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Reconstructing long term annual deforestation dynamics in Pará and Mato Grosso using the Landsat archive

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ABSTRACT

Remote sensing based monitoring of deforestation in the tropics is crucial to better understand global land use change and related changes in ecosystem service provision and to inform governments and civil society on the effectiveness their forest protection policies. In Brazil, deforestation has been closely coupled to the expansion of grazing and cropping systems primarily in the tropical forest, but no spatially explicit high resolution database on deforestation exists that captures tropical forest clearing prior to 2000. The open Landsat archive provides > 45 years of imagery and is well suited for wall-to-wall assessments of historic deforestation dynamics which are valuable to policy development and environmental impact assessments. Image analysis procedures for reconstructing long-term deforestation dynamics over large areas need to cope with regions and time periods for which the archive contains heterogeneous data densities on a yearly and decadal basis. We create for the first time yearly 30 m maps of long term, annual deforestation dynamics (LTAD) covering the period from 1984 to 2014 for Pará and Mato Grosso, two Brazilian federal states that cover much of the Brazilian arc-of-deforestation. Our results provide valuable insights into historic deforestation trends, with annually increasing deforestation from 1990 to 1999 for both Pará and Mato Grosso. Peak deforestation occurred in 2004 after which deforestation leveled off – with a more pronounced decrease in Mato Grosso than in Pará. Contrary to Mato Grosso, Pará again experienced increasing annual forest clearing in recent years. For the time period after 2000, we provide an in-depth comparison with two widely used products, the Brazilian PRODES and the Global Forest Change maps (GFC, Hansen et al., 2013). Our deforestation estimates (407,000 ± 42,000 km^2 at 95% confidence level) are above those provided by PRODES, while GFC results are closer to our estimates for the comparison period. Recent PRODES estimates are consistently below our and the GFC results. Overall, our results exemplify the potential of open image archives for multi-decadal, wall-to-wall and fine grain reconstruction of forest change. The presented approach prototypes similar assessments of tropical forest dynamics globally faced with issues of data scarcity.

1. Introduction

Tropical forests are of global relevance with regard to climate regulation, carbon sequestration and the high levels of biodiversity they sustain (Barlow et al., 2007; Kindermann et al., 2008; Lawrence and Vandecar, 2015). Spatio-temporal deforestation dynamics are essential inputs to carbon modeling (Aguiar et al., 2012), to ascertain the effects on regional climate and water cycles (Lejeune et al., 2015) and to limit its detrimental effects on biodiversity (Foley et al., 2007; Barlow et al., 2016). Moreover, long term, spatially explicit assessments of deforestation dynamics allow inferring the effects of environmental policies and regulations or the role of economic activities (Nepstad et al., 2013). Earth observation based monitoring plays an essential role to keep track of tropical forest cover and deforestation processes as it allows for synoptic coverage of vast and often inaccessible areas.

Brazil has been a focal point of global deforestation dynamics as the Brazilian Amazon is the largest expanse of tropical rainforest globally and has until recently also experienced the highest levels of deforestation (FAO, 2010). Brazil has at the same time been at the forefront of environmental policy implementation based on monitoring efforts to

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combat illegal deforestation and has been overall successful in reducing illegal deforestation (Nepstad et al., 2009). The country has set ambitious goals for a further reduction of carbon emissions resulting from land use change (Federative Republic of Brazil, 2015). The Brazilian land change monitoring programs are an integral part of the country's effort to reduce land change related carbon emissions (Rajão et al., 2017). The real time monitoring program DETER uses visual interpretation of daily MODIS imagery to generate alerts that inform the Brazilian Institute of Environment and Renewable Natural Resources (IBAMA) in support of law enforcement (www.obt.inpe.br/degrad). Recently, DETER-B uses spatially higher resolved Advanced Wide Field Sensor (AWiFS) data to perform real-time alerts. The TerraClass program additionally produces land cover and land use information for the deforested areas in Amazonia (Almeida et al., 2016). These maps are produced in a bi-yearly manner since 2008 and are based on visual interpretation of 17 land cover and use classes using imagery from Landsat, ResourceSat and other platforms. The cornerstone of Brazil's monitoring initiatives has been the deforestation monitoring program PRODES, which provides spatially explicit information on deforestation in the Amazon (Instituto Nacional de Pesquisas Espaciais, 2013). PRODES has been produced annually in a spatially explicit version since 2000 (PRODES digital) with a baseline layer created for 1997 but only state-wise gross deforestation estimates exist for earlier years starting in 1988 (PRODES analog, INPE, 2014). PRODES is mainly based on visual interpretation of mostly Landsat but also China–Brazil Earth Resources Satellite (CBERS) and Indian Remote Sensing (IRS) imagery. More details on how PRODES digital is produced can be found in INPE (2014) and Hansen et al. (2008).

Spatially explicit information on deforestation that occurred prior to 2000 would be valuable though for better understanding the long-term impacts of policies and regulations. This is also important as an input for modeling of long-term carbon sequestration potentials (Brienen et al., 2015; Hissa et al., 2016; Müller et al., 2016). Moreover, PRODES does not capture forest clearings smaller than 6.25 ha (internally 1 ha, Bustamante et al., 2017), while an increasing share of the annual deforestation might be attributed to smaller scale clearings (Richards et al., 2017).

Visual interpretation can ensure low commission errors for products like PRODES, which is required to support Brazil's environmental policies in court. A higher degree of automation would be desirable to support re-analyses and transferability to other tropical regions suffering from illegal deforestation. Landsat data is of special relevance for developing cost effective and semi-automated monitoring approaches. First, the spatial and spectral resolution is well suited to detect most deforestation activities while at the same time the sensor's field-of-view covers relatively large extents (Cohen and Goward, 2004). Second, Landsat data has been acquired beginning in 1972 with the Multispectral Scanner (MSS) instrument and starting in 1982 at 30 m grain with the Thematic Mapper (TM) sensor on Landsat-4 and spectral bands in the visible, near- and shortwave infrared (Loveland and Dwyer, 2012). Third, the Landsat record is radiometrically well calibrated and orthorectified to sub-pixel accuracy, which is mandatory for automated time series and/or wall-to-wall mapping (Chander et al., 2009). Fourth, the free data policy has boosted innovative use and algorithmic advances for Landsat data, while at the same time computational capacities for storage and processing of the data greatly improved (Wulder et al., 2012). Finally, the development and availability of higher level products, such as surface reflectance and cloud masking, simplifies pixel-based workflows for compositing and many time series approaches (Schmidt et al., 2013). Additional significance of the Landsat program for monitoring tropical forest dynamics relates to Landsat data continuity being ensured for the next decade, with Landsat-9 currently being under construction and Landsat-10 beeing in the requirements definition stage.

Forest cover change detection and deforestation monitoring with Landsat-like data has advanced considerably during the recent decades (Hostert et al., 2015). Several review papers provide overviews on change detection techniques, mainly with foci on vegetation change and forest cover change analysis (Coppin et al., 2004; Lu et al., 2004). More recent developments include time series approaches focusing on annual intervals, which have generally proven to be well suited to describe forest clearings and vegetation recovery alike (Huang et al., 2009; Kennedy et al., 2010). For example, the combined use of annual time series temporal segmentation and large area annual reflectance composites has allowed the quantification of forest change history and attribution to main change agents over Canada (Hermosilla et al., 2016). Other recent time series approaches utilize all available pixel observations and fit harmonic mathematical models to the data, which allows detecting changes by comparing predicted with observed values (Zhu et al., 2012). The first global 30 m map of forest cover change from 2000 to 2012 was based on automated analysis of a very large volume of Landsat data in a distributed processing environment (Hansen et al., 2013).

Many state-of-the-art time series approaches targeting forest change require sufficiently high observation densities, often also to be evenly distributed over space and time (e.g. Kennedy et al., 2014). The Landsat archive, however, features major regional differences in the data density over time. This is especially the case during the 1980s and 1990s (Wulder et al., 2016) and for many regions in the tropics. This relates to different programmatic and technical aspects, including issues related to the ground segment and the network of receiving stations, but also environmental factors. During the Landsat-7 mission a coordinated global acquisition strategy mitigated this imbalance to a large degree (Arvidson et al., 2001). Historically, international receiving stations held imagery not replicated in the United States Geological Survey (USGS) global Landsat archive. In many cases, the international holdings were inaccessible and in danger of being lost due to storage media degradation. Consequently, much of the historic data has been archived in various ways and locations with some data having never been processed, while others having been lost due to storage media degradation. In recognition of this problem, the Landsat global archive consolidation (LGAC) effort has been very successful in repatriating all globally available data for integration in the Landsat archive (Wulder et al., 2016). Nevertheless, the number of acquired scenes during the 1980s and 1990s is far below what could have been acquired with the nominal 16-day repeat cycle with a single Landsat satellite for many regions of the world. Data densities in North America or Australia are therefore considerably higher than in other regions such as South America or Africa. The unique data holdings from the Brazilian Landsat archive have been successfully integrated in the USGS archive during the earlier phase of LGAC (Wulder et al., 2016). The effective observation density, i.e. the number of actual clear sky observations per pixel, is nevertheless regionally constrained, primarily due to cloud cover. Moreover, the effective observation density in Brazil is considerably lower than in higher latitudes due to the smaller across-track overlap between adjacent paths. The failure of the Landsat-7 Scan-Line-Corrector (SLC-off) leads to further reduction of effective observation densities for data acquired after May 2003.

Limited data acquisitions, small across track overlaps, and persistent cloud cover, but also dynamic ecosystems that allow quick vegetation recovery complicate monitoring approaches that seek to reconstruct long-term and wall-to-wall tropical deforestation dynamics. Time series approaches that explicitly model seasonal land surface reflectance and derive changes by comparing predictions with observations therefore do not perform well in regions with lower observation densities and less pronounced seasonality (Zhu et al., 2012). Also, approaches utilizing temporal segmentation do not readily capture fast changing tropical land use dynamics related to swift post-deforestation dynamics or circular slash and burn land use practices unfolding over several decades (Kennedy et al., 2010; Hermosilla et al., 2016).

Our overall objective was to develop an approach that enables wall-to-wall reconstruction of long term, annual deforestation dynamics