

High spatial resolution land use and land cover mapping of the Brazilian Legal Amazon in 2008 using Landsat-5/TM and MODIS data

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ABSTRACT

Understanding spatial patterns of land use and land cover is essential for studies addressing biodiversity, climate change and environmental modeling as well as for the design and monitoring of land use policies. The aim of this study was to create a detailed map of land use land cover of the deforested areas of the Brazilian Legal Amazon up to 2008. Deforestation data from and uses were mapped with Landsat-5/TM images analysed with techniques, such as linear spectral mixture model, threshold slicing and visual interpretation, aided by temporal information extracted from NDVI MODIS time series. The result is a high spatial resolution of land use and land cover map of the entire Brazilian Legal Amazon for the year 2008 and corresponding calculation of area occupied by different land use classes. The results showed that the four classes of Pasture covered 62% of the deforested areas of the Brazilian Legal Amazon, followed by Secondary Vegetation with 21%. The area occupied by Annual Agriculture covered less than 5% of deforested areas; the remaining areas were distributed among six other land use classes. The maps generated from this project – called TerraClass - are available at INPE's web site (http://www.inpe.br/cra/projetos_pesquisas/terraclass2008.php).

KEYWORDS: Remote Sensing, Tropical Deforestation, TerraClass, Image Processing.

Mapeamento do uso e cobertura da terra na Amazônia Legal Brasileira com alta resolução espacial utilizando dados Landsat-5/TM e MODIS

RESUMO

Entender o padrão espacial do uso e cobertura da terra é essencial para estudos de biodiversidade, mudanças climáticas e modelagem ambiental, bem como para concepção e acompanhamento de políticas direcionadas ao uso da terra. O objetivo deste estudo foi criar um mapa detalhado do uso e cobertura da terra para a porção desflorestada da Amazônia Legal Brasileira, até 2008. Dados de desflorestamento e uso foram mapeados usando imagens Landsat-5/TM analisadas com técnicas como modelo linear de mistura espectral, fatiamento e interpretação visual, auxiliados por informações temporais de NDVI extraídas de série temporal de dados MODIS. O resultado deste estudo é um mapa de uso e cobertura da terra com alta resolução espacial para toda Amazônia Legal Brasileira, para o ano de 2008, e os respectivos percentuais da área ocupada por diferentes classes de uso da terra. O resultado mostrou que, quatro classes de pastagens cobrem 62% da área desflorestada da Amazônia Legal Brasileira, seguida pela vegetação secundária com 21%. A área ocupada pela agricultura anual cobriu menos de 5% das áreas desflorestadas; as áreas restantes estavam distribuídas em outras seis classes de uso da terra. Os mapas gerados por este projeto, chamado TerraClass, estão disponíveis no site do INPE (http://www.inpe.br/cra/projetos_pesquisas/terraclass2008.php).

PALAVRAS-CHAVE: Sensoriamento Remoto, Desflorestamento Tropical, TerraClass, Processamento de Imagens.

INTRODUCTION

Over the last decades, many global scale, land use and land cover products based on coarse spatial resolution remote sensing data, have become available. For example, in the early 2000s, land cover maps at 1000 m spatial resolution such as Global Land Cover (GLC) 2000 (Bartholome *et al.* 2002) and MODIS Global Land Cover (Friedl *et al.* 2002) were released. Later, higher resolution data of land cover were made available, including the MODIS collection 5 Global Land Cover (Friedl *et al.* 2010) at 500 m spatial resolution and the GLOBCOVER 2005 and 2009 products (Arino *et al.* 2007; Bontemps *et al.* 2010) at 300 m spatial resolution. While these products offered important advances in mapping global trends, applications relevant for national or regional decision-making require even finer resolution, particularly as the results of land use change analysis have been reported to differ depending on the scale of mapping. (Rozon *et al.* 2015).

In this work, the area under study is the Brazilian Legal Amazon. The Brazilian National Institute for Space Research (INPE) has been producing data on spatial extent of deforestation in this region since 1988 through the Program for Deforestation Monitoring in the Brazilian Legal Amazon (PRODES). TerraClass is a complement to PRODES by adding information about what was the land use and land cover spatial distribution and regional statistics in the deforested areas up to 2008. According to PRODES, deforestation in the Brazilian Amazon up to 2008 amounted to 719,710 km² (INPE 2015) nearly twice the size of Germany's land area, for comparison. The scale of this deforestation has an impact on ecosystem services, biodiversity, water cycle and the carbon cycle (Fearnside 2006). Yet, in addition to the biological impacts of deforestation in the region, this deforested area is an issue of interest as it now encompasses highly diverse socio-economic environments (Margulis 2003; Morton *et al.* 2006; Barona *et al.* 2010) as one example, research within the Brazilian Amazon has suggested that over the last two decades, macro-economic forces have played an increasing role in deforestation in the Brazilian Amazon: large-scale cattle raising, industrial timber and wood, soybean and infrastructure investments are thought to have an increasingly greater role (Margulis 2003; Coutinho 2009).

TerraClass projects represents a concerted effort to monitor Land Use and Land Cover in the Brazilian Legal Amazon. This study offers to researchers a greater ability to trace out different classes of land use change over time, which can shed further light into the original land-uses post-deforestation and test how land use land cover and socio-economic dynamics may be changing over time across the entire region. Access to more historical data, along with continued monitoring in the years ahead, will allow make more rigorous analysis of both

the drivers of deforestation and more accurate estimates of greenhouse gas sinks and emissions.

Therefore, to assist and promote better-informed land use planning and decision making for the Amazon region, INPE and the Brazilian Agricultural Research Corporation (Embrapa) have started a technical partnership in this study, which aimed to create a detailed map of land use land cover of the deforested areas of Brazilian Legal Amazon up to 2008.

MATERIALS AND METHODS

Study area

The Brazilian Legal Amazon Region (Figure 1) extends over an area of approximately 5,200,000 km² and represents 59% of Brazil's land mass. Its population of twenty four million people (IBGE 2012) are distributed over 775 municipalities and the region is home to a very high ecological and socio-economic diversity. Figure 1 shows a map of the study area defined as the deforested area of the Amazon.

Datasets

This study uses a combination of deforestation vector data from PRODES (INPE 2015) and satellite orbital images (Landsat-5/TM, MODIS and SPOT-5).

Since 1988, PRODES data has recorded the annual increment (August-July) of deforestation larger than 6.25 ha. In 2008, total deforestation amounted to 719,210 km². Measured deforestation between August 2007 and July 2008 was of 11,457 km². This area was denoted as '2008 deforested area' and was not further classified, as we could not track its

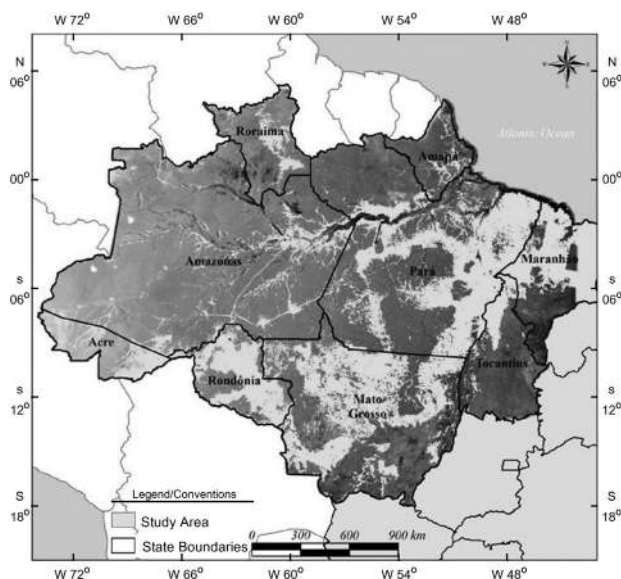


Figure 1. The Brazilian Legal Amazon.

evolution into other land cover types using 2008 images. The PRODES data was used to provide a mask of areas for use in the subsequent land cover classification procedures.

Landsat images have been successfully used in deforestation monitoring and land use and land cover studies, due mainly to its high spatial resolution (30 m) and capacity to discriminate objects and vegetation typology (Dubreuil *et al.* 2008; Bodart *et al.* 2011). This study used 214 geo-referenced Landsat-5/TM images available from the INPE's Image catalog (<http://www.dgi.inpe.br/CDSR/>). The Landsat images are the same used to generate PRODES deforestation products. This set of images was collected mainly for the period July-September 2008 (187 scenes) when cloud cover is at its lowest in the Amazon. The Landsat images were the primary key source data for our land cover classification.

Due to its high temporal resolution of 1-2 days (compared to Landsat's 16-18 days), Moderate Resolution Imaging Spectroradiometer (MODIS) images have been widely used for continuous land use and land cover mapping, despite their limited spatial resolution of 250-1000 m (Eva *et al.* 2010; Verbesselt *et al.* 2012; Atzberger 2013). This study employs data from the MODIS Normalized Difference Vegetation Index (NDVI) MOD13Q1 product (NASA 2001) over the period from August 2007 to July

2008 to identify annual crop areas based on their seasonal phenology. The MODIS product used is a 16-day composite of the highest quality pixels from daily images at a spatial resolution of 250 m.

TerraClass land cover classification was validated using SPOT-5 HRG (High Geometric Resolution) data in "panchromatic" mode (PAN, 0.51 – 0.73 μm) at 2.5 m spatial resolution. The geometric accuracy of these images is sufficient for their use in photointerpretation (Jensen 2009) and they were used here to assess our mapping accuracy.

Land Cover Classification

The methodology combines products of high spatial and temporal resolution to increase the mapping efficiency of land use and land cover (LULC) in the Brazilian Amazon. Table 1 lists the twelve classes of land uses used this region, which also represent the main types of land use land cover in the region. Figure 2 provides a flowchart of the methodological approach described in this paper. Land cover classification was attained by a sequence of operations, each one solving a classification decision and defining the region to be addressed by the next operation. The sequence of operations occurred in the order described in the following text.

Table 1. Main types of Land Cover in deforested areas of the Brazilian Amazon.

Thematic Categories	Description
Deforestation 2008	Areas recently deforested covered by soil, shrubs, herbage and felled trees with no defined land use at this stage, defined as areas that were mapped by PRODES project as deforested in 2008.
Urban area	Population concentration forming small inhabited places, villages and cities that present differentiated infrastructure from the rural areas with street design and higher density of dwellings such as houses, buildings and other public spaces.
Mining	Areas of mineral extraction with the presence of bare soil and deforestation in the proximity of water bodies.
Mosaic of Uses	Characterized by land cover units that, due to the spatial resolution of the satellite images, cannot be broken down further into specific components. For example, this classification might include family agriculture practiced in conjunction with the traditional cattle raising.
Annual Crops	Extensive areas with predominance of annual crops, specially grains, highly technological such as certified seeds, enriched soil, chemicals, fertilizers, mechanization among other resources.
Herbaceous Pasture	Pasture in productive process with predominance of herbage and coverage between 90 and 100% by different species of grass.
Shrubby Pasture	Areas of pasture in productive process with predominance of herbage and coverage by species of grass between 50% and 80% associated to the presence of shrubby vegetation with coverage between 20% and 50%.
Pasture with exposed soil	Pasture areas, exhibiting signs of severe degradation, containing at least 50% bare soil.
Regeneration with Pasture	Areas that were clear-cut, later developed as pasture and are at the beginning of a regenerative process containing shrubs and early successional vegetation.
Secondary Vegetation	Areas that were clear-cut and are at an advanced stage of regeneration with trees and shrubs. Includes areas that were used for forestry (silviculture) or permanent agriculture with use of native or exotic species.
Others	Areas not encompassed by other categories such as rocky or mountain outcrops, river shores and sand banks, among others.
Non-observed area	Areas not possible to be interpreted due to clouds or cloud shade at the moment of the satellite overpass or recently burned areas.

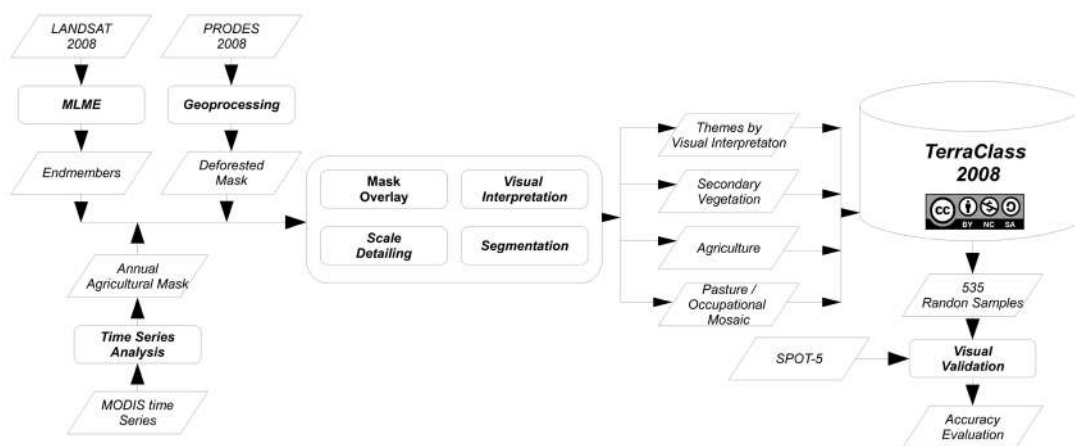


Figure 2. TerraClass project flowchart.

Deforestation mask

TerraClass has as study area the polygons defined as deforested areas by PRODES up to 2007.

Generation and clipping of fraction images

Second, to aid in the analysis, we applied a linear spectral mixture model methodology, developed by Mello *et al.* (2003) to obtain the soil, shade and vegetation fractions for each single pixel in the Landsat-5/TM images. The endmembers spectral signatures were acquired directly from each Landsat-5/TM images using representative targets of green vegetation, soil and shade. This procedure has been widely used in literature (Shimabukuro *et al.* 1998; Lu 2003; Mello *et al.* 2003) We then used the deforestation mask to eliminate already classified areas from analysis (i.e. forested areas), leaving only deforested areas for subsequent classification.

Visual Interpretation

Through visual interpretation step four low-frequency land cover classes were identified and mapped: urban areas, mining, others and non-observed areas due to cloud cover. This visual interpretation procedure has been reported in the literature to as a reliable method to characterize specific features (Novo 2008; Jensen 2009; Ponzoni *et al.* 2012), and it is based on the analysis of color, shape, texture, size and attributes of neighbouring pixels. An interpretation key was developed (shown in Table 2) so as to minimize errors due to subjective interpretation as well as to standardize the process among the technical personnel involved. These areas were then masked out from the deforested area.

Secondary vegetation

In this study, secondary vegetation consisted of originally forested areas that had been clear cut, used for silviculture,

agriculture or pasture and then left to regenerate, taking on a forest appearance again.

The areas mapped as secondary vegetation are in various stages of development, from initial stages, when the canopy is homogeneous and few species are found, to advanced stages when canopy heterogeneity and species diversity is similar to the original forest (Vieira *et al.* 2003).

Secondary vegetation areas were identified using the fraction images and color composite images of Landsat-5/TM bands 3, 4 and 5. With the vegetation fraction images from the linear mixture model, it was possible to identify a threshold above which land cover is dominated by secondary vegetation. These values varied for each image and once the spectral pattern was identified, the technique of image slicing was applied to create a thematic image (Almeida *et al.* 2010).

The image slicing results were used to create a group of thematic images of the secondary vegetation. Additional editing of imperfections found in secondary vegetation mapping was conducted with the aid of the color composites and the final secondary vegetation polygons were masked out of the fractional images.

Agriculture

To map annual crops, we used an automatic classification procedure based on the spectral and temporal characteristics of the MODIS Normalized Difference Vegetation Index (NDVI) (Rouse *et al.* 1974). Areas covered by annual crops present a particular seasonal biomass variation which allows the distinction of this class from other land covers based on behaviour of the NDVI time series of each pixel during the growing cycle (Adami *et al.* 2005; Rudorff *et al.* 2011; Arvor *et al.* 2012a).

Table 2. Visual interpretation key.

Urban Area			
Color <i>Magenta and Cyan</i>	Tonality <i>Medium to High</i>	Texture <i>Roughened with systematic pattern</i>	Form <i>Regular</i>
Mining			
Color <i>Magenta and Cyan</i>	Tonality <i>Medium to High</i>	Texture <i>Smoother</i>	Form <i>Irregular</i>
Mosaic of Uses			
Color <i>Magenta</i>	Tonality <i>Medium to High</i>	Texture <i>Roughened and heterogeneous</i>	Form <i>Irregular</i>
Annual Crops			
Color <i>Magenta</i>	Tonality <i>Medium to Light</i>	Texture <i>Smoother</i>	Form <i>Regular</i>
Herbaceous Pasture			
Color <i>Magenta</i>	Tonality <i>Light</i>	Texture <i>Smoother</i>	Form <i>Regular or Irregular</i>
Shrubs Pasture			
Color <i>Magenta or light green</i>	Tonality <i>Light</i>	Texture <i>Smoother</i>	Form <i>Regular or Irregular</i>
Pasture with exposed soil			
Color <i>Magenta and Cyan</i>	Tonality <i>Light or Medium</i>	Texture <i>Smoother</i>	Form <i>Regular or Irregular</i>
Regeneration with Pasture			
Color <i>Magenta or light green</i>	Tonality <i>Light or Medium</i>	Texture <i>Smoother or Slightly Roughened</i>	Form <i>Regular or Irregular</i>
Secondary Vegetation			
Color <i>Green</i>	Tonality <i>Light or Medium</i>	Texture <i>Smoother or Roughened</i>	Form <i>Regular or Irregular</i>
Others			
Color <i>Does not apply</i>	Tonality <i>Does not apply</i>	Texture <i>Does not apply</i>	Form <i>Irregular</i>
Non-observed area			
Color <i>White and various shades of black</i>	Tonality <i>High</i>	Texture <i>Smoother</i>	Form <i>Irregular</i>

The analysis was applied over 23 dates of MODIS-NDVI composites, acquired for the nine Amazon States between August 2007 and July 2008. The applied method has been demonstrated as useful for crop identification and mapping, especially in large mechanized agriculture areas (Adami *et al.* 2005; Arvor *et al.* 2012b; Vuolo and Atzberger 2012).

The adopted mapping method used the maximum and minimum NDVI values identified throughout the time series, based on the premise that each target presents a typical temporal behaviour. That is, in the case of the annual crops, the vegetation indices present low values at the beginning of the growing cycle, when the amount of biomass is low and the spectral response is influenced by the soil and, as the crops grow and gain biomass, the indices respond with higher values until reaching the vegetative peak. There is a decrease in value at the beginning of senescence, until they reach the same levels of the beginning of the cycle. This pattern is represented in figure 3. Considering this typical

temporal behaviour of the farming areas, the annual crop pixel mapping was done using the difference between the NDVI values at vegetative peak and the values at the cycle beginning, when there is greatest distance between them.

To minimize clouds interference in the temporal analysis, prior to classification, we applied an image filtering technique on the MODIS images based on harmonic analysis using HANTS algorithm, Harmonic Analysis of NDVI Time Series (Roerink *et al.* 2000)

The standard amplitude between maximum and minimum NDVI values was estimated based on known agricultural areas previously identified on Landsat-5/TM scenes. MODIS NDVI temporal profiles were generated for those areas to evaluate the seasonal variation of the biomass during the growing cycle and determine best periods to obtain maximum and minimum NDVI values. Once the standard difference value was established, a classification procedure based on an IDL (Interactive

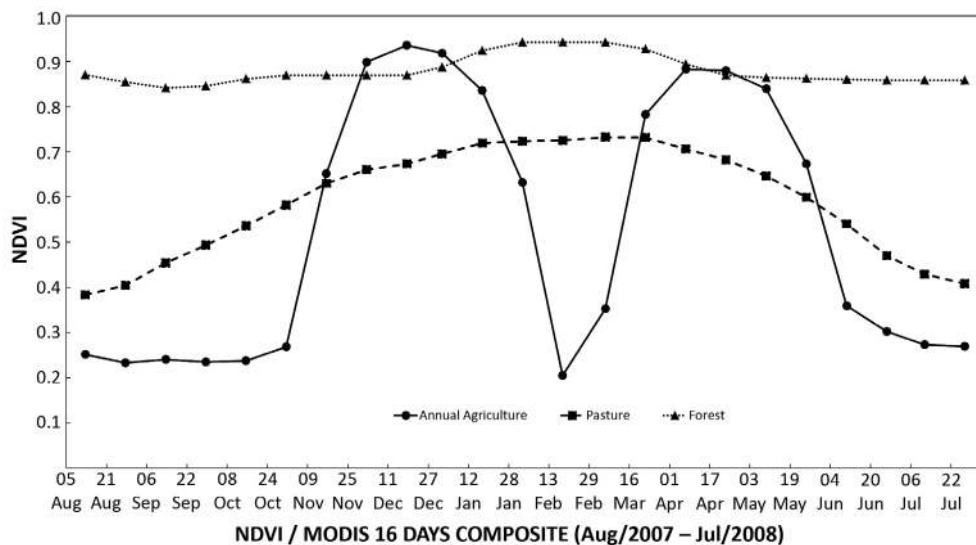


Figure 3. MODIS/NDVI temporal profiles of annual agriculture, forest and pasture between August 2007 and July 2008.

Data Language) code (Roerink *et al.* 2000) was applied to produce a binary image with the location of the MODIS pixels classified as annual crops, named “agricultural MODIS mask”.

The agricultural MODIS mask was employed to choose sample areas for the supervised classification of Landsat-5/TM images. First, image segmentation was conducted to discriminate spectrally homogeneous fields. Segmentation was based on the Regional Growth the algorithm available in the SPRING software (Câmara *et al.* 1996). It requires two parameters to aggregate pixels into homogeneous fields: the *similarity* and *area* thresholds. The similarity threshold is defined as the Euclidian distance between the grey values of two adjacent pixels or fields while the area threshold is defined as the minimum area in number of pixels to be considered as a field. There is no standard value for these thresholds as they depend on the land use spatial patterns present in each landscape. Consequently, the user has to make several approximations until a segmentation scheme is considered adequate. In our study, we found optimal similarity values between 10 and 20 grey levels and an optimal minimum area of 49 pixels giving a minimum mapping area of 4.4ha.

Following segmentation, supervised classification of the Landsat-5/TM images was conducted using the Bhattacharya classifier available in SPRING (Câmara *et al.* 1996). The final map of the annual crops therefore combines the temporal information of the MODIS images with the spatial resolution of Landsat-5/TM images. Following final classification and additional manual editing of eventual misclassifications, the agricultural polygons were identified in the deforested area and masked out of the fraction image.

Pasture and mosaic of uses

The final stage of analysis involved the classification of the remaining area dominated by pasture into four categories, Herbaceous Pasture, Shrubs Pasture, Regeneration with Pasture and Bare Soil Pasture, and a final miscellaneous ‘mosaic of uses’ category among the remaining land areas. Segmentation of fraction images was conducted as described above which was followed by a visual classification of polygons based on the interpretation key presented in Table 2 to attain consistent and precise identification of individual categories (Kelly *et al.* 1999; Jensen 2009).

These five land cover classes represent distinct land occupation patterns in the Amazon, as suggested by Pocard-Chapuis *et al.* (2005), and identifying them allows researchers to observe the land abandonment and forest regeneration processes. As reported by Uhl *et al.* (1988), abandoned pastures appear as forest regeneration with distinct biomass accumulations that vary according to time since last land use and the its intensity and duration. Other authors (Morton *et al.* 2006; Barona *et al.* 2010) pointed out that part of the soy development in the Amazon region has occurred by replacing pastures with soybeans, which may have been associated with have induced pasture expansion towards the deforestation frontier. Thus identifying and quantifying pastures spatial distribution according to its vegetative condition is essential to examine these hypothesis.

Fieldwork, final verification and data mosaic

During our study, we collected 3,800 geo-referenced photographs, in a field mission that covered more than 10,000 km in the Brazilian Amazon. These photographs were used as support material during the interpretation process, and are

publicly available on the INPE's website (www.obt.inpe.br/fototeca/fototeca.html).

At the end of the interpretation step, technicians external to the project verified the entire classification process aiming to reduce errors from divergent interpretation. The interpretation key showed in Table 2 was used in this step.

The validation consisted of taking a geographically random sample of 535 points from all of the 12 categories identified. The number of sample points was determined so as to reach a statistical consistency with the level of confidence (95%) and a confidence interval of 5% for the polygon population of approximately 2.5 million cases.

The procedure adopted for the validation of points was based initially on the visual identification of classes using SPOT-5 HRG at 2.5 m spatial resolution images, which were then overlapped and compared to the map produced by TerraClass.

The final TerraClass map covering the entire Brazilian Amazon was composed by the final classified product combined with PRODES regional data of forested areas in 2008, non-forested vegetation and water bodies.

RESULTS

Table 3 summarizes the results of the land use and land cover classification in the deforested areas of the Brazilian Legal Amazon. The land use category with the largest territorial coverage is Herbaceous Pasture which occurred in 46.7% of the deforested areas. When Shrubs and Regeneration Pasture

are also considered, this figure goes up to 62.1% of the total deforested area. In the table 4 it can see that Herbaceous Pasture is found in 335,700 km² of the Amazon deforested area with the largest incidence in Mato Grosso (MT), Para (PA) and Rondonia (RO) States with areas of 107,500 km², 107,300 km² and 52,900 km², respectively, representing 79.6% of total Herbaceous Pasture cover.

Table 3. Land Use and Land Cover by class for the Brazilian Amazon in 2008.

	Area (km ²)	Percentage Cover	Cumulative Percentage Cover
Herbaceous Pasture	335,714.94	46.68	46.68
Secondary Vegetation	150,815.31	20.67	67.65
Shrubs Pasture	62,823.75	8.74	76.38
Pasture with Regeneration	48,027.37	6.68	83.06
Non-observed Area	45,406.27	6.31	89.37
Annual Crops	34,927.24	4.86	94.23
Mosaic of Uses	24,416.57	3.39	97.63
Urban Area	3,818.14	0.53	98.16
Mining	730.68	0.10	98.26
Pasture with exposed soil	594.19	0.08	98.34
Others	477.88	0.07	98.41
Deforestation 2008	11,458.64	1.59	100.00
TOTAL	719,210.98	100	

Table 4. Distribution of the areas corresponding to each thematic category mapped by State (km² x 1000). Hyphens are used to denote the lack of occurrence of specific land use categories in particular states.

Class	Acre	Amapa	Amazonas	Maranhao	Mato Grosso	Para	Rondonia	Roraima	Tocantins	TOTAL
Forest	144.6	110.8	1,426.5	36.0	316.9	888.5	128.1	152.6	10.0	3,214.0
Non-forest	0.1	25.6	48.3	112.6	377.3	73.7	24.4	60.9	230.3	953.3
Hydrograph	0.2	3.6	52.2	4.4	4.8	44.3	2.1	1.8	1.5	114.9
Deforestation 2008	0.3	0.1	0.5	1.2	3.2	4.8	0.9	0.4	0.1	11.5
Annual Crops	-	<0.05	0.1	0.2	31.0	2.1	1.4	<0.05	0.1	34.9
Mosaic of Uses	1.5	0.2	2.9	4.5	2.3	11.4	0.8	0.7	<0.05	24.4
Urban area	0.2	0.1	0.5	0.8	0.5	1.3	0.4	0.0	0.1	3.8
Mining	-	<0.05	<0.05	<0.05	0.2	0.3	0.1	<0.05	<0.05	0.7
Others	<0.05	<0.05	0.1	0.1	0.1	0.1	<0.05	<0.05	<0.05	0.5
Herbaceous Pasture	11.5	0.4	6.6	31.1	107.5	107.3	52.9	2.7	15.8	335.7
Shrubs Pasture	0.9	0.1	1.7	7.1	18.0	22.7	6.9	0.9	4.6	62.8
Regeneration with Pasture	0.6	0.3	2.2	8.8	11.2	16.2	5.9	0.9	1.9	48.0
Bare Soil Pasture	<0.05	-	<0.05	<0.05	0.3	0.2	<0.05	-	<0.05	0.6
Secondary Vegetation	3.8	1.0	15.7	21.5	28.0	57.6	13.3	2.5	7.4	150.8
Non-observed area	0.4	0.5	1.7	22.2	2.1	17.4	0.3	0.8	<0.05	45.4
TOTAL	164.2	142.8	1,559.0	250.6	903.4	1,247.8	237.6	224.3	271.8	5,001.4

The three pasture categories (Herbaceous, Shrub and Regeneration with Pasture) cover a total of 79.1% of the deforested area in Rondonia State, 66.9% of the deforested area in Mato Grosso State and 60.6% of the deforested area in Para State. Thus, in Rondonia and Mato Grosso the percentage of deforested area converted to pasture is higher than the Amazon average (62.1%). Conversely, pastures cover only 31.2% and 32.8% of the total deforested areas in Amapa (AP) and Amazonas (AM), well below the Amazonian average.

Secondary Vegetation accounted for 150,800 km² (21%) of the total deforested area. The largest proportion of secondary vegetation was verified in the Amazonas (49%) and in Amapa (37%) States. The lowest values, by contrast, were those in the States of Mato Grosso and Rondonia, with respectively 13.7% and 16.1% of the total deforested area of these States.

Annual crops were observed over an area of 34,900 km² (for comparison, an area approximately as large as the land

area of the Netherlands), mainly in Mato Grosso where the total area amounted to 31,000 km², or approximately 88.6% of the total Amazon annual crop area. Conversely, the State of Acre had no identifiable annual crop cover.

Table 4 reports the classification figures by state; and figure 4 shows the final land use and land cover map in the Brazilian Legal Amazon. Figure 5 highlights the Mato Grosso State land use and land cover.

The TerraClass mapping results were visually verified using SPOT 5 very high spatial resolution (2.5 m) satellite images from which 535 reference sample points were randomly selected from the Para and Mato Grosso States. These States were chosen because they had many high resolution images available, they represent 62% of the Brazilian Legal Amazon and they feature every land use and land cover classes mapped in this study. Based on the 535 reference points, it was possible to determine the classification error showed in Table 5.

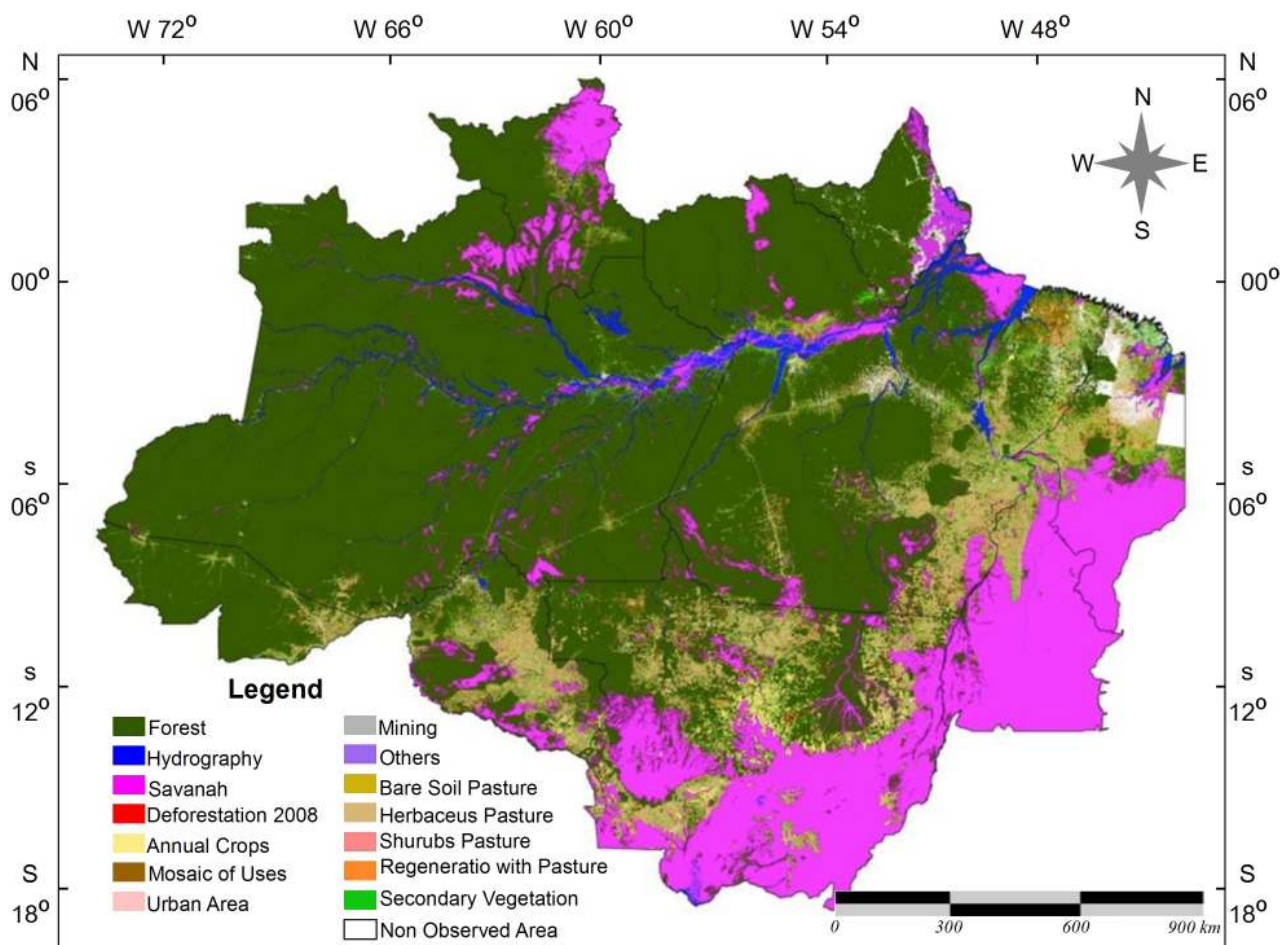


Figure 4. TerraClass 2008 map for the entire Brazilian Amazon. This figure is in color in the electronic version.

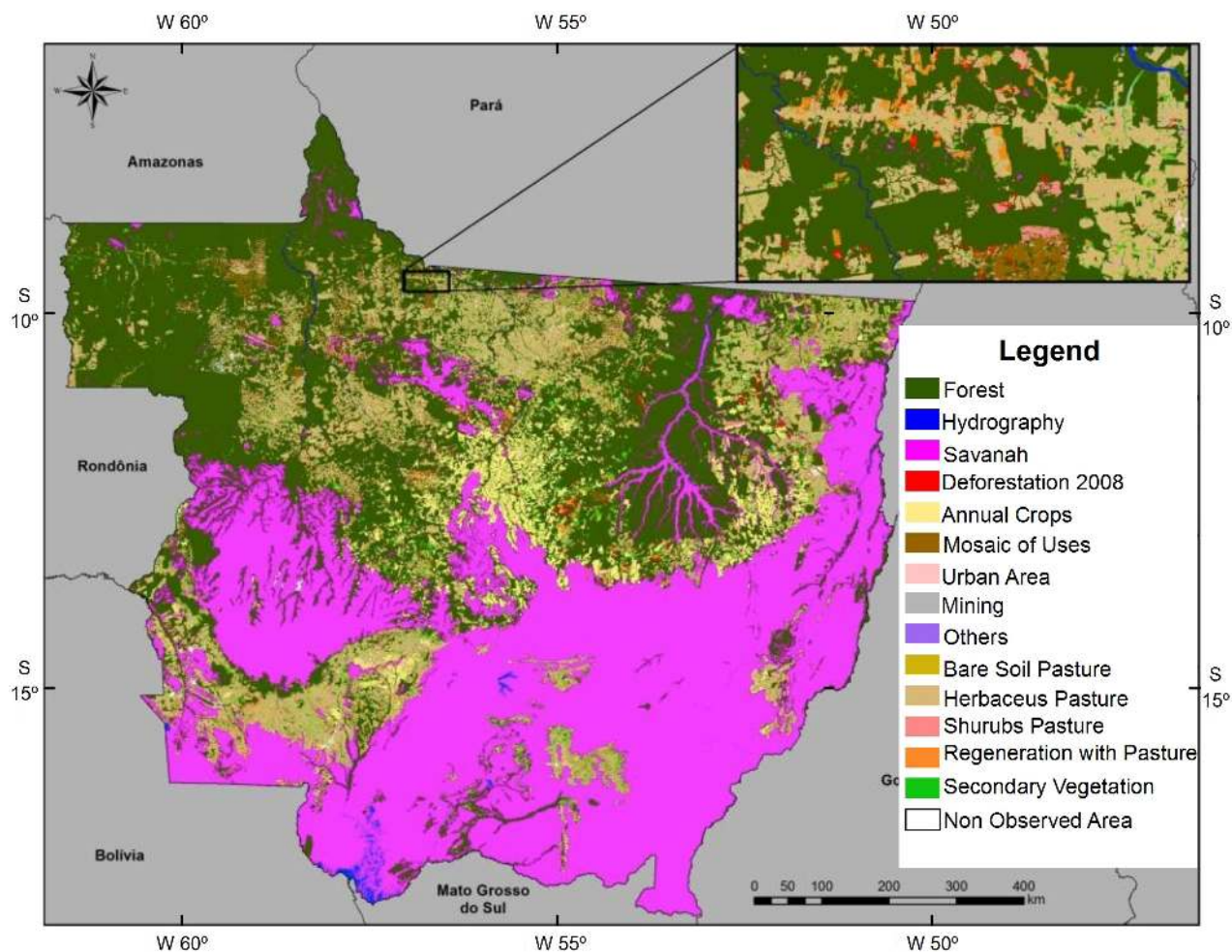


Figure 5. Detailed TerraClass mapping of Mato Grosso (MT). This figure is in color in the electronic version.

Table 5. TerraClass classification validation verified against SPOT satellite images.

Thematic classes	Spot images (Reference)						Total	Inclusion Error (%)
	Annual Crops	Mosaic of Occupations	Herbaceous Pasture	Shrub Pasture	Pasture with regeneration	Secondary Vegetation		
	AC	MU	HP	SP	PR	SV	Total	Commission Error
Annual Crops (AC)	33		2			1	36	8.3
Mosaic of Uses (MU)		19	1	1		3	24	20.8
Herbaceous Pasture (HP)			199	39	12	10	260	23.5
Shrub Pasture (SP)		1	10	45	7	5	68	33.8
Pasture with regeneration (PR)			2		19	7	28	32.1
Secondary Vegetation (SV)	1	3	7	6	7	95	119	20.2
Total	34	23	221	91	45	121	535	
Omission Error (%)	2.9	17.4	10.0	50.5	57.8	21.5		
Global accuracy map						76,64%		
Kappa index						0.67		

DISCUSSION

The dominance of pasture-based areas in deforested areas (62.1%) evidence the importance of this land use in the region (Poccard-Chapuis *et al.* 2005; Brandão *et al.* 2006; Bowman *et al.* 2012). Other studies have already suggested that livestock expansion ranks among the most important driver of deforestations in the region (Wassenaar *et al.* 2007; Barona *et al.* 2010; Espindola *et al.* 2012). While the 2008 TerraClass result alone cannot conclusively state that cattle expansion has been causing deforestation, per se, it does show that cattle has come to occupy a significant portion of the areas under direct use. Combined with further analysis forwards and backwards in time, researchers can then assess at what point the forest was converted, and which land uses subsequently occurred on those areas.

When merged, two classes of pasture -- Shrubs Pasture and Pasture with Regeneration, characteristically with low level of management and consequently low productivity, accounted for 15.42% of the land use in deforested areas. This represents more than three times the area occupied by annual agriculture, and also a third of the area occupied by the other classes of pasture. These figures may suggest that if guided by appropriate public policies, it is feasible to induce the expansion of both agriculture and livestock production with a minor impact on deforestation (Sayer and Cassman 2013; Ceddia *et al.* 2014; Villoria *et al.* 2014).

The second largest land cover is Secondary Vegetation, which represents 21% of the total deforested area – a number that agrees with previous estimates (MMA 2006; Almeida *et al.* 2010). These areas play an important role in biodiversity conservation in tropical forest fragments (Pardini *et al.* 2005).

Yet secondary forests are also affected by their neighbouring land uses: recent studies suggest that secondary forest areas adjacent to areas of high deforestation often suffer a similar fate. (Soler *et al.* 2014; Jakovac *et al.* 2015).

Annual crops thought of by many as a key force for deforestation in the Amazon, covered circa 5% of the area mapped as deforested by PRODES in 2008. This result differs from Morton *et al.* (2006), which suggested that soybeans crops were one of the major deforestation vectors in Mato Grosso, between 2001 and 2004. Part of this difference can be explained by the temporal limitation, 2001 up to 2004, when deforestation data indicated a high rate of forest conversion (INPE 2015). But this period is also marked by a sharp change in the soybean market, caused mainly by the establishment of the soy moratorium by the major traders and the implementation of the Rural Environmental Registry (Rudorff *et al.* 2011; Gibbs *et al.* 2014;). All these types of dynamics underscore the importance of monitoring changes over time within of the Brazilian Amazon so as to assess the advance of agriculture within the Amazon biome in face of other drivers for land use change.

The agreement index between the map obtained by TerraClass and the validation points using SPOT data was 76.64% and the Kappa index 0.67. Over half the classification errors (75 of 125) as consequence of the split of the pasture land use into three categories. These classification errors can be attributed to the difficulty in distinguishing among these classes, as all pasture categories exhibit similar ground structure (grasses, weeds and shrubs), and differ primarily in the relative prevalence of these components. As pointed out by Powell *et al.* (2004), classifying areas by degree of transition frequently involves significant subjective judgment and possibly disagreement even among experienced interpreters. When some time interval rests between mapping and validation, even as little as few months of difference can result in conflicting classification of pastures between the analysis and validation, since distinct management, stocking, or even changes in the rainfall can affect the area's condition. To mitigate this problem in future analyses, detailed spectral characterization of pasture types may help minimize classification errors. Nevertheless TerraClass classification was able to efficiently distinguish major land use and land cover classes. When pasture classes are merged into one single class the agreement rise to 89.7% and the Kappa index increases to 0.79.

CONCLUSIONS

The results of TerraClass 2008 Project showed the predominance of pastures (62%) and secondary vegetation (21%) among the Amazonian post-deforestation landscape. At the same time, annual crop cultivation, historically referred as one of the most important vectors of deforestation, was present in less than 5% of the deforested areas in the Brazilian Legal Amazon in 2008. In general, results from validation with high spatial imagery (SPOT 5) indicate that the TerraClass classification methodology, using MODIS and Landsat data, appears reasonably accurate for the discrimination of the major land use and land cover classes in the Amazon region. Further editions of TerraClass Project opens up new opportunities for scientists and policy makers to track changes in land cover and land use in the Brazilian Amazon at high resolution, as well as to assess the initial drivers of deforestation and monitor how deforestation dynamics may also be changing over time and space.

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