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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 $-0.6\%\,\mathrm{yr}^{-1}$ 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.

2. Materials and methods

2.1. Study area

The study area consists of three protected areas of the Cerrado: Parque Nacional da Chapada das Mesas (PNCM) with 160,000 ha, Estação Ecológica Serra Geral do Tocantins (EESGT) with about 708,000 ha, and Parque Estadual do Jalapão (PEJ) with about 160,000 ha. PNCM is located in the state of Maranhão, while EESGT and PEJ are found in Tocantins. Around 1500 mm of rain falls annually, mainly between October and March. The protected areas considered in this study have a wide variation in Cerrado type (Fig. 1), with some areas differing greatly by spatial scale of landscape units, and others by fire regimes or water availability. The dominant vegetation types are campo limpo/sujo and Cerrado ralo, with some areas of Cerrado sensu stricto/típico and denser woodland on hilly plateaus (Pereira Júnior et al., 2014). Dense gallery forest and typical wetland vegetation can also be found along waterways that carve the landscape (Fig. 2 shows an example of a Cerrado vegetation map for the EESGT study site). With such diverse Cerrado types and varying fire histories, robust fuel condition maps are imperative for fire management.

2.2. Definitions and data

In general, fuel load is equivalent to total biomass available. However, fires do not necessarily burn all standing biomass (Van Leeuwen et al., 2014). Cerrado fuel loads consist mainly of surface fuels such as grass, litter and fine woody debris (Miranda et al., 2002; Miranda et al., 2009). In the Cerrado, about 94% of the fuel consumed during frequent surface fires comes from the herbaceous layer (Miranda et al., 2002), with representative fuel loads of 5.6 t ha^{-1} and burned biomass amounts of 3.1 t ha^{-1} (median of 25 savannah fire experiments in Africa, Australia, and Brazil; (Pereira, 2003)). Fire ecologist and fire managers in the Cerrado mainly consider fine surface biomass with a diameter < 6 mm across to be fuel load, as this portion of total Cerrado biomass burns under typical fire conditions. According to the requirements of fire management in the Cerrado, this study therefore defines its extended definition for fuel load as a quantitative measure of fine surface biomass available for burning in the layer up to 2 m above ground. This includes green and dry grasses, herbs, litter and fine woody debris with diameters < 6 mm across. This study follows the definition for "fuel condition" presented by Roberts et al. (2003). Fuel condition represents the relative proportion of live to dead (or senesced) fuels, where live fuels contain a higher percentage of liquid water. Fuel condition is thus linked, but not equal, to fuel moisture.

Satellite images from the Landsat 8 Operational Land Imager (OLI) and Sentinel-2 were acquired for the dry seasons (April/May to October) from 2013 to 2016 and across all study areas. Landsat 8 OLI data have a 30 m spatial resolution, nine multispectral bands in the visible (VIS), near infrared (NIR) and shortwave infrared (SWIR), and a 16-day revisit cycle (Roy et al., 2014). The European satellite constellation Sentinel-2 (Sentinel-2A and 2B) has 13 spectral bands in the visible, red-edge, NIR and SWIR, with four bands at 10 m, six bands at 20 m and three bands at 60 m spatial resolution (ESA, 2015). Sentinel-2's orbital swath width is 290 km with a revisit frequency of 5 days over the equator, which increases the probability of acquiring cloud-free images. Standardised pre-processing was applied to all images, including atmospheric correction in ATCOR (Richter, 1997). Landsat band 8 (panchromatic), band 9 (cirrus band) and the three 60 m Sentinel-2 bands (band 1, 9 and 10) were not used in this study, as these bands are not relevant for vegetation analysis. For the fuel condition mapping and the analysis of quantitative fuel loads, 27 Landsat 8 images from 2014 and 2015 were processed. An additional three Landsat 8 images from 2013 to 2015 and a Sentinel-2 image from 2016

Fig. 1. Examples of different Cerrado types, namely Campo sujo (A), Cerrado ralo (B), an open form of Cerrado sensu stricto/típico that recently burned left of the trail (C), and Cerrado denso (D).

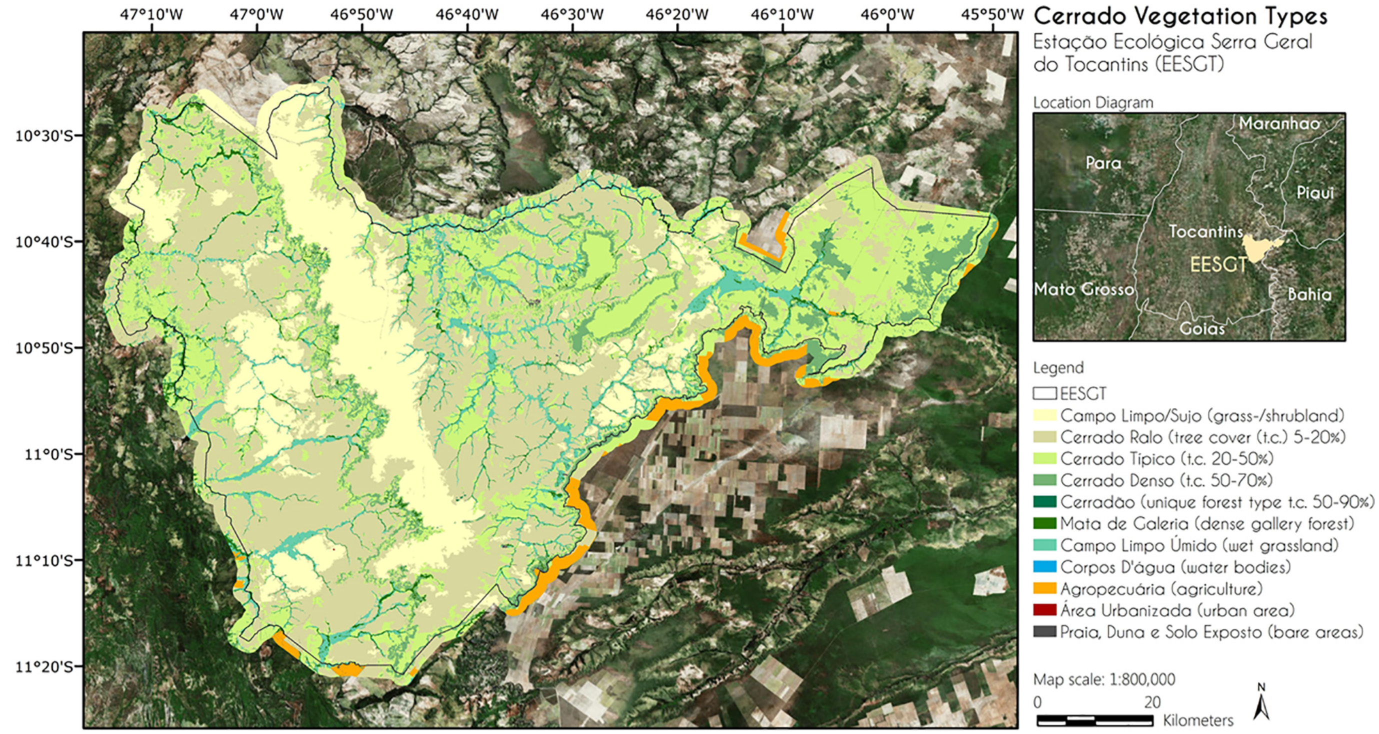

Fig. 2. Example of a Cerrado vegetation type map for EESGT, where open Cerrado types are dominant. Maps for all three study areas were created and provided by Universidade de Brasília (data sources: RapidEye/BlackBridge 2014 (c); Background: ESRI World Imagery.

were used for evaluating the prescribed EDS burning activities in EESGT.

Fire ecology scientists of the Universidade de Brasília established 98 permanent plots (Schmidt et al., 2018) and collected GPS-coded field data on biomass [kg/m^2] to assess fuel consumption rates. The benefit of samples collected pre- and post-fire, is their wide range of biomass values which provide the necessary data base to evaluate the relationship between sub-pixel estimations (dry vegetation, green vegetation, soil) and weighed biomass. The samples were taken in PNCM, EESGT and PEJ in 2014 and 2015, mostly in open savannah areas of Campo sujo and Cerrado ralo. Five plots of 0.5 m × 0.5 m were set at each sample location (pre- and post-fire sampling), from which all biomass with a diameter $\leq$ 6 mm was collected, dried and weighed. To validate the results, each location's averages were compared with sub-pixel estimations of dry vegetation, green vegetation and soil derived from either the previous (for pre-fire samples) or next (for post-fire samples) satellite image. In total, 120 samples could be used from the cloud-free sample locations (some samples could not be used as their locations were cloud-covered in the satellite images).

2.3. Methodology

In the past, fire management in the Cerrado solely used Landsat- or MODIS-derived burned areas as ancillary geo-information. In order to compare this approach with the fuel condition mapping, burned areas were mapped using a novel methodology that can use Landsat TM, ETM + and OLI scenes (Melchiori et al., 2014). The method employs a multi-temporal approach that looks for variations in the Normalized Difference Vegetation Index (NDVI) and the Normalized Burn Ratio (NBR) to recognise sudden changes in vegetation conditions (Key and Benson, 2006). This approach is fully automated and currently implemented by the Instituto Nacional de Pesquisas Espaciais (INPE) for mapping the whole Cerrado. Cloud and cloud shadows were avoided by selecting cloud free images, or those with a maximum of 10% cloud coverage. The burned area algorithm uses at sensor reflectance without atmospheric correction.

The proportion of live and dead vegetation in surface layers strongly influences fire ignition and the rate of fire spread (Cheney et al., 1998; Chuvieco et al., 2004; Cochrane and Ryan, 2009). The amount of green and dry vegetation (i.e. live and dead fuel) per unit area is the main determining factor of fuel load, and in this study, this was estimated from satellite data using a partial unmixing method. The spectral properties of vegetation with decreasing water content or senescence are well known, and can be observed using remote sensing (Knipling, 1970; Qi et al., 2014). Leaf reflectance varies strongly in the water absorption bands of the NIR and SWIR, depending on moisture content. In addition, changes in pigment concentration (e.g. reduced chlorophyll) and internal leaf structure (e.g. changes in cell walls due to dehydration) result in spectral changes mainly in the VIS and NIR bands. However, the presence of photosynthetically active vegetation (green vegetation (GV)), non-photosynthetic dry vegetation (NPV) and soil within the instantaneous field of view of the sensor, as well as the small spatial scale of different vegetation types and vegetation status in the Cerrado, result in a mixed pixel problem. The spectrum of a Landsat pixel with 30 m or a Sentinel-2 pixel with 10 m or 20 m spatial resolution is often mixed, being composed of the three components (GV, NPV and soil), and varying depending on their proportion in each pixel. The sub-pixel fractions of these dominant components vary depending on elapsed time since the last fire, recent precipitation and Cerrado type, and can cause a wide range of fuel loads across short distances. The spatial heterogeneity of vegetation within a pixel presents a major issue when assessing fuel condition and loads. Spectral Mixture Analyses (SMA) holds great potential for estimating fuel condition and fuel moisture content at a subpixel level (Roberts et al., 2003; Yebra et al., 2013).

A partial unmixing method, the Mixture Tuned Matched Filtering (MTMF), was tested in this study to derive the fuel condition and fuel load from Landsat 8 OLI and Sentinel-2 data, using ENVI/IDL (Exelis, Boulder, CO, USA). MTMF combines parts of a Linear Spectral Mixing Model with parts of a statistical Matched Filter Model, and allows subpixel target abundance estimation (Boardman et al., 1995; Boardman, 1998; Mundt et al., 2007). MTMF only requires one defined endmember spectrum from the spectral library, although more endmembers can be considered if required. Matched filtering (MF) assesses the input data for good matches to the endmember spectrum while suppressing background spectra, so that an MF score of 1.0 is a perfect match and background material (unknown endmembers) is centred around zero (Mundt et al., 2007; Mitchell and Glenn, 2009). Unlike classical linear SMA results, the MF scores of various endmembers generally do not sum to one. Previous studies showed that when considering only few endmembers in MTMF, the MF scores proved to be sub-pixel abundance estimates (Williams and Hunt Jr., 2002; Mitchell and Glenn, 2009; Barbosa et al., 2016).

In the protected savannah areas of the Cerrado, GV, NPV and soil are the dominant ‘materials’, and the amount of NPV represents the main part of available fuel. By considering the amount of GV in relation to NPV, fuel condition can be better assessed. The soil fraction is an additional proxy for quantifying vegetation (the higher the soil fraction, the lower the vegetation density). Potential endmembers for GV, NPV and soil were identified in Landsat 8 OLI and Sentinel-2 images with the help of field surveys and ancillary, high-resolution RapidEye data with 5 m spatial resolution. The resulting spectral libraries, one for Landsat 8 and one for Sentinel-2, include typical green vegetation and soil spectra, as well as spectra for dry vegetation with increased reflectance in the VIS, reduced reflectance in the NIR and increased SWIR reflectance (Fig. 3). From this set of spectral signatures, representative endmembers were derived for each of the three components (represented as black lines in Fig. 3). These representative Landsat 8 and Sentinel-2 endmembers were then used in the MTMF of all images that were analysed in this study. As an input, MTMF requires minimum noise fraction (MNF) transformed images (Green et al., 1988). This study only used the first five MNF bands to reduce impacts of noise in the data. The MTMF produces grey-scale MF images that represent the estimated relative degree to which each pixel matches the reference spectra. In addition, infeasibility values for each MF score are provided, which can be used to indicate false positives (Boardman et al., 1995; Boardman, 1998).

The resulting values of the MF images for NPV, GV and soil were equally scaled and shown as composites representing the fuel condition maps. The maps were used by the fire managers for the planning of EDS burning and the benefits for different fire management purposes were investigated. Fuel load maps of EESGT from 2013 to 2016 were analysed to monitor and evaluate the long-term goal of fragmentation of large fuel load patches through targeted prescribed EDS burning. Each NPV fraction image was classified by an object-based approach using eCognition (Trimble, Munich, Germany). All areas with NPV fractions larger than the soil and GV fraction were classified as high fuel load fragments. The year 2013 is considered as the pre-IFM reference year, as the first prescribed burning in EESGT took place in 2014. The size of the fragments and their changes were then compared in different fire management zones against the reference year, with the goal to quantitatively evaluate the fuel load fragmentation process.

The fuel condition maps, consisting of the three matched fraction images (Red:NPV, Green:GV, Blue:Soil), were first validated through field surveys in PNCM on 30.10.2014 and 02.11.2014, at which time 119 GPS pictures were taken and compared with the previous fuel condition map from 09.09.2014. The end of the dry season was chosen for the survey since this allowed for an in-field assessment of burned areas of various fuel conditions and loads (recently burned as well as regenerating areas). Fuel load was investigated by incorporating pre- and post-fire collected biomass data. 120 biomass samples, each representing the average of five plots of 0.5 m × 0.5 m, were used to analyse the regression of matched fractions from the MTMF with biomass values. In addition, benefits and limitations of the fuel load maps were assessed from a practical fire management perspective by the fire managers involved in the planning and implementation of prescribed burns within or around protected areas.

3. Results & discussions

3.1. The fuel condition map and comparison to the burned area map

In the fuel condition maps, red colours indicate a high amount of dead vegetation and blue colours indicate a high soil fraction, with a continuous mixture of both in purple (example of PNCM given in Fig. 4A & B). Green areas mainly represent dense Cerrado, gallery forests and moist grass areas in wetlands. The main fuel load in the Cerrado consists of fine surface fuels, such as dry grass, litter and woody debris ≤6 mm (Miranda et al., 2002; Oliveras et al., 2013), and the abundance of these components, indicated in bright red in the fuel condition map, characterise fire-prone areas (priority areas for EDS prescribed burning). The blue colours mainly indicate areas in which fuel loads were consumed by fires during the previous fire season prior to the image date. These areas are characterised by dominant soil fractions.

Large parts in the mid-south of PNCM were burned by uncontrolled

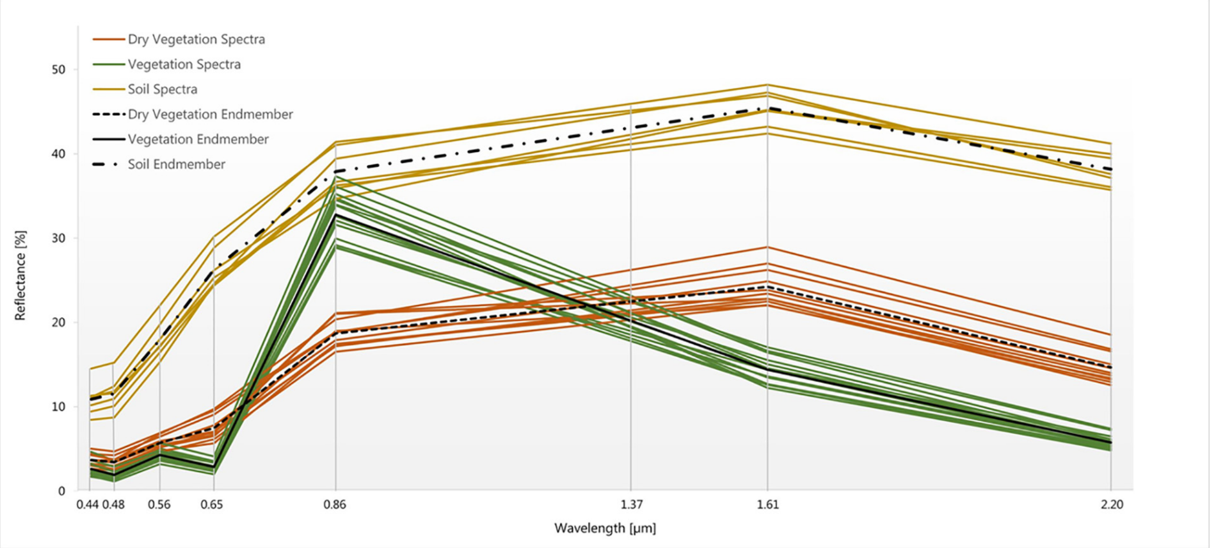

Fig. 3. Spectral library of Landsat 8 OLI-derived vegetation spectra, dry vegetation spectra (NPV) and soil spectra with the final endmembers. A similar spectral library was created for Sentinel-2.

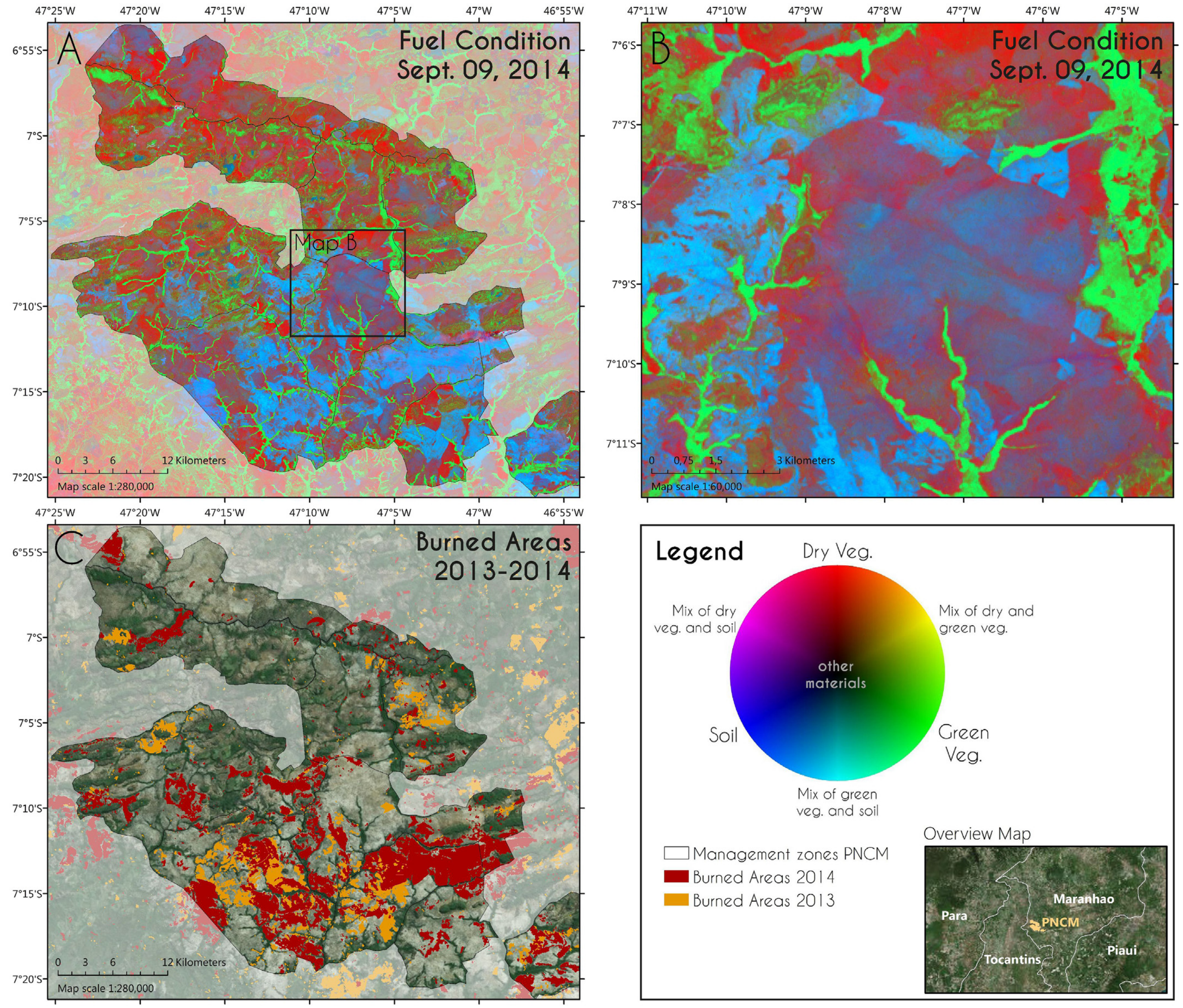

Fig. 4. Fuel condition map consisting of the three sub-pixel fraction images of Parque Nacional da Chapada das Mesas (R:NPV, G:GV, B:Soil) for September 2014 (A) with a detailed map (B) and the burned areas from 2013 until Sept. 09, 2014 (C). The surrounding area of the National Park is masked in A and C (semi-transparent); Background image: ESRI World Imagery.

fires in the 2014 dry season. As the fraction of green vegetation (e.g. sprouting grass after rainfall) increases in an area, it will appear more and more turquoise on the fuel condition map and thus show the vegetation regrowth after a fire. Purple areas in the map mainly indicate areas that have burned in the last two years, but have since accumulated some fuel through the drying of regrown vegetation. Even slight sub-pixel variations of NPV, GV and soil can be differentiated in the map, and reflect the recent fire history. The fuel condition map allows for pre- and post-fire fuel monitoring, providing not only mapped variations in pre-fire fuel conditions, but also information on small areas that did not burn, natural firebreaks as well as regrowth and fuel accumulation after a fire. All of this information helps to better understand fire behaviour. Fuel continuity is a major determining factor of fire spread and any discontinuities can act as firebreaks (Cochrane and Ryan, 2009). This supports the claim that landscape patch mosaics from varying fire regimes could reduce large-scale fires occurring late in the dry season. Hence, IFM can use the EDS fuel condition map for planning purposes, enabling the implementation of patch mosaic burning to mitigate large-scale LDS fire risk.

In very dense Cerrado areas where tree canopies partially or fully cover surface fuels in the understory, the fuel condition maps have higher uncertainties (Merrill et al., 1993; Chladil and Nunez, 1995). However, these areas are of lower relevance for the planning of the prescribed EDS burning, as burns are primarily implemented in open Cerrado areas.

By comparing the fuel condition map (Fig. 4A) with the burned area map (Fig. 4C), it is obvious that areas with the highest soil fraction in the fuel condition map spatially correspond to the areas that burned in 2014, prior to the map date. The burned area map can be used in conjunction with the fuel condition map to better interpret relations to recent fire history. Depending on the recent fire history, fuel load conditions may allow for safe prescribed burning under various fire weather conditions, enabling low intensity fires during a wider time window of the season and day. This geo-information may also indicate areas that are unsuitable for prescribed burning, for example due to lacking fuel loads or low dead fuels. The automated burned area mapping approach is dependent on cloud-free satellite images and some burned areas could not be detected when the fire occurred in periods

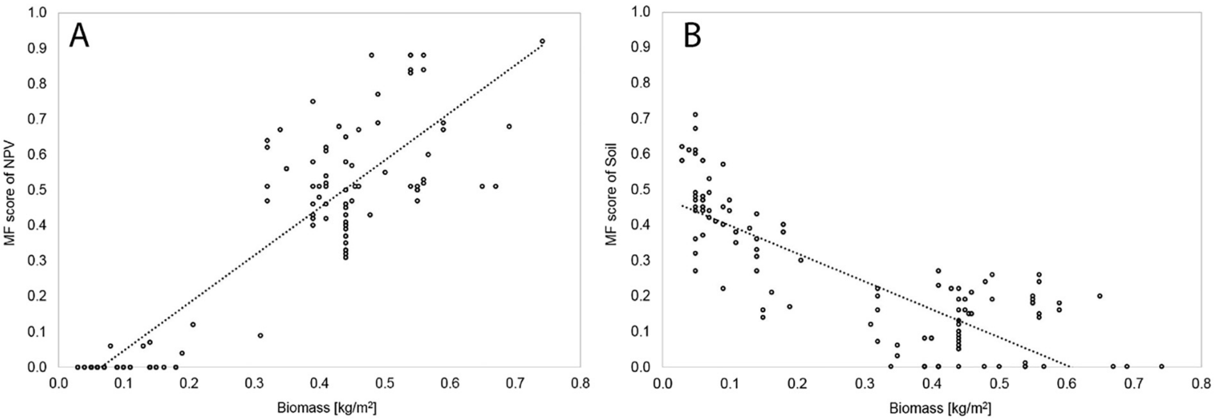

Fig. 5. (A) Plots of NPV MF score versus sampled fine surface fuels (n = 120) with r^2 of 0.81 and RMSE of 0.15 (regression function: y = 1.342x − 0.0867) and (B) soil MF score versus sampled fine surface fuels with r^2 of 0.65 and RMSE of 0.38 (regression function: y = −0.7871x + 0.4774).

with persistent cloud cover. This is more likely to occur at the beginning and end of the dry season. An example of this can be seen in Fig. 4, in the South-eastern corner of PNCM, where the fuel condition map shows high soil fractions, indicating an area of a prescribed burn that was carried out on May 06–07, 2014. The effect, however, is underestimated in the burned area map. This demonstrates the advantage of the fuel condition mapping approach that requires only one cloud-free image to represent the fuel load variability as well as the recent fire history. Nevertheless, the burned area map is considered a very suitable complementary dataset when planning prescribed burns and fire suppression efforts.

3.2. Incorporating field data and validation

Field samples (n = 120) were used in order to validate the results and to investigate the relationship between the MF scores and the

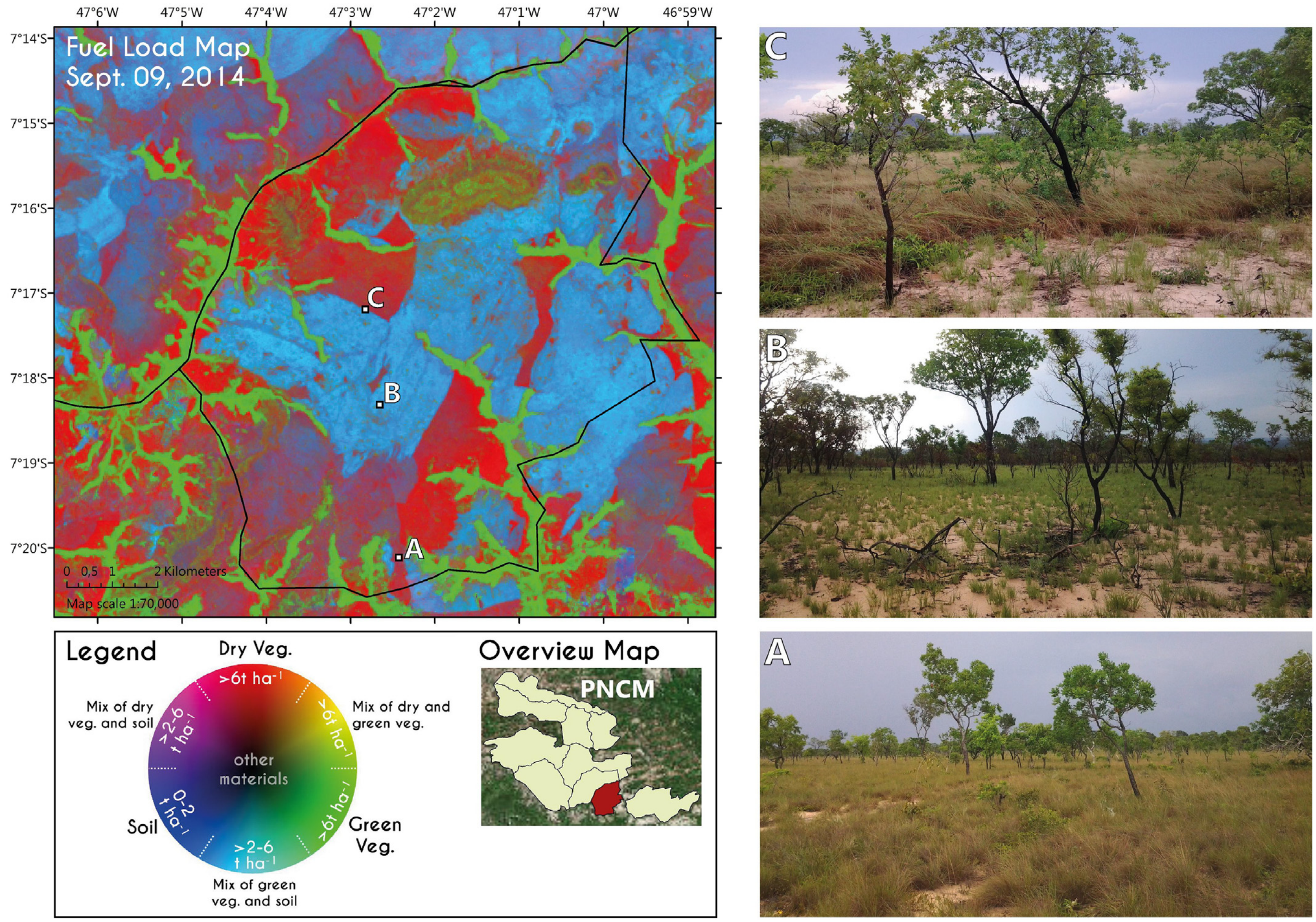

Fig. 6. Fuel load map of management zone 1 in PNCM, from 09.09.2014 (left) and three photographs taken at different locations during the field validation campaign on 30.10.2014 (right). Location A: Cerrado ralo area that burned in August 2013; location B: Cerrado ralo area that burned in June 2014 with some sprouting grass; location C: edge of a burned area (June 2014) with high level of surface fuel in the background area and exposed soil with sprouting grass in the burned area.

sampled fine surface fuels. In situ values range between 0.32 and 0.74 kg/m^2 for the assessed pre-fire samples and 0.03 to 0.31 kg/m^2 for post-fire samples. Ottmar et al. (2001) found similar values in campo limpo and campo sujo areas. The linear regression of in situ data and the pixel-based NPV matched fractions showed a coefficient of determination of $r^2 = 0.81$ (RMSE = 0.15) (Fig. 5A). In addition, a negative correlation was found between matched fractions of soil and biomass, with an $r^2 = 0.65$ (RMSE = 0.38) (Fig. 5B). The results indicate a relationship between the matched fractions and fine surface fuels. These regressions allow quantitative fuel load to be predicted. A multiple linear regression analysis was carried out with MF scores of NPV and soil as predictors, and an adjusted r^2 of 0.86 was found ($p < 0.001$, standard error = 0.075). The MTMF proved to be a suitable method not only for deriving fuel condition maps, but also for quantifying fuel load at a sub-pixel level. Few previous studies have demonstrated that the MF scores can be used for sub-pixel abundance estimates (Williams and Hunt Jr., 2002; Mitchell and Glenn, 2009; Barbosa et al., 2016). It must be considered, that unlike classical linear SMA approaches with a sum constraint of 100%, the sum of MF scores from different endmembers can exceed 1.0 per pixel. This is particularly important when using many endmembers in the analysis. In this study, we only used three endmembers in an environment where not many other 'background' materials other than NPV, GV and soil are present. The results suggest that under such circumstances, the MF scores are good predictors of fuel load with quantitative values. With this achievement, the calculation of GHG emission estimates from fires based on the pre-fire fuel load maps becomes a possibility. We therefore suggest establishing permanent sample plots in all protected areas of the Cerrado, in order to be able to create locally adjusted fuel load maps. As fire managers are interested in fuel condition and fuel load, we developed a fuel load map legend for the study area that combines the fuel condition and fuel load (as categories), as shown in Fig. 6 and Fig. 7.

Further qualitative assessments of the fuel load maps were conducted through various field surveys by the fire managers and fire brigades of the protected areas. During these surveys, 119 GPS-coded pictures were taken and the validity of the maps was assessed in detail. High levels of congruity were found between the ranges of fuel load indicated on the map and surface fuel loads found in field (examples given in Fig. 6).

3.3. Evaluation of prescribed EDS burning activities

The main objective of IFM is to mitigate late season wildfire risk and to shift the fire regime from biennial cycles of large-scale and high intensity fires to a small-scale mosaic of various fire regime classes and ages by using prescribed EDS burns. This mid-term goal should be achieved independent of interannual variations in fire weather or fuel moisture. Since this is a new approach in the protected areas of the Cerrado, the challenge is to define measurable criteria and target values such as target fragment size. Kelly and Brotons (2017) state that identifying appropriate limits for fire characteristics, such as severity and patch size, is in its infancy, and that critical limits or thresholds in patterns of fires are not defined yet. Therefore, measurable and

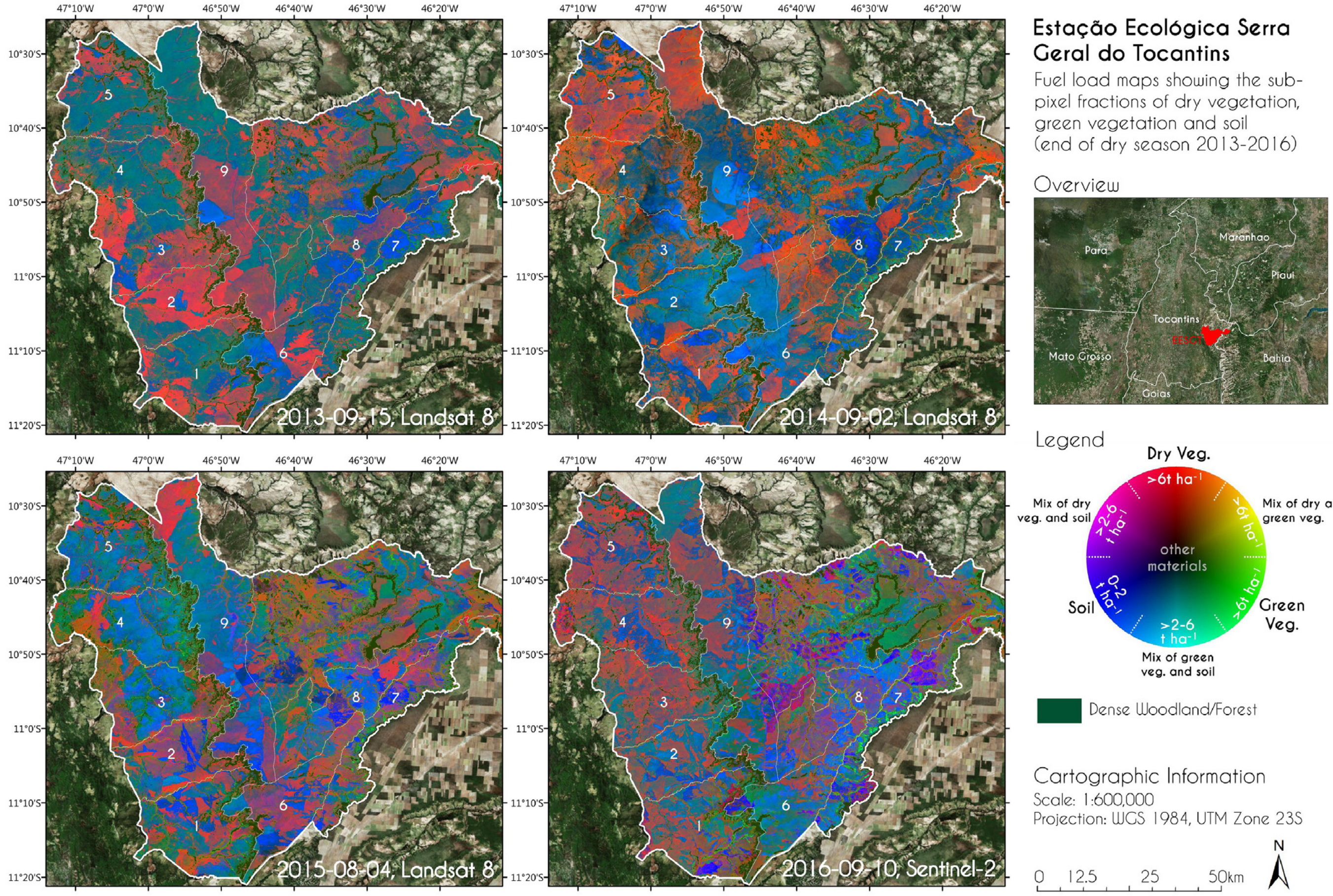

Fig. 7. Fuel load map time series of the nine established fire management zones (FMZ) in EESGT. The maps show the late dry season situations from 2013 (pre-IFM reference year) to 2016 as derived from Landsat 8 OLI and Sentinel-2 data, and show the success of the fuel load fragmentation through early dry season burning. In FMZ 1, prescribed burning was conducted in 2014, 2015 and 2016; in FMZ 2 and FMZ 6, prescribed burning was conducted in 2015 and 2016; in the other FMZs, prescribed burning was conducted in 2016 only.

traceable variables must be identified in order to provide a basis for defining IFM strategy goals and for evaluating the success of IFM activities. In this study, the use of spatial variables describing fuel patch size characteristics and fragmentation were tested based on classified fragments of dominant dry vegetation from the maps shown in Fig. 7. In EESGT, nine IFM zones (FMZ) were established, whose borders mainly follow topographic features such as streams or steep slopes that can act as natural firebreaks. The first prescribed burning took place in FMZ 1 in 2014. In 2015, prescribed burning was repeated in FMZ1 and first implemented in FMZ 2 and FMZ 6, followed by prescribed burning in all nine FMZs in 2016. Yearly late dry season fuel load maps for the FMZs from 2013 (pre-IFM reference year) to 2016, as derived from Landsat 8 OLI (2013–2015) and Sentinel-2 (2016), show the process of fuel load fragmentation (Fig. 7). The maps demonstrate the success of the fragmentation in those FMZs where prescribed burning has been implemented since 2014 or 2015. The rather large and connected areas of high fuel loads in FMZ 1, 2 and 6 (southernmost FMZs), that are obvious in the 2013 and 2014 map, were fragmented until 2016. The 2016 map also shows the prescribed burns that were conducted in all FMZ in 2016, with first fragmentation effects in those FMZs that were not previously managed through prescribed EDS burning.

Table 1 lists the ratio of largest NPV fragment [ha] and total NPV area [ha] for the pre-IFM (2013) and with-IFM (2016) situation as well as their percentage difference between 2013 and 2016 for each FMZ of EESGT. According to the fire management objectives in the protected areas, a low ratio value in 2016 together with a strong decrease of the percentage difference since the reference year, indicates a successful fragmentation of previously large and connected fuel load areas. In addition, Table 1 also lists the mean fragment size with the standard deviation (SD) for each FMZ in 2013 and 2016 with their percentage differences. The reduction of the mean fragment size is another indicator for the fragmentation process, but should only be considered together with the ratio described above. This means that a low ratio value in 2016, together with a strong decrease of its value compared to the reference year and a decrease of the mean fragment size, indicate the successful implementation of prescribed patch mosaic burning. According to Table 1, this is the case for the FMZs 1, 2 and 6, in which prescribed burning has been implemented since 2014 or 2015. A similarly satisfying combination of indicator values, representing fragmentation of fuel loads, are also present in FMZ 7, although no prescribed burning was implemented there before 2016. This is mainly because of the rather small-scale topography of FMZ 7, given how it is long, narrow, and orthogonally intersected by streams at regular intervals that act as natural firebreaks. Other FMZs that only received prescribed burns in 2016, show indicator values which suggest that one year of prescribed burning activities is not enough to achieve the fire management objectives. The SD can also act as an indicator, since it represents the variation in fragment sizes. Depending on the fire management goals, and whether high or low variation in fragment sizes is envisaged, the SD is a measure to evaluate this. The SD is also listed in Table 1, but was not used for evaluation purposes here because there was no definition of fire management goals regarding fragment size variation in the observed protected areas.

3.4. *Evaluation from a fire management perspective and implications for IFM policies in Brazil*

Yebra et al. (2013) stated that further assessments of fuel load map accuracies and errors beyond quantitative accuracy measures such as r^2 are necessary, and that long-term, operational and viable products as well as the interaction with their end-users is fundamental. We involved fire managers in this study to evaluate the benefits and limitations of the fuel load maps from a practical perspective. The protected area managers operating in the study area started to utilise the described remote sensing-based fuel load maps in 2014. By mapping fuel load and using the maps in the field on mobile devices with on-site tracking functionality, the protected area managers together with the local communities can jointly establish land and fire management objectives. In addition, priority areas to be protected and areas of high fire risk can be identified that helps to finally determine when and where prescribed burnings or firebreaks should be applied. Before park managers started using fuel load maps, zoning for management activities in the parks was completed solely based on Landsat- or MODIS-derived burned areas. Although this methodology assesses the spatial distribution of burned and non-burned areas, it does not evaluate burn severity or indicators such as the loss of aboveground organic matter, nor does it monitor the

Table 1

Spatial variables used as indicators for success of fuel load fragmentation through prescribed burning in EESGT. The values are given per FMZ for the pre-IFM case (2013) and with-IFM case (2016) together with their changes. Prescribed burning is implemented in FMZ 1 (green) since 2014, in FMZ 2 and 6 (blue) since 2015 and in the other FMZs (white) only in 2016. Best value combinations regarding the fire management objectives are in bold.

	2013 max. fuel fragment [ha]/total fragment area [ha]	**2016 max. fuel fragment [ha]/ total fragment area [ha]**	**Percentage difference**	**2013 mean fuel fragment size [ha] with SD**	**2016 mean fuel fragment size [ha] with SD**	**Percentage difference**
FMZ 1	0.34	**0.30**	**−10%**	102.5 ± 568.7	74.4 ± 545.9	**−38%**
FMZ 2	0.89	**0.16**	**−81%**	322.3 ± 2474.8	50.0 ± 257.5	**−545%**
FMZ 3	0.49	0.45	−8%	268.7 ± 1672.3	121.9 ± 971.2	−120%
FMZ 4	0.39	0.75	92%	90.6 ± 484.8	110.5 ± 1422.3	18%
FMZ 5	0.41	0.39	−4%	79.9 ± 461.2	145.0 ± 1186.6	45%
FMZ 6	0.76	**0.19**	**−75%**	98.9 ± 799.9	35.5 ± 167.9	**−179%**
FMZ 7	0.48	**0.16**	**−66%**	46.3 ± 348.2	14.6 ± 80.2	**−217%**
FMZ 8	0.27	0.66	140%	106.4 ± 435.5	38.8 ± 507.8	−174%
FMZ 9	0.65	0.59	−9%	297.7 ± 2376.6	71.6 ± 955.8	−316%

recovery of plants in burned areas or consider fuel load variation in areas that did not burn. From a management perspective, the method presented in this study proved to be more efficient than planning based on burned areas alone. The fuel load maps assist in defining fire management zones, indicate the connectivity of areas with high fuel loads, and help to more clearly define the temporal window for prescribed burning in high-risk areas. The timing of strategic EDS burning is critical to the success of fire management programmes but the window of opportunity can be small and dynamic as fuel loads develop rapidly after the wet season ends. When financial, technical and human resources are scarce, it is essential to choose the optimum window for the fire management activities in protected areas. The information provided through the fuel condition map contributes significantly to the decision making process, hence supporting an adaptive and integrated management approach according to local conditions and needs. The Cerrado vegetation type map is a helpful complementary dataset, since different Cerrado types with similar fuel loads can require different fire management and hence burning strategies.

In addition to the aforementioned benefits, fuel load maps can be used to evaluate the impact of prescribed burning as part of an overall IFM program such as how prescribed burning affects the change and alteration of fire regimes at the landscape level. Furthermore, the use of the fuel load maps in the planning and implementation of community-based fire management programmes together with park management, proved to be an invaluable tool for trust building and mutual understanding of the various land and natural resource management objectives. There is often a lack of clearly defined, measurable objectives, or only insufficient data available to determine if existing prescribed burning programmes have been successful (Penman et al., 2011). The fuel load mapping approach provides measurable and comparable parameters regarding the impact of IFM programmes, which can be used to demonstrate their advantages and therefore promote further implementation of IFM elsewhere. Only successful IFM programmes with measurable objectives can help overcome the persisting general constraints on fire management activities in the Cerrado (e.g. lack of personnel resources, promoting environmental laws etc.) (Quinn-Davidson and Varner, 2011). Earth observation-based monitoring can support IFM programmes by providing quantitative proof of their impact. The approach presented here generally follows the concept of fuel condition mapping presented by Roberts et al. (2003) who used hyperspectral airborne data. From a practical IFM perspective, however, cost intensive airborne data (hyperspectral or LiDAR) is not a suitable option for annual or even biennial large-scale assessments of fuel conditions. The use of free data, in combination with a straightforward spectral mixture analysis, is key to make fuel condition/load mapping relevant for operational fire management.

Supported by the fuel load mapping approach, IFM was successfully introduced and applied in protected and indigenous areas of Brazil. The Brazilian project partners, the Ministry of the Environment, and its national and state level authorities, have successfully institutionalized the approach, and a bill of an IFM National Fire Policy has been submitted to the Parliament for approval. The experiences from the IFM implementation of the fuel load mapping approach have also been incorporated into the Cerrado Prevention and Control Action Plan (PPCerrado). The University of Brasilia, with its accompanying scientific services on IFM, has also made a purposeful contribution to the international debate on savannah ecology, by incorporating the fuel load mapping approach as an integral part of IFM planning (Schmidt et al., 2018).

4. Conclusions

Earth observation can significantly support prescribed burning in savannah ecosystems, not only through mapping fuel condition and fuel load over large areas, but also through mapping burned areas and vegetation types. While Cerrado type maps should be updated in five year intervals, mapping fuel condition, load, and burned areas should continuously accompany prescribed burning planning and implementation. We suggest using all three geo-information datasets, namely, fuel condition/load, Cerrado vegetation type and burned areas, to plan, monitor and evaluate prescribed burning activities. Fuel condition, fuel load, Cerrado type, associated characteristics of land use, fire history, topography, climate and field data all need to be jointly assessed by local experts to establish effective protected area and land management strategies. Each protected area should have a customised monitoring concept adjusted to the different management objectives.

Vegetation type and condition determine fuel load, which in turn influences the propagation of fires. This is especially the case among Cerrado types dominated by fine fuel such as grasses and bushes. Thus, mapping and monitoring fuel load distribution and accumulation, as well as recovery in burned areas, helps to identify priority management areas and priority management periods. Fuel condition maps proved to be valuable for supporting IFM because they help fire managers better deal with uncertainties and unpredictable factors which are typical for adaptive management. Furthermore, if matched fractions of dry and green vegetation from the MTMF image analysis can be calibrated through field samples in order to generate fuel load maps, an estimation of fire-related GHG emissions and carbon sequestration can be carried out. The fuel condition and fuel load maps additionally aid fire management because they also reflect recent fire history. When employed properly, they help to plan and adjust pyrodiversity and thus to maintain heterogeneous habitats in Cerrado landscapes. We suggest creating two fuel load maps per dry season, one representative of the early dry season (for IFM planning) and one representative of the late dry season (for IFM evaluation and pre-planning for the subsequent year's activities). Capacity building on the production and use of fuel load maps from remote sensing is a crucial element in order to support the institutionalisation of these methods. Governmental institutions responsible for fire management in protected areas such as the Instituto Chico Mendes de Conservação da Biodiversidade (ICMBio), Instituto Brasileiro do Meio Ambiente e dos Recursos Naturais Renováveis (IBAMA), Ministério do Meio Ambiente (MMA), Instituto Natureza do Tocantins (NATURATINS) and Instituto Nacional de Pesquisas Espaciais (INPE) were trained on satellite-based fuel load mapping during this project. Through these capacity-building activities, the fuel load mapping approach could be established as an operational tool of IFM in the Cerrado. Using the map on mobile tracking devices allowed for adaptive IFM planning to be carried out and for prescribed burning in the fire management zones to be implemented. It also facilitated dialogue and cooperation with the local communities living in or adjacent to the respective management zone. The findings of this study directly influenced fire management policies such as the Brazilian IFM National Fire Policy and the Cerrado Prevention and Control Action Plan (PPCerrado).

Today's suite of modern satellites that provide free data is the key to operational geospatial fire management. By combining Landsat 8 OLI and Sentinel-2 data, fuel load maps can be created more frequently, and at time scales that allow management decisions to be made effectively. As such, earth observation is a valuable and indispensable part of integrated fire management and should be employed when monitoring fire-dominated ecosystems. Fuel load maps will enhance the knowledge of fire behaviour and help trigger a paradigm change in the Brazilian savannah from a zero burning policy towards IFM implementation with prescribed burning measures.

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