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Mapping major land cover types and retrieving the age of secondary forests in the Brazilian Amazon by combining single-date optical and radar remote sensing data

João M.B. Carreiras [a,*], Joshua Jones [b], Richard M. Lucas [c], Yosio E. Shimabukuro [d]

[a] NERC National Centre for Earth Observation (NCEO), University of Sheffield, Hicks Building, Hounsfield Road, Sheffield, S3 7RH, United Kingdom
[b] Department of Geography and Earth Sciences, Aberystwyth University, Ceredigion, Aberystwyth, SY23 3DB, Wales, United Kingdom
[c] Centre for Ecosystem Science, School of Biological, Earth and Environmental Sciences, University of New South Wales, Sydney 2052, NSW, Australia
[d] Remote Sensing Division, National Institute for Space Research, Avenida dos Astronautas 1758, São José dos Campos, 12227-010 São Paulo, Brazil

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ABSTRACT

Secondary forests play an important role in restoring carbon and biodiversity lost previously through deforestation and degradation and yet there is little information available on the extent of different successional stages. Such knowledge is particularly needed in tropical regions where past and current disturbance rates have been high but regeneration is rapid. Focusing on three areas in the Brazilian Amazon (Manaus, Santarém, Machadinho d'Oeste), this study aimed to evaluate the use of single-date Landsat Thematic Mapper (TM) and Advanced Land Observing Satellite (ALOS) Phased Arrayed L-band Synthetic Aperture Radar (PALSAR) data in the 2007–2010 period for i) discriminating mature forest, non-forest and secondary forest, and ii) retrieving the age of secondary forests (ASF), with 100 m × 100 m training areas obtained by the analysis of an extensive time-series of Landsat sensor data over the three sites. A machine learning algorithm (random forests) was used in combination with ALOS PALSAR backscatter intensity at HH and HV polarizations and Landsat 5 TM surface reflectance in the visible, near-infrared and shortwave infrared spectral regions. Overall accuracy when discriminating mature forest, non-forest and secondary forest is high (95–96%), with the highest errors in the secondary forest class (omission and commission errors in the range 4–6% and 12–20% respectively) because of misclassification as mature forest. Root mean square error (RMSE) and bias when retrieving ASF ranged between 4.3–4.7 years (relative RMSE = 25.5–32.0%) and 0.04–0.08 years respectively. On average, unbiased ASF estimates can be obtained using the method proposed here (Wilcoxon test, p-value > 0.05). However, the bias decomposition by 5-year interval ASF classes showed that most age estimates are biased, with consistent overestimation in secondary forests up to 10–15 years of age and underestimation in secondary forests of at least 20 years of age. Comparison with the classification results obtained from the analysis of extensive time-series of Landsat sensor data showed a good agreement, with Pearson's coefficient of correlation (R) of the proportion of mature forest, non-forest and secondary forest at 1-km grid cells ranging between 0.97–0.98, 0.96–0.98 and 0.84–0.90 in the 2007–2010 period, respectively. The agreement was lower (R = 0.82–0.85) when using the same dataset to compare the ability of ALOS PALSAR and Landsat 5 TM data to retrieve ASF. This was also dependent on the study area, especially when considering mapping secondary forest and retrieving ASF, with Manaus displaying better agreement when compared to the results at Santarém and Machadinho d'Oeste.

1. Introduction

Land use and land cover change, and particularly conversion from forest to non-forest (i.e., deforestation), is the second largest source of carbon dioxide emissions after fossil fuel combustion, accounting for 9% of annual emissions between 2004 and 2013 (Le Quéré et al., 2015). Deforestation across tropical and subtropical biomes was estimated to account for over 60% of total deforestation between 2000 and 2012 (Hansen et al., 2013), with almost two thirds in areas with high tree cover (>75%). This has severe consequences not only in terms of carbon stocks depletion (Harris et al., 2012) but also losses of biodiversity (Laurance et al., 2014; Lewis et al., 2015).

In the Amazon region, annual deforestation (clear cut) mapping primarily from Landsat data has been carried out by the Brazilian National Institute for Space Research (Instituto Nacional de Pesquisas

* Corresponding author.
E-mail address: j.carreiras@sheffield.ac.uk (J.M.B. Carreiras).

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Espaciais, INPE) since 1988 under the *Projeto de Monitoramento do Desmatamento na Amazônia Legal por Satélite* (PRODES) project (INPE, 2015). Reported deforestation rates have been highly variable over time, reaching their highest value in the mid-1990s (~ 30,000 km^2yr^{-1}), but have progressively decreased since the mid-2000s to a record low of ~4500 km^2yr^{-1} in 2012. Several socio-economic factors contributed to these observed changes in deforestation rates (Brondizio and Moran, 2012; Ewers et al., 2008). Large-scale deforestation, which started in the 1970s and continued throughout the 1980s and 1990s, was linked to policies aimed at encouraging colonisation of the region (e.g., fiscal incentives), expanding the road network and granting land titles to settlers (Fearnside, 2005). Since the late 1990s, however, and up until today, global demand for commodities (mainly soy and beef) started playing a stronger role in the temporal variations of annual deforestation rates. Rates of deforestation observed in the late 1990s and early 2000s were successfully reduced by a combination of stronger forest monitoring-based law enforcement, expansion of protected areas, and interventions at the supply chain level (Nepstad et al., 2014).

Deforestation typically results in the replacement of forests by croplands and pastures but these are often abandoned after a few years and replaced with secondary forests. These serve to accumulate carbon and restore biodiversity lost previously during the initial deforestation process (Brown and Lugo, 1990). The age, structure and species composition of secondary forests establishing on abandoned lands are a consequence of several factors, such as land use history, soil fertility and distance to mature primary forests (Chazdon, 2003). For this reason, knowledge of the age and land use history of areas under regeneration is needed to better understand patterns of carbon accumulation and recovery (or otherwise) of biodiversity. Mapping the age of tropical secondary forests often relies on comparing time-series of land cover maps (including a secondary forest class) obtained from classification of high-resolution optical data (Carreiras et al., 2014; Nelson et al., 2000; Prates-Clark et al., 2009). Other approaches use single-date remote sensing (often optical) data to map the age of secondary forests into classes (e.g., initial, intermediate and advanced secondary forests) (Lucas et al., 2000; Vieira et al., 2003). Recently, Chazdon et al. (2016) used an above-ground forest biomass map of the Neotropics (Baccini et al., 2012) in combination with ~1500 plots in secondary forests of known age to derive a large-scale map of the age of secondary forests. All these approaches rely on the availability of reference information about i) areas occupied by secondary forests (time-series approach) or ii) areas of known age or age class (single-date approach). The application of these methods is sometimes severely hampered by frequent cloud cover in tropical regions, thus leading to some regions having poor coverage by optical sensors. For this reason, all-weather Synthetic Aperture Radar (SAR) data are increasingly being used and promoted to improve land use/land cover change monitoring over tropical regions (Reiche et al., 2016). SAR data can provide information related to structural parameters of the forest (above-ground biomass, canopy height) (Carreiras et al., 2012; Cartus et al., 2012; Lucas et al., 2010; Santoro et al., 2011) that could prove useful when retrieving the age of secondary forests and complement that provided by optical sensors.

The objective of this study was to investigate the combined use of single-date optical (Landsat 5 Thematic Mapper) and Advanced Land Observing Satellite (ALOS) Phased Array L-band Synthetic Aperture Radar (PALSAR) to a) map major land cover types (mature forest, non-forest and secondary forest) and b) retrieve the age of secondary forests across three sites (~5000 km^2) in the Brazilian Amazon: Manaus (2.6° S, 60.2° W), Santarém (3.1° S, 54.8° W) and Machadinho d'Oeste (9.5° S, 62.4° W) (Fig. 1A). Since the inception of deforestation in the Amazon, these regions have experienced different but distinct patterns of land use and land cover change thus leading to present day landscapes characterised by a dissimilar spatial arrangement and frequency of land cover classes, namely secondary forests of varying age. By knowing, as a minimum, the age of these forests, a better estimation of the contribution of these landscapes to the regional carbon balance and biodiversity recovery can be achieved.

2. Study areas

The Manaus site, north of Manaus (Amazonas state) (Fig. 1B) encompasses the majority of a Federal conservation unit, the Biological Dynamics of Forest Fragments Project (BDFFP) (Laurance et al., 2011). Other county and state conservation units are also included in this study area. In the early 1970s, the construction of a highway connecting Manaus with Boa Vista (BR-174) was the key cause of deforestation in the region. Agricultural expansion was the main deforestation driver, which occurred across both sides of the highway. The BDFFP was established in 1985, but as far back as 1979, several forest fragments were preserved prior to deforestation of the surrounding forest. These were used to study the impacts of deforestation (and corresponding forest fragmentation) on ecosystem structure and function, thereby informing future conservation programmes in the Amazon (Laurance et al., 2011).

The Santarém site is located approximately 80 km to the south of Santarém (Pará state) (Fig. 1C). The study area is partially within a Federal conservation unit - Tapajós National Forest (FLONA Tapajós) - between the Tapajós River and the BR-163 highway connecting Santarém with Cuiabá (Mato Grosso). This unit was created in 1974 and has been used successfully to implement some novel forest management practices, such as the benefits of reduced impact logging on social welfare and biodiversity (Bacha and Rodriguez, 2007; van Gardingen et al., 2006).

The Machadinho d'Oeste site (Fig. 1D) is mainly located within the Machadinho d'Oeste municipality (Rondônia state). Its origins are a settlement project, initiated by the Brazilian Federal Government in 1982 with the support of the World Bank to colonize some regions of the Amazon (Miranda, 2009). The original vegetation is dominated by open rainforests (Miranda, 2009) and, according to Batistella and Moran (2005), most of its inhabitants depend on subsistence agriculture. This site includes several state-level conservation units, mainly extractive reserves, established in the mid-1990s.

The geographic location of these three sites has implications in terms of climate, although the mean annual temperatures are all around 25 °C to 26 °C (Bierregaard, 2001; Miranda, 2009; Silver et al., 2000). At Manaus, a relatively strong dry season occurs between June and October, with annual rainfall between 1900 and 3500 mm (Laurance et al., 2011). At Santarém, the dry season lasts from May to October and average annual rainfall is approximately 2000 mm (Silver et al., 2000). At Machadinho d'Oeste, the dry season occurs between April and November, with an annual rainfall around 2400 mm (Miranda, 2009). Forest types at the study areas are determined partially by topography and soils. Topography ranges from moderately flat (Manaus: up to 160 m elevation, Santarém: between 50 and 240 m) to moderately hilly (Machadinho d'Oeste: 90–370 m). Overall, soils are nutrient poor; ferralsols at Manaus (Laurance et al., 1999), ferralsols and nitosols in Santarém (Keller et al., 2005; Silver et al., 2000), and ferralsols, nitosols and fluvisols at Machadinho d'Oeste (Miranda, 2009).

3. Data

3.1. Time-series of land cover maps and age of secondary forests (ASF)

Existing time-series of land cover maps depicting three primary classes (mature forest, non-forest, secondary forest) were obtained through automatic classification of Landsat sensor data over the three selected sites. Carreiras et al. (2014) and Prates-Clark et al. (2009) provide detailed information about remote sensing data pre-processing and methods used to generate these land cover maps and the corresponding accuracy assessment. In this section, only a summary is presented.