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Mapping Brazilian savanna vegetation gradients with Landsat time series

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ABSTRACT

Global change has tremendous impacts on savanna systems around the world. Processes related to climate change or agricultural expansion threaten the ecosystem's state, function and the services it provides. A prominent example is the Brazilian Cerrado that has an extent of around 2 million km^2 and features high biodiversity with many endemic species. It is characterized by landscape patterns from open grasslands to dense forests, defining a heterogeneous gradient in vegetation structure throughout the biome. While it is undisputed that the Cerrado provides a multitude of valuable ecosystem services, it is exposed to changes, e.g. through large scale land conversions or climatic changes. Monitoring of the Cerrado is thus urgently needed to assess the state of the system as well as to analyze and further understand ecosystem responses and adaptations to ongoing changes. Therefore we explored the potential of dense Landsat time series to derive phenological information for mapping vegetation gradients in the Cerrado. Frequent data gaps, e.g. due to cloud contamination, impose a serious challenge for such time series analyses. We synthetically filled data gaps based on Radial Basis Function convolution filters to derive continuous pixel-wise temporal profiles capable of representing Land Surface Phenology (LSP). Derived phenological parameters revealed differences in the seasonal cycle between the main Cerrado physiognomies and could thus be used to calibrate a Support Vector Classification model to map their spatial distribution. Our results show that it is possible to map the main spatial patterns of the observed physiognomies based on their phenological differences, whereat inaccuracies occurred especially between similar classes and data-scarce areas. The outcome emphasizes the need for remote sensing based time series analyses at fine scales. Mapping heterogeneous ecosystems such as savannas requires spatial detail, as well as the ability to derive important phenological parameters for monitoring habitats or ecosystem responses to climate change. The open Landsat and Sentinel-2 archives provide the satellite data needed for improved analyses of savanna ecosystems globally.

1. Introduction

Savanna ecosystems cover an estimated 20% of the global terrestrial surface (Lehmann et al., 2011), providing essential ecosystem goods and services such as food, pollinators and carbon storage (Marchant, 2010). They occur in tropical and sub-tropical climate zones across all continents, but are particularly prevalent in Australia, Africa and the Americas (Solbrig, 1996). Global land use change processes related to a growing demand for natural resources led to a conversion of approximately 50% of the global savannas with a direct impact on biodiversity and carbon storage (Foley et al., 2011). Climate change, invasive species and fertilizer pollution rapidly impact savanna biodiversity (MEA, 2005), while global change is likely to alter the global distribution of savannas and might even lead to a change of biome states (Staver et al., 2011).

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The Brazilian savanna, better known as Cerrado, is a prominent example of global change impacts on savanna ecosystems. It is the second largest eco-region in Brazil with an extent of about 2 million km^2 (Ratter et al., 1997). Landscape formations that range from open grass and shrub dominated lands to dense forests are characteristic (Oliveira-Filho and Ratter, 2002) and form a gradient of vegetation structure and biomass, which is often differentiated into discrete structural physiognomy classes (Ribeiro and Walter, 2008). The climate of the Cerrado is characterized by a wet and a dry season, which influence the vegetation's spatial and temporal dynamics. It's harsh environmental conditions led to a high floristic diversity and a variety of phenological adaptation strategies (Ferreira and Huete, 2004). The Cerrado is thus considered as the biodiversity-richest savanna globally (Silva and Bates, 2002) with approximately 160,000 species of fungi, flora and fauna (Furley, 1999). However, a weak land conservation status has led to large-scale conversions from natural to agricultural land that already affected more than 40% of the Cerrado, which is likely to aggravate in the future (Ferreira et al., 2012; Sano et al., 2010). This conversion of primary vegetation threatens the stability of the ecosystem and related services provided, such as carbon sequestration and climate regulation. It further impacts its biodiversity, rendering the Cerrado as an under-researched global biodiversity hotspot in need of in-depth monitoring as basis for profound conservation planning (Myers et al., 2000). Thus, accurate mapping and monitoring of the temporal and spatial dynamics of Cerrado vegetation is essential to understand ecosystem properties and responses to ongoing change processes to support decision makers (Rocha et al., 2011; Sano et al., 2010).

Field based mapping and ecological assessments that rely on established classification schemes are indispensable for a detailed analysis of local processes, but at the same time costly and thus restricted to relatively small areas. Remote sensing data, on the other hand, have successfully been used to map the Cerrado across large areas and in inaccessible terrain. Sano et al. (2010) created a land cover map of the entire Cerrado based on a mosaic of 170 Landsat scenes from 2002. They differentiated anthropogenic and natural (grass-, shrub- and forestlands) land cover classes by image segmentation and visual interpretation with an overall accuracy of 71%. Spatially less extended studies investigated the usability of combined radar and optical data (Sano et al., 2005) or spectral unmixing of Landsat data (Ferreira et al., 2007) to discriminate Cerrado vegetation physiognomies (structural classes). Other studies have shown that analyzing multi-temporal imagery is advantageous over single-date images for the distinction of spectrally similar vegetation types (e.g. Mesquita Junior, 2000; Mueller et al., 2015).

Using high temporal resolution satellite data time series not only allows to discriminate vegetation types but also to describe different phenological vegetation phases throughout a season (Zhang et al., 2003). Ferreira and Huete (2004) assessed the seasonal dynamics of the Cerrado vegetation using time series of AVHRR vegetation indices. In spite of the drawbacks inherent to the data (e.g. coarse spatial resolution, sensor uncertainties and broad bandwidths) they were able to derive phenological patterns capable of depicting the seasonal cycle and which allowed to distinguish between savanna formations, pastures, croplands and forests. Ratana et al. (2005) explored the potential of MODIS 16-day composite time series to analyze phenological patterns of different Cerrado physiognomies, revealing their distinct responses to seasonal contrasts with a 250 m spatial resolution. Even though both studies provided valuable insights on phenological differences between Cerrado vegetation formations, they did not aim at mapping their spatial distribution. As the analysis of phenology derived from remote sensing data is based on measures of temporal changes in surface reflectance at the pixel scale (Hanes et al., 2014), it usually relates to a signal mixture of different canopy or understory layers and depicts rather a vegetation community instead of a single species' phenology. The sensor's spatial resolution is therefore critical for the potential detail of the derived information, which is particularly important for analyzing and mapping the complex vegetation gradients in the Brazilian Cerrado. The analysis of Landsat data with a spatial resolution of 30 m is promising, but has mostly been restricted to multi-temporal imagery with low temporal resolution, which is not sufficient to derive continuous phenological information. However, the opening of the extensive data holdings of the Landsat archive (Wulder et al., 2012) allows to combine data from the Landsat Thematic Mapper (TM) with Enhanced Thematic Mapper (ETM+) and Operational Land Imager (OLI) sensors. This improves the temporal resolution to potentially eight days, rendering Landsat a system with capabilities for detailed phenological information retrieval and offers a great opportunity to observe vegetation gradients over long time periods with sufficient spatial resolution.

In order to deepen the knowledge on Cerrado vegetation, we aim to derive spatially explicit phenological information, using state of the art remote sensing techniques. We focus on the applicability and limitations of the combined use of Landsat time series and an established physiognomy classification scheme (Ribeiro and Walter, 2008), which enables the expansion of field based ecological assessments to broader scale studies. Therefore we evaluate how i) phenological parameters can be derived at a 30 m spatial resolution, ii) which phenological differences between the main Cerrado vegetation physiognomies can be revealed based on these

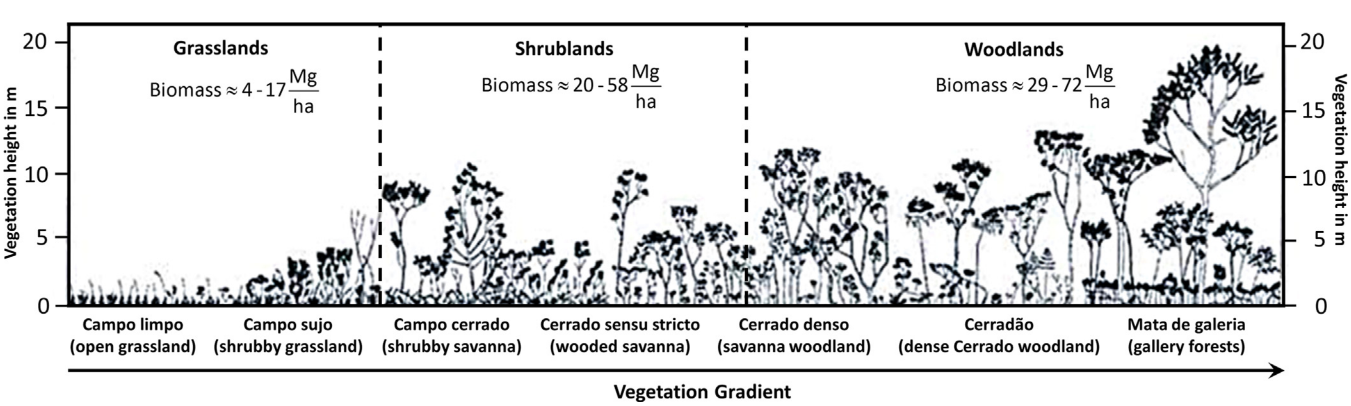

Fig. 1. Cerrado physiognomies describing gradients of vegetation height and density (adapted from Mesquita Junior (2000)). Hereafter only the Portuguese physiognomy names will be used. The above ground biomass values of woody vegetation were comprehended from several studies by de Miranda et al. (2014).