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Beyond deforestation: Differences in long-term regrowth dynamics across land use regimes in southern Amazonia

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ABSTRACT

The loss of tropical forests threatens a broad range of ecosystem services. Particularly, tropical deforestation is a major driver of biodiversity decline and substantial carbon emissions. Regrowth of secondary vegetation may help to restore habitat for many threatened species and improve ecosystem services that deteriorated due to deforestation. However, spatial-temporal patterns of regrowing secondary vegetation in the tropics remain weakly understood. We therefore analyze regrowth dynamics across two different land use systems in southern Amazonia: the extensive pastoralism in Pará and the capital-intensive agriculture in Mato Grosso. Both systems are connected by the BR-163 highway, which represents a major axis of deforestation and agricultural development in the Brazilian Amazon since decades. We used a 29 year time series of Landsat images to extract regrowth extent, duration, lag time between deforestation and regrowth, and frequency of regrowth cycles. Our results reached an overall accuracy of 89% and showed regrowth on up to 50% of the deforested area in Pará and a maximum of 25% in Mato Grosso. In both states, annual regrowth rates drastically dropped after 1996, which coincided with socioeconomic transformations and drought events. The majority of regrowth was concentrated within 60 m distance to forest edges and cleared again after an average of 5 years. Our approach bears great potential for mapping post deforestation regrowth dynamics within and beyond the Brazilian Amazon based on long-term and freely accessible remote sensing data collections, such as the Landsat and the forthcoming Sentinel-2 archives.

1. Introduction

Tropical forests exhibit the highest rates of forests converted to agricultural land globally (Hansen et al., 2013), rendering tropical deforestation one of the key processes driving climate change and global biodiversity loss (Lambin and Meyfroidt, 2011). At the same time, many tropical areas recover from initial forest removal (Grainger, 2008) due to afforestation projects or abandonment of degraded lands (Silver et al., 2000; Aide and Grau, 2004). Furthermore, post deforestation land use systems in the tropics are often characterized by low land use intensity, due to unsuitable biophysical conditions and limited access to markets, finance, labor and machinery (Lambin et al., 2013). In such extensive land-use settings, regrowth is triggered by extended agricultural fallow periods or shifting cultivation (Fearnside, 2000). As a result, regrowth of secondary vegetation reached 10–22% of annual tropical deforestation rates in the 1990s and 2000s (FAO, 2000; Achard et al., 2002; Achard et al., 2010; Hansen et al., 2013) and provides essential ecosystem services, such as improved soil fertilization, water purification or soil erosion prevention (Aide and Grau, 2004; Cramer et al., 2008).

So far, existing global estimates of secondary vegetation are restricted to secondary forests and give no indication on stand age which strongly limits biophysical interpretation (FAO, 2000; Achard et al., 2002; Achard et al., 2010; Hansen et al., 2013). Mapping secondary vegetation should therefore not rely on snapshots in time but include longer time periods, which would additionally allow to study the underlying regrowth process. The regrowth process not only depends on biophysical factors such as climate, soil type and seed availability, but is often influenced by the legacies of previous land use practices, which shaped local soil and water conditions (Zarin et al., 2001; Wandelli and Fearnside, 2015). Past and present land management determines regrowth duration, the lag time between deforestation and regrowth onset, the number of regrowth cycles in case of fallow periods and changes of spatial regrowth configuration over time. These attributes are essential to determine landscape structure (Batistella et al., 2003), to indicate local recovery potential (Zarin et al., 2001) and to differentiate active and fallow land use periods (Kuemmerle et al., 2013; Estel et al., 2015). Understanding such underlying drivers of regrowth is of major importance for evaluating past and current land management and to balance ecosystem restoration on the one hand and land use intensification on the other hand.

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One key area for monitoring regrowth dynamics are the deforestation frontiers in the Brazilian Amazon. Within the Brazilian Amazon, land use systems strongly differ between federal states, such as the extensive pasturelands in Pará and the intensively used agricultural lands in Mato Grosso (Coy and Klingler, 2014; Pacheco and Poccard-Chapuis, 2012). In both states, secondary vegetation plays a key role in land management as the federal law requires illegal deforested and areas to be restored for improving soil fertility, carbon sequestration and biodiversity (Soares-Filho et al., 2014). A better understanding of regrowth processes can therefore aid in evaluating land management practices, strategies of law enforcement, and the influence of socio-economic development in this highly dynamic region.

Remote sensing plays a major role in characterizing secondary vegetation dynamics over large areas. Current datasets on the extent of secondary vegetation, like the Amazon-wide land use product TerraClass (INPE, 2015) or the global forest change dataset provided by Hansen et al. (2013), provide a good indication on the importance of secondary vegetation, but they do not capture its spatio-temporal regrowth dynamics over long time periods. With the opening of the Landsat archive, the longest record of consistent Earth observation data became available free of charge (Wulder et al., 2008; Hansen and Loveland, 2012), which now allows for analyzing deep time series of Landsat data and long term regrowth processes. The challenge for time series analysis based on Landsat data involves reducing the effects of the atmosphere, topography, view angle and irregular image acquisitions with data gaps of months or even years (Song et al., 2001; Kovalskyy and Roy, 2013). Since atmospheric correction and cloud screening became operationalised (Masek et al., 2006; Zhu et al., 2012), compositing methods (Griffiths et al., 2013; Roy et al., 2014; White et al., 2014; Nelson and Steinwand, 2015) helped to overcome those challenges by creating equidistant cloud free time series on a seasonal or annual basis.

Several studies have demonstrated the potential of Landsat time series to describe various aspects of secondary vegetation dynamics in the tropics. Carreiras et al. (2014) employed three different mono-temporal classification approaches on three different study sites in the Brazilian Amazon to detect forest, secondary forest and non-forest areas based on near-annual Landsat time series from 1973 to 2011. In a post classification approach, regrowth duration and frequency of regrowth cycles was determined, but reliability of results suffered from the difference in classification methods between study sites. Rufin et al. (2015) used spectral-temporal metrics derived from intra-annual Landsat time series to describe trajectories of woody vegetation on pastures in southern Pará, Brazil between 1984 and 2012. Schmidt et al. (2015) employed phenological breakpoint detection and trend analysis to detect regrowth of woody vegetation in a forest-savanna landscape in Australia between 2000 and 2012. DeVries et al. (2015) applied structural change monitoring to measure regrowth in forest systems of southern Peru between 1990 and 2013.

As Landsat time series are increasingly used to monitor regrowth of secondary vegetation, algorithms and concepts for extracting temporal regrowth characteristics are in continuous development. Kennedy et al. (2010) developed the regression based trend analysis "LandTrendR" for temperate forest systems but the underlying concept of gradual processes hampers applying this algorithm to fast and cyclic regrowth in agricultural systems across the tropics (Fearnside, 2000). Regarding fast regrowth processes, great advances have been made by optimizing the Breaks for Additive Season and Trend (BFAST) family of methods (Verbesselt et al., 2010; Verbesselt et al., 2012) for the use in tropical forest systems. This largely data driven approach integrates the decomposition of time series into trend, seasonal, and remaining components. While the approach is most promising for intra-annual time series, it requires a high observation density through e.g. the combined use of Landsat and MODIS imagery (Schmidt et al., 2015) or careful re-calibration towards data gaps (DeVries et al., 2015). It has also not been designed to detect long term regrowth processes (DeVries et al., 2015). For annual time series, parsimonious procedures are needed to extract complex dynamics of tropical regrowth characteristics without requiring additional intra-annual observations. In this context, knowledge based approaches, for instance decision trees as employed by Hansen et al. (2013), or spectral-temporal thresholding provide great opportunities for regrowth characterization as such methods can be specifically tuned to regional characteristics of vegetation succession. Moreover, spectral-temporal thresholding is highly intuitive and the transparency of the method greatly supports the interpretation of mapping results and facilitates cross study comparisons.

Building up on a previous long-term deforestation study by Müller et al. (2016) we used Landsat data coupled with a threshold-based regrowth detection approach to monitor secondary vegetation and regrowth dynamics in two different land use systems: the extensive pastoralism in Pará and the capital-intensive agriculture in Mato Grosso. The study areas follows the BR-163 highway, which crosses the entire Southern Amazon from Cuiabá in Mato Grosso to Santarém in Pará and represents a major axis driving deforestation and agricultural development in Brazil since decades (Fearnside, 2007). From a land systems perspective, the BR-163 region covers a gradient of socio-economic development, which is exemplary for the majority of states in the Brazilian Amazon. In this context, we address the following research questions:

– What are the annual rates and spatial patterns of secondary vegetation establishment along the BR-163 highway?

– How do regrowth extent, duration, frequency of regrowth cycles and lag times vary between Mato Grosso and Pará?

2. Data and methods

2.1. Study area

Our study area represented a corridor of 50 km to each side of the BR-163 highway, which is the suggested distance of clearing activities related to road networks (Soares-Filho et al., 2006). The corridor is almost equally divided between the states of Mato Grosso and Pará, covering a distance of 1000 km from Lucas de Rio Verde in the South to Novo Progresso in the North (Fig. 1). Its extent is congruent with regional colonisation and settlement processes over the last 30 years (Coy and Klingler, 2011; Coy et al., 2016) and allows to investigate long term regrowth dynamics across a spatio-temporal gradient of socio-economic development.

Highway construction started in the early 1970s to build an export corridor for agricultural products from Cuiabá to Santarém. The BR-163 now represents the main artery connecting central Mato Grosso and Pará and has become an important deforestation frontier in the Brazilian Amazon (Coy and Klingler, 2011; Fearnside, 2007). Until the early 2000s, deforestation activity along the BR-163 highway mainly concentrated around the cities of Sinop and Guarantã do Norte in Mato Grosso with annual deforestation rates of 1–4% (Müller et al., 2016). However, from 2000 to 2004, deforestation activity drastically declined in Mato Grosso and moved northwards into the forests of Pará, resulting in a new deforestation hotspot around the city of Novo Progresso.

The region's development since the 1970s resulted in different land use systems along the BR-163. While capital intensive cropland and pasture systems dominate in Mato Grosso, extensive and traditional cattle farming are the main land use in Pará (Fig. 1). In traditional pasture systems of Pará, regrowth of secondary vegetation lowers grass productivity several years after initial pasture establishment. To remove secondary vegetation, pasture burning and resowing of forage grasses often takes place towards the beginning of the wet season (Asner et al., 2004; Landers, 2007). Consequently, regrowth remains a temporary phenomenon with estimated durations of regrowth cycles between 4 and 5 years (Almeida, 2009). In contrast, pasture systems in Mato Grosso are managed with higher input of machinery and fertilizer, due to better access to markets, labor and finance (VanWey et al., 2013; Coy and Klingler, 2014). Here, fallow periods and farmland