical forests are susceptible to multiple disturbances from logging (Fraser, 2014; Matricardi et al., 2013), expansion of industrial forest plantations and agricultural land (le Maire et al., 2014; Morton et al., 2006), drought (Brando et al., 2014), and fires (Fanin and van der Werf, 2015). Therefore, it is important for the scientific community to design and implement operational forest monitoring, reporting, and verification (MRV) systems that are reproducible, consistent, and accurate at national and continental scales, which is also a requirement of a successful REDD+ (Reduce Emissions from Deforestation and Forest Degradation) mechanism under the United Nations Framework Convention on Climate Change (UNFCCC). There is an urgent need for high accuracy forest maps so that land managers, policy makers, and scientists can investigate the changes in carbon fluxes, carbon stock, and ecological services, such as the degradation in the carbon stocks near tropical

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forest edges (Chaplin-Kramer et al., 2015), habitat fragmentation (Haddad et al., 2015), and the effects of conservation policy on forest recovery (Viña et al., 2016).

Spaceborne remote sensing technology has the advantage of observing large areas of Earth's landscape at high temporal resolution with frequent revisits, and therefore is widely used for global and continental forest mapping. Optical remote sensing images, which have been collected since the 1970s, are the major data source for forest mapping because they are relatively easy to process and interpret. The optical sensor-based forest products are mainly produced based upon the 1000-m Advanced Very High Resolution Radiometer (AVHRR) (Achard et al., 2001), 500-m and 250-m Moderate Resolution Imaging Spectroradiometer (MODIS) (Friedl et al., 2010; Hansen et al., 2003; Townshend et al., 2011), and 30-m Landsat (Hansen et al., 2013; Kim et al., 2014). Selective logging is common in tropical forests and cannot be observed by relatively coarse spatial resolution images, especially for AVHRR and MODIS images (Asner et al., 2005). Active microwave remote sensing images are becoming more applicable to tropical forest mapping, especially as wall-to-wall global observations become available, such as C-band Sentinel-1, L-band Japanese Earth Resource Satellite 1 (JERS-1), and Advanced Land Observing Satellite (ALOS) Phased Array type L-band Synthetic Aperture Radar (PALSAR). Active microwave sensors can penetrate clouds and smoke haze, and monitor land surface conditions day and night without interference from weather conditions. The short wavelength X- and C-band SAR have been applied to forest mapping (Ranson and Sun, 1997), although these bands are easily saturated at the forest canopy. The L-band ALOS PALSAR has a long operating wavelength (23.6 cm), which is sensitive to forest structure and biomass under the canopy and is well suited to tropical forest monitoring. PALSAR imagery has also been successfully applied for global and regional forest mapping (Dong et al., 2012; Qin et al., 2016; Shimada et al., 2014).

Mapping tropical forests with high accuracy, either from optical or active microwave remote sensing, is very challenging. Tropical forest loss and recovery is occurring at high rates. For example, Brazil experienced a decreasing trend in forest cover from 2000 to 2012, with the annual average rate about $3 \times 10^4\,\mathrm{km}^2\,\mathrm{year}^{-1}$ (Hansen et al., 2013). Conversely, the industrial forest plantations are expanding due to the increased demand for pulp and wood, such as Eucalypt. The Eucalypt plantations have a short clear-cut and afforestation rotation in Brazil (le Maire et al., 2014). Time series remote sensing images are preferred for tracking these fast changes in forest cover. The availability of data from optical remote sensing is largely restricted by persistent clouds, which is the major barrier to tropical forest mapping (Achard et al., 2007; Asner, 2001). Many recent studies have generated forest cover maps by combining the increasing number of good quality optical remote sensing images from multiple years (European Space Agency, 2016; Hansen et al., 2013). However, the use of images from multiple-year periods might not detect intra-annual changes of forest cover in the Amazon Basin. A recent study evaluated eight global forest cover maps and showed that relatively large uncertainty existed among current forest maps (Sexton et al., 2015), particularly in the tropical zone (hotspots). Most of these forest maps are produced using image data from a single source. Single-data source based forest maps have moderate to large commission and omission errors because of complex landscapes. Different land cover types may have similar phenology and structural features, and the same land cover types may have different greenness attributes in different seasons.

Optical remote sensing can track the phenology of land cover types and active microwave remote sensing image can observe the structure and biomass of forests. There is a need to integrate active microwave and optical remote sensing imagery to map tropical forests (Dong et al., 2013; Qin et al., 2015; Reiche et al., 2016). Several studies have demonstrated the potential of combining SAR and optical remote sensing images for mapping land cover types (e.g., ice shelf change, urban areas, crops, and forests) (Ban, 2003; Khazendar et al., 2007; Qin et al., 2017; Ranson et al., 2003) and forest biomass (Lucas et al., 2006). The associated technical challenges of fusing microwave and optical remote sensing images for mapping changes in forest cover has also been addressed by several recent studies (Lehmann et al., 2015; Reiche et al., 2015). These studies have demonstrated a reduction in cloud–induced gaps in the observational data and improved accuracy in forest cover and forest cover change, even for areas with persistent cloud cover. However, these data fusion approaches were only demonstrated at a local scale and were not applied and tested for large-scale forest mapping in South America (Reiche et al., 2016).

In this study, we selected South America as the study area, which encompasses the Amazon Basin and contains the world's largest area of tropical rainforests and hosts the richest biodiversity (Malhi et al., 2008). South America had the highest forest loss rate with over 50% of tropical forest loss occurring since 2000 (Hansen et al., 2013). Both the forest loss rate and the net forest loss rate decreased after 2005, especially between 2010 and 2015 (Hansen et al., 2013; Keenan et al., 2015). The objectives of this study are three-fold. First, we produce annual maps of forest in South America at the spatial resolution of 50 m through the integration and analyses of PALSAR images (50-m spatial resolution) and time series MODIS NDVI images (250-m spatial resolution) during 2007–2010. This reflects (1) an improvement in terms of optical and microwave image data integration over a previous work in Southeast Asia that used only PALSAR images (Dong et al., 2012), and (2) an effort for expansion of the same mapping approach used in China (Qin et al., 2015) and monsoon Asia (Qin et al., 2016) towards global mapping of forests. Second, we compare and analyze the consistency and uncertainty among eight forest cover products for the year 2010, which were generated from various data sources and methods. Third, we quantify the spatio-temporal changes of forests in South America from 2008 to 2009, based on the resultant annual PALSAR/MODIS forest maps. This study provided improved forest cover maps for the user community of forests maps, which can be used for the development and application of forest management techniques in South America.

2. Materials and methods

We built a detailed workflow for forest cover mapping and forest cover product comparison in South America (Fig. 1). This workflow included two major components. First, we produced the annual 50-m PALSAR/MODIS forest maps from 2007 through 2010 based on the integration of PALSAR and MODIS NDVI data. Second, we analyzed the area and spatial differences in forest cover estimation from the PALSAR/MODIS forest cover map and seven other major forest cover products in 2010.

2.1. Study area

South America is mainly located from 56° S to 12° N, from 35° W to 81° W and covers an area of about 18 million square km^2. The elevation ranges from sea level to over 7000 m. South America can be divided into three major natural regions: the Andes Mountains, Eastern Highlands, and Plains. South America has humid tropical and semi-humid tropical climate in the north and humid subtropical climate in the southeast.

2.2. PALSAR data and pre-processing

The 50-m ALOS PALSAR Fine Beam Dual polarization (FBD) product from 2007 through 2010 were downloaded from the Earth Observation Research Center, Japan Aerospace Exploration Agency (JAXA). PALSAR HH and HV backscatter data are slope corrected and ortho-rectified with a geometric accuracy of about 12 m, and radiometrically calibrated. The Digital Number (DN) values (amplitude values) were converted into gamma-naught backscattering coefficients in decibels (γ°)