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Mapping pasture management in the Brazilian Amazon from dense Landsat time series

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ABSTRACT

Intensification of cattle ranching has the potential to reduce deforestation rates in the Brazilian Amazon by decreasing the demand for new agricultural land. Explicit spatial knowledge on where, when and how pastures are managed and intensification takes place is needed to better estimate potentials of more sustainable management. Monitoring the frequency of management practices like burning of pasture land and tillage treatment with adequate spatial resolution therefore offers novel indicators for describing land use intensity. With dense time series of Landsat data, it appears possible to quantify land use intensity also in heterogeneous landscapes where fine-scale processes cannot be monitored with previously available datasets.

Our overarching goal is to describe the occurrence or absence of extensive or intensive management regimes over time. For this study, we focused on detecting fire and tillage events in the region of Novo Progresso, Pará, Brazil, where deforested land is mostly used for cattle ranching by both largeholders and smallholders. We used a dense time series of Landsat-7 and Landsat-8 surface reflectance data to mitigate the problem of varying cloud cover. For each acquisition date, we extracted a temporal sequence of three subsequent clear observations at pixel level. The temporal variation in each clear observation sequence was characterized by a stack of spectral and temporal features. These feature stacks were classified with a random forest to identify the management events. We aggregated the classification results based on the random forest class probabilities and derived normalized annual class scores for land management events. The yielded class score maps show burned and tilled areas on a yearly basis and provide a measure of model confidence.

We detected burned pastures with area adjusted user accuracies of 80–98%, burned secondary regrowth with 63–80% and tilled pastures with 74–78%. Our approach was able to discriminate management events even when they succeeded very fast. This way, the mapping approach with clear observation sequences allows us to contextualize management events directly from dense time series of high resolution satellite data. This opens new pathways to disentangle how management practices between smallholders and agribusinesses vary in the Brazilian Amazon. With sensor constellations from Sentinel-2 and Landsat data becoming a unified source for much denser time series soon, our method bears great potential to better understand and map pasture dynamics in the Amazon.

1. Introduction

Deforestation and cattle ranching that establishes on most of the recently deforested land in Brazil are the largest contributors to Brazil's greenhouse gas (GHG) emissions (Davidson et al., 2012; Lapola et al., 2014; Malhi et al., 2008). Sustainable intensification of grazing regimes on existing pastoral land therefore bears great potential to avoid further deforestation, to protect ecological diversity in the Amazon and ultimately to reduce Brazilian GHG emissions (Bustamante et al., 2012; Cohn et al., 2014; Lambin et al., 2013). Detailed maps on current pasture management practices are hence needed to describe land use intensity (Erb et al., 2013), to better quantify carbon budgets and GHG emissions (Bustamante et al., 2016; Sánchez-Azofeifa et al., 2009) and to support land management policies, such as "Reducing Emissions from Deforestation and Forest Degradation" (REDD +, Barlow et al., 2012) and Brazil's program for low carbon agriculture (ABC, Stabile et al., 2012).

The management of cattle pastures in the Amazon often follows traditional practices, leaving high potential for intensification. Fire is a common land management practice with long cultural tradition

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(Carmenta et al., 2013; Pivello, 2011). Burning land serves numerous goals, including nutrient mineralization, forage growth stimulation, control of weeds and pest species, and the removal of shrubs and trees (Bowman et al., 2008; Lima et al., 2012). The lack of protective measures like fire breaks often causes uncontrolled fires, which also affect adjacent forests on a regular basis (Aragão and Shimabukuro, 2010; Uhl and Buschbacher, 1985). Secondly, grazing traditionally follows sub-optimal patterns that promote shrub encroachment in under-grazed areas, while simultaneously over-using forage grasses e.g. close to water supply. Thirdly, soil fertility is naturally low (Cerri et al., 2007) and demands for liming and fertilization. Fallows, in Brazil known as *capoeira*, are required to recuperate soil fertility through regrowth of secondary vegetation (Hohnwald et al., 2015; Uhl et al., 1988). Estimates show that secondary vegetation regrowth takes place on around one third of the deforested areas of the Amazon (Moran et al., 1996; Pacheco, 2012), forcing additional forests to be transformed into pastures.

Recent studies suggest that sustainable pasture intensification could spare deforestation for new pasture land to an amount, where future demands for cattle production comply with national aims of GHG reduction (Barbosa et al., 2015; Strassburg et al., 2014). Such intensification can be achieved by improved management practices, for example (i) avoidance of burning and hence of related volatilization of carbon stocks, (ii) soil-conserving tillage schemes to minimize erosion and soil compaction, (iii) grazing rotations optimized towards recuperating forage grass, as well as (iv) implementation of integrated crop-livestock-forestry systems for increased ecosystem diversification and sustainability (Gil et al., 2015; Latawiec et al., 2014; Undersander et al., 2014).

These management practices and the frequency of related events affect the spectral-temporal properties of pasture lands, which renders remote sensing a powerful tool to monitor intensification processes. However, most studies that describe intensification on pastures in the Amazon are rather based on census data or exist at spatially coarse resolutions only (Barretto et al., 2013; de Espindola et al., 2012; Soler et al., 2014). One reason for the lack of better information sources is that spectral-temporal patterns of pasture systems are often very heterogeneous in space and time compared to croplands that exhibit more distinct phenologies (Arvor et al., 2012; Maus et al., 2016). Pasture vegetation ranges from fragmented agro-forestry systems to grass-mono-cultures. Grazing pressure varies, e.g. due to terrain, fodder quality, distance to water sources and grazing duration. Grazing periods last from a few weeks in well-managed rotation systems to years on extensively managed pastures and are superimposed on climate-driven phenology. Land ownership has shown to influence spatial-temporal patterns of management, since smallholders often operate subsistence-based and on finer scales than largeholders (Godar et al., 2012; Hohnwald et al., 2015; Pacheco, 2012). Determining the extent and frequency of management events like (i) burning of vegetation and (ii) tillage to prepare re-sowing of forage grass therefore provide key information to characterize land use intensity and potential for further intensification.

The Landsat missions provide optical time series data with 30 m spatial resolution and with two simultaneously operating platforms that theoretically observe land surface properties with a temporal resolution of 8 days (Roy et al., 2014; Wulder et al., 2012). This allows to detect fine scale land management, e.g. in small-holder agriculture systems (DeVries et al., 2015b; Grogan et al., 2015). Besides its importance in forest monitoring in the Amazon (Shimabukuro et al., 2012; Souza et al., 2013), Landsat has been used e.g. to describe grazing intensities (Numata et al., 2007), pasture degradation (Davidson et al., 2008), succession of woody vegetation (Rufin et al., 2015) or regrowth of secondary forests (Mausel et al., 1993). With respect to fire, Landsat was used e.g. to map burned areas (Bastarrika et al., 2014; Bastarrika et al., 2011; Shimabukuro et al., 2014) or to describe agricultural slash-and-burn cycles (Dutrieux et al., 2016). So far, tillage was described only on croplands outside the tropics (Bricklemyer et al., 2006; Zheng et al., 2014).

Tropical areas with high cloud coverage do not allow for high frequent, equidistant observations (Sánchez-Azofeifa et al., 2009). Moreover, timing of pasture management like tillage is not necessarily linked to specific months of the year. Pastures can change rapidly and spectral characteristics might get superposed quickly by follow up events, e.g. burned land that is tilled or greening of tilled land. It is therefore crucial to consider all available clear observations, i.e. pixels that are free of clouds, cloud shadows, or – in the case of Landsat-7 data - scan-line-corrector (SLC) off errors and any other artefacts. For this work, we were accordingly interested in the overarching question on how pasture management practices in the Brazilian Amazon can be mapped accurately by means of dense Landsat time series. We specifically aimed at

a) Exploiting the entire spectral-temporal information from Landsat time series to disentangle pasture management events, namely the burning of pastures or secondary regrowth and tillage, and to
b) Provide a method for mapping yearly pasture management practices in tropical environments.

2. Study area

Our study area (Fig. 1) was the region of Novo Progresso, Pará, Brazil, covered by Landsat footprint 227/065. The area consists of evergreen and seasonal tropical forests, while few savanna patches occur on rock outcrops. The Cuiabá-Santarém highway BR-163 transverses our study area from SE to NNW. It links the soy production areas in Mato Grosso with the northern arc, Brazil's fastest growing exportation route of soy to Europe and China. The BR-163 marks a forefront of deforestation and agricultural expansion in the region (Fearnside, 2007). Most of the deforested land is converted into extensively managed pastures, while conversion into cropland has recently occurred as well (Boy et al., 2016; Fearnside, 2007; Gollnow and Lakes, 2014). The study region entails both largeholder pasture plots and smallholder rangelands with mosaic land use patterns, which dominate in settlement projects planned by the Brazilian National Institute for Colonization and Agrarian Reform (INCRA), i.e. traditional rural settlement projects (PA) and sustainable development projects (PDS), where landowners are supposed to focus on traditional management with low environmental impact (Alves Filho and Ribeiro, 2014). A national park was established in the western part of the study region in 2006, following the creation of pastures in this area. This causes conflicts between landowners and aims of environmental protection, leading to different strategies of pasture management.

3. Data and preprocessing

We downloaded 80 Landsat-7 (37) and Landsat-8 (43) images for footprint 227/065 (all available datasets recorded between January 2013 and November 2015) as surface reflectance products with systematic terrain correction from the USGS Landsat Data Archive (Masek et al., 2006; USGS, 2016a, 2016b). To support the analysis of the Landsat time series, we also downloaded 43 RapidEye images processed to level 3A, PRODES deforestation maps (INPE, 2015) and the TerraClass (Almeida et al., 2016) datasets for 2012 and 2014, which describe post-deforestation land use based on visual image interpretation. We further took > 1000 geo-located field photographs during a field survey in August 2014 that document land cover and land use around Novo Progresso. The photographs characterize the state of pastures with respect to different times of establishment and management practices. GPS located photos from earlier field trips and interviews with local farmers and experts complemented our knowledge on land management practices (Müller et al., 2016; Rufin et al., 2015).

We applied the Function of Mask algorithm (Fmask, Zhu and Woodcock, 2012) with a conservative cloud-probability threshold of