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Fuel load mapping in the Brazilian Cerrado in support of integrated fire management

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ABSTRACT

The Brazilian Cerrado is considered to be the most species-rich savannah region in the world, covering ~2 million km^2. Uncontrolled late season fires promote deforestation, produce greenhouse gases (~25% of Brazil's land-use related CO_2 emissions between 2003 and 2005) and are a major threat to the conservation of biodiversity in protected areas. Governmental institutions therefore implemented early dry season (EDS) prescribed burnings as part of integrated fire management (IFM) in protected areas of the Cerrado, with the aim to reduce the area and severity of late dry season (LDS) fires. The planning and implementation of EDS prescribed burning is supported by satellite-based geo-information on fuel conditions, derived from Landsat 8 and Sentinel-2 data. The Mixture Tuned Matched Filtering algorithm was used to analyse the data, and the relationship between the resulting matched fractions (dry vegetation, green vegetation and soil) and in situ surface fuel samples was assessed. The linear regression of in situ data versus matched filter scores (MF scores) of dry vegetation showed an r^2 of 0.81 (RMSE = 0.15) and in situ data versus MF scores of soil showed an r^2 of 0.65 (RMSE = 0.38). To predict quantitative fuel load, a multiple linear regression analysis was carried out with MF scores of NPV and soil as predictors (adjusted $r^2 = 0.86$; $p < 0.001$; standard error = 0.075). The fuel load maps were additionally evaluated by fire managers while planning EDS prescribed burning campaigns. The fuel load mapping approach has proven to be an effective tool for integrated fire management by improving the planning and implementation of prescribed burning, promoting pyrodiversity, prioritising fire suppression and evaluating fire management efforts to meet overall conservations goals. National and state level authorities have successfully institutionalized the approach and it was incorporated into IFM policies in Brazil.

1. Introduction

With 204 million ha, the Cerrado (Brazilian savannah) is the second largest biome in South America, occupying approximately 24% of Brazilian territory and extending across 12 of its central states (Ratter et al., 1997; IBGE, 2004; Sano et al., 2010). The Cerrado is regarded as the most biologically rich savannah in the world, and a global biodiversity hotspot for conservation priorities (Myers et al., 2000; Da Fonseca et al., 2005). The Cerrado can be categorised into vegetation types defined by the varying abundance of woody species: campo limpo (pure grassland), campo sujo (grassland with sparse presence of shrubs), Cerrado ralo (grass/shrub-dominated with scattered trees), Cerrado sensu stricto/típico (tree-dominated with scattered shrubs and a grass understorey), Cerrado denso (tree dominated) and Cerradão (closed forest). Dense gallery forests or dense graminoid wetland vegetation can be found along small streams and rivers (De Castro and Kauffman, 1998; Silva et al., 2006; Miranda et al., 2009).

The Cerrado is Brazil's primary region for agricultural production. Beginning in the seventies, intensified agriculture changed the Cerrado drastically, with far-reaching and negative implications for the ecosystem and its biodiversity (Fearnside, 2001; Sano et al., 2010; Grecchi et al., 2014). Cattle ranching is a major driver of deforestation and

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increases the frequency of fires, as fires are mostly started to stimulate grass growth for fodder production (Miranda et al., 2002; Silva et al., 2006; Pereira Júnior et al., 2014). Beuchle et al. (2015) identified a net loss of natural Cerrado vegetation with an average annual rate of $-0.6\%\,\text{yr}^{-1}$ between 1990 and 2010. Although the savannah ecosystem and its species are highly adapted to fire, the increasing frequency of high intensity fires in the LDS is negatively affecting the ecosystem through increasing the mortality in small woody plants and promoting grasses (Ratter et al., 1997; Moreira, 2000; Miranda et al., 2002; Oliveras et al., 2013). Fire return intervals in the Cerrado can be short (one to five years), and the common biennial LDS fire regime is changing the Cerrado to a more open, grass-dominated landscape, which in turn increases fire intensity and frequency (Mistry, 1998; Miranda et al., 2002; Pereira Júnior et al., 2014). The spatial pattern of fine fuels in the surface grass/herbaceous layer is a major determining factor of fire occurrence and behaviour. Fuel loads, consisting of both dead and live biomass, are thus critical elements for strategic fire management interventions (Keane et al., 2001), such as prescribed EDS burning to reduce the negative impacts on biodiversity, promote pyrodiversity and reduce greenhouse gas emissions (Price et al., 2012).

Fuel loads are highly variable in space and time, and fuel accumulation is a result of complex interactions of biotic and abiotic factors (Harmon et al., 1986; Keane, 2013). Fire managers can directly manipulate fuel to achieve land management and conservation goals, but fuel management through fire is difficult without an accurate quantification of the fuel load (Agee and Skinner, 2005). Accurate geo-information on fuel load has become increasingly important, along with raising awareness of controlled fire as a viable treatment alternative to reduce the potential for severe large-scale fires (Keane et al., 2001). Besides technical and traditional knowledge, the planning and implementation of fire management, including prescribed burning (where, when and how to burn), relies on accurate information regarding the distribution, condition, and amount of fuel loads.

In the protected areas of the Brazilian Cerrado, assessing the annual fire hazard is mainly based on information from the date of the last fire, derived from burned area mapping via remote sensing. This approach has been used to support the planning and implementation of both fire prevention and suppression activities over the last decade. Increasing fire intensity with longer time spans since the previous fire is a pattern known to exist in many of the world's biomes (Fernandes et al., 2004; Collins et al., 2007; Murphy and Russell-Smith, 2010). However, the approach of assigning fuel values to large polygons based on coarse resolution burned area analyses may not produce reliable fire spread predictions because it does not reflect actual fuel variability across large areas (Finney, 1998; Keane et al., 2001).

Since 2012, integrated fire management (IFM) strategies have been implemented in protected and indigenous areas of the Brazilian Cerrado, to manage and protect biodiversity as well as enhance community livelihoods through sustainable land management practices using fire. These strategies acknowledge the ecological role of fire in savannah ecosystems as well as the socio-economic need for fire as a land management tool (FAO, 2006; Myers, 2006; King et al., 2008). Fire is not only considered the most important ecosystem driver in the Cerrado, but also required to manage and maintain various biodiversity levels. Fire can be used to promote biodiversity, if tailored to local conditions, and its benefits are considered interdisciplinary (Kelly and Brotons, 2017). Martin and Sapsis (1992) presented the hypothesis that pyrodiversity promotes biodiversity. They found that the pattern of anthropogenic burning carried out by traditional communities in fire-prone environments promoted environmental heterogeneity, as it created and maintained habitat mosaics by permitting the recovery of native vegetation. Based on these findings, the authors recommended the implementation of heterogeneous fire regimes for promoting biodiversity. The key to successful fire management lies in reintroducing traditional fire use practices as well as mimicking 'natural' fire effects as far as possible, while maintaining and protecting fire sensitive habitats. To achieve this goal, the negative impacts from uncontrolled, high intensity LDS fires need to be reduced (Penman et al., 2011; Williamson et al., 2012; Pereira Júnior et al., 2014). Controlled, low intensity EDS fires aim to lessen fuel loads and emulate patchy fire regimes with various vegetation succession stages in the landscape. Ultimately, fire regimes should shift from biennial cycles of large-scale, high intensity fires to a landscape mosaic of small-scale fire regimes, each of different ages, to increase habitat variation. Fine-scale fuel condition maps are required in the planning and implementation of EDS burning, to conceptualise the spatial heterogeneity of EDS fragmentation burning, and allow patches of long-unburnt vegetation to be more effectively compartmentalised.

Remote sensing has been used in various studies for fuel load or fuel moisture mapping in forest areas using hyperspectral (Kötz et al., 2004), airborne laser scanning (Riaño et al., 2003 and 2004; Morsdorf et al., 2004; García et al., 2010) or radar data (Harrell et al., 1995). However, these forest-related approaches have limited use for the mapping of surface fuels in open savannah ecosystems. Some review articles provide an overview of existing methods for fuel type mapping (Arroyo et al., 2008), direct and indirect fuel load mapping (Keane et al., 2001) or estimating fuel moisture content for fire risk assessments (Yebra et al., 2013). A common approach is the use of vegetation indices or classifications, where a "stratify and assign" approach is applied to determine the fuel type or assign a fire risk value to each vegetation class (Maselli et al., 2000; Van Wagtendonk and Root, 2003; Arroyo et al., 2006). Since fuel condition and loads not only depend on vegetation types/classes (Harmon et al., 1986; Keane, 2013), this 'classify and assign' approach cannot resolve the spatio-temporal variability of fuel loads within vegetation type classes, which is an important determinant for fire occurrence and spreading. In contrast to vegetation indices, spectral mixture analyses make use of all vegetation-relevant spectral bands and are suitable to assess the fractional green photosynthetic vegetation (GV), non-photosynthetic vegetation (NPV), and bare substrate (soil) from satellite data (Roberts et al., 1993; Asner et al., 2003; Asner et al., 2005). In open savannah ecosystems, the amount of GV and NPV per unit area well represents the present fuel loads. Roberts et al. (2003) presented an approach for fuel type, fuel moisture and fuel condition mapping using hyperspectral data from both the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) and from Hyperion in the Santa Ynez Mountains, California. The data was analysed through a multiple-endmember spectral mixture analysis (MESMA) and they found that full-spectrum measures outperform band ratios. The use of shortwave infrared (SWIR) bands proved to be particularly useful for estimating fuel moisture content (Chuvieco et al., 2002; Dennison et al., 2005; Verbesselt et al., 2007; Yebra et al., 2008).

The existing studies about fuel load mapping in open, non-forested areas showed promising results, but their operational implementation in IFM is hindered either by the high data costs, the complexity of the data analysis or insufficient thematic detail. The objective of this study is to investigate how free remote sensing data from Landsat 8 and Sentinel-2 can be used to map variations of fuel conditions over large areas, benefit the planning, implementation and evaluation of prescribed EDS burning, and prioritise fire suppression efforts. A partial unmixing method, the Mixture Tuned Matched Filtering (MTMF), was tested on satellite data in order to determine the amount, distribution and variation of live and dead fuel. Another objective was to link the fuel condition maps with field data in order to derive fuel load maps that represent quantitative categories. The novelty of the presented approach is that it incorporates free satellite data, existing knowledge about the spectral behaviour of different vegetation conditions, a straightforward image analysis method and requirements from fire management practitioners, in order to facilitate its operational implementation in protected area management in the Brazilian Cerrado. Fire managers used the fuel load maps for IFM zoning, evaluated their use in operational prescribed fire decision-making in the field and in impact assessments of IFM activities.