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Land use and land cover changes determine the spatial relationship between fire and deforestation in the Brazilian Amazon

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A B S T R A C T

An increased frequency of droughts is predicted for the Amazon rainforest in the 21st century, which, combined with deforestation, could exacerbate fire occurrence in the region. There is ample evidence of the association between fire use and deforestation in the land use and land cover change (LULCC) processes occurring in the Amazon region, but there are no studies on the actual spatial structuring and spatial association between these events. The present study evaluates the existence of such relationships through the use of remotely sensed data and spatial analysis techniques for an active deforestation frontier covering portions of the states of Rondônia and Mato Grosso in the Brazilian Amazon. A map of burn scars for the year 2005 was produced using a Linear Spectral Mixture Model (LSMM) transformation of Landsat Thematic Mapper (TM) images, with subsequent unsupervised classification and manual editing. Annual and aggregated maps of deforested areas up to 2005, produced by the Brazilian Amazon Deforestation Estimation Project (PRODES), were also used. The amount of burn scar occurrences inside both recent (2002–2005) and old (prior to 2002) deforested areas was then determined, and the spatial structure of both variables was assessed using Mantel tests for multiple aggregation scales. A partial Mantel test was also used to test the spatial correlation between burn scars and deforested areas, accounting for the existence of spatial structure. The results show that there is a significant spatial association between recent deforestation and the occurrence of fires. In addition, we identified a large amount of burned areas (~55%) within older deforested areas. These results highlight the following: 1) the direct role of fire in the land use and land cover change processes in the Brazilian Amazon, and 2) that fire also widely affects previously degraded vegetation, with significant implications for current estimates of forest fire-associated atmospheric carbon emission in the Amazon region.

Introduction

It is predicted that the Amazon, the world's largest rainforest, will be exposed to an increased frequency of drought in the 21st century (Li, Fu, & Dickinson, 2006). This drier climatic condition, when combined with ongoing deforestation processes, is likely to exacerbate fire use and occurrence in the Amazon (Aragão et al., 2007; Cochrane et al., 1999; Laurance & Williamson, 2001). Observations have already detected an increased fire occurrence in the Brazilian Amazon in recent years (Aragão & Shimabukuro, 2010).

The increased likelihood of fires is expected to negatively impact carbon stocks, biological diversity, and human health. Moreover, fires can potentially compromise the efficacy of emission reduction policies, such as Reducing Emissions from Deforestation and Degradation (REDD). Therefore, Amazonian fires are becoming increasingly important worldwide, not only for understanding and predicting their future environmental impacts on the Amazon biome, but also for implementing efficient climate change mitigation policies.

In the Amazon, fire is widely used for the initial conversion of extensive areas of natural vegetation into agricultural fields and pasture areas, and for the subsequent maintenance of deforested areas (Bowman, Amacher, & Merry, 2008; Cochrane et al., 1999; Giglio, Csiszar, & Justice, 2006; Kodandapani, Cochrane, & Sukumar, 2004; Sorrensen, 2008). Natural fire occurrences and accidental burning are extremely rare, with the vast majority of

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burning events resulting from deliberate fire use (Cochrane et al., 1999; Uhl & Kauffman, 1990).

However, land use dynamics and consequent fire patterns in the region may vary according to the price of agricultural commodities and due to various biophysical and socioeconomic factors, such as planned settlement, changes in infrastructure and accessibility, and policy changes (Brondizio & Moran, 2008; Carmenta, Parry, Blackburn, Vermeylen, & Barlow, 2011; Lorena & Lambin, 2009; Siren & Brondizio, 2009; Soler, Escada, & Verburg, 2009; Sorrensen, 2008). For instance, when commodity prices are high, land is generally converted for the purpose of intense agricultural use. This type of conversion, which is mostly aimed at international markets, uses heavy machinery for clearing with subsequent complete combustion of the deforested vegetation (Morton et al., 2006). However, when large economic incentives are absent, deforested areas tend to be used initially as pasture for cattle ranching, and clearing of the slashed vegetation may take up to three years. Finally, with few or nonexistent economic incentives, small landowners opt to establish pastures indefinitely, until better infrastructure and/or higher crop prices take place. In the last two cases, repeated burning has been used for pasture renewal and maintenance (Aragão & Shimabukuro, 2010; Morton et al., 2006).

Several studies have demonstrated a temporal association between fire and deforestation, in the Brazilian Amazon and elsewhere (Bowman et al., 2008; Bucini & Lambin, 2002; Morton et al., 2008; Sorrensen, 2000, 2004, 2008). This relationship is consistent with the fact that burning events in Amazonian forests are usually restricted to anthropogenic ignition sources. Theoretically, spatial patterns of fire occurrence in the region are expected to follow the patterns of forest conversion and subsequent land use. However, despite the extensive evaluation of the temporal links between fire and deforestation, as far as we know, there is a lack of studies focusing on the spatially explicit analysis of spatial structuring, the association between fire and deforestation, and the influence of past and present land use and land cover change (LULCC) on these patterns.

The present study, therefore, aims to use one of the most active deforestation frontiers in the southwestern Brazilian Amazon to test the hypotheses that fire and deforestation follow a similar spatial structure and that both variables are spatially correlated. Moreover, we aim to evaluate how LULCC patterns determine the spatial structure of fires in this region.

Methods

Study area

The study area is located between 9°15′S, 62°50′W and 10°40′S, 60°00′W, comprising the boundaries of the Landsat 5 TM scene 231/67. This area encompasses the southeast portion of the state of Rondônia and the northwest portion of the state of Mato Grosso in the Brazilian Amazon (Fig. 1). This area was selected because both states are currently under heavy anthropogenic pressure, with high rates of deforestation (INPE, 2009).

The predominant forest type in the region corresponds to dense tropical semi-deciduous forest on lightly undulating terrain (RADAMBRASIL, 1978). Heavy human occupation in the region started in the 1970's as a result of migratory policies introduced by the federal government and has occurred mostly along the BR-364 highway, where numerous colonization projects from the Brazilian Institute for Colonization and Agricultural Reform (INCRA) were established (Becker, 1990).

The study area is characterized by a diverse land ownership structure. Settlement projects coordinated by INCRA are predominant in the region concurrent with small properties and followed by intermediate and large properties (Escada & Alves, 2003). This structure leads to a mosaic of spatial configurations, a multiplicity of stakeholders (small, medium and large producers), and varying stages of occupation.

Data acquisition

A set of four Landsat 5 TM images was used in the present study, corresponding to scene 231/67 in the WRS-2 indexing system. These images were acquired on July 13, August 14, September 15 and October 01 of 2005—dates that encompass the burning season in the region. These images were georeferenced to an ortho-rectified Landsat TM scene obtained from the NASA GeoCover dataset (Gutman et al., 2008) using the WGS-84 datum and the

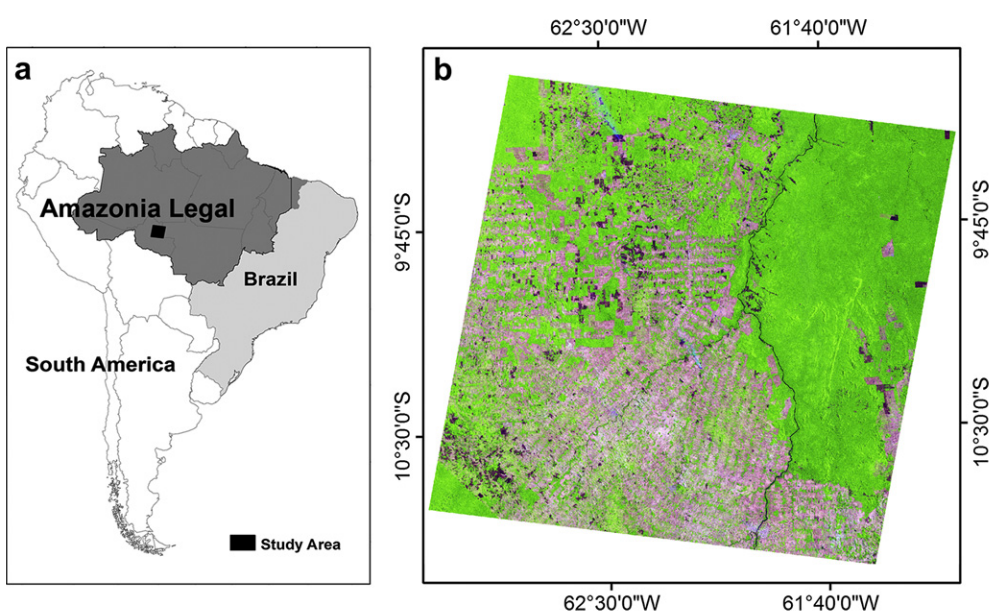

Fig. 1. a) Geographic location of the study area, corresponding to Landsat 5 TM scene 231/67, encompassing the southeast portion of Rondônia and the northwest portion of Mato Grosso in the Brazilian Amazon. b) Landsat scene 231/67, color composition R5G4B3, acquired on 10/01/2005, showing the ample occurrence of deforestation (pink areas) and burning (dark purple). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

UTM Projection, Zone 20. Because all further image processing was applied to each available image separately, atmospheric correction was deemed unnecessary (Song, Woodcock, Seto, Lenney, & Macomber, 2001).

In addition to the above images, a deforestation map was obtained from the Brazilian Amazon Deforestation Estimation Project (PRODES, http://www.obt.inpe.br/prodes/index.html, Fig. 2). The PRODES project has mapped deforestation in the Amazon region intermittently in analog form since 1988 and annually in digital form since 2000. The baseline used for deforestation assessment is the "vegetation domains" map produced by the RADAMBRASIL program in the 1970s. Because the RADAMBRASIL mapping was based on the combined analysis of airborne radar imagery and geomorphological, pedological and geobotanical field information, the resulting map can be considered a "potential" vegetation map (i.e., a map in which areas with altered vegetation cover were still classified as belonging to the original vegetation domain if evidence of its prior existence was found in the supporting data).

As with all PRODES maps, the map used in the present study was produced manually by experienced image interpreters using Landsat TM imagery, and it discriminates the following land cover classes: remaining Amazon Forest areas (hereupon referred to as "Forest"), cumulative deforestation up to 1997, cumulative deforestation between 1997 and 2000, and yearly deforestation from 2001 to 2005 (Fig. 2). Areas belonging to other cover types (e.g., savanna, scrubland, wetlands) in the baseline RADAMBRASIL map are collectively labeled as "Other", and deforestation is not assessed for these areas. More importantly, once an area has been labeled as "deforested" in the map, it will not be further revisited by the analyst in subsequent years, which implies that forest regeneration is not assessed by the current PRODES method.

Image classification and mapping

Burn scar mapping was performed by first applying a Linear Spectral Mixing Model (LSMM) to the acquired TM images. This procedure combines the original spectral information present in multispectral image bands, and it generates three components, or "fraction bands", labeled "Vegetation", "Soil" or "Shade" according to the predominant type of spectral contribution in each component (Shimabukuro, Dossantos, Lee, & Pereira, 1991). The method was chosen because burn scars are particularly well evidenced in the Shade fraction image. The LSMM transformation was applied to TM bands 3 (630–690 nm, red), 4 (760–900 nm, near infrared) and 5 (1550–1750 nm, short-wave infrared) of each of the acquired images.

The resulting fraction bands were then subjected to an object-based unsupervised classification algorithm, as implemented in the SPRING 5.0 software (Camara, Souza, Freitas, & Garrido, 1996). Image objects (polygons) were first generated by a region-growth segmentation algorithm, which takes similarity and size parameters as inputs. The similarity parameter defines a digital number (DN) threshold below which adjacent objects should be merged, and the size parameter defines a minimum area, in number of pixels, for individual objects (Shimabukuro et al., 2009). The parameter values used in the present study were similarity = 8 and area = 25. These values were selected based on the iterative visual analysis of parameter combination results.

After the objects' generation, the ISOSEG algorithm was applied to each set of LSMM bands with an acceptance threshold of 75% (Shimabukuro et al., 2009). From the resulting classes, those corresponding to burned areas were merged into a single "Burn Scars" class, and the remaining classes were discarded. As the ISOSEG algorithm could not entirely differentiate between burn scars and relief shadow or open water areas, careful manual editing of the mapping results was performed after classification. In most cases, burn scars were present only in a single image, while shadows and water bodies were consistently found in all evaluated dates for a given location, thus facilitating differentiation by the interpreter. Finally, all maps produced for each date were combined into a single yearly map depicting the total area of burn scars in 2005.

The assessment of mapping results was performed through visual evaluation by superposing the burn scar map to the shade fraction images used as input to the mapping algorithm. Any misclassification errors were corrected manually during this procedure, as described above.

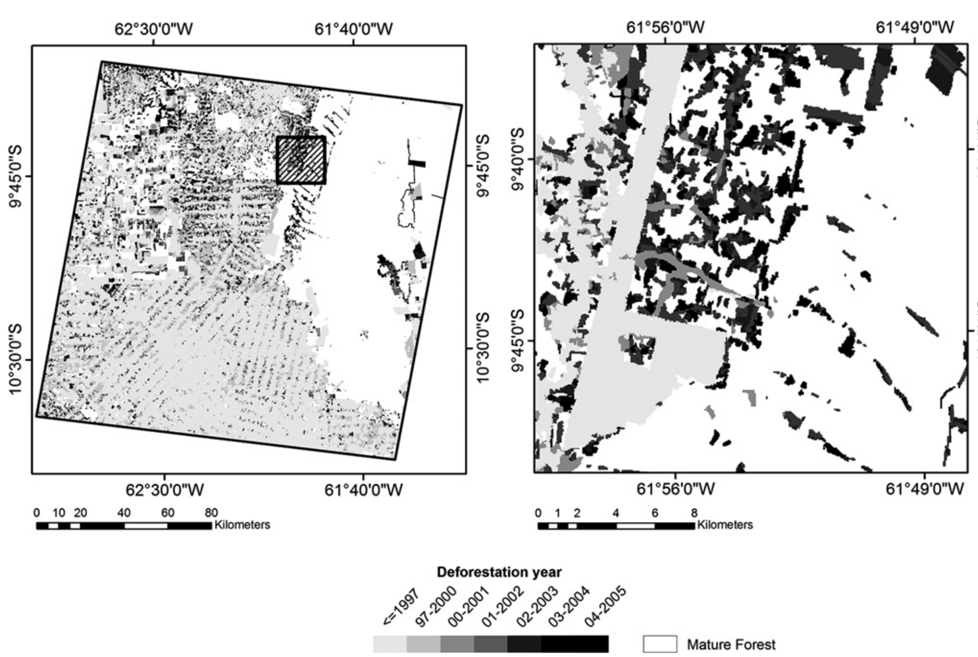

Fig. 2. Deforestation map produced by the Brazilian Amazon Deforestation Estimation Project (PRODES), showing cumulative deforestation prior to 1997 and between 1997 and 2000 and yearly deforestation from 2002 to 2005. Area shown corresponds to Landsat TM scene 231/67 (WRS-2 reference system).

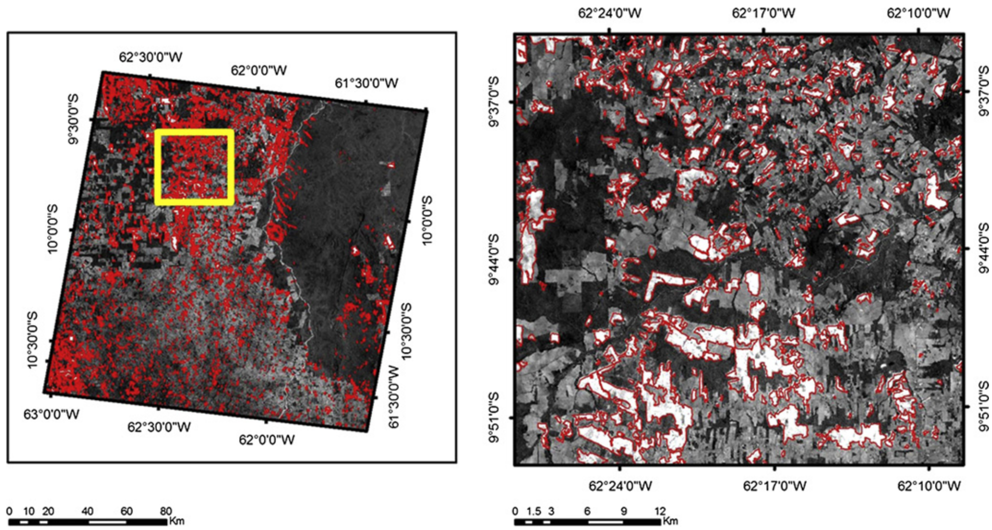

Fig. 3. Classification of burn scars using non-supervised classification algorithm on shade fraction image. The image on the left shows the total area of burn scars mapped (in red), corresponding to areas of greater brightness in the shade fraction image (detailed at left).

Spatial analysis

The initial analysis of burned area versus deforested areas was performed by simply overlaying the burned area and deforestation maps and computing the amount of burned area contained within the area that were deforested each year.

Spatial analysis of the relationship between the occurrence of fire and deforestation was assessed using Mantel correlograms and bivariate and partial Mantel tests (Urban, Goslee, Pierce, & Lookingbill, 2002). The Mantel test measures the degree of association between two or more distance or dissimilarity matrices. When standardized, the Mantel test produces an r statistic analogous to a coefficient of correlation, varying between -1 and $+1$ (Urban et al., 2002). For simple spatial autocorrelation measurements, a matrix of geographical distances is compared to a matrix of feature distances (e.g., the difference in burned area for each pair of observations). Similar to a variogram, a correlogram can be generated by pooling observations within distance brackets and calculating the r statistic for each bracket (Legendre & Fortin, 1989).

The Mantel test can also be modified to test for the association between two variables while controlling for the spatial autocorrelation present in the data, constituting a partial Mantel test. Similar to a multivariate regression, the test formulation for partial correlations is based on partitioning the sums of squares (Legendre & Fortin, 1989). Significance testing for the Mantel correlation coefficients is usually accomplished through Monte Carlo simulation by randomly permuting the elements of the distance matrices and recalculating r, thus producing a frequency distribution. A total of 1000 permutations were used in the present study. All tests were performed using the *ecodist* package (Goslee & Urban, 2007) of the R statistical environment, version 2.13.0 (R Development Core Team, 2011).

Because the most recurrent burns occur three to four years after the initial deforestation activity, deforested areas were grouped into two categories for the purpose of spatial analysis: “recent deforestation”, corresponding to areas mapped as deforestation between 2002 and 2005, and “old deforestation”, comprising all deforestation mapped up to and including 2001. This categorization aimed to identify which proportion of burned areas was directly related to each deforestation process (conversion of mature forest to cropland and cattle land use versus recurrent burning of degraded sites).

Also, for the purpose of spatial analysis, the original vector maps were converted into a regular grid, where the total areas of “Burn Scars”, “Recent Deforestation” and “Old Deforestation” were computed for each cell. This transformation was necessary to

Table 1
Extent of areas burned in the year 2005 corresponding to each of the PRODES deforestation and land cover classes for Landsat TM scene 231/67, Amazon region, Rondônia, Brazil.

Class	Burned area (km^2)	Burned area (%)
Area deforested up to 1997	562	33
Area deforested in 2000	258	15
Area deforested in 2001	118	7
Total Old Deforestation	*938*	*55*
Area deforested in 2002	159	9
Area deforested in 2003	150	9
Area deforested in 2004	90	5
Area deforested in 2005	134	8
Total Recent Deforestation	*533*	*31*
Mature Forest	180	11
Other[a]	59	3
Total	1711	100

[a] This class represents areas occupied mainly by savannas and other types of non-forested formations; therefore, these areas are not monitored by the PRODES project.

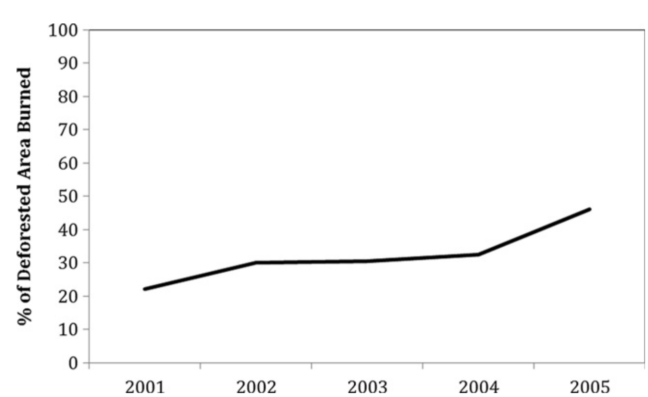

Fig. 4. Trends in the percentage of burned area for areas deforested in successive years in the Rondônia region, Brazilian Amazon. Deforestation prior to 2000 was omitted because yearly deforestation mapping was not performed before that year.

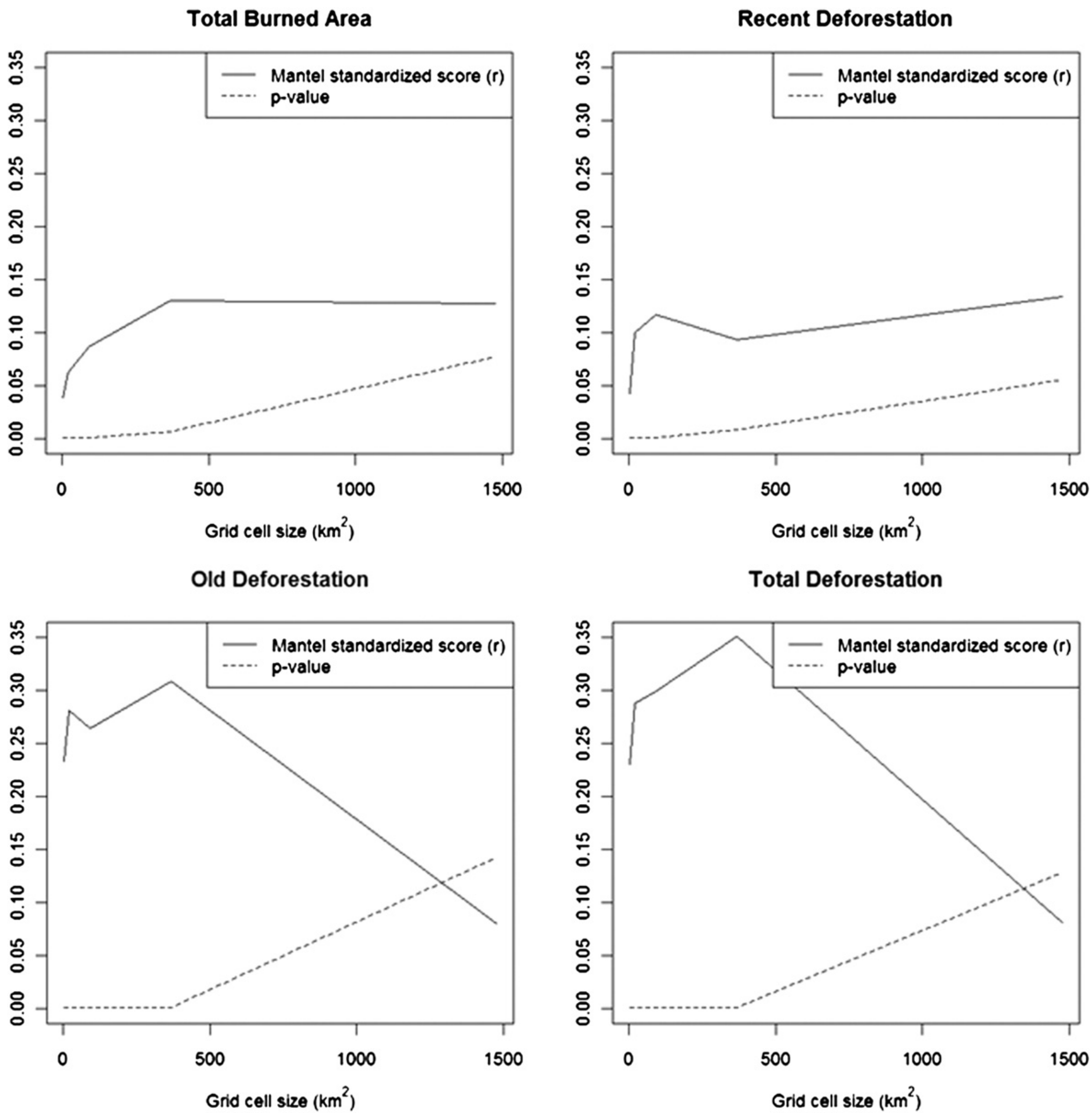

Fig. 5. Mantel standardized scores showing spatial autocorrelation of Burned Area, Recent Deforestation, Old Deforestation and Total Deforestation over multiple scales.

normalize the effect of variable polygon areas resulting from the mapping procedure (e.g., a single burned plot could be composed of multiple polygons traced separately during digitization, affecting neighborhood and area calculations).

To assess the effect of scale on the results of spatial analysis, multiple grid sizes were generated with increasing cell sizes: 2400 × 2400 m (~6 km^2), 4800 × 4800 m (~23 km^2), 9600 × 9600 m (~92 km^2), 19,200 × 19,200 m (~369 km^2) and 38,400 × 38,400 m (~1475 km^2). The initial cell size was determined based on the assumption that the minimum mappable area in a given remote sensing image consists of a 2 × 2 pixel area, or 60 × 60 m for Landsat TM images. Given the extent of the study region and the computing power required for spatial analysis calculations, the starting cell size was defined as the smallest multiple of 60 × 60 m capable of being processed by the available computing resources. Subsequent cell sizes were determined by doubling the previous size, and the upper limit was defined at 38,400 × 38,400 m cells, beyond which the number of cells was considered too small for statistical analysis (<24 cells).

The first step in the spatial analysis was the generation of Mantel correlograms and the calculation of overall r values for burned areas and recent, old and total deforestation to determine the spatial structure of the original data. Afterward, the degree of association between burned area and recent and old deforestation was determined for all scales, controlling for the spatial structure of each dataset by applying a partial Mantel test to the following combinations: Burned Area = f (Recent Deforestation, location), Burned Area = f(Old Deforested Area, location) and Burned Area = f (Total Deforested Area, location).

Results

The mapping of burn scars for the Landsat TM scene 231/67 in the year 2005 resulted in a total burned area of ~1700 km^2, or 6% of the entire study area (Fig. 3).

Approximately a third of this total burned area (533 km^2) occurred over areas deforested during the 2002–2005 period ("recent deforestation" – Table 1). These areas correspond to

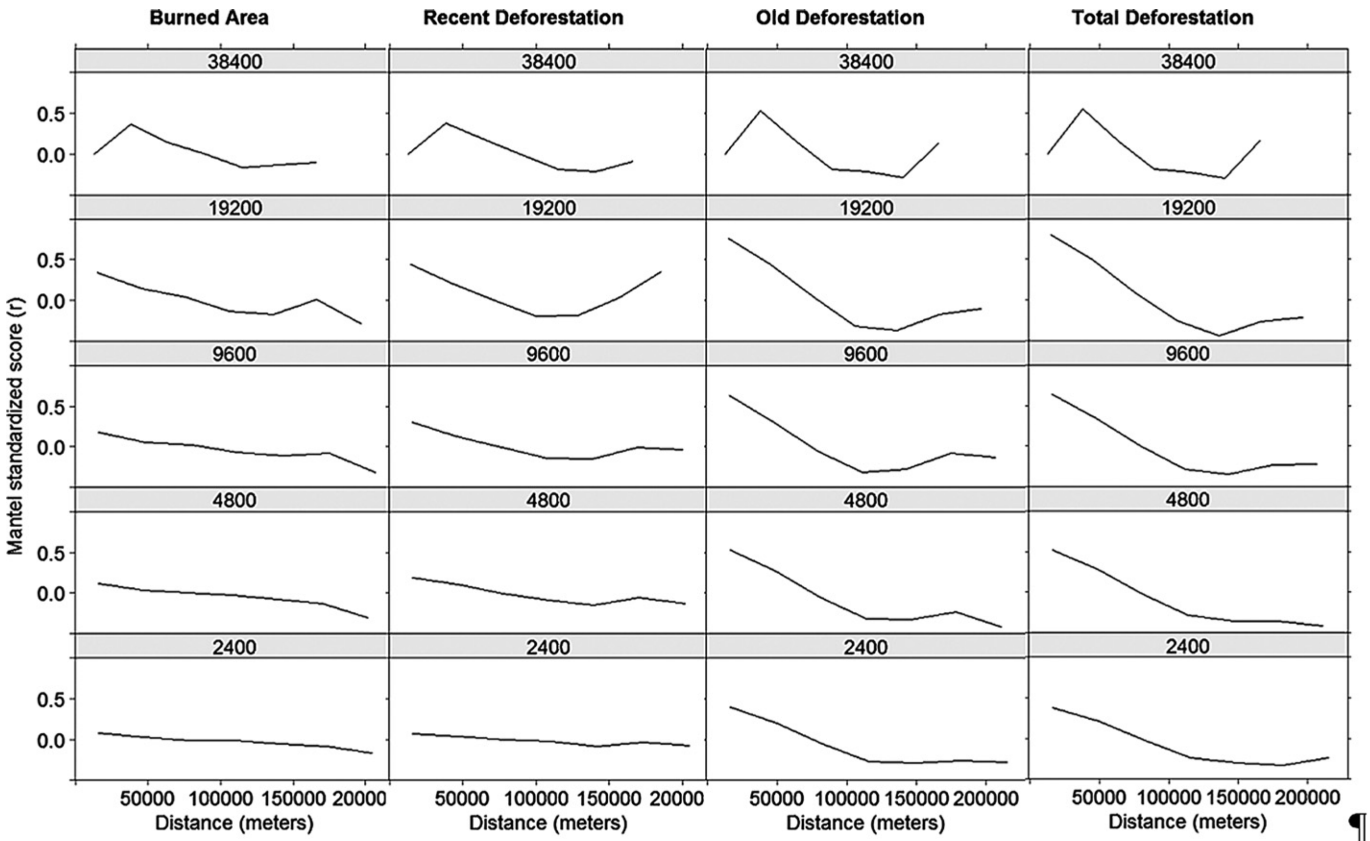

Fig. 6. Mantel correlograms showing the relationship between spatial correlation and distance for Burned Area, Recent Deforestation, Old Deforestation and Total Deforestation at multiple scales.

locations where burning is directly associated with deforestation in preparation for agricultural purposes and as a means to prepare the land for the introduction of heavy machinery (Morton et al., 2008). Interestingly, however, the results also show that approximately 55% (938 km^2) of the burned area observed in 2005 occurred in areas that were deforested prior to 2002 (labeled as “old deforestation”), where the rationale for the use of fire is less evident. Furthermore, 11% of the total burning was observed over Forested areas (180 km^2), corresponding to burning without or very soon after the removal of vegetation.

The results also indicate that the area burned depends, to some extent, on the deforested area. Ninety percent of the burning occurred inside areas already deforested prior to 2005, with yearly percentages of burned deforested area remaining within the 20%–50% range throughout the study period (Fig. 4).

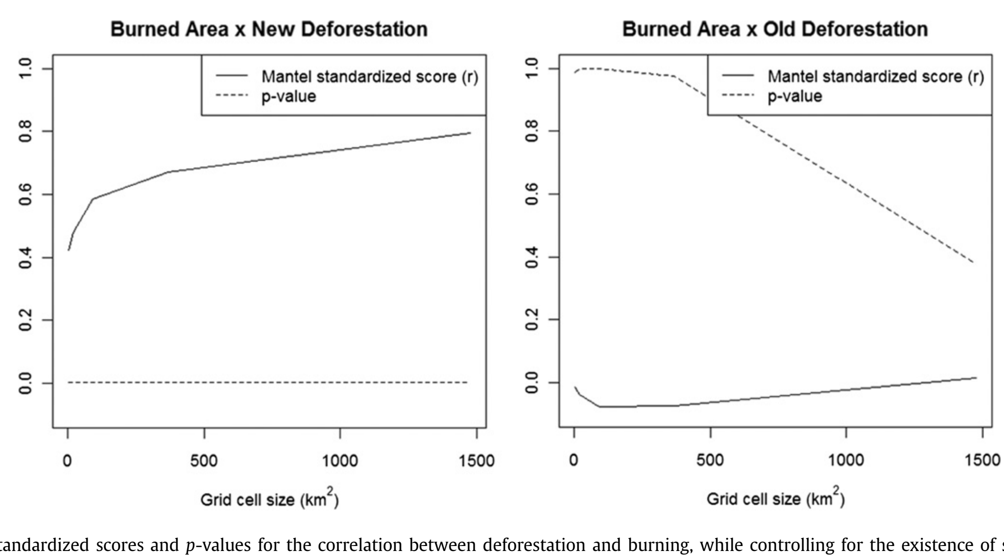

Fig. 7. Partial Mantel standardized scores and *p*-values for the correlation between deforestation and burning, while controlling for the existence of spatial structuring, in the Rondônia region, Brazilian Amazon.

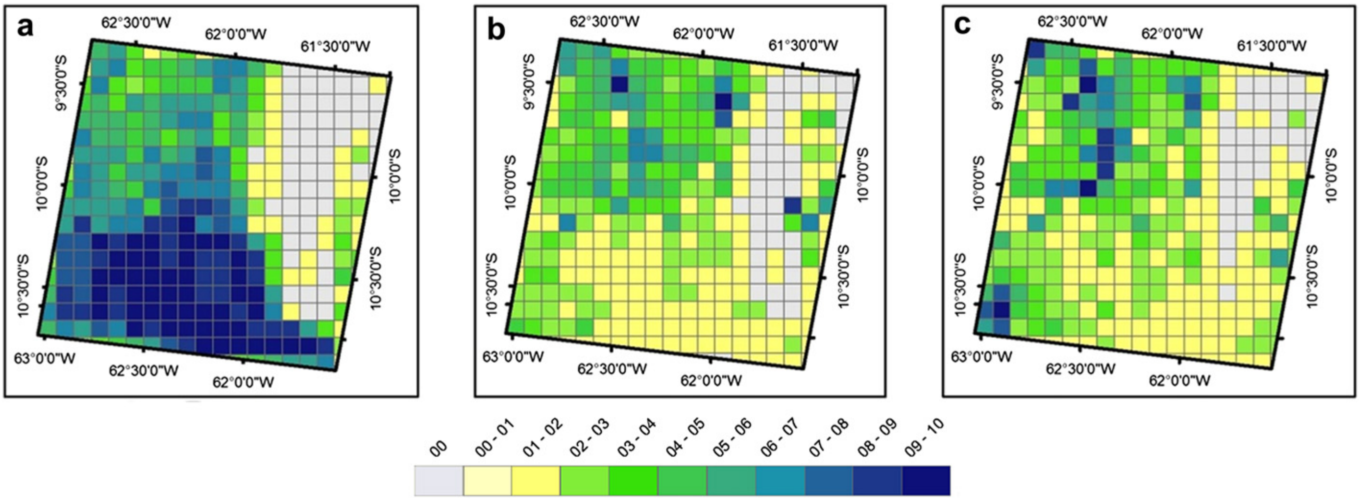

Fig. 8. Visual representation of the spatial relationship between burn scars and deforestation: a) old deforestation, b) recent deforestation, and c) burned area. The cell sizes are 9600 × 9600 m.

In terms of spatial structure, burned area and recent deforestation exhibited small and similar spatial autocorrelation coefficients (maximum significant $r \sim 0.13$, $p < 0.05$), while a slightly stronger spatial structure was observed for old deforestation (maximum significant $r \sim 0.31$, $p < 0.05$). Total deforestation mirrored the results of old deforestation, emphasizing the effect of cumulative deforestation events on the overall spatial structure of deforestation. The correlograms indicated an overall decrease in spatial correlation with distance, with the occasional artifacts introduced by the regular gridding of the data at larger cell sizes. The stronger spatial structure detected for recent deforestation emphasizes the influence of anthropogenic factors on LULCC processes in the Brazilian Amazon (Fig. 5).

When assessing the correlation between burning and deforestation while controlling for the spatial structure of the data, it was possible to observe a stronger relationship between the burned area and recent deforestation, which rose together with the increase in cell size, reaching its maximum at $r \sim 0.8$ ($p < 0.05$, Fig. 6). However, there was no significant evidence of spatial association between burned area and old deforestation, regardless of scale ($-0.1 < r < 0.1$, $p > 0.05$, Fig. 6), which was likely due to the difference in the proportions of burned area in each deforestation class. Even though 55% of the mapped burning occurred inside old deforestation areas, this only amounts to 7% of the total class area (938 km^2 out of 13,200 km^2) as compared to 34% of the recent deforestation class area (534 km^2) burned in the same year.

Both the spatial structure and the spatial association of the studied variables are visualized on Fig. 7. Distinct landscape configurations can be observed for each deforestation class, mainly resulting from the different lengths of the time intervals that constitute each class. The visual assessment of the spatialized deforestation and burn scar data also reveals a higher incidence of burning, together with recent deforestation, in the northwest and extreme southwest portions of the studied area (green/blue tones in Fig. 8). Such a pattern of spatial co-occurrence is also observed for areas with less density of burning/recent deforestation (yellow tones), visible toward the southeast of the study area.

Discussion and conclusions

The above results underscore the direct use of burning for initial LULCC processes in the Brazilian Amazon; approximately 90% of the burning that was observed in 2005 occurred in previously deforested areas. However, the results also emphasize that, for tropical regions, deforestation and burning events are related (Bucini & Lambin, 2002; Cochrane, 2003; Nepstad et al., 2004; Uhl & Kauffman, 1990) but cannot be considered equivalent, as other means of mature forest removal are utilized prior to the application of fire. This result is also confirmed by the existence of spatial structuring and the correlation between burning and deforestation, in agreement with previous studies that hypothesize such association as part of the LULCC process in the Brazilian Amazon (Lorena & Lambin, 2009; Morton et al., 2008; Siren & Brondizio, 2009; Soler et al., 2009; Sorrensen, 2004, 2008).

The "old deforestation" class identified the cumulative land use/land cover change over the area for the ~30 years of modern human occupation in the Amazon up to 2002, where fire should theoretically be less used over time. Recent deforestation areas (2002–2005) represent ongoing LULCC processes, where the use of fire is expected to be predominant. Interestingly, the comparison of burned and deforested areas also revealed that the largest portion of the burn scars that were mapped for 2005 occurred in areas deforested prior to 2002 (55% of the 1711 km^2 burned), seemingly contradicting the assumption that the amount of burning is directly related to the estimates of recent deforestation in areas of mature forest. Evidence of such dissociation was previously given by Aragão and Shimabukuro (2010), who showed that reductions in the rate of deforestation were accompanied instead by an increase in the occurrence of burning events for the Amazon region between the years 2000 and 2007. Two possible explanations for such a high incidence of burning over old deforestation areas are the following: a) the use of fire for renewal of existing pasture areas (i.e., the removal of weeds and remineralization of dead biomass) and/or b) the removal of regenerating vegetation for new crop or pasture implementation (Aragão & Shimabukuro, 2010).

It is important to note that when considering the relative amount of burning in relation to the total deforested area (7% of the old deforestation areas were burned versus 35% of the recent deforestation areas) together with the strong correlation between burning and recent deforestation versus low correlation with old deforestation, it is clear that a large portion of the burning process is still related to recent deforestation events for the conversion of mature forest to agricultural purposes. Nevertheless, the present findings raise an important question: if the reduction in deforestation is not followed by a reduction in burning and the absolute values of burned area for locations long since converted to human use are remarkably high, what type of fuel is supporting the burning activity outside recently deforested areas? We hypothesize that the answer lies in re-burning processes, such as pasture recovery and the removal of secondary vegetation.

Answering this question is of utmost importance for properly estimating greenhouse gas (GHG) emissions associated with tropical deforestation, which are often computed solely based on the emission of C stored in the mature forest biomass (Aragão & Shimabukuro, 2010). Because these estimates determine, in turn, the directives for GHG emission reduction policies and initiatives such as REDD, properly accounting for the amount of burning occurring on different land cover/land use types becomes paramount for managing carbon emissions in the Amazon region (Aragão & Shimabukuro, 2010).

Unfortunately, there are no studies to date that address the amount and dynamics of Amazonian forest regeneration at regional scales, nor is there a systematic program for mapping and monitoring forest regeneration in the region, thus making it impossible to quantify the actual proportion of burning occurring in each of the above two scenarios. Furthermore, the land use patterns observed for the presently studied region may not be the same as those observed for the remaining regions of the Amazon due to differing economic and social factors. The lack of systematic data on specific land cover/land use processes at a regional, Amazon basin-wide scale prevents all of the above issues from being properly addressed. Thus, we urge stakeholders to consider monitoring programs that properly assess the different and transient states of LULCC in the region as a major, immediate necessity to enable the reduction of current uncertainties in GHG emission estimates and for properly establishing policies for reducing such emissions in the Amazon region.

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