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Land cover changes in the Brazilian Cerrado and Caatinga biomes from 1990 to 2010 based on a systematic remote sensing sampling approach

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A B S T R A C T

The main objective of our study was to provide consistent information on land cover changes between the years 1990 and 2010 for the Cerrado and Caatinga Brazilian seasonal biomes. These areas have been overlooked in terms of land cover change assessment if compared with efforts in monitoring the Amazon rain forest. For each of the target years (1990, 2000 and 2010) land cover information was obtained through an object-based classification approach for 243 sample units (10 km × 10 km size), using (E)TM Landsat images systematically located at each full degree confluence of latitude and longitude. The images were automatically pre-processed, segmented and labelled according to the following legend: Tree Cover (TC), Tree Cover Mosaic (TCM), Other Wooded Land (OWL), Other Land Cover (OLC) and Water (W). Our results indicate the Cerrado and Caatinga biomes lost (gross loss) respectively 265,595 km^2 and 89,656 km^2 of natural vegetation (TC + OWL) between 1990 and 2010. In the same period, these areas also experienced gain of TC and OWL. By 2010, the percentage of natural vegetation cover remaining in the Cerrado was 47% and in the Caatinga 63%. The annual (net) rate of natural vegetation cover loss in the Cerrado slowed down from −0.79% yr^{-1} to −0.44% yr^{-1} from the 1990s to the 2000s, while in the Caatinga for the same periods the rate increased from −0.19% yr^{-1} to −0.44% yr^{-1}. In summary, these Brazilian biomes experienced both loss and gains of Tree Cover and Other Wooded Land; however a continued net loss of natural vegetation was observed for both biomes between 1990 and 2010. The average annual rate of change in this period was higher in the Cerrado (−0.6% yr^{-1}) than in the Caatinga (−0.3% yr^{-1}).

Introduction

Consistent information on vegetation cover, and more specifically on forest cover, and its dynamics over time is critical for managing and protecting forest and supporting related political decisions. In South America, historically, most of the efforts for estimating forest cover changes have been focused on the tropical rain forests, with far less attention dedicated to the less humid seasonal regions (Pennington, Lewis, & Ratter, 2006; Portillo-Quintero & Sánchez-Azofeifa, 2010; Santos, Leal, Cortez, Fernandes, & Tabarelli, 2011). Although the Neotropics encompass considerable areas of savannas and seasonally dry tropical forests (SDTF), research and conservation efforts focussing on these tropical seasonal ecosystems are still very limited (Barreda-Bautista, López-Caloca, Couturier, & Silván-Cárdenas, 2011; Pennington et al., 2006).

The Cerrado and Caatinga Brazilian biomes, which together cover an area of circa 2.8 million km^2 (IBGE, 2004) or approximately 35% of the Brazilian territory, are placed among the most endangered eco-regions on Earth due to high rates of conversion and few protected areas (Hoekstra, Boucher, Ricketts, & Roberts, 2004). The Cerrado (Brazilian savannas) is the second most extensive biome in South America (Sano, Rosa, Brito, & Ferreira, 2010) and has been identified as one of the world's biodiversity hotspots (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000). Since the

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1970s, this region has suffered heavy losses of natural vegetation due to agricultural expansion (Fearnside, 2001; Silva, Farinas, Felfili, & Klink, 2006). According to Pennington et al. (2006) the areas cleared in the Brazilian Cerrado are greatly exceeding the clearing of the Amazon rain forest. The Caatinga is a heterogeneous biome consisting of a mosaic of shrubs and areas of seasonally dry forest (Leal, Silva, Tabarelli, & Lacher, 2005; Santos et al., 2011), occurring mainly under semi-arid conditions. According to Queiroz (2006), the Caatinga encompasses the largest areas of SDTF in South America. Regardless of the land cover changes and of the unsustainable use of its land resources, the Caatinga has been indicated as one of the least known and most neglected of Brazilian biomes (MMA, n.d.; Santos et al., 2011).

The current understanding of land cover changes in the Cerrado and the Caatinga biomes is still limited. The Brazilian territory is divided into six continental biomes (Amazônia, Cerrado, Caatinga, Mata Atlântica, Pantanal and Pampa) (IBGE, 2004), from which only the Amazônia and Mata Atlântica biomes have been targeted by permanent monitoring initiatives since the 1980s, such as PRODES (Monitoring Brazilian Amazon Forest by Satellite), DETER (Detecting Deforestation in Real Time) for the Amazon or the SOS Mata Atlântica to monitor deforestation over the Mata Atlântica biome (MMA, 2014). Although some study cases have focused on assessing land cover changes in the Cerrado and Caatinga biomes based on medium-resolution satellite imagery (Brannstrom et al., 2008; Coelho et al., 2014; Grecchi, Gwyn, Bénié, Formaggio, & Fahl, 2014), only recently biome-scale mapping for these biomes has been carried out by the PROBIO program (Projeto de Conservação e Utilização Sustentável da Diversidade Biológica), in which the percentage of vegetation cover was estimated using Landsat imagery from year 2002 (MMA, 2014). Subsequently, using PROBIO as a baseline, the project *Monitoramento do Desmatamento dos Biomas Brasileiros por Satélite* (PMDBBS) mapped newly cleared areas for 2008 and 2009 for both biomes and for 2010 for the Cerrado biome only. The project estimated deforestation rates for the 2002–2008, 2008–2009 and 2009–2010 periods (MMA, 2009, 2010, 2011a, 2011b, 2011c). PMDBBS has assessed only gross vegetation losses, since vegetation regrowth was not considered. Moreover, there are no data available on annual deforestation rates prior to 2002 for the two biomes (MMA, 2011).

Other initiatives for estimating and monitoring land cover change in these regions include the study of Mantovani and Pereira (1998). They assessed the Cerrado biome's “degrees of anthropization” based on Landsat imagery, mostly from 1992/1993, finding that there were approximately 35% of undisturbed areas, 35% of disturbed Cerrado vegetation (e.g. natural grasslands mixed with pasture) and 30% of heavily disturbed Cerrado vegetation (e.g. intensive agriculture, urban areas). Their results have been reported as difficult to use either because of irreproducible categories (Brannstrom et al., 2008) or for the lack of spatial information (Sano, Rosa, Brito, & Ferreira, 2007). Machado et al. (2004) assessed the entire biome using a MODIS image mosaic (at 1 km × 1 km spatial resolution) for the year 2002 and estimated that approximately 55% of the original (natural) Cerrado vegetation were already converted to other land cover. For the Caatinga, Castelletti, Silva, Tabarelli, and Santos (2003) focused on answering the question “how much of the Caatinga is still remaining?” by assessing the 1:5,000,000 scale Brazilian vegetation map (IBGE, 1993) within the limits of the biome, combined with other auxiliary data (e.g. road maps).

The main initiatives for estimating and monitoring land cover change in the Cerrado and Caatinga biomes are summarized in Table 1.

Many studies claim these biomes have suffered heavy losses (Castelletti et al., 2003; Klink & Machado, 2005; Machado et al., 2004). However, considerable vegetation gain in these areas has also been reported. Aide et al. (2012), for example, assessed the deforestation and reforestation in Latin America and the Caribbean region between 2001 and 2010 using 250-m Moderate Resolution Imaging Spectroradiometer (MODIS) data anddetected that Brazil has experienced both loss and gain of woody vegetation, the gain occurring mainly in the dry areas of northeast Brazil (Caatinga biome). Redo, Aide, and Clark (2013), assessed land cover changes in the Brazil's “dryland ecoregions” (Cerrado, Caatinga and Mato Grosso seasonal forests) based on MODIS data from 2001 to 2009, and reported increases in woody vegetation both in the Cerrado and the Caatinga biomes. However, these dynamics of loss and regrowth of natural vegetation has neither been assessed through medium resolution satellite imagery (e.g. Landsat (E) TM), nor prior to year 2000.

While remote sensing technology has been the major provider of cost-effective, high-quality datasets for land surface monitoring in the past decades (Lunetta, Ediriwickrema, Johnson, Lyon, & McKerrow, 2002), mapping large forest areas continuously (“wall-to-wall”) with medium to high resolution satellite imagery (e.g. with 30 m × 30 m resolution Landsat images) is still challenging and also often unrealistic for large areas due to the lack of resources. Lately, an attempt of global wall-to-wall mapping of tree cover and tree cover changes (between the years 2000 and 2012) has been made by Hansen et al. (2013). However, the usability and the consistency of the results is under question in particular for the seasonal tropical domain (Bellot, Bertram, Navratil, Siegert, & Dotzauer, 2014; Hansen et al., 2014; Tropek et al., 2014). Sampling approaches have been proposed (Mayaux et al., 2005; Ridder, 2007) and used as an alternative, implying advantages such as reducing costs and efforts while providing accurate estimates of forest cover and forest cover changes (Achard et al., 2002; Hansen et al., 2008; Potapov et al., 2011). In this context, the aim of the present work is to provide consistent information on historical and recent vegetation cover changes in the Brazilian Cerrado and Caatinga biomes based on the analysis of Landsat imagery acquired over a systematic sample of 10 km × 10 km size units.

Materials and methods

Study area

The Cerrado and Caatinga biomes are seasonal ecosystems characterized by distinct dry and wet seasons. They are located in the centre and the Northeast of Brazil, covering nearly 35% of the Brazilian territory (Fig. 1).

The Caatinga biome occupies an area mostly coincident with the region called “Brazilian semi-arid”, which is described as the most biodiverse and the most populated semi-arid region in the world (MMA, 2011). The Caatinga vegetation ranges from the deciduous low shrub to small patches of tall dry forests, often fragmented, with a height of up to 20 m (Prado, 2003). This region receives from 240 to 1500 mm annual rainfall, but mostly it receives less than 750 mm/year (Leal et al., 2005; Prado, 2003). Rainfall in this region is extremely irregular, in both its temporal and geographical distribution; usually more than 75% of the total annual rainfall occurs within three months (Prado, 2003). The annual variations are large; droughts can last for years (Leal et al., 2005). The climatic conditions of the Cerrado are less extreme compared to those of the Caatinga: the rainy season is longer (6–7 months) and the overall amount of rain is higher with 800–2000 mm/year (Ratter, Ribeiro, & Bridgewater, 1997). The typical Cerrado vegetation (outside the often tall and dense evergreen gallery forests) ranges from closed or open canopy deciduous and semi-deciduous forest with a

Table 1
Biome scale Initiatives for estimating and monitoring land cover changes in the Cerrado and Caatinga biomes.

Publication/institution	Area extent	Objective/temporal aspect	Dataset used	% of the Biome remaining/converted	Observation
Mantovani and Pereira (1998)	Cerrado and Pantanal	Estimate of the "degrees of anthropization"	144 LANDSAT scenes (1992/1993)	~35% of Undisturbed Cerrado	Preliminary study; lack of spatial information
Machado et al. (2004)	Cerrado	Estimates of Cerrado loss	MODIS 2002 (1 × 1 km)	54.9% Converted by 2002	Authors mentioned over estimation, no field validation
PROBIO (MMA, 2007; MMA, n.d.)	Cerrado and Caatinga	Biome-scale mapping Year 2002	LANDSAT	Remaining Cerrado: 60.5% Caatinga: 62.7%	
SIAD (Rocha, Ferreira, Ferreira, & Ferreira, 2011)	Cerrado	Annual mapping of cleared areas from 2002 to 2012	MODIS	3.6 Million ha cleared between 2002 and 2009	
PMDBBS	Cerrado and Caatinga	Deforestation mapping from 2002–2008, 2009, and 2010	LANDSAT	Remaining Cerrado: 2002: 55.7% 2010: 50.8% Caatinga: 2002: 55.7% 2009: 53.4%	
Castelletti et al. (2003)	Caatinga	Assessing the areas altered by anthropic activities	Vegetation map 1:5,000,000 + road map	~28% Converted (increasing to ~45% when considering the roads impact)	Preliminary

SIAD: Sistema Integrado de Alertas de Desmatamentos.
PMDBBS: Projeto de Monitoramento do Desmatamento dos Biomas Brasileiros por Satélite.
PROBIO: Projeto de Conservação e Utilização Sustentável da Diversidade Biológica Brasileira.

maximum height of 15 m to (closed or open) shrub to natural grasslands (Eiten, 1977; Ratter et al., 1997).

Sampling design and processing

The overall process was developed as part of the Tropical Ecosystem Environment Observation by Satellite (TREES-3) project, carried out by the European Commission's Joint Research Centre (JRC), and consists in a systematic sampling grid with samples at every full degree confluence point of latitude and longitude on land in the pan-tropics (covering 106 countries), with each sample unit covering an area of 10 km × 10 km. The sampling was designed in conjunction with the Food and Agriculture Organization (FAO) of the United Nations in the context of the Forest Resources Assessment 2010 Remote Sensing Survey (FRA 2010 RSS) (FAO & JRC, 2012; Mayaux et al., 2005; Ridder, 2007). The Cerrado and Caatinga biomes are covered by 175 and 68 sample units, respectively (altogether 243 sample units).

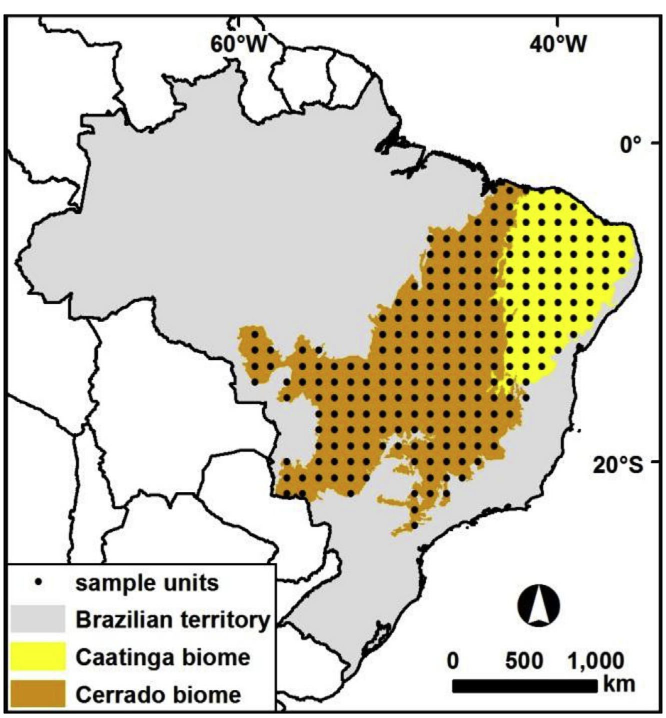

Fig. 1. Study area: Cerrado and Caatinga biomes in Brazil, with the distribution of the sample units.

For each sample unit, ortho-rectified (E)TM Landsat images were acquired at no cost from the Global Land Survey (GLS) archives, created and made available by the United States Geological Survey (USGS), which provide the best Landsat imagery in terms of radiometric quality and cloud cover and the most accurate images in terms of geometric quality (Gutman, Huang, Chander, Noojipady, & Masek, 2013). For each sample unit, four images were selected with the lowest possible cloud cover and as close as possible to the target dates of 30 June for the years 1990, 2000, 2005 and 2010. Year 2005 was included in order to obtain more detailed temporal information during the more recent study decade. Where GLS data was unavailable, of bad quality (e.g. Landsat 7 SLC-off data) or cloudy for the area of the sample units, alternative satellite scenes were acquired from the Landsat archives of USGS or of the Brazilian National Space Research Institute (INPE) (Beuchle et al., 2011). The range of image acquisition dates was 1986–1993, 1999–2003, 2004–2007, and 2009–2011 for the years 1990, 2000, 2005 and 2010 respectively. The maximum average distance to target date was 9 months for year 2000, the minimum was just under four months for year 2010. Of the altogether 972 images (243 sample units × 4 epochs), only 9 images contained some cloud cover; the highest percentage of area covered by cloud and cloud shadow in an image was 16%, the average area covered by cloud and cloud shadow in the cloudy images was 8%.

The selected images underwent an extensive pre-processing, including image geo-location check, conversion to top-of-atmosphere reflectance, cloud-masking, de-hazing and image normalization on basis of pseudo-invariant features (Bodart et al., 2011). For multi-temporal image analysis a good geometric match of the images is fundamental (Jensen, 2005). In this context, the geo-location of some of the images had to be enhanced. For this purpose, the Landsat ETM image (from the year 2000 epoch) was defined as 'master image', in consequence the 'slave image', consisting mostly in Landsat 5 imagery, was shifted until a correct overlay with the master image was achieved.

For each sample unit, the pre-processed images from the four 'epochs' (years 1990, 2000, 2005 and 2010) went through a multistep segmentation using eCognition software (Trimble©), followed by an object-based classification process based on membership functions defined by a collection of spectral signatures taken across the tropical belt (Raši et al., 2011, 2013). Objects were classified into five land cover classes (Table 2); the Tree Cover class was defined in compatibility with the definition of forest by FAO (FAO, 1998). Examples of the Landsat imagery and land cover classification results are shown in Fig. 2. The resulting classified objects, with a minimum mapping unit (MMU) of 5 ha, underwent an intensive process of correction of the land cover information assigned for each target year (Eva et al., 2012).

The class Tree Cover Mosaic was used for spatial objects containing patches of tree cover varying from 30% to 70% of coverage within the object. In the statistical analysis, an object labelled as Tree Cover Mosaic was considered as 50% Tree Cover, defined by the average of the upper and lower percent limit. The two biomes encompass heterogeneous landscapes predominantly composed by a mix of shrubland, woodland and grassland physiognomies, occurring in different proportions throughout the biome (Sano & Ferreira, 2005); consequently, the remaining 50% of TCM objects were considered as Other Wooded Land. As the overall area covered by objects of the class Tree Cover Mosaic is relatively small (ca. 5% for the Cerrado biome), the error introduced during the statistical analysis by defining an object labelled as TCM as 50% covered by Other Wooded Land (rather than Other Land) is very small. The Tree Cover and Other Wooded Land are aggregated together as "natural vegetation" when compared with land cover estimates from Brazilian datasets like PROBIO and PMDBBS.

Statistical analysis

The land cover and land cover change information available for all sample units is used to produce statistical estimates for the whole area of interest. Considering that very few satellite images were acquired at the exact same date of their respective epochs, the land cover (change) information of each sample unit is first linearly 'normalised' (as best approximation) to the target dates of 30 June for years 1990, 2000, 2005 and 2010 to produce land cover statistics. For this purpose we assume that the detected land cover changes occurred linearly over time. It is also necessary to correct for the non-equal probability sampling, i.e. for the densification of the systematic sample with increasing distance from the Equator. This was accounted for by introducing a weighting factor for each sample unit, defined as the cosine of the latitude of the sample unit centre. Finally, the Horvitz–Thompson Direct Expansion Estimator (Brink & Eva, 2009; Särndal, Swensson, & Wretman, 1992) was used to extrapolate the sample statistics to the full areas of interest (Cerrado and the Caatinga biomes). The biome statistics are based on the total biome areas of 2,038,520 km^2 for the Cerrado and 826,411 km^2 for the Caatinga, according to CSR/IBAMA (2014).

Table 2
Land cover classes used in this study.

Class name	Class description
Tree cover (TC)	Objects covered by 70–100% of trees, where trees are defined as plants higher than 5 m and with a wooden stem, and tree canopy density is greater than 30%
Tree cover mosaic (TCM)	Objects covered by 30–70% of trees
Other wooded land (OWL)	Objects covered with more than 50% of plants lower than 5 m with one or more wooden stem(s)
Other land cover (OLC)	Land not covered by the TC, TCM or OWL classes, comprising natural grassland, agricultural land, built-up areas, bare soil and rock
Water (W)	Rivers and lakes

Consistency assessment

Field data or high resolution imagery are usually required for assessing the quality of land cover maps produced from Landsat-type imagery (Liu, 2008; Strahler et al., 2006). Due to the lack of appropriate data for our study period, we opted for a consistency assessment, based on the assumption that a series of measurements over a small subset and carried out by an independent interpreter using the same method should produce similar or more accurate results (Monge, Marco, & Cervigón, 2002).

For a subset of 49 sample units, a consistency assessment was carried out for the land cover maps produced for years 1990, 2000 and 2010, comparable to the approach used by Bodart et al. (2013). This subset was randomly selected from the global systematic sample in the context of the validation exercise of the Climate Change Initiative's Land Cover Project (Bontemps et al., 2012). For each selected sample unit, 81 points regularly distributed at 1 km linear distance across the 10 km × 10 km sample unit were considered for selecting polygons for land cover labelling by an independent interpreter, based on the same Landsat imagery used for the production of the land cover maps. Two sets of polygons were considered: the first set was selected based on five points, one in the centre of the sample unit and the others closest to the sample unit's corners. This set was designed for the 'land cover' assessment, as only a very small percentage of the polygons would be likely to contain changes. The second set of polygons (based on the remaining 76 points) was designed for the consistency assessment of land cover changes. The polygons were only selected if a land cover change was identified in at least in one of the two decades. Altogether 944 polygons were used for the consistency assessment, representing ca. 1% of all objects within the area of interest, thereof 255 polygons in the first set and 699 polygons with a land cover change.

Statistical estimates of land cover and land cover change

Land cover changes were estimated by assessing the matrices of change (see Table 3), for the two decades 1990–2000 and 2000–2010, and, in addition, for the half decades 2000–2005 and 2005–2010, in order to get more detailed information on the land cover change dynamics during the second decade. Tree Cover (TC) loss, for example, was calculated as 100% of the TC converted to Other Wooded Land (OWL), Other Land Cover (OLC) or Water (W) plus 50% of TC converted to Tree Cover Mosaic (TCM) and 50% of TCM converted to OL, OWL or W, as shown in Table 3.

The annual rates of change were calculated according to Puyravaud (2003) using a formula derived from the Compound Interest Law:

$$r = \left(\frac{1}{t2 - t1}\right) * \ln\left(\frac{A2}{A1}\right) \quad (1)$$

where $A1$ and $A2$ are the land cover at time t_1 and t_2 (per year or percentage per year).

Results

Our results indicate that in 1990 approximately 24.2% of the Cerrado biome was covered by Tree Cover and 28.9% by Other Wooded Land, adding up to 53.1% of the Biome area as natural vegetation. In 1990, the percentage of Tree Cover and Other Wooded Land in the Caatinga biome was 18.8% and 48.6% respectively, or a total of 67.4% of natural vegetation cover (Table 4). By 2010, the percentage of Tree Cover and Other Wooded Land was

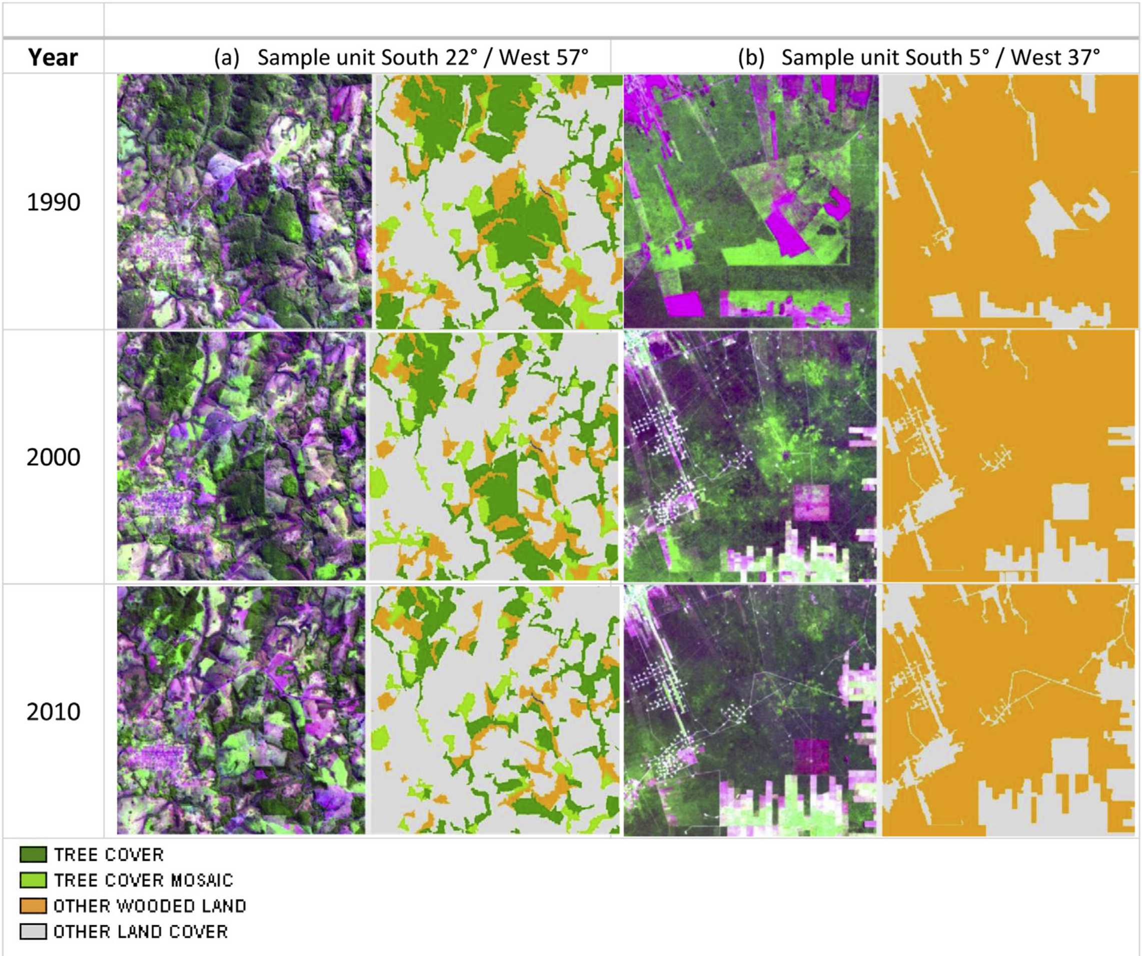

Fig. 2. Examples of Landsat imagery and land cover maps for two sample units, (a) in the Cerrado biome with clearing of forest and shrubland for pastures near Caracol municipality in southeast Mato Grosso do Sul State, (b) in the Caatinga biome with clearing of shrubland for agriculture and mineral oil extraction and with some regrowth of shrubland occurring between 1990 and 2000 in the Serra do Mel near Areia Branca municipality (Rio Grande do Norte State).

reduced to 21.1% and 25.9% respectively in the Cerrado and to 16.9% and 46.3% in the Caatinga.

The sample units that show the highest percentage of Tree Cover for the Cerrado in 2010 are located in the Northeast and the Southwest of the biome, whereas high percentages of OWL cover can be found in the centre and central North (Fig. 3). In the Caatinga Tree Cover is located in the higher elevations of the Western and Central–north Caatinga, OWL cover is high in the lowlands of the

Table 3
Calculation of land cover changes.

Year 1/Year 2	TC	TCM	OWL	OLC	Water	Total year 1
TC		0.5	1	1	1	TC
TCM	0.5		0.5	0.5 / 0.5	0.5 / 0.5	TCM
OWL	1	0.5		1	1	OWL
OLC	1	0.5	1			OL
Water	1	0.5	1			Water
Total year 2	TC	TCM	OWL	OL	Water	

Tree Cover (TC) loss
Tree Cover (TC) gain
Other Wooded Land (OWL) loss
Other Wooded Land (OWL) gain

Table 4
Percentage of natural vegetation cover and annual rates of (net) natural vegetation loss.

Biome	% of "Natural vegetation cover"[a]			Annual rates of change		
	1990	2000	2010	1990–2000	2000–2010	1990–2010
Cerrado	53.1	49.1	47.0	−0.79	−0.44	−0.61
Caatinga	67.4	66.1	63.2	−0.19	−0.44	−0.32

[a] Tree cover + other wooded land.

Centre and the North of the biome, as also observed by Rodal and Nascimento (2006). In the South of the Cerrado biome the proportion of Other Land Cover is very dominant, due to the conversion of a great part of the original Cerrado vegetation to agricultural lands (Sano, Barcellos, & Bezerra, 2000; Sano et al., 2010). In the Central West of the biome, the high percentage of Other Land Cover is mostly due to natural grasslands and pastures. For many areas in the Southern Caatinga (Northern Bahia State) the natural Caatinga vegetation has been converted to agricultural land, as stated by Vieira et al. (2013).

Land cover changes in the Cerrado

We estimated that the Cerrado lost approximately 117,870 km^2 of Tree Cover (gross loss) between 1990 and 2010. For the same period, we also detected 54,550 km^2 of Tree Cover gain (Table 5). The net loss of Tree Cover was higher from 1990 to 2000 (36,670 km^2) than from 2000 to 2010 (26,650 km^2) with the rate of net change slowing down from −0.77% yr^{-1} (1990–2000) to −0.60% yr^{-1} (2000–2010). Tree Cover and Other Wooded Land together ("natural vegetation cover") totalled 53.1% of the biome area in 1990, being reduced to 47.0% by 2010. Considering these two categories combined, the overall average annual rate of change from 1990 to 2010 was −0.61% (Table 4). Tree cover loss and gain for the two main time periods and each sample unit are shown in Fig. 4.

The assessment of changes from periods 2000–2005 and 2005–2010 evidences that net Tree Cover losses were more pronounced from 2000 to 2005 than from 2005 to 2010, dropping from 19,886 km^2 to 4710 km^2 ha respectively. In fact, the 2000–2005 period presented the highest rate of change (−0.89% yr^{-1}). Tree

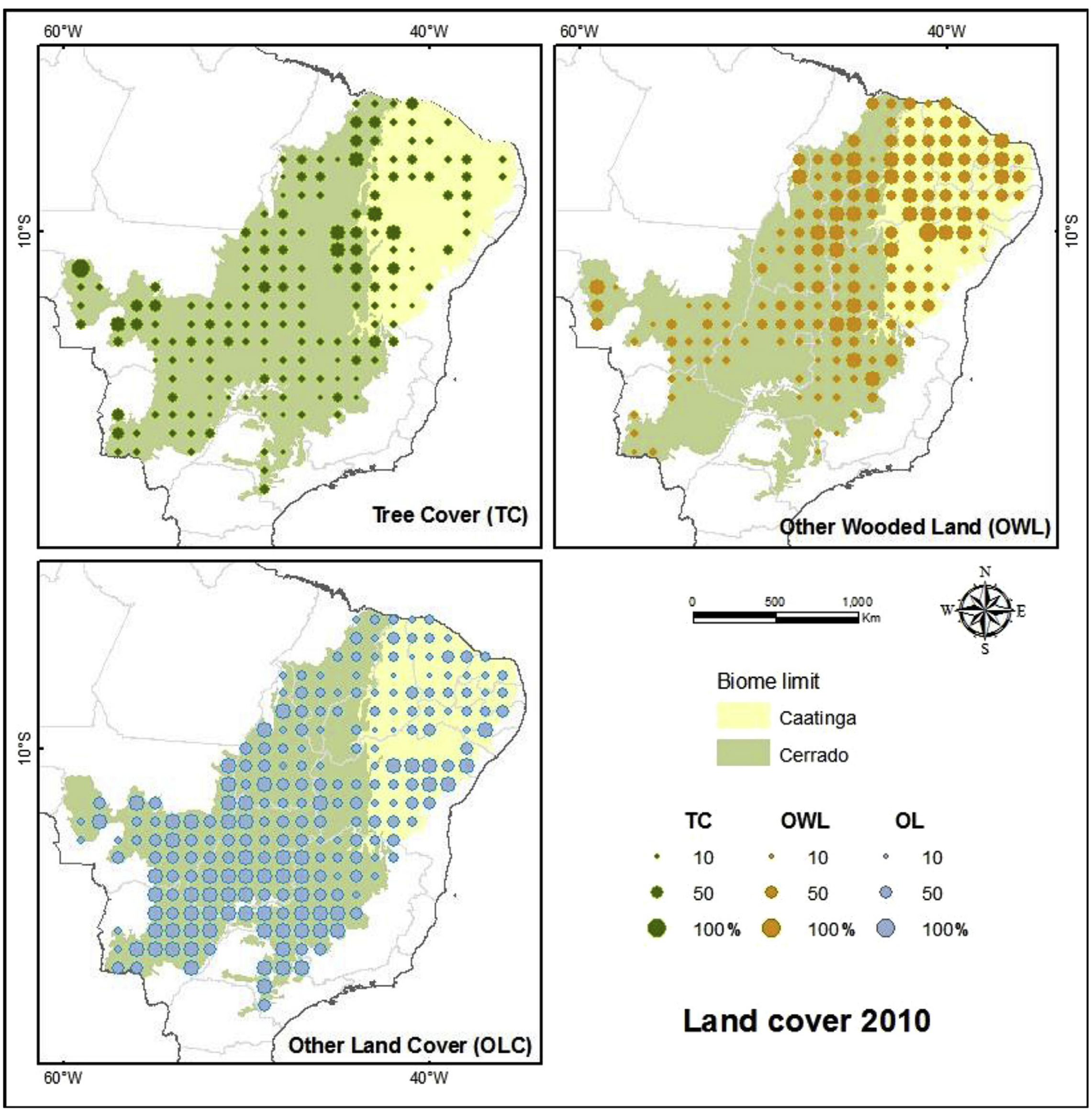

Fig. 3. Proportion of Tree Cover, Other Wooded Land and Other Land Cover for each sample unit, for year 2010.

Table 5
Estimates of tree cover and other wooded land total area and changes from 1990 to 2010.

	Land cover	Total area (km^2)			Changes from 1990 to 2000 (km^2)			Changes from 2000 to 2010 (km^2)		
		1990	2000	2010	Gross loss	Gross gain	Net loss	Gross loss	Gross gain	Net loss
Cerrado	Tree cover	492,540	455,880	429,235	62,930	26,260	36,670	54,940	28,290	26,650
	Other wooded land	589,430	544,270	528,255	87,430	44,680	42,750	60,295	43,880	16,415
Caatinga	Tree cover	155,349	147,676	139,777	13,636	5963	7673	11,700	3801	7899
	Other wooded land	401,409	398,539	382,872	32,385	28,199	4186	31,936	14,625	17,311

Cover gain was higher during the 2005–2010 period compared to the precedent half-decade. Gross and net losses of other wooded land also decreased from 1990–2000 to 2000–2010. However, the net loss of OWL was lowest from 2000 to 2005.

The yearly net loss of Tree Cover increased slightly from 1990–2000 to 2000–2005, and dropped significantly in the years from 2005 to 2010, while net loss of OWL dropped sharply during the period 2000–2005 in relation to the other time intervals (Fig. 5).

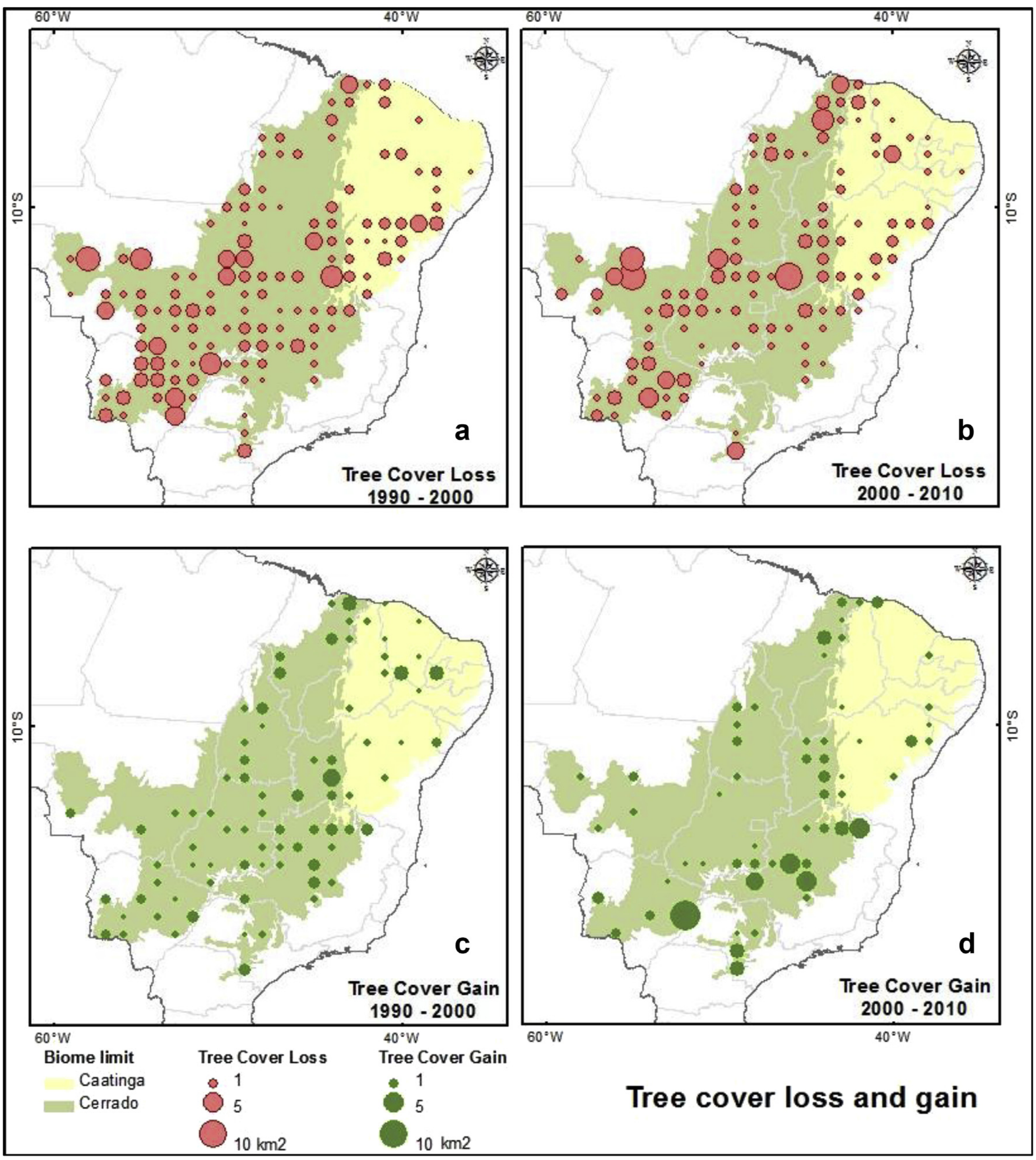

Fig. 4. Gross Tree Cover loss and gain per sample unit (in km^2), for the two time periods assessed: (a) Tree Cover loss from 1990 to 2000; (b) Tree Cover loss from 2000 to 2010; (c) regrowth/afforestation from 1990 to 2000 and (d) afforestation from 2000 to 2010.

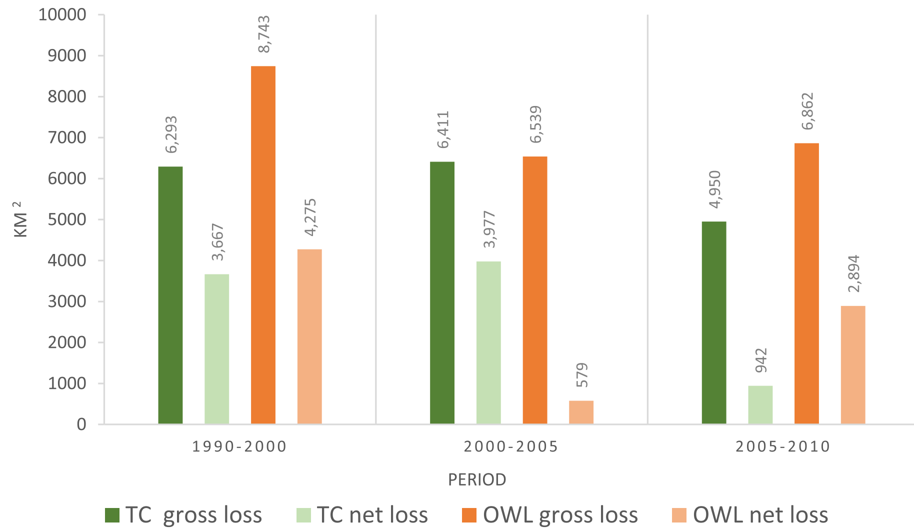

Fig. 5. Annual loss (gross and net) of Tree Cover and Other Wooded Land for the time intervals 1990–2000, 2000–2005, and 2005–2010 for the Cerrado biome (in km^2).

Land cover changes in the Caatinga

For the Caatinga our results show that the gross Tree Cover loss between 1990 and 2010 was 25,335 km^2. In the same period we also detected 9764 km^2 of Tree Cover gain, and consequently an overall net loss of 15,571 km^2 over the two decades which standing for an annual rate of net forest cover change of −0.53%. The net loss of Tree Cover was similar for the two main periods (7673 km^2 from 1990 to 2000 and 7899 km^2 from 2000 to 2010). The gross loss of OWL from 1990 to 2010 was 64,321 km^2, with an OWL gain of 42,824 km^2. Gross OWL loss was similar for the two main periods assessed (1990–2000 and 2000–2010), while the gain was considerably higher in the first decade. In consequence, the net OWL loss increased from 4186 km^2 to 17,310 km^2 for 1990–2000 and 2000–2010 respectively (Table 5).

Annual Tree Cover gross and net losses show a more or less stable pattern of change over the three study periods (Fig. 6). On the other hand, annual gross loss of OWL shows a small decrease from the 1990–2000 period to the 2000–2005 period and increases again in the following period (2005–2010), while the annual net losses show increasing rates.

In the Caatinga the area of “natural vegetation” (TC + OWL) decreased from 67.4% to 63.2% between 1990 and 2010, or a mean net annual rate of change of −0.32% (Table 4). However, the annual rate was lower in the first decade (1990–2000), −0.19% yr^{-1}, increasing to −0.44% yr^{-1} in the following decade, mainly because changes in Other Wooded Land.

In summary, from 1990 to 2010, the Cerrado and the Caatinga biomes lost together 143,205 km^2 of Tree Cover and 212,046 km^2 of Other Wooded Land (gross loss). In the same period, these biomes also experienced gain of these land cover categories, totalling 64,314 km^2 and 131,384 km^2, respectively. The global trend observed for both biomes was a continued loss of natural vegetation in the two study decades. In 1990, “natural vegetation cover” was the predominant land cover type in the Cerrado (53.1%). However, by year 2010, the percentage of “natural vegetation” cover went down to 47.0%. In the Caatinga the percentage of natural vegetation cover remained higher than Other Land Cover during the two decades.

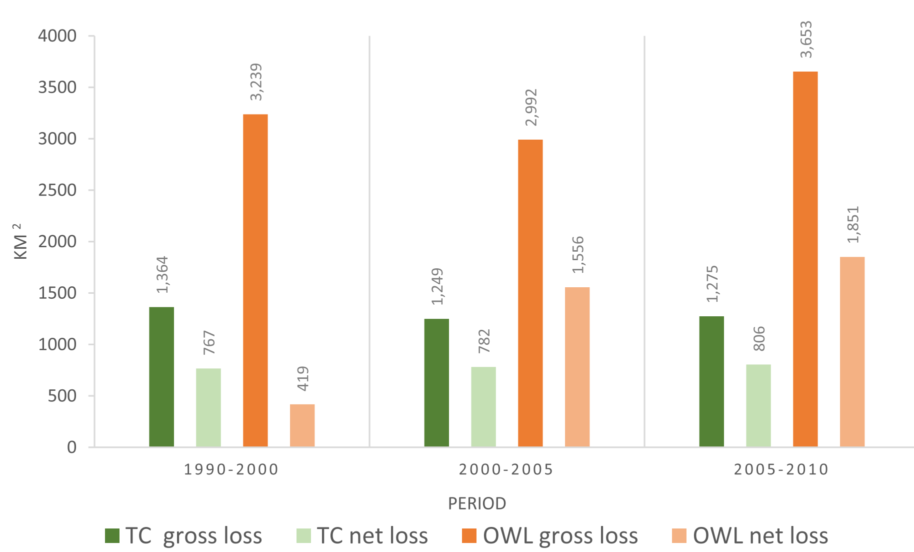

Fig. 6. Annual loss (gross and net) of Tree Cover and other wooded land for the 1990–2000, 2000–2005 and 2005–2010 time periods for the Caatinga biome.

Discussion

The results of our consistency assessment show that the overall agreement between the land cover maps for the different years, obtained through the remote sensing classification approach and the interpretation from independent experts varied from 85 to 90% considering a broader legend of natural vegetation (combined TC and OWL) and Other Land Cover. When all land cover classes are considered the overall agreement is lower (from 63% to 78% depending upon the classes). This lower agreement is mainly due to the fact that differentiating Tree Cover from Other Wooded Land, with a threshold of 5 m height is difficult, especially for heterogeneous – seasonal landscapes like the Cerrado and the Caatinga, with generally lower tree heights (Sampaio & Silva, 2005) e.g. compared to the Amazon biome.

We compare our results with those of PROBIO (MMA, 2007; MMA, n.d.), and PMDBBS (MMA-IBAMA, 2009, 2010, 2011a, 2011b, 2011c) which are the most recent, official national biome scale estimates for the Brazilian biomes (Table 6), and with the Global Forest Cover product by Hansen et al. (2013) (Fig. 7 and Table 7). For the Cerrado, we estimate that natural vegetation (TC + OWL) covers 49.1% of the biome in 2000. PROBIO estimate of the percentage of natural vegetation remaining in 2002 for the Cerrado biome is 60.5%. IBAMA reassessed PROBIO's data by accounting for the 2–40 ha deforested areas not considered by PROBIO and reported 55.7% of remaining natural vegetation in 2002. The discrepancies between PROBIO and our results can be in part explained by what is considered as natural vegetation. According to Sano et al. (2010), PROBIO mapping result includes about 8 million hectares of natural grasslands in this category. On the other hand, in our study all grasslands were classified as Other Land Cover and therefore not included in the natural vegetation class. For the Caatinga, PROBIO estimate of percentage of natural vegetation remaining in 2002 is 62.7% when our estimate of percentage of natural vegetation remaining in 2000 is 66.1%, dropping to 63.2% in 2010. According to MMA-IBAMA (2010), the remaining vegetation for the Caatinga in 2002 was 55.7%, dropping to 53.4% in 2009 (MMA-IBAMA, 2011a).

As illustrated in Fig. 7a and b, according to MMA-IBAMA (2009, 2011b), the deforestation rates in the Cerrado and the Caatinga are decreasing: in the Cerrado from 14,200 $km^2\ yr^{-1}$ between 2002 and 2008 to 6,469 $km^2\ yr^{-1}$ between 2009 and 2010, and in the Caatinga from 2763 $km^2\ yr^{-1}$ from 2002 to 2008 to 1921 $km^2\ yr^{-1}$ from 2008 to 2009. Lapola et al. (2013) called the attention to the fact that deforestation rates in the Cerrado were decreasing in the second half of the last decade, following the trend observed in the Amazon biome, according to PRODES estimates (INPE, 2014). In our study (gross) losses of natural vegetation in the Cerrado decreased from 12,949 $km^2\ yr^{-1}$ from 2000 to 2005 to 11,812 $km^2\ yr^{-1}$ from 2005 to 2010. On the other hand, in the Caatinga, the annual gross loss of natural vegetation increased slightly from 2000–2005 (4240 $km^2\ yr^{-1}$) to 2005–2010 (4928 $km^2\ yr^{-1}$).

Regarding the percentage of forest cover, PROBIO reported (Sano et al., 2010) that the Cerrado had in 2002 40.3 million ha of forestlands, 3.16 million ha of forest plantation (mainly Eucalyptus), and 6.97 million ha of secondary regrowth, which add up to approximately 24.5% of the biome area. In our study, for year 2000, Tree Cover was estimated in 22.4%. For the Caatinga, this comparison was not possible because PROBIO adopted a combined legend making it impossible to separate Tree Cover from other classes.

We also compared our results for year 2000 with the study carried out by Hansen et al. (2013), focussing on our areas of interest (Fig. 7 and Table 7). In Hansen's study, trees are defined as "all vegetation taller than 5 m in height" and the results are reported as percentage of Tree Cover per pixel. However, what is considered "forest" is not clearly stated (Achard et al., 2014). If we consider pixels from Hansen's product with a Tree Cover percentage of 30% and higher as forest pixels – in accordance with the TREES-3 approach (Achard et al., 2014; Eva et al., 2012) - this would make up 35.6% of 'forests' in the Cerrado biome in 2000. A good agreement between our results and the Hansen et al. product was obtained when considering forest cover in Hansen's product as pixels having more than 55% Tree Cover. If our class Other Land Cover is compared to the pixels having 0% of crown cover in Hansen's study, the results are quite similar: our study contains 50.1% of the total area and Hansen's 53.8%. For the Caatinga, in year 2000 Tree Cover was estimated in 17.8% in our study, compared to 25.9% in Hansen's study (considering pixels with ≥30% of Tree Cover). A good agreement of both studies was observed when the forest definition in Hansen's product was considered as pixels with more than 45% of Tree Cover. For Other Land Cover the discrepancies are higher. The amount of pixels with 0% of canopy cover in Hansen's study corresponds to 62.9% of the biome area in 2000, while our Other Land Cover class covers 33.2% of the biome area. The forest areas for both biomes in Hansen's study are considerably larger compared to our results. This can be explained by the differences in the legends of the two studies: while we have a specific class called 'Other Wooded Land', representing woody vegetation lower than 5 m, Hansen's study maps 'percent tree cover' (per pixel). Hansen's study will include many areas assigned as tree cover higher than 30%, which were mapped as 'Other Wooded Land' in our study.

Our estimates of total loss and gain for the Cerrado, for the year 2000–2010 period, are 54,940 km^2 (2.7% of the biome) and 28,290 km^2 (1.4% of the biome area) respectively. For the same area, but slightly different time period (year 2001–2012), Hansen et al. (2013) identified 93,335 km^2 of forest loss (~4.5% of the biome area) and 22,124 km^2 of forest gain (1.1% of the biome area). For the Caatinga from year 2000–2010 we mapped 11,622 km^2 of forest loss (1.4% of the biome area) and 3860 km^2 of forest gain (0.47% of the biome area). For this biome Hansen et al. (2013) results indicate 19,178 km^2 of Tree Cover loss (2.32% of the biome area) and 1825 km^2 of Tree Cover gain (0.2% of the biome area).

Table 6
Comparison with PROBIO and PMDBBS results.

	Land cover (%)						
		1990	2000	2002		2009/2010[a]	
		Current study	Current study	PROBIO	PMDBBS	PMDBBS	Current study
Cerrado	Converted areas	46.2	50.2	38.9	43.7	48.5	52.2
	Natural vegetation	53.1	49.1	60.5	55.7	50.8	47.0
Caatinga	Converted areas	31.9	33.3	36.3	43.4	45.9	36.0
	Natural vegetation	67.4	66.1	62.7	55.7	53.4	63.2

[a] PMDBBS assessment: 2009 for the Caatinga and 2010 for the Cerrado.

Fig. 7. Comparison of yearly net and gross losses of natural vegetation from this study, from MMA-IBAMA (2009, 2011b) and from Hansen et al. (2013) (Tree Cover losses) (a) for the Cerrado and (b) for the Caatinga.
Adapted from Lapola et al., 2013.

Conclusions

The Brazilian Cerrado and Caatinga biomes have been under increasing anthropic pressure since many years, but land cover and land cover change in these seasonal ecosystems have been largely overlooked up to now, especially if compared to the attention given to the Amazon region, resulting in an insufficient knowledge on historical transformation and present status of the natural vegetation cover in the area. In this context our study represents the first attempt to assess forest cover changes since the 1990s and to carry out a detailed analysis of land cover changes, including forest loss and gain. Our method, based on the analysis of systematic sampling of Landsat images allowed the assessment of land cover changes consistently over time while reducing the necessary resources and costs as compared to “wall-to-wall” mappings.

Our results show that these Brazilian biomes lost together (gross loss) 143,205 km^2 of forest and 212,046 km^2 of Other Wooded Land in past two decades. These areas also experienced considerable gains of Tree Cover (in part due to forest plantations) and Other Wooded Land. Overall, we identify a continued net loss of natural vegetation for both biomes during the two decades of assessment; however, their changes are following different patterns. The average annual rate of change is higher in the Cerrado (-0.6% yr^{-1}) than in the Caatinga (-0.3% yr^{-1}). Moreover, in the Cerrado, the percentage of remaining natural vegetation by 2010 is lower than the percentage of Other Land Cover. On the other hand, in the

Table 7
Comparison of our year 2000 results with Hansen et al. (2013) year 2000 percent tree cover map.

	Our study year 2000		Percent tree cover 2000 (Hansen et al., 2013)	
	Land cover classes	%	Land cover classes	%
Cerrado	Tree cover	22.4	>30% Tree cover	35.6
	Other wooded land	26.7	1–30% Tree cover	10.6
	Other land cover	50.2	0% Tree cover	53.8
	Water	0.8		
Caatinga	Tree cover	17.8	>30% Tree cover	25.9
	Other wooded land	48.1	1–30 % Tree cover	11.2
	Other land cover	33.2	0% Tree cover	62.9
	Water	0.6		

Caatinga, the percentage of natural vegetation remained higher than Other Land Cover over the decades.

Our study brings a new contribution to the knowledge and ongoing discussion on historic and current status of vegetation cover in the Brazilian Cerrado and Caatinga biomes in the past two decades. It provides key information to institutions concerned with land cover change assessment or environmental conservation on how much of the natural vegetation in the region has already been lost and on the pace of forest and woodland loss occurring in the different historical time periods. Especially the look back to the 1990s and the use of a consistent approach in terms of satellite imagery and techniques applied (multi-temporal object-based image analysis) makes it a valuable source of information as reference dataset for further environmental analysis. All land cover information and imagery will be made publicly available.

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