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MAPPING DEGRADED FOREST AREAS CAUSED BY FIRES DURING THE YEAR 2010 IN MATO GROSSO STATE, BRAZILIAN LEGAL AMAZON USING LANDSAT-5 TM FRACTION IMAGES

Mapeamento de Áreas de Florestas Degradadas Causadas por Incêndios Durante o Ano De 2010 no Estado do Mato Grosso, Amazônia Legal Brasileira usando Imagens Fração do Tm Landsat-5

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ABSTRACT

The objective of this study was to assess the extent of burned forest in 2010 in Mato Grosso State, located in the southern Brazilian Amazon region. Landsat TM images were acquired over the 2010 dry season. Overall, the approach consisted on mapping burned areas over the entire study area and then overlaying it with the land cover types and biomass classes. Specifically, the forest areas degraded by fires were mapped by combining the burned areas map and the forest map. The method to map burned areas was based on following procedure: (i) linear spectral mixing model applied to TM images to derive soil, vegetation and shade fraction images and (ii) the burned areas are identified and mapped from the shade fraction images. The forest/non forest map was derived from Hansen *et al.* (2013) dataset and the biomass map was derived from Baccini *et al.* (2015). The mapped burned areas were then distributed in the three land cover types, i.e., forest, non-forest (Cerrado and old deforestation), and deforested areas from 2001 to 2010. Our results showed that 22,633 km2 (32%) of forests in Mato Grosso were burned during the year 2010, likely degrading the forest ecosystem. In addition, 5,175 km2 (7%) of burning occurred in the deforested areas from 2001 to 2010 and 42,510 km2 (61%) occurred in the Cerrado and old deforestation areas. In addition the burned areas were distributed in the the biomass classes. These types of information are important for the carbon emission estimation.

Keywords: Remote Sensing, Forest Degradation, Burned Areas, Forest Fires, Amazon Region.

RESUMO

O objetivo deste estudo foi avaliar a extensão da floresta queimada em 2010 no estado de Mato Grosso, localizado na região sul da Amazônia Brasileira. As imagens TM Landsat foram adquiridas durante a estação seca do ano de 2010. A abordagem consistiu basicamente no mapeamento das áreas queimadas sobre toda a área de estudo e então sobrepondo os tipos de cobertura da terra e classes de biomassa. Especificamente as áreas de floresta degradadas pelo fogo foram mapeadas pela combinação dos mapas de áreas queimadas e um mapa de áreas de floresta e não-floresta. O método para mapear as áreas queimadas é baseado no seguinte procedimento: (i) modelo linear de mistura espectral aplicado as imagens TM para derivar imagens fração de solo, vegetação e sombra e (ii) as áreas queimadas são identificadas e mapeadas a partir das imagens fração de sombra. O mapa de áreas de floresta /não floresta é derivado dos dados de Hansen *et al.* (2013) e o mapa de biomassa é derivado de Baccini*et al.* (2015). As áreas de queimadas mapeadas são então distribuídas nos três tipos de cobertura da terra, ou seja, floresta, não-floresta (Cerrado e desmatamento antigo) e as áreas desflorestadas no período de 2001 a 2010. Os resultados mostraram que 22.633 km2 (32%) de florestas no Mato Grosso foram queimados durante o ano de 2010, degradando o ecossistema florestal. Além disso, 5.175 km2 (7%) de queimada ocorreram nas áreas desmatadas no período de 2001 a 2010 e 42.510 km2 (61%) ocorreram nas áreas de Cerrado e áreas de desmatamento antigo. Além disso as áreas queimadas afetaram as classes de biomassa. Essas informações são importantes para a estimativa de emissão de carbono.

Palavras-chave: Sensoriamento Remoto, Seca de 2010, Degradação Florestal, Áreas Queimadas, Incêndios Florestais, Região Amazônica

1. INTRODUCTION

A large part of the gross carbon emissions into the atmosphere due to land cover changes is attributable to deforestation in the tropics. It is estimated that during the 1990s and 2000s the humid tropics have contributed to two-thirds of the total 880 MtC yr−1 of all carbon losses from conversion of forest and other wooded lands into other land cover types (ACHARD *et al.*, 2014). However, these estimates do not explicitly take into account pervasive impact of the degradation effect that is experienced by these forests due to logging and fire disturbances (ACHARD *et al.*, 2014). Forest degradation, defined as long-term disturbance in forested areas (SIMULA, 2009), is considered to represent up to 40% of the gross emissions from deforestation in the Brazilian Amazon (ARAGÃO *et al.*, 2014). In this region deforestation is defined as forest clear cut with conversion to other land uses (INPE, 2008), while forest degradation is related to a combination of selective logging and forest fires (SOUZA *et al.*, 2009, ASNER *et al.*, 2009, EVA *et al.*, 2012, BERENGUER *et al.*, 2014). Forest degradation can be a precursor of deforestation especially in the Amazon basin (ASNER *et al.*, 2006, NUMATA *et al.*, 2010).

It has been estimated that understory forest fires burned more than 85,500 km2 between 1999 and 2010. From those, forests that burned more than once accounted for 16 per cent of all understory fires, leading to forest degradation. Moreover, only 2.6 per cent of forests that burned from 1999 to 2008 were sub-sequentially cleared for agricultural practices (MORTON *et al.*, 2013). According to the same authors, repeated fires were concentrated in Mato Grosso and eastern Pará.

Hansen *et al.* (2013) mapped global tree cover extent, loss, and gain for the period from 2000 to 2012 at a spatial resolution of 30 m, with loss allocated annually. Then from this dataset, the forest/non forest map can be extracted for the year 2000 to 2012 by selecting some tree cover threshold value.

The map of aboveground live woody biomass density for the year 2000 with 30 m resolution (BACCINI *et al.*, 2015) is available for the pan-tropical region. It is produced by the methodology developed by Baccini *et al.* (2012). These maps allow the co-location of biomass estimates with Hansen *et al.* (2013) tree cover loss estimates at similar spatial resolution.

Quantification of tropical forest distur-bances is not trivial, as these events cause gentle changes in the canopy. However, the use of medium resolution remote sensing data and appropriate image processing techniques allow the quantification of these areas over large geographical extent. Fraction images derived from different remote sensing sensors have been used for many tropical forest applications, especially in the Brazilian Amazon. Specifically the ones derived from the Landsat Thematic Mapper were tested for this region for mapping areas of degraded forests due to the following characteristics: a) vegetation fraction images highlight the forest cover conditions and allow differentiating between forest and non-forest areas similarly to vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI); b) shade fraction images highlight areas with low reflectance values such as water, shadow and burned areas;

and c) soil fraction images highlight areas with high reflectance values such as bare soil and clear-cuts (SHIMABUKURO *et al.*, 2014). Therefore, in this context the main purpose of this study is to present an estimate of the extent of degraded forest due to fires in Mato Grosso State, Brazilian Amazon, using a semi-automated procedure based on fraction images derived from TM sensor.

MATERIALS AND METHODS

In this section is presented the materials used in this research, which includes: the description of the study area, satellites images (Landsat) and products (forest cover, and biomass map). Then the methodology is described.

2.1 Study Area

The study area corresponds to the Mato Grosso State located in the Brazilian Amazon region (Figure 1). Due to variable climate, topography, precipitation patterns, and length of the dry season, the Mato Grosso State comprises parts of three Brazilian biomes, the Amazon, the Cerrado, and the Pantanal, and has a naturally very high biodiversity with vegetation types ranging from dense evergreen forest to deciduous open forest, savannas, natural grasslands and seasonal wetlands. This region has been exposed to high rates of vegetation cover conversion of not only due to the recent use of mechanized agriculture but also due to smaller scale deforestation processes, selective logging and burning (INPE, 2005, 2008). Therefore forests in this region have a high probability of being affected by human-induced actions leading to degradation, such as fire and selective logging activities.

2.2 Landsat TM images

For this work, were selected 42 Landsat TM images at 30 m spatial resolution acquired during the dry season of year 2010 (Table 1, Figure 2) to adapt a methodology developed by Anderson *et al.* (2005) and Shimabukuro *et al.* (2009) for burned area estimation.

The burning season typically lasts from June to early October in Mato Grosso, intensifying towards the end. The purpose was to obtain cloud-free images acquired at the end of the burning season of year 2010, as it has been demonstrated the persistence of the burn scar in the shade fraction image. However, due to increasing cloud coverage towards the end of the dry season, cloud-free Landsat data were acquired for the period beginning in September to mid October, varying spatially. The majority of the cloud free images selected for this study were acquired during the first half of September (Table 1).

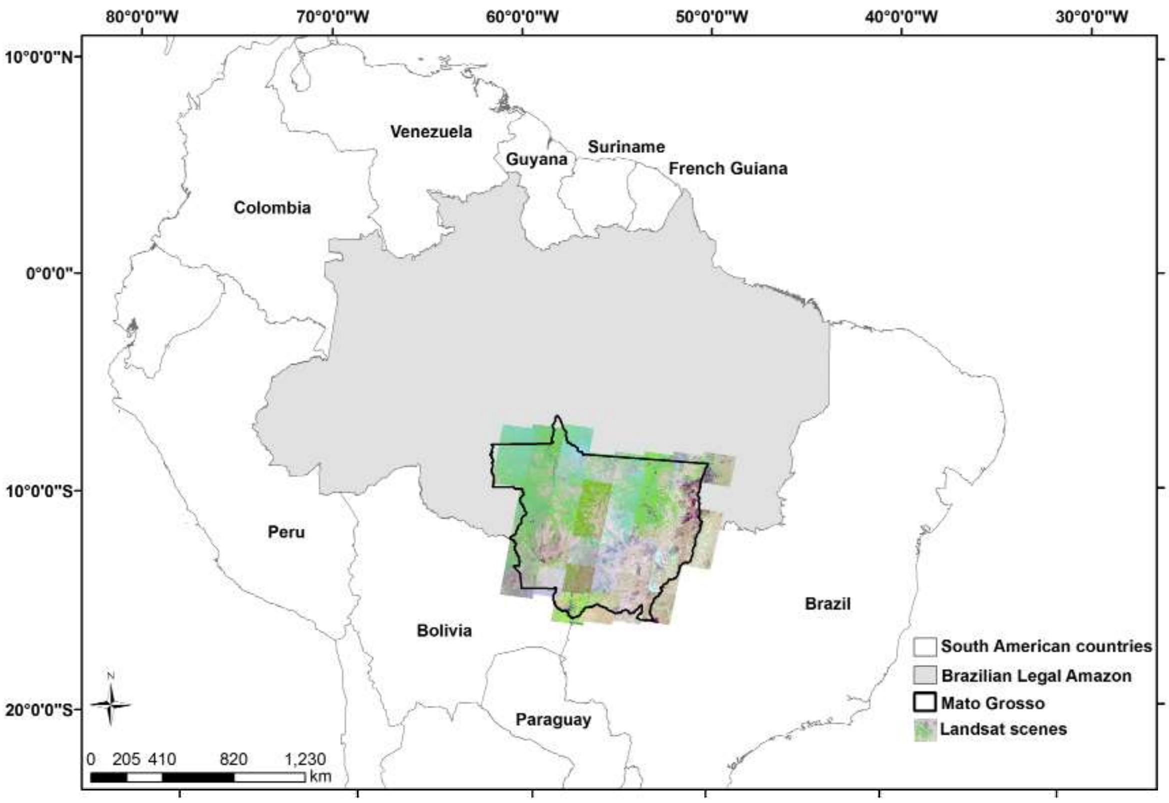


Fig. 1 - Location of the Mato Grosso State selected as the study area.

Table 1: Landsat TM data used in this work

Path/Row	Date	Path/Row	Date
223/067	05/Sept/2010	**227/067**	01/Sept/2010
223/068	05/Sept/2010	**227/068**	31/Jul/2010
223/069	21/Sept/2010	**227/069**	31/Jul/2010
223/070	21/Sept/2010	**227/070**	01/Sept/2010
224/067	12/Sept/2010	**227/071**	31/Jul/2010
224/068	12/Sept/2010	**227/072**	04/Nov/2010
224/069	12/Sept/2010	**228/066**	08/Sept/2010
224/070	12/Sept/2010	**228/067**	08/Sept/2010
224/071	12/Sept/2010	**228/068**	08/Sept/2010
224/072	27/Aug/2010	**228/069**	08/Sept/2010
225/067	03/Sept/2010	**228/070**	08/Sept/2010
225/068	03/Sept/2010	**228/071**	24/Sept/2010
225/069	03/Sept/2010	**229/066**	14/Aug/2010
225/070	19/Sept/2010	**229/067**	14/Aug/2010
225/071	19/Sept/2010	**229/068**	14/Aug/2010
225/072	19/Sept/2010	**229/069**	14/Aug/2010
226/067	10/Sept/2010	**229/070**	14/Aug/2010
226/068	10/Sept/2010	**229/071**	14/Aug/2010
226/069	26/Sept/2010	**230/066**	06/Sept/2010
226/070	26/Sept/2010	**230/067**	06/Sept/2010
226/071	26/Sept/2010		
226/072	12/Oct/2010		

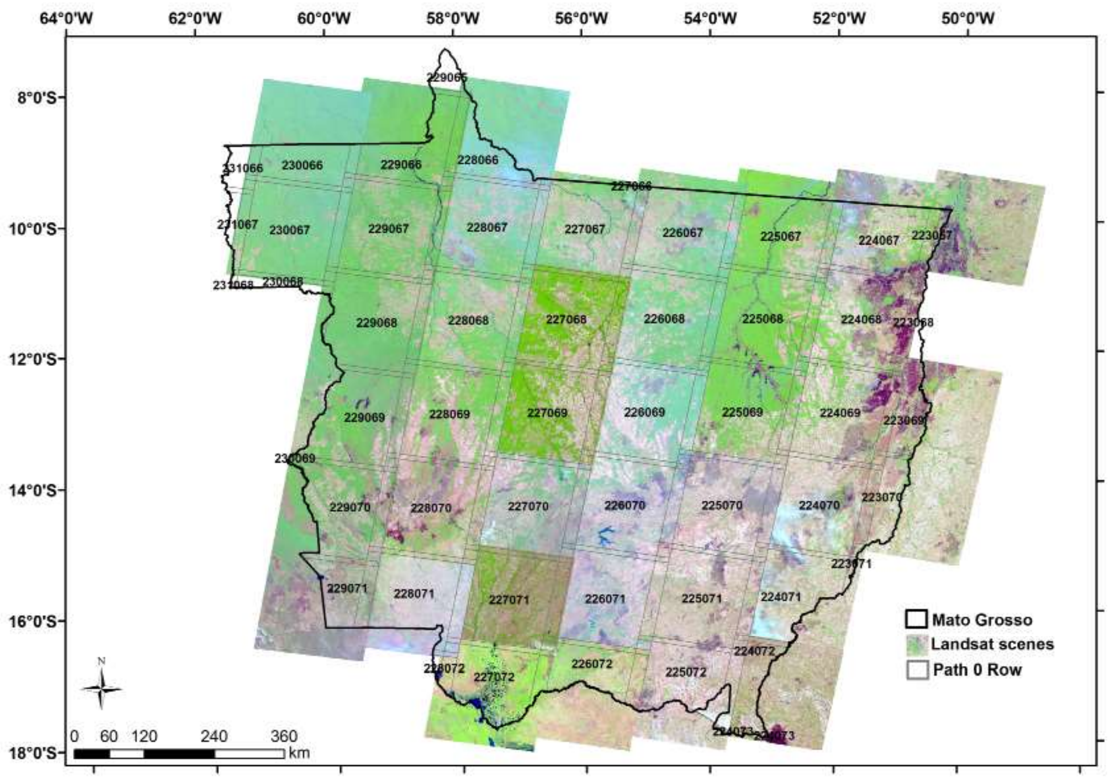


Fig. 2 - Mosaic of Landsat TM images used in this work.

2.3 Forest / Non forest map

The forest/non forest mask was derived from Hansen *et al.* (2013) for the year 2010 (Figure 3). "Forests" were defined as the areas with 50% or higher tree cover for year 2000 and included the "forest loss" data from 2001 to 2010. In this context, the resulting "forest areas" also includes some vegetation physiognomies located in the Cerrado biome.

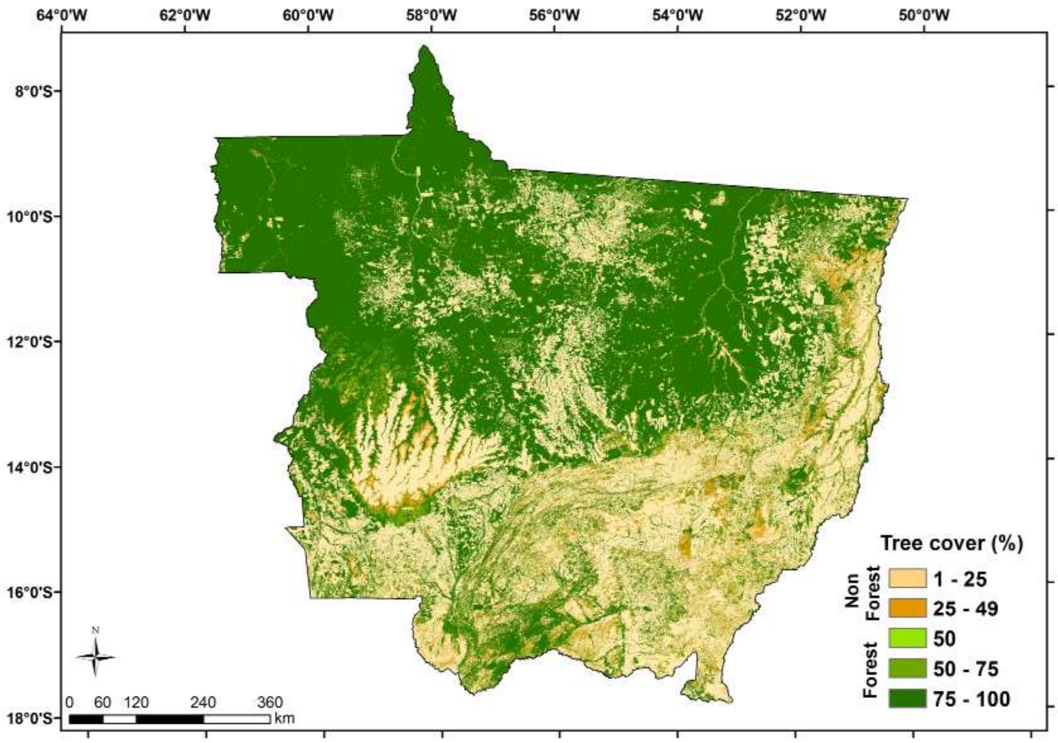


Fig. 3 - Tree cover map derived from Hansen *et al.* (2013) for the year 2010.

2.4 Biomass map

The 30 m resolution biomass product (Figure 4) is produced by the methodology developed by Baccini *et al.* (2012) to generate a pan-tropical map of aboveground live woody biomass density for the year 2000. The statistical relationship derived between ground-based measurements of forest biomass density and co-located Geoscience Laser Altimeter System (GLAS) LiDAR waveform metrics as described by Baccini *et al.* (2012) were used to estimate the biomass density of more than 40,000 GLAS footprints throughout the tropics. Then, using Random Forest model (BREIMAN, 2001), the GLAS-derived estimates of biomass density were correlated to continuous, gridded variables including Landsat 7 ETM+ satellite imagery and products (e.g., reflectance), elevation, and biophysical variables. By using continuous gridded datasets as inputs to the Random Forest model, a wall-to-wall 30 m resolution map of aboveground woody biomass density across the tropics was produced as well as the associated uncertainty layer. The uncertainty layer takes into account the errors from allometric equations, LiDAR based model, and Random Forest model. All the errors are propagated to the final biomass estimate. A detailed description of the work will be available in a new paper under preparation by Baccini´s group.

2.5 Methodological approach

The proposed method for mapping forest degradation by fire consists in four steps. The first step (i) of the approach focused on generating a forest mask map. In this case, was used the Hansen *et al.* (2013) dataset for the year 2000. The second step (ii) consisted in the generation of fraction images (SHIMABUKURO & SMITH, 1991) for the 42 Landsat TM images selected during the dry season of year 2010 (Table 1). The burned areas were quantified based on the shade fraction images considering that the shade fraction images highlight areas with low reflectance corresponding to burned areas (Figure 5).

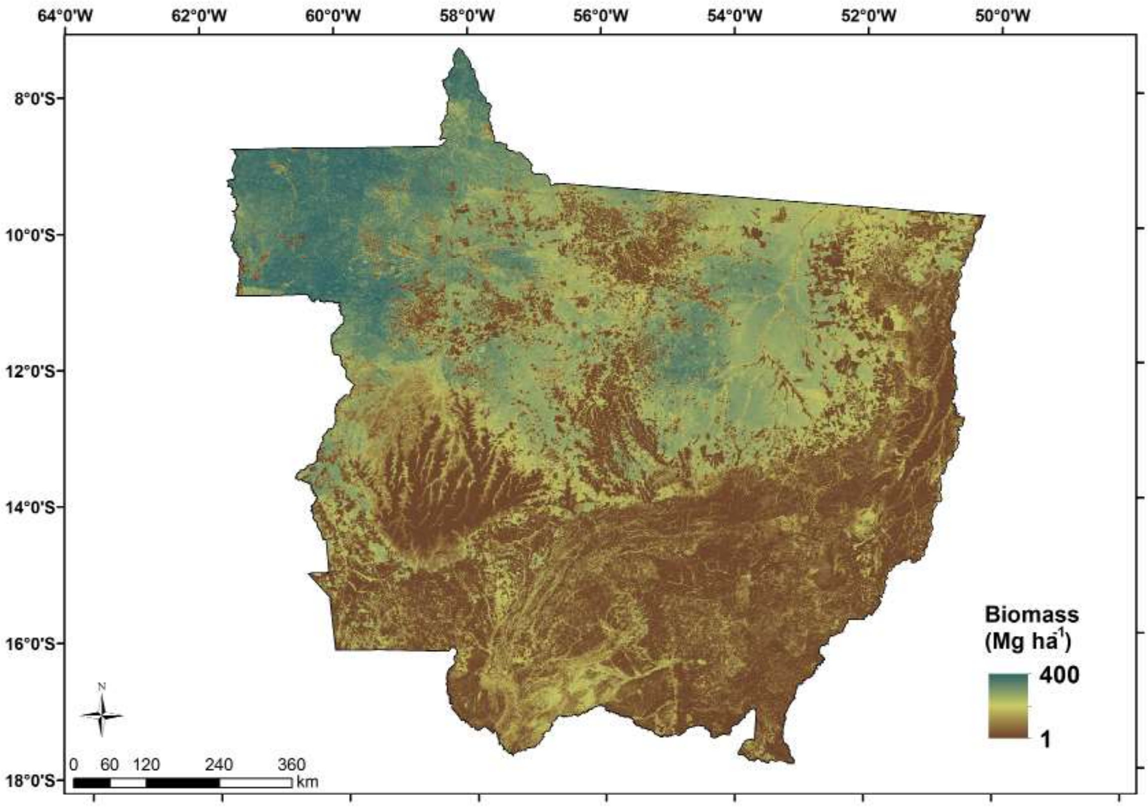
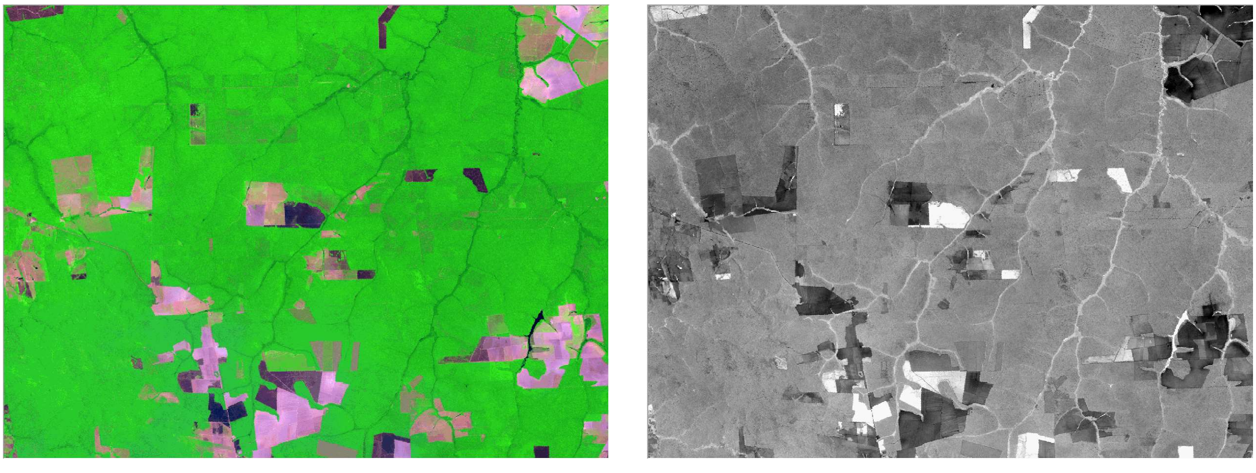


Fig. 4 - Biomass map from Baccini *et al.* (2015) for the year 2000.

The third step (iii) of the approach was divided in two parts. First, a shade fraction image was segmented and then an unsupervised classification algorithm was applied in order to derive individual and explicit objects (polygons). Secondly, the resulting clusters of objects were assigned as unburned or burned areas from their spectral and textural properties derived from shade fraction images.

The fourth step consisted in producing the forest degradation areas due to forest fires (burned forest), by combining the resulting maps of forest/non-forest areas (first step) with the burned area maps (from the third step), i.e. the forested areas that were burned without clear cut during the year 2010.



(a) (b)

Fig. 5 - a) Landsat TM (R5 G4 B3) image showing the burned areas in dark color (low reflectance), and b) Shade fraction image highlighting the burned areas in bright gray.

3. RESULTS AND DISCUSSION

The forest/non forest map derived from Hansen *et al.* (2013) shows that forest cover (> 50% of tree cover) is 458,677 km2 and 74,129 km2 of forest loss from 2000 to 2010 (5,403 km2 from 2010). The results showed that 70,317 km2 was burned in Mato Grosso State during the year 2010 (Figure 6). From this amount 5,175 km2 was deforested and burned and 22,633 km2 was forest burned, i.e. forest degraded by fire (Figure 6 and Table 2). The most burned areas (42,510 km2) occurred in the non-forest areas (Cerrado and old deforested areas).

The depicted burned areas in Amazonia are related to management activities using fire, to deforestation process, or to a degradation process: in the case of deforestation the forest cover is first clear cut and then the remaining vegetation is burned to allow using the land for agriculture (cropland or grassland). In the case of forest degradation, the forest cover is burned through an uncontrolled fire without removal of wood nor conversion to another land use. This makes the use of a forest/non-forest map essential for differentiating between deforestation and forest degradation processes. Deforested areas will appear as non-forest areas (cropland or grassland) in the successive months or years after the initial deforestation event while burned forests (degraded forest) will recover as forest regrowth (SHIMABUKURO *et al.*, 2014).

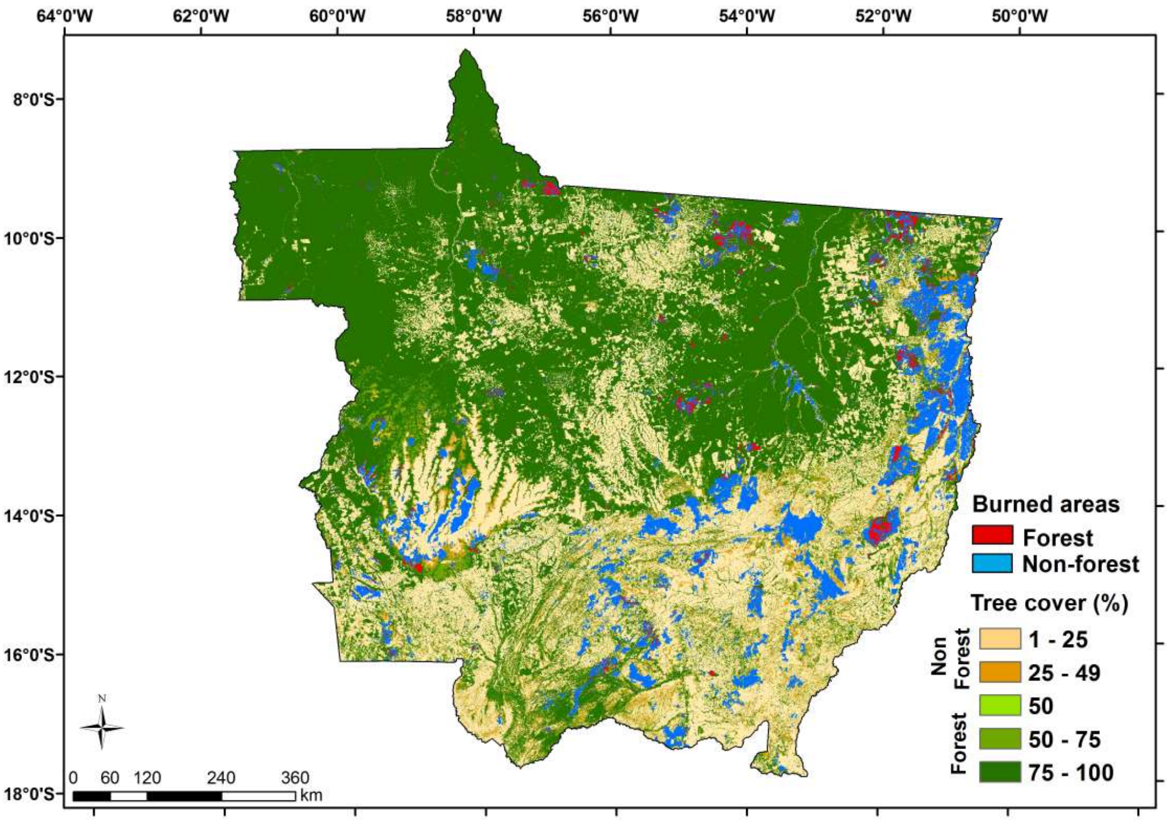


Fig. 6 - Burned areas depicted by the proposed method: in red over the forest areas and in blue over the non forest areas.

Table 2: Estimated burned areas over land cover types

	Land Cover (km2)	Burned Areas (km2)	(%)
Forest (Tree Cover > 50%)	458,677	22,633	32
Non Forest (Cerrado and old deforestation)	420,551	42,509	61
Deforestation (2001 to 2010)	74,129	5,175	7
Total	903,357	70,317	100

The biomass map derived from Baccini *et al.* (2015) was divided into five classes: 1) 0 – 78 (Mgha-1), 2) 79 – 157 (Mgha-1), 3) 158 – 235 (Mgha-1), 4) 236 – 314 (Mgha-1), 5) 315 – 400 (Mgha-1). 49,115 km2; 11,442 km2; 8,541 km2 ; 1,185 km2 ; and 34 km2 of burned area occurred in the first, in the second, in the third, in the fourth, and in the fifth class of biomass, respectively (Figure 7, Table 3).

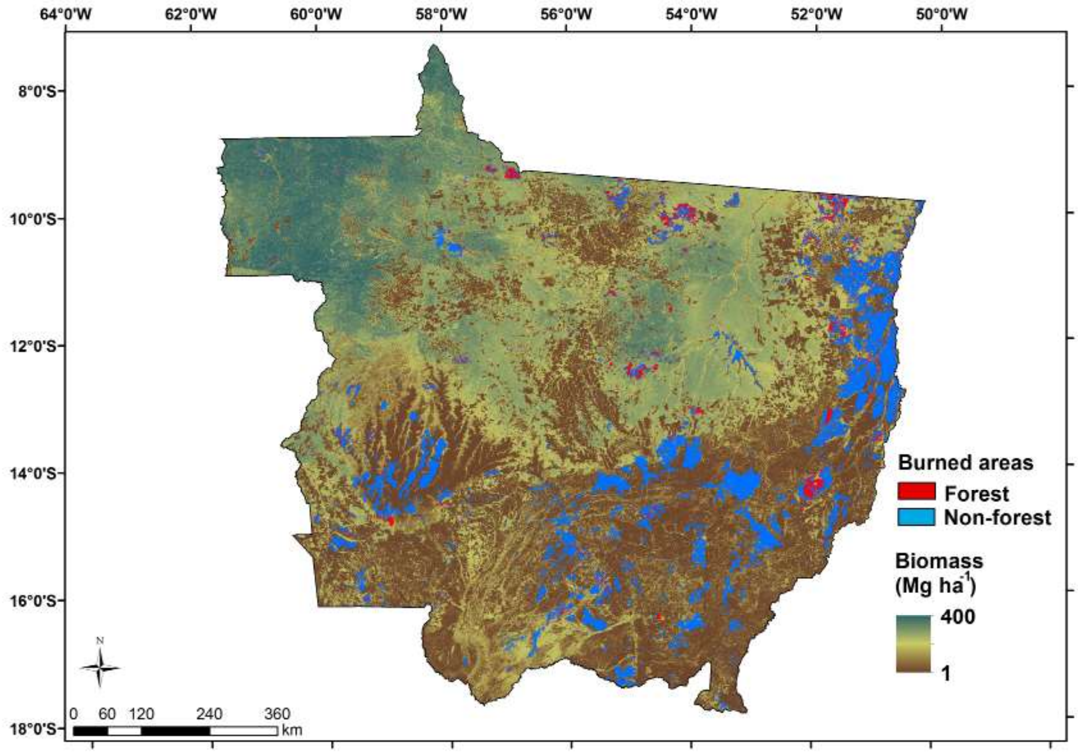


Fig. 7 - Burned areas depicted by our method: in red over the forest areas and in blue over the non forest areas associated with biomass classes.

Table 3: Estimated burned areas over biomass classes

Biomass (Mg ha^{-1}) Classes	(km^2)	Burned Areas (km^2)	(%)
0 – 78	430,828	49,115	70
79 - 157	133,040	11,442	16
158 - 235	231,021	8,541	12
236 - 314	102,078	1,185	2
315 - 400	6,390	34	0
Total	903,357	70,317	100

4. CONCLUSIONS

The proposed method was efficient for mapping burned forest areas (degraded forest areas due to fires). The Landsat TM images provide the information needed for mapping of forest/non forest areas and burned areas over the Amazonas basin. An initial forest/non forest map is essential for developing a procedure for mapping degradation areas due to forest fires.

The shade fraction image generated from the application of spectral linear mixing model on Landsat TM images allowed to identify and to map burned areas semi automatically. Then combining these results with the forest/non forest map derived from Hansen *et al.* (2013) dataset allowed to estimate the degradation forest areas due to forest fire. Also, combining the burned areas map with biomass map (Baccini *et al.*, in preparation) allowed to observe the biomass classes affected by the fire. This information is very important for the carbon emission estimation.

The availability of 5-days temporal resolution imagery of 10 m spatial resolution data from Sentinel-2 satellites is expected to enable efficient implementation of the monitoring approach presented in this paper. Then it will considerably improve the assessment and monitoring capabilities of forest degradation processes, consequently facilitating the implementation of actions in the framework of

UNFCCC REDD+ mechanism (Reduction of Emissions from Deforestation and forest Degradation).

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