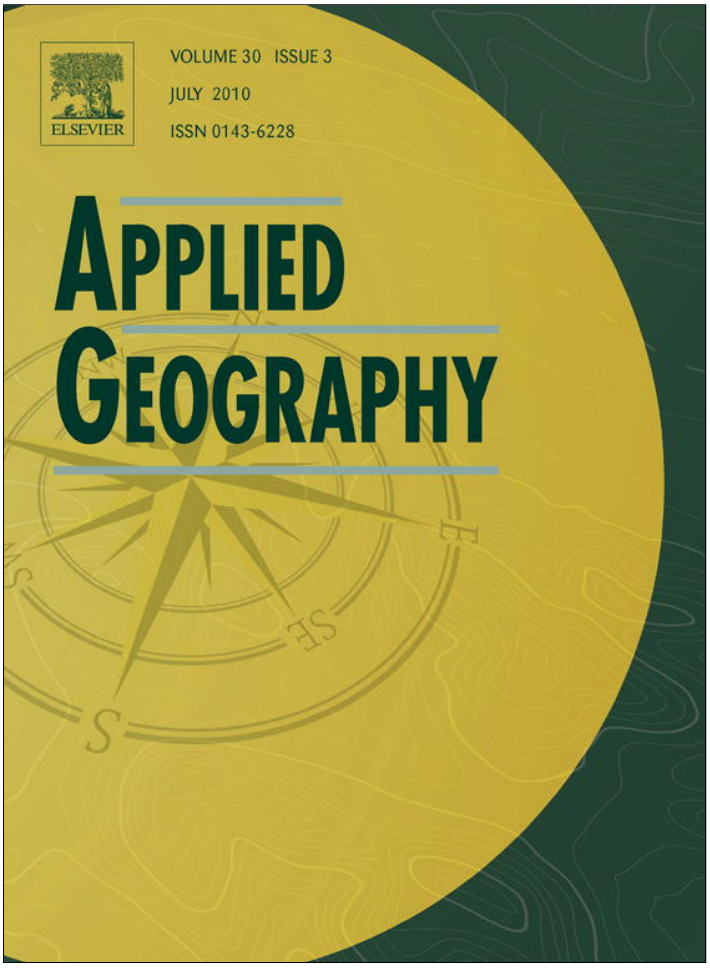
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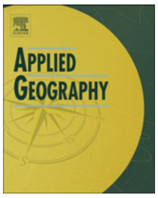

Agricultural land use dynamics in the Brazilian Amazon based on remote sensing and census data

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Keywords:
Brazilian Amazon
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Land use dynamic
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ABSTRACT

The potential impact of deforestation in the Brazilian Amazon on greenhouse gas emissions to the atmosphere calls for policies that take account of changes in forest cover. Although much research has focused on the location and effects of deforestation, little is known about the distribution and reasons for the agricultural uses that replace forest cover. We used Landsat TM-based deforestation and agricultural census data to generate maps of the distribution and proportion of four major agricultural land uses throughout the Brazilian Amazon in 1997 and 2007. We built linear and spatial regression models to assess the determinant factors of deforestation and those major agricultural land uses – pasture, temporary agriculture and permanent agriculture – for the states of Pará, Rondônia, and Mato Grosso. The data include 30 determinant factors that were grouped into two years (1996 and 2006) and in four categories: accessibility to markets, public policies, agrarian structure, and environment. We found an overall expansion of the total agricultural area between 1997 and 2007, and notable differences between the states of Pará, Rondônia, and Mato Grosso in land use changes during this period. Regression models for deforestation and pasture indicated that determinant factors such as *distance to roads* were more influential in 1997 than in 2007. The *number of settled families* played an important role in the deforestation and pasture, the effect was stronger in 2007 than 1997. *Indigenous lands* were significant in preventing deforestation in high-pressure areas in 2007. For temporary and permanent agricultures, our results show that in 1997 the effect of small farms was stronger than in 2007. The mapped land use time series and the models explain empirically the effects of land use changes across the region over one decade.

Introduction

Deforestation is considered to be one of the largest sources of greenhouse gas emissions into the atmosphere. Using the estimated emissions from land use change deforestation and other land use data it has been calculated that carbon dioxide (CO_2) from land use change contributed to 12% (in terms of CO_2 equivalents) of the total anthropogenic greenhouse gas emissions in 2008 (Quéré et al., 2009). From 2000–2009 the rate of tropical deforestation in the Brazilian Amazon was amongst the fastest in the world, averaging 17,486 sq km per year (INPE, 2010). Significant negative externalities have been created as a result, such as loss of biodiversity, erosion, floods, lowered water tables, as well as increased release of carbon into the atmosphere (Fearnside, 1996; Shukla, Nobre, & Sellers, 1990). All these effects make the Brazilian Amazon region one of the hotspots of global environmental change (Achard et al., 2002; IPCC, 2007a, 2007b; Laurance, Albernaz, Fearnside, Vasconcelos, & Ferreira, 2004).

Critical problems, such as tropical deforestation, are relatively well understood at regional level. At this level, considerable research has focused on estimating rates of forest conversion (mainly by using satellite remote sensing) and on evaluating the factors that influence these rates (Alves, 2002; Chambers et al., 2007; Fearnside, 1990; Fearnside, Tardin, & Filho, 1990; Margulis, 2004; Skole & Tucker, 1993). The most frequently mentioned determinant factors of deforestation include regional variants of driver combinations in which economic factors, institutions and national policies are prominent (Geist & Lambin, 2001; Geist et al., 2006; Lambin, 1994; Margulis, 2004). It is clear that multiple processes influence the spatial and temporal dynamics of deforestation, and that there are significant gaps in knowledge to be filled (Dietz, Ostrom, & Stern, 2003; Gibson, McKean, & Ostrom, 2000).

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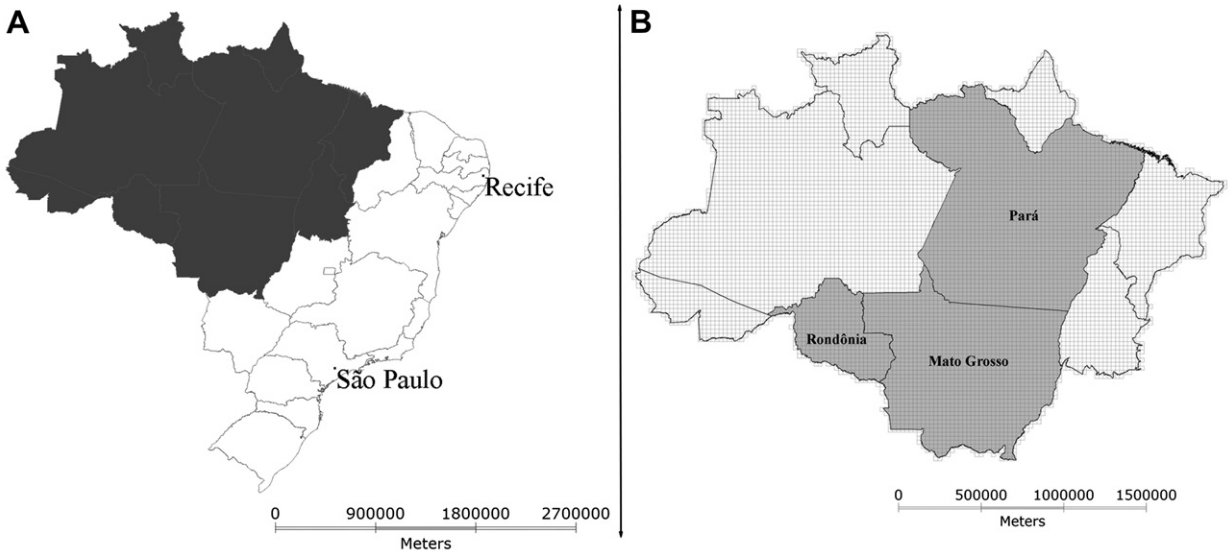

Fig. 1. (A) Map of Brazil showing the location of the Brazilian Amazon region (all in darker gray), and the location of São Paulo and Recife cities. (B) Regular grid of 25 km × 25 km over the Brazilian Amazon region; the states of Pará, Rondônia and Mato Grosso are shown in gray.

Assessments of factors associated with land use change in the Brazilian Amazon have so far mostly used econometric models and grid-based models. Using a non-spatial and region-wide level econometric analysis, Reis and Guzmán (1992) found that the most important factors of change in the region were *population density*, *road network density* and *extension of cultivated areas*. Andersen and Reis (1997) also used an econometric model. They found that 11 factors were responsible for the land use change in the Brazilian Amazon from 1975 to 1995, among them *distance to the federal capital*, *earlier deforestation in area*, *rural population density*, *land prices* and *size of cattle herd*. Pfaff (1996) focused on the period from 1978 to 1988 and analyzed the relevance of biophysical variables (*soil quality* and *vegetation type*), transport-related variables (*road network*, *density in the area* and *its neighbors*) and government-related variables (*development policies*). Margulis (2004), however, presented an econometric model for analyzing the occupation of the Brazilian Amazon, quantifying the spatial and temporal relationships of the main agricultural activities (*timber extraction*, *pasture* and *crops*). Based on grid models, Perz and Skole (2003) developed a spatial regression model for secondary vegetation in the Amazon Basin and showed that determinant factors have significant spatial variation among different regions. Laurance et al. (2002) performed statistical analysis to assess the relative importance of determinant factors. They found the three most important factors were *population density*, *distance to roads*, and *dry season duration*. The results reported by Soares-Filho et al. (2006) indicate that the most important factors for predicting deforestation location in the Amazon Basin are *proximity to roads*, *indigenous reserves* and *proximity to urban centers*. More recently, Soares-Filho et al. (2010) showed that *indigenous lands*, *strictly protected areas* and *areas of sustainable use* inhibited deforestation between 1997 and 2008.

Although the rates of forest loss have been examined across the Brazilian Amazon, little is known about the transition from mature forest to agricultural uses. Most information about agricultural land use in the Brazilian Amazon comes from agricultural censuses (IBGE, 1996, 2006). These censuses form the most complete survey of land management provide data on areas under different land use categories (pasture and crops, for example), levels of mechanization and agricultural inputs, allowing for detailed analyses of social, economic, and environmental aspects of agriculture across the region (Cardille & Foley, 2003).

The most compelling reason to monitor land use change is the strong effect of the land use trajectory[1] on the state of changed areas. Concepts of land use trajectories have been used to identify some dominant pathways leading to specific land use outcomes, and have been presented as typical sequences of causes of tropical deforestation[2] (Alves, Morton, Batistella, Roberts, & Jr., 2009; Alves, Morton, Batistella, Roberts, & Souza, 2009). The potential transition pathway from forest to other land uses depends on the state of the human occupation and on site conditions, such as: proximity to roads (Alves, 2002); presence of settlements and land tenure (Moran, Brondízio, & VanWey, 2005); the soils, environment and climate (Nobre et al., 1997); and market conditions. The techniques now available to integrate satellite and census data could improve the corresponding spatial details needed to monitor different suites of possible transitions (Alves, Morton, Batistella, Roberts, & Jr., 2009; Morton, DeFries, & Shimabukuro, 2009).

In the 1960s and 1970s, the migration into the Brazilian Amazon region was stimulated by government policies and subsidies (Becker, 2005), in a bid to populate the region and integrate it into the rest of the country. After the 1990s, migration continued apace, as did the deforestation, largely because of private investments in agricultural expansion, associated with large-scale cattle ranching, soybean cultivation, and small-scale subsistence farming. Since then, land use practices have been affected by market arrangements, including legal and illegal market chains, and by the requirement to certify timber, beef, and soybean products that has been imposed by market chain consumers. In addition, initiatives to value the forest, such as alternative technologies and market chains based on biodiversity products, and payment for ecosystem services have also impacted land change dynamics.

A review from the 1985–2006 period shows that the significant amount of deforestation from 1985 to 1995 forced the Brazilian government to take actions to protect endangered areas. From the

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[1] The same land use trajectory can result from different suites of transitions, depending on the type of initial forest disturbance. For example, a forest to pasture trajectory can occur directly, if mature forest is clear-cut to sow grass, or indirectly, if pasture is created after logging or crop cultivation (Alves, Morton, Batistella, Roberts, & Souza, 2009).

[2] In this study, we use the term "deforestation" to describe the situations of complete removal of tree cover.

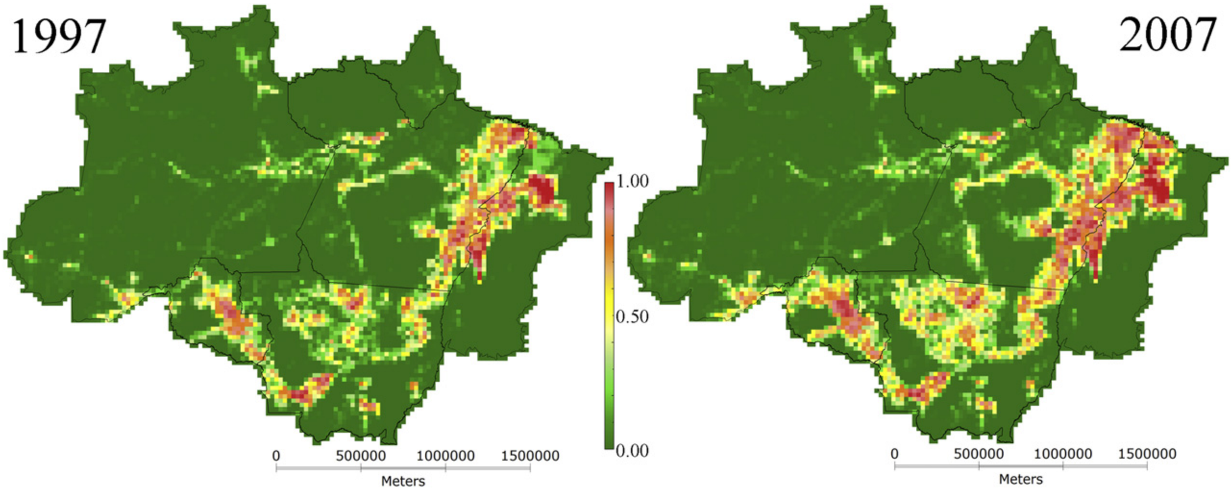

Fig. 2. Proportion of cumulative deforestation for each cell in 1997 (left) and 2007 (right).

mid to late 1990s, major initiatives emerged and are still influencing the rates of deforestation. One of the initiatives was the adoption of a systematic and consistent approach to areas designated as national parks (Rylands & Brandon, 2005). As a result, Brazil has expanded the network of Amazon protected areas from 1.26 to 1.82 million sq km since 2005. As well as the growth in the protected areas, the indigenous lands have also expanded: they currently cover about 20% of the Brazilian Amazon, and some play a very significant role in protecting the forest from ongoing development. In the ten years from 1996 to 2006, various other initiatives were taken to reduce deforestation in the Amazon region (Nepstad et al., 2009), and these have produced significant land use changes. These measures have succeeded in slowing down deforestation. Since 2004, when the area deforested was 27,772 sq km in 2004 (the highest annual total for 10 years), the annual area deforested has declined steadily: to only 6451 sq km in 2010 (INPE, 2010). These lowest deforestation rates since 2005 reflect lower commodity prices in the international market, and also the stricter control exercised by the Brazilian government. Despite this, between 1996 and 2006 the area under agricultural land uses in the Brazilian Amazon, including permanent and temporary crops, and natural and sown pasture, increased from 568,949 sq km to 663,177 sq km (IBGE, 1996, 2006).

Against this background, the present study aims to integrate satellite and census data in order to quantify the distribution and proportions of major agricultural land uses in the Brazilian Amazon. We developed linear and spatial regressions of determinant factors associated with land use change for the states of Pará, Rondônia and Mato Grosso, to reveal how variations in these factors relate to census data. We quantitatively compared the distribution and deforestation factors in 1996/1997 and 2006/2007, as well as the main land uses (pasture, temporary and permanent agricultures). Our analysis was based on a subset of 30 potential explanatory variables selected on the basis of Aguiar, Câmara, and Escada (2007).

The paper is organized as follows. Section 2 presents the data and methods used. Section 3 presents the results. We conclude

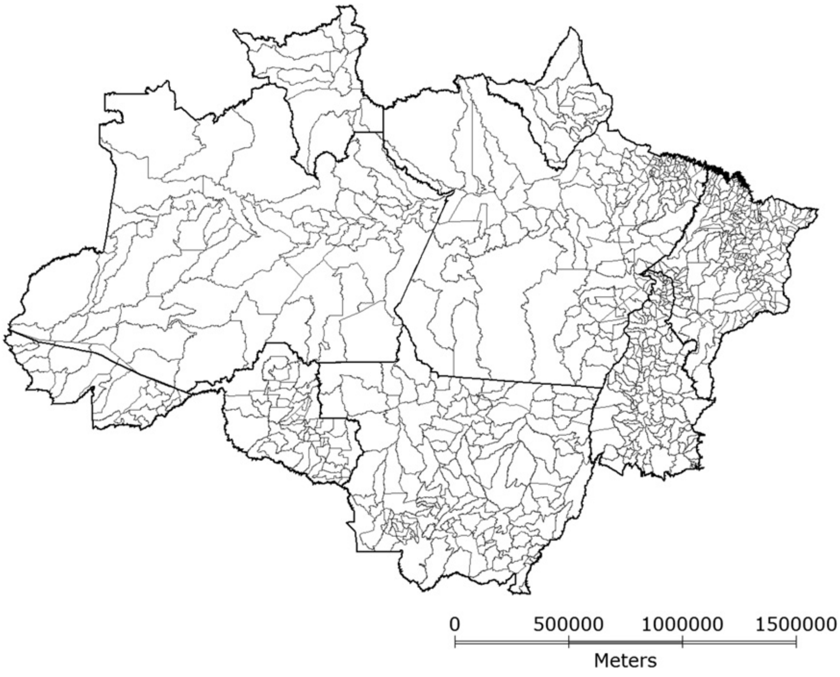

Fig. 3. Spatial extent of municipality polygons within the states of the Brazilian Amazon.

Table 1
Explanatory variables in 1996/1997 and 2006/2007.

Subset of Potential Explanatory Variables						
Category	1996/1997		2006/2007		Unit	Source
	Variable	Description	Variable	Description		
Land Use	Deforestation 1997	Deforestation until 1997 (log10)	Deforestation 2007	Deforestation until 2007 (log10)	% Area	INPE
	Pasture 1997	Pasture in 1997 (log10)	Pasture 2007	Pasture in 2007 (log10)	% Area	INPE
	Temporary 1997	Temporary agriculture in 1997 (log10)	Temporary 2007	Temporary agriculture in 2007 (log10)	% Area	INPE
	Permanent 1997	Permanent agriculture in 1997 (log10)	Permanent 2007	Permanent agriculture in 2007 (log10)	% Area	INPE
Accessibility to Markets	Distance to Roads 1996	Euclidean distance to roads in 1996 (log10)	Distance to Roads 2006	Euclidean distance to roads in 2006 (log10)	Km	IBGE
	Distance to Urban Centers 1996	Euclidean distance to urban centers in 1996 (log10)	Distance to Urban Centers 2006	Euclidean distance to urban centers in 2006 (log10)	Km	IBGE
	Distance to Wood Extraction 1996	Euclidean distance to wood extraction in 1996 (log10)	Distance to Wood Extraction 2006	Euclidean distance to wood extraction in 2006 (log10)	Km	IBGE
	Distance to Rivers	Euclidean distance to large rivers (log10)	Distance to Rivers	Euclidean distance to large rivers (log10)	Km	IBGE
	Distance to Mineral Deposits 1996	Euclidean distance to mineral deposits in 1996 (log10)	Distance to Mineral Deposits 2006	Euclidean distance to mineral deposits in 2006 (log10)	Km	IBGE
	Connection to Ports 1996	Indicator of strength of connection to ports through roads network in 1996	Connection to Ports 2006	Indicator of strength of connection to ports through roads network in 2006	–	IBGE
	Connection to São Paulo 1996	Indicator of strength of connection to São Paulo through roads network in 1996	Connection to São Paulo 2006	Indicator of strength of connection to São Paulo through roads network in 2006	–	IBGE
	Connection to National Markets 1996	Indicator of strength of connection to national markets (São Paulo and Recife) through roads network in 1997	Connection to National Markets 2006	Indicator of strength of connection to national markets (São Paulo and Recife) through roads network in 2006	–	IBGE
Public Policies	Number of Settled Families 1996	Number of settled families until 1996 (log10)	Number of Settled Families 2006	Number of settled families until 2006 (log10)	Number of families	MMA
	Protected Areas 1996	Protected areas in 1996	Protected Area 2006	Protected areas in 2006	% Area	MMA
	Indigenous Lands 1996	Indigenous lands in 1996	Indigenous Lands 2006	Indigenous lands in 2006	% Area	MMA
Agrarian Structure	Small Properties 1996	Area of small properties in 1996	Small Properties 2006	Area of small properties in 2006	% Area	IBGE
	Medium Properties 1996	Area of medium properties in 1996	Medium Properties 2006	Area of medium properties in 2006	% Area	IBGE
	Large Properties 1996	Area of large properties in 1996	Large Properties 2006	Area of large properties in 2006	% Area	IBGE
Environment	High Fertility	High fertility soils	High Fertility	High fertility soils	% Area	IBGE
	Seasonal Index	Seasonal index	Index Seasonal	Seasonal index	–	INPE
	Humidity Index	Humidity index	Humidity Index	Humidity index	–	INPE

Table 2
Subset of statistical models: *roads and settlements* and *urban centers and agrarian structure*.

Subset of Statistical Models		
Models	01 - Roads and Settlements	02 - Urban Centers and Agrarian Structure
Independent Variables	Deforestation	
	Pasture	
	Temporary Agriculture	
	Permanent Agriculture	
Dependent Variables	Distance to Roads	Distance to Urban Centers
	Number of Settled Families	Small Properties
	Distance to Wood Extraction	Distance to Wood Extraction
	Distance to Rivers	Distance to Rivers
	Connection to National Markets	Connection to National Markets
	Protected Areas	Protected Areas
	Indigenous Lands	Indigenous Lands
	High Fertility	High Fertility
	Humidity Index	Humidity Index

with a discussion in which we consider the land use dynamics in the region and summarize the main findings.

Material and methods

Study area and spatial resolution

The study area was the Brazilian Amazon region, which covers an area of more than 5 million sq km. We generated land use maps for the entire Brazilian Amazon, but for our statistical analysis we focused solely on the states of Pará, Rondônia, and Mato Grosso. These three states cover an area of more than 2 million sq km, representing around 46% of the area of the total region. Over the past three decades, these states have had the highest rates of deforestation in the region, and have accounted for 82% of the region's deforestation (INPE, 2010). For our analyses, all variables representing deforestation, land uses (pasture, temporary and permanent agricultures) and potential determinant factors were aggregated to grid cells of 25 km × 25 km (Fig. 1).

Deforestation and land uses

We used Landsat TM-based 1997–2007 deforestation maps produced under the Amazon monitoring program of the Brazilian National Institute for Space Research (INPE, 2010). The percentages of cumulative deforestation in 1997 and 2007 were computed for each cell. Cells with large proportion (>20%) of cloud cover, non-forest vegetation, or cells outside the Brazilian Amazon were omitted from our statistical analyses. The cells omitted due to cloud cover accounted for less than 5% of the number of cells covering the study area. We were left with 2232 cells in total for the states of Pará, Rondônia, and Mato Grosso (Appendix A). Fig. 2 shows that from 1997 to 2007 deforestation increased and tended to occur close to previously deforested areas, producing a distinctive pattern (Alves, Morton, Batistella, Roberts, & Jr., 2009; Alves, Morton, Batistella, Roberts, & Souza, 2009).

The cumulative deforestation in 1997 and 2007 was decomposed into the main agricultural uses – pasture, temporary and permanent agricultures – by combining the TM-based 1997–2007

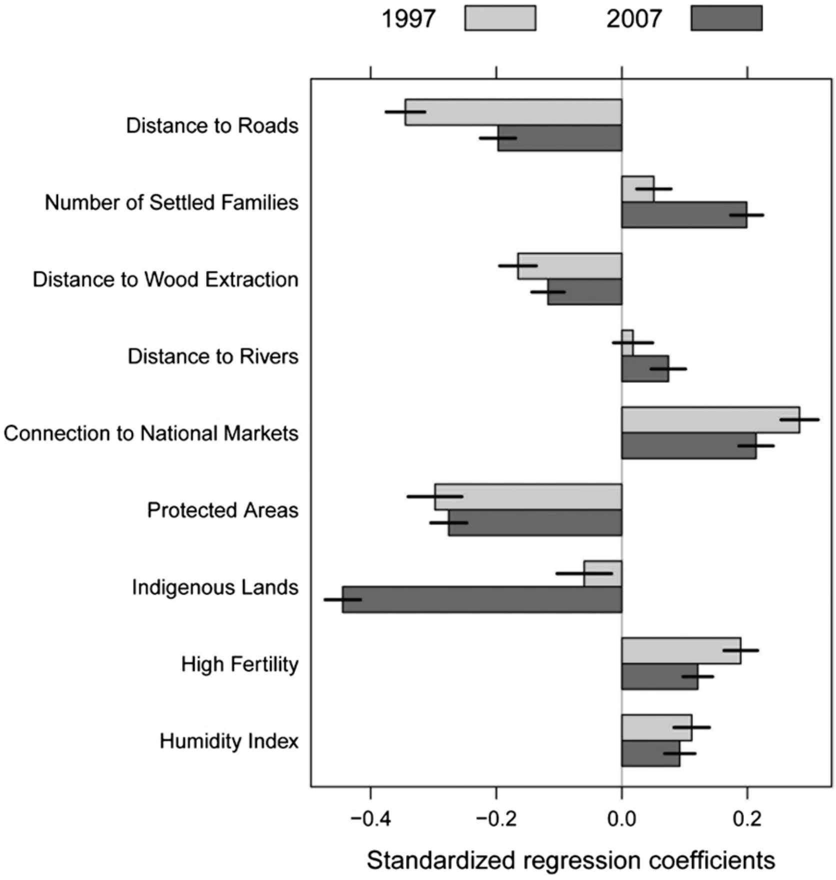

Fig. 4. Standardized regression coefficients for deforestation, and for the *roads and settlements* models of 1996/1997 and 2006/2007, approximate 95% confidence intervals were computed by +/− 2 standard errors.

deforestation maps from INPE (2010), and census information from the agricultural censuses in 1996 and 2006 (IBGE, 1996, 2006). Municipality-based census data (Fig. 3) was converted from polygon-based information to grid cells of 25 km × 25 km. The total agricultural area for each municipality was taken from the deforestation maps; the proportion of each agricultural use was taken from the census data. This computation assumed that the proportion of land use types was uniformly distributed over the deforested areas of each municipality.

Potential determinant factors

For each of the two years 1996/1997 and 2006/2007, the data included 30 variables that were grouped into four main categories: accessibility to markets, public policies, agrarian structure, and environment. According to Aguiar et al. (2007), these variables could potentially explain differences in land use in 1997. As pointed out in the Introduction, so far, most studies in the Brazilian Amazon have been restricted to deforestation, though Aguiar et al. (2007) also decomposed deforestation into the main agricultural land uses. In addition, Aguiar et al. (2007) included the socioeconomic and biophysical factors adopted in previous work, added measures of connectivity to ports and to markets, and introduced agrarian structure indicators that had not been used before. Summarizing, Table 1 shows our subset of potential explanatory variables in 1996/1997 and 2006/2007. All the variables were aggregated to the grid cells of 25 km × 25 km. Appendix A contains maps of the main determinant factors used in our statistical analyses.

The accessibility to markets initially included Euclidean *distance to roads*, *distance to urban centers*, *distance to wood extraction* (or timber extraction) and *distance to mineral deposits* in 1996 and 2006. Euclidean *distance to rivers* was considered invariant over time. The *Distance to Roads 1996* variable, for example, measures the Euclidean distance from each cell to the nearest paved or non-paved road in 1996. Euclidean *distance to roads* and *distance to urban centers* were considered as a proxy for accessibility to local markets and basic services. Following IBGE (2008), *urban centers* were defined as places with a cluster of permanent residents. Appendix A shows that the density of roads and urban centers in the north of Mato Grosso was higher in 2006 than in 1996. Euclidean *distance to wood extraction* and *distance to mineral deposits* were measured in the same way, and showed no large differences between 1996 and 2006. Other measures of accessibility to markets included the *connection to ports* and markets in 1996 and 2006. For our analyses we computed connectivity indicators for each cell, measuring the minimum path distance through the road network from each cell to ports and markets. As described by Aguiar (2006), we distinguished paved from non-paved roads using the *generalized proximity matrix* (GPM). In the group of markets, we recognized *connection to São Paulo* and *connection to national markets* (São Paulo and Recife, see Fig. 1).

The public policies variables are all related to government actions, such as the creation of planned settlements, protected areas and indigenous lands. The *number of settled families* was computed taking the average of this value in each municipality weighted by the area intersection between the municipality and the grid cell. The *protected areas* and *indigenous lands* variables reflect the percentage of each cell that is covered by (or intersects with) the polygons of these areas. The agrarian structure variables were based on municipality-level information, indicating the proportion in terms

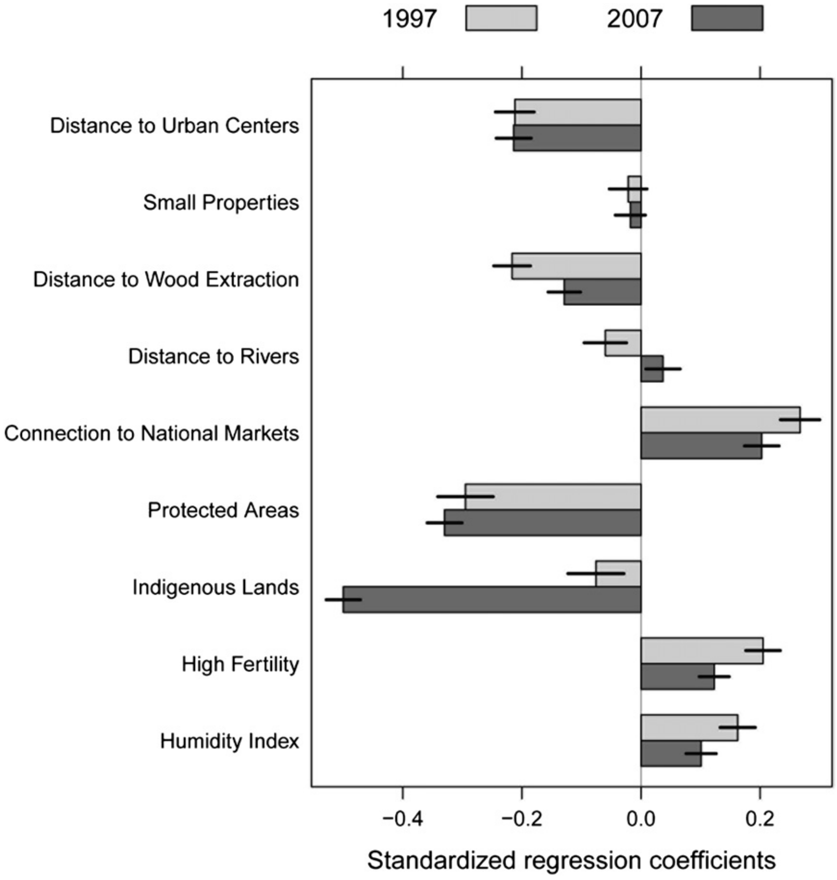

Fig. 5. Standardized regression coefficients for deforestation, and for the *urban centers and agrarian structure* models of 1996/1997 and 2006/2007, approximate 95% confidence intervals were computed by +/− 2 standard errors.

Table 3
Spatial lag regression models for log transformed deforestation determinant factors.

Lag Regression					
Roads and Settlements			Urban Centers and Agrarian Structure		
1996/1997					
Variable	Beta	Std. Error	Variable	Beta	Std. Error
R-squared:	0.848		R-squared:	0.843	
W Deforestation 1997	0.777	0.014	W Deforestation 1997	0.819	0.013
Distance to Roads	−0.121	0.011	Distance to Urban Centers	−0.031	0.010
Number of Settled Families	0.005	0.009	Small Properties	0.003	0.010
Distance to Wood Extraction	−0.033	0.010	Distance to Wood Extraction	−0.052	0.010
Distance to Rivers	0.012	0.010	Distance to Rivers	−0.008	0.011
Connection to National Markets	0.058	0.010	Connection to National Markets	0.048	0.010
Protected Areas	−0.111	0.014	Protected Areas	−0.107	0.014
Indigenous Lands	−0.028	0.014	Indigenous Lands	−0.033	0.014
High Fertility	0.037	0.009	High Fertility	0.038	0.009
Humidity Index	0.035	0.009	Humidity Index	0.043	0.009
2006/2007					
Variable	Beta	Std. Error	Variable	Beta	Std. Error
R-squared:	0.879		R-squared:	0.876	
W Deforestation 2007	0.743	0.014	W Deforestation 2007	0.751	0.013
Distance to Roads	−0.040	0.009	Distance to Urban Centers	−0.084	0.011
Number of Settled Families	0.080	0.008	Small Properties	−0.010	0.008
Distance to Wood Extraction	−0.015	0.009	Distance to Wood Extraction	0.005	0.009
Distance to Rivers	0.024	0.009	Distance to Rivers	0.015	0.009
Connection to National Markets	0.037	0.009	Connection to National Markets	0.026	0.009
Protected Areas	−0.128	0.010	Protected Areas	−0.139	0.010
Indigenous Lands	−0.201	0.011	Indigenous Lands	−0.215	0.011
High Fertility	0.024	0.008	High Fertility	0.017	0.008
Humidity Index	0.030	0.008	Humidity Index	0.036	0.008

of area inside the municipality of small (<200 ha), medium (200–1000 ha) and large (>1000 ha) farms. The environment variables were related to land conditions such as soil fertility and climate. Fertility data was derived from IBGE natural resource maps, integrating soil type, morphology, texture, and drainage information. Climate data was derived from CPTEC/INPE, where the *seasonal index* was used to represent the soil moisture seasonality, and the *humidity index* was used to distinguish between wet and dry climates (Piribauer, 2010; Salazar, Nobre, & Oyama, 2007).

Exploratory analyses and selection of variables

In the statistical models we describe in this paper, dependent variables are those associated with land uses (the proportions of deforestation, pasture, temporary agriculture and permanent agricultures in each cell), and the independent variables (or potential explanatory variables) are those grouped into four main categories: accessibility to markets, public policies, agrarian structure and environment. An initial exploratory analysis showed that some of the relationships between dependent and independent variables were not linear. We applied a logarithmic transformation to all dependent variables and to some independent variables. Table 1 shows these variables annotated with 'log10'. This transformation shows that the independent variables are related to the initial choice of forest areas to be cut.

We also found a high degree of correlation among pairs of independent variables. This high correlation was used to exclude variables like *seasonal index* which is highly correlated with *humidity index*. The set of independent variables selected for the regression analysis (Table 2) were chosen on the basis of model selection by exhaustive searching, considering separate best models of all sizes. As the model search does not actually fit each

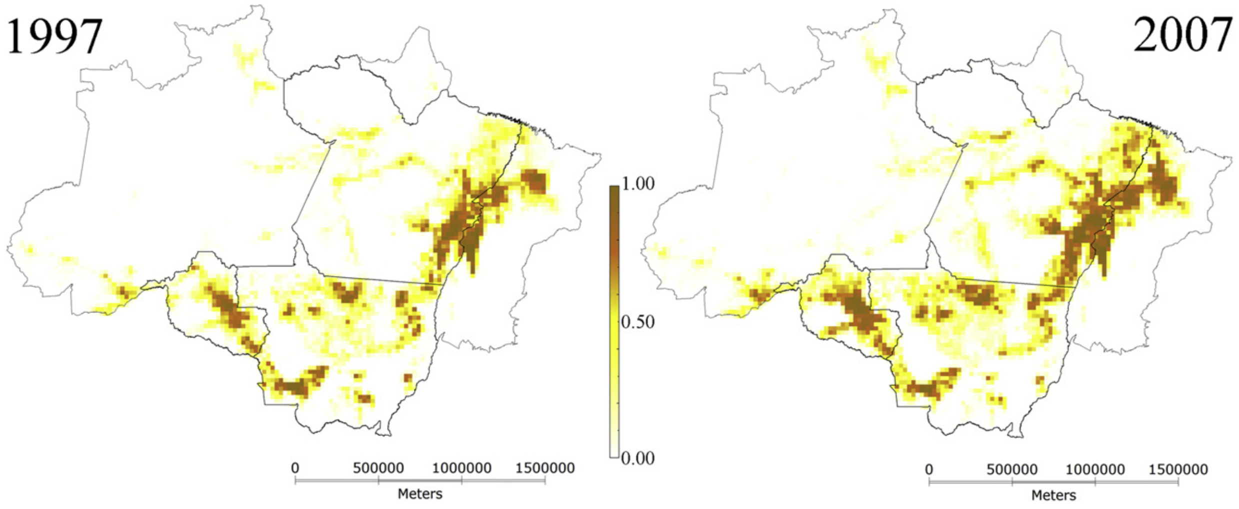

Fig. 6. Proportion of pasture in 1997/1996 (left) and 2007/2006 (right).

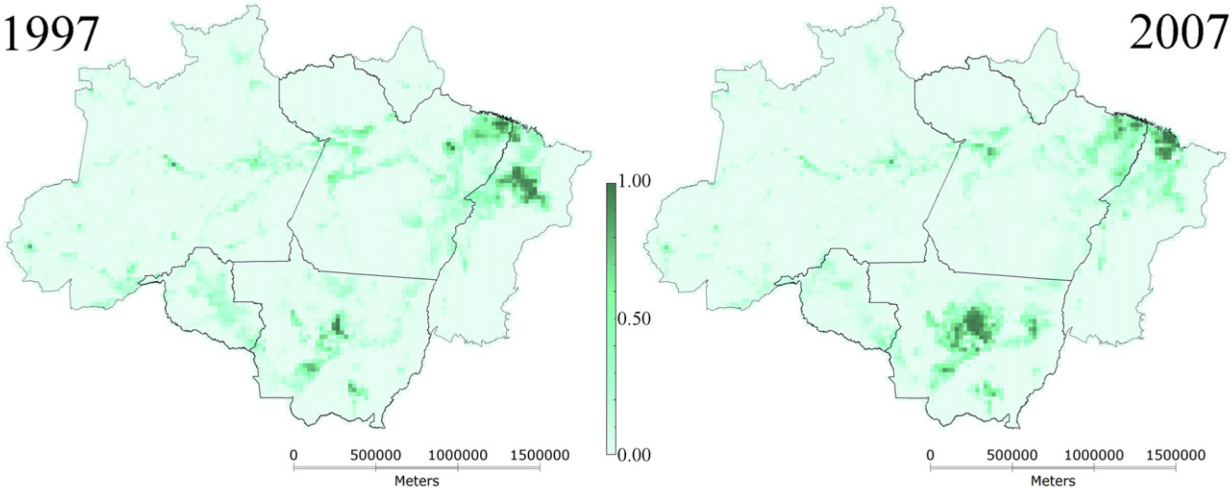

Fig. 7. Proportion of temporary agriculture in 1997/1996 (left) and 2007/2006 (right).

model, the results do not contain coefficients or standard errors. Thus, the statistical analyses were done with two subsets of independent variables, covering the broadest possible range of categories while minimizing correlation problems.

Regression modeling

The statistical analyses were done using R, a language and environment for statistical computing and graphics (R-Team, 2005). We used ordinary linear and spatial lag regression models to establish the relative importance of the determinant factors for different land uses. The linear regression analyses were done to model the relationship between the dependent and independent variables, and the spatial regression analyses were to model the autocorrelation of the dependent variables. For land use data, the assumption underlying ordinary linear regression that observations are independent does not hold, because neighboring land use observations are typically spatially correlated. We applied a spatial lag regression model to assess the spatial dependence of the variables using maximum likelihood estimation (Bivand, Pebesma, & Gómez-Rubio, 2008). Our models are shown in Table 2, which summarizes our two explanatory variable subsets: *roads and settlements* and *urban centers and agrarian structure*.

Differences among variables in groups of models were found to be significant in some of the models but non-significant in others. In order to compare the performance of different models, the R-squared value (coefficient of determination) is used. To compare the relative importance of each determinant factor in each model we will present the standardized regression coefficients (*Beta*) and the corresponding standard error for each variable.

Results

This section summarizes the main findings and compares the results obtained from land use time series, and by regression modeling for 1996/1997 and 2006/2007. The comparison shows how the deforestation was impacted by land use changes, and also shows how the importance of determinant factors changed over time.

Models of deforestation

The regression models for deforestation in 1997 and 2007 revealed some important changes in the patterns of human occupation in the Brazilian Amazon. They are summarized in Fig. 4, Fig. 5 and Table 3. Figs. 4 and 5 show error bars of approximate 95%

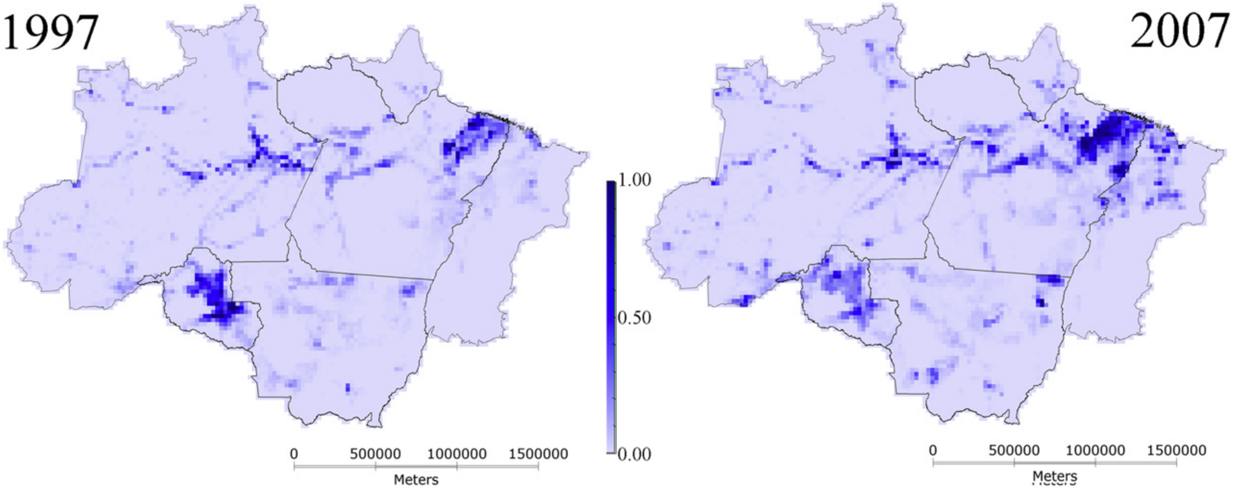

Fig. 8. Proportion of permanent agriculture for 1997/1996 (left) and 2007/2006 (right).

Table 4
Land use trends in the four land uses over the states of Pará, Rondônia and Mato Grosso: numbers express the cells under the given land use changed by more than 10%.

Quantitative Land Use Trends		
	1996/1997	2006/2007
Number of valid cells	2232	2232
Number of cells with more than 10% deforestation	986	1300
Number of cells with more than 10% pasture	832	1196
Number of cells with more than 10% temporary agriculture	84	221
Number of cells with more than 10% permanent agriculture	11	68

confidence intervals (estimate +/− 2 standard errors). The confidence intervals were used to infer which determinant factors changed from 1996/1997 to 2006/2007: when the confidence intervals did not overlap for a particular factor, we assumed this indicated a significant difference (change) in this factor's influence on the dependent variable. When 95% confidence intervals are used and they do not overlap, the indication of significant difference in that factor is conservative (Payton, Greenstone, & Schenker, 2003).

Fig. 4 shows the *Beta* values in *roads and settlements* models, and compares the determinant factors in 1997 and 2007. The R-squared values performed better in 2007 (0.71) than that in 1997 (0.63), however, the difference was smaller for the spatial lag models (0.88 for 2007 and 0.85 for 1997: see Table 3). The variables *distance to wood extraction*, *distance to rivers*, *protected areas* and *humidity index* did not change their influence from 1997 to 2007, although some of them affect the linear models. All the other variables changed their influence, most notably *distance to roads*, *number of settled families* and *indigenous lands*. *Connection to national markets* and *high fertility* changed very little between these two years. *Distance to roads* was more influential in 1997 than in 2007, indicating that the tendency to deforest along the roads decreased. Previous studies tended to emphasize the distance to roads as the main factor determining deforestation (Laurance et al., 2004), but our results indicate that even in 1997 other variables were also important, and in 2007 the distance to roads was not so relevant. *Number of settled families* was also important in the deforestation process, having a higher positive impact in 2007 than it did in 1997, mostly because during this period the number of settlements increased. Finally, *indigenous lands* variables were crucial in preventing deforestation in areas of high population pressure.

Fig. 5 shows the *Beta* values for the *urban centers and agrarian structure* models of 1997 and 2007. For these models, the R-squared values also performed better in 2007 (0.68) than in 1997 (0.57), and the spatial lag models had values similar to those of the *roads and settlements* models (0.87 for 2007 and 0.85 for 1997: see Table 3). Fig. 5 also indicates that the effects of the variables *distance to urban centers* and *small properties* did not change over time. However, when both variables are considered, the *distance to wood extraction* and *distance to rivers* variables showed a change from 1997 to 2007. In addition, in 1997 the *distance to rivers* variable had an opposite response for the *urban centers and agrarian structure* model in 1997, indicating that at this date the deforestation tended to occur along the main rivers. The variables *connection to national markets*, *protected areas* and *humidity index* did not reveal a change in their influence from 1997 to 2007, and still seem to be key factors in explaining the deforestation process in the Brazilian Amazon. *High*

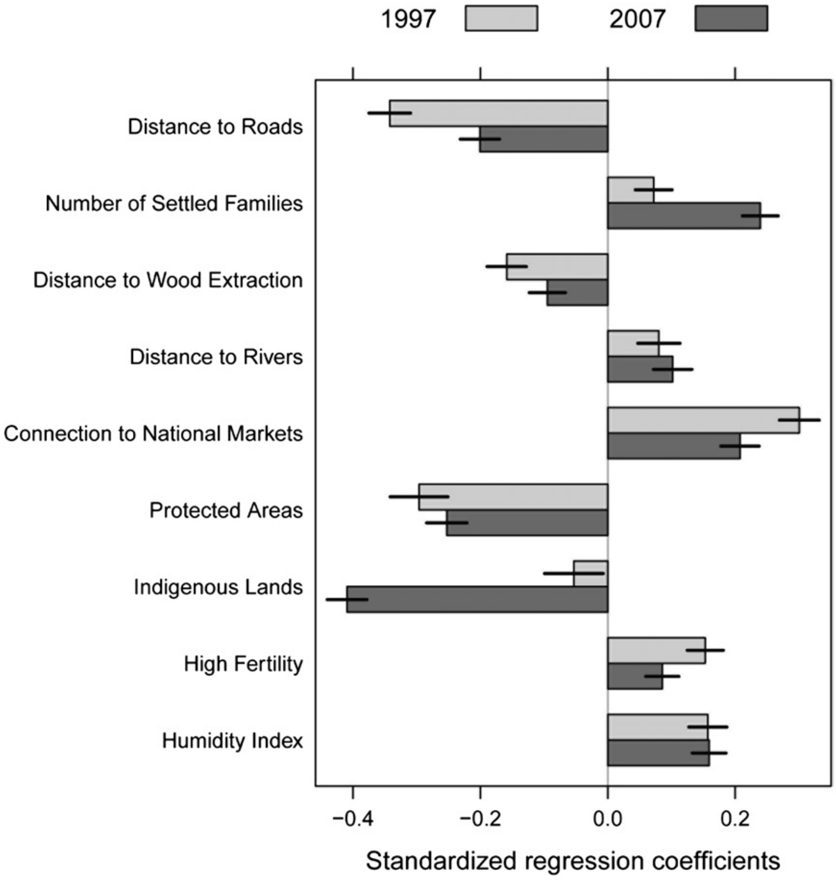

Fig. 9. Standardized regression coefficients for pasture, and for the *roads and settlements* models of 1996/1997 and 2006/2007, approximate 95% confidence intervals are computed by +/− 2 standard errors.

fertility did not change much either during the period considered, but *indigenous lands* variables were crucial in 2007.

The results are similar for the spatial lag regression models. They included one additional variable (*W Deforestation*), which indicates the degree to which the dependent variable is spatially autocorrelated. The R-squared values of the spatial lag models are significant and in all the models of deforestation they are higher than 0.84 (see Table 3). This is the quantitative evidence that corroborates earlier assessments that indicated that the regional pattern of deforestation is a diffusive process, and tends to occur close to previously cleared areas. As expected, when the spatial lag regression models are used, all betas decrease, but not uniformly.

Maps and models of land uses

This section presents the maps representing 1996/1997 and 2006/2007 agricultural distribution and density for the entire Brazilian Amazon. At the end, we present the results for the best model (*roads and settlements* versus *urban centers and agrarian structure*) for the states of Pará, Rondônia, and Mato Grosso when the dependent variables are pasture, temporary agriculture and permanent agriculture. Our analyses in this section are based on those discussed in Section 3.1.

Figs. 6, 7 and 8 show, respectively, the resulting pasture, temporary agriculture and permanent agriculture patterns in 1996/1997 and 2006/2007. Pasture occurred throughout the deforested areas and was the major land use in both years (1996/1997 and 2006/2007). It increased concomitantly with the increase in deforestation (Fig. 6). In 1997, pasture covered approximately 84% of the total deforested area of the states of Pará, Rondônia and Mato Grosso, and by 2007 had increased to 92% of the total deforested area. Temporary agriculture (Fig. 7) represented about 8% of the total deforested area in 1997 and 17% of the total deforested area in 2007. It is important to notice the high concentration of temporary agriculture in the central region of Mato Grosso in 2007, where it is directly associated with commercial soybean production on large farms. Finally, permanent agriculture (Fig. 8) covered around 1% and 5% of the total deforested area in 1997 and 2007. Regarding permanent agriculture, it should be noticed that between 1997 and 2007 its concentration decreased in the central region of Rondônia; the reason is that land change trajectories in Rondônia are strongly connected to policies for land reform and the change from small-scale subsistence farming to cattle-raising (Soler & Verburg, 2010). Table 4 shows the trends in the four land uses over the states of Pará, Rondônia and Mato Grosso, expressed as number of grid cells in which the area under the given land use changed by more than 10%.

Table 5
Spatial lag regression models for log-transformed land uses determinant factors.

Lag Regression					
1996/1997			2006/2007		
Pasture - Roads and Settlements					
Variable	Beta	Std. Error	Variable	Beta	Std. Error
R-squared:	0.854		R-squared:	0.857	
W Pasture 1997	0.807	0.012	W Pasture 2007	0.770	0.014
Distance to Roads	−0.111	0.010	Distance to Roads	−0.073	0.010
Number of Settled Families	0.008	0.009	Number of Settled Families	0.058	0.009
Distance to Wood Extraction	−0.029	0.009	Distance to Wood Extraction	−0.017	0.009
Distance to Rivers	0.025	0.010	Distance to Rivers	0.012	0.010
Connection to National Markets	0.054	0.010	Connection to National Markets	0.037	0.010
Protected Areas	−0.104	0.014	Protected Areas	−0.107	0.011
Indigenous Lands	−0.024	0.014	Indigenous Lands	−0.136	0.011
High Fertility	0.022	0.009	High Fertility	0.018	0.008
Humidity Index	0.046	0.009	Humidity Index	0.062	0.009
Temporary Agriculture - Urban Centers and Agrarian Structure					
Variable	Beta	Std. Error	Variable	Beta	Std. Error
R-squared:	0.814		R-squared:	0.816	
W Temporary Agriculture 1997	0.831	0.013	W Temporary Agriculture 2007	0.813	0.013
Distance to Urban Centers	−0.020	0.011	Distance to Urban Centers	−0.090	0.013
Small Properties	0.071	0.011	Small Properties	0.026	0.010
Distance to Wood Extraction	−0.054	0.011	Distance to Wood Extraction	0.003	0.011
Distance to Rivers	−0.005	0.012	Distance to Rivers	−0.029	0.011
Connection to National Markets	0.042	0.011	Connection to National Markets	0.009	0.011
Protected Areas	−0.100	0.016	Protected Areas	−0.080	0.012
Indigenous Lands	0.004	0.015	Indigenous Lands	−0.092	0.011
High Fertility	0.043	0.010	High Fertility	0.029	0.010
Humidity Index	0.026	0.010	Humidity Index	0.023	0.010
Permanent Agriculture - Urban Centers and Agrarian Structure					
Variable	Beta	Std. Error	Variable	Beta	Std. Error
R-squared:	0.838		R-squared:	0.839	
W Permanent Agriculture 1997	0.871	0.011	W Permanent Agriculture 2007	0.886	0.010
Distance to Urban Centers	−0.026	0.010	Distance to Urban Centers	−0.068	0.012
Small Properties	0.079	0.010	Small Properties	0.020	0.009
Distance to Wood Extraction	−0.051	0.010	Distance to Wood Extraction	−0.005	0.011
Distance to Rivers	0.013	0.011	Distance to Rivers	−0.009	0.010
Connection to National Markets	0.005	0.010	Connection to National Markets	−0.024	0.010
Protected Areas	−0.083	0.014	Protected Areas	−0.056	0.011
Indigenous Lands	0.024	0.014	Indigenous Lands	−0.053	0.010
High Fertility	0.026	0.009	High Fertility	0.013	0.009
Humidity Index	0.024	0.009	Humidity Index	0.018	0.009

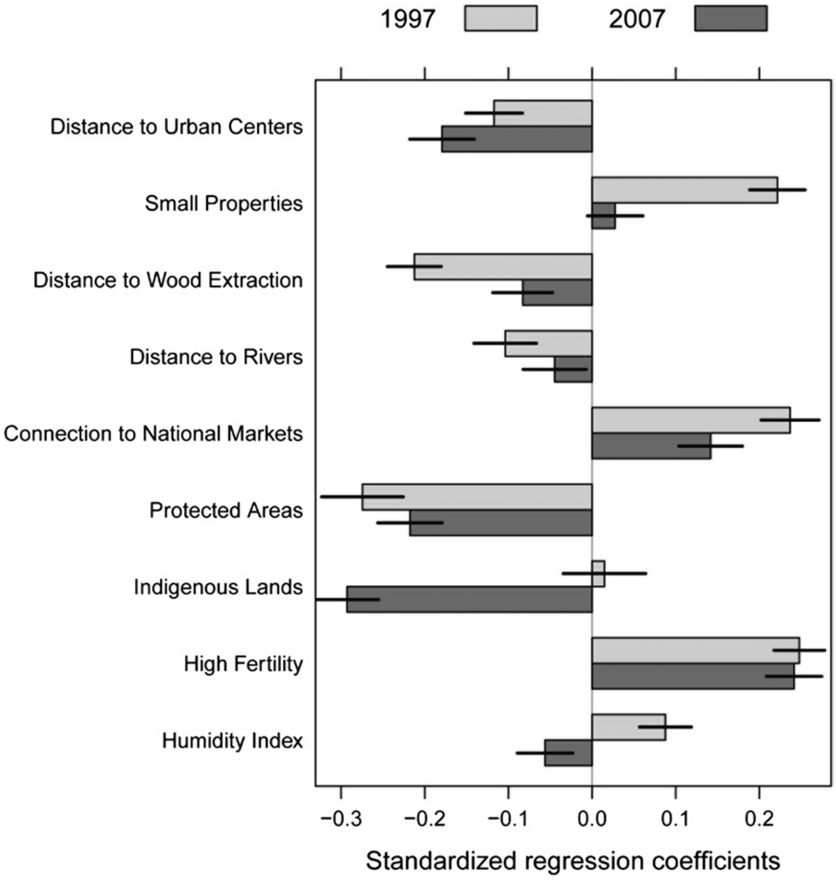

Fig. 10. Standardized regression coefficients for temporary agriculture, and for the *urban centers and agrarian structure* models of 1996/1997 and 2006/2007, approximate 95% confidence intervals are computed by +/− 2 standard errors.

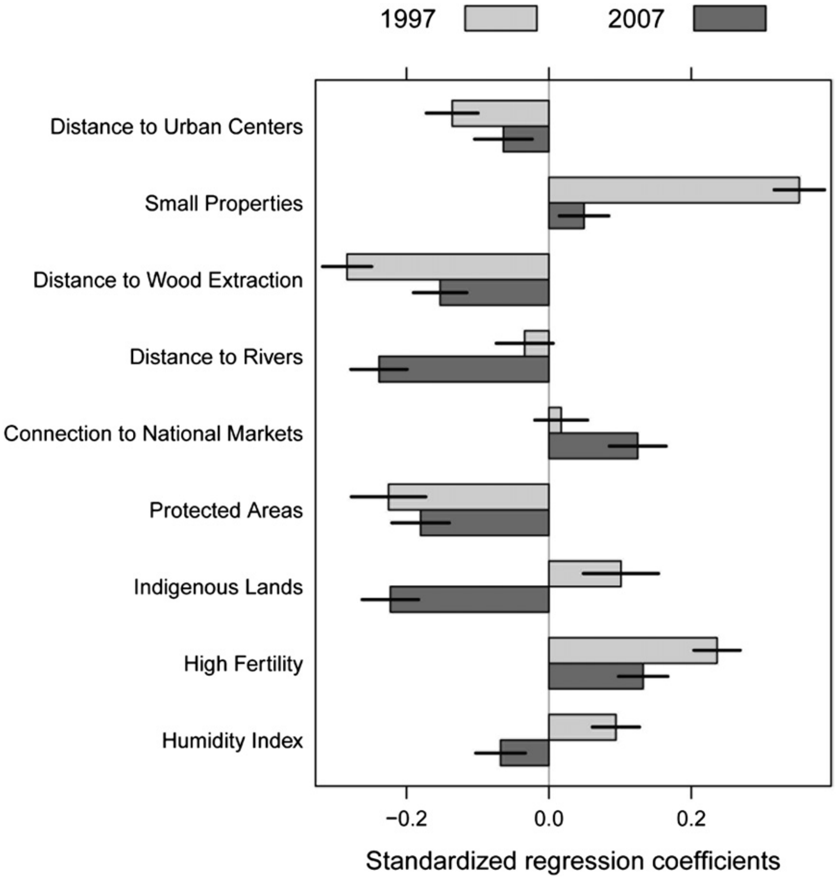

Fig. 11. Standardized regression coefficients for permanent agriculture, and for the urban centers and agrarian structure models of 1996/1997 and 2006/2007, approximate 95% confidence intervals are computed by +/− 2 standard errors.

The regression models also revealed that pasture was spread throughout the region; its determinant factors are very similar to deforestation ones (Fig. 9 and Table 5). This is not surprising, given the large deforested area converted into pasture. For these models, the R-squared values for the linear regressions were 0.58 in 1997 and 0.65 in 2007; the corresponding values yielded by the spatial lag models were 0.85 in 1997 and 0.86 in 2007. Temporary and permanent agricultures presented differentiated and concentrated patterns (Figs. 10 and 11, and Table 5). The R-squared values for these models were 0.52 and 0.45 for temporary agriculture in 1997 and 2007, compared with 0.82 and 0.81 for the spatial lag models. For permanent agriculture they were 0.39 in 1997 and 0.45 in 2007 (compared with 0.84 and 0.84 for the spatial lag models). The variables *distance to urban centers* and *protected areas* had the same trend as the deforestation models, and their values did not differ significantly between 1997 and 2007. Our results also indicate a tendency for temporary and permanent agriculture to occupy areas associated with small farms in 1997. This trend was stronger in 1997 than it was in 2007, which was caused by the fact that in certain locations small farms had been aggregated to form medium and large farms. The *distance to wood extraction* variables showed a change from 1997 to 2007 that was similar to that yielded by the deforestation models. The *distance to rivers* variable did not change for temporary agriculture but did change for permanent agriculture. *Connection to national markets* played a role in both models, but had more influence on temporary agriculture, because this kind of agriculture is highly correlated with the expansion of the soybean area in Mato Grosso. Contrary to the deforestation models, here *indigenous lands* variables followed an opposite trend in 1997, having a positive effect on temporary and permanent agricultures. In 2007, the *humidity index* variables also showed a trend opposite to those of the deforestation models.

Discussion and conclusions

Although the maps in Figs. 6, 7 and 8 show an overall increase in agricultural area, some areas with agricultural activity expanded rapidly over the 1997–2007 period, while others showed little or no growth in agricultural activity. Pasture intensified and spread across eastern Pará, central Rondônia, and the north of Mato Grosso. The influence of temporary agriculture decreased in those regions, and increased in central Mato Grosso. Permanent agriculture remained unchanged, but decreased in Rondônia. Eastern Pará and central Rondônia experienced a large increase in pasture and a decrease in the area of land under crops. The results are consistent with observations that in areas of pioneer occupation much cropland is converted into pasture, and in areas of recent frontier much forest is converted into pasture (Leite, Costa, Lima, Ribeiro, & Sediyama, 2010).

The census data revealed that pasture was the most common land use in the Brazilian Amazon, and that the conversion of newly deforested areas to pasture increased from 70% in 1997 to 80% in 2007. Of the three states investigated, Pará had the greatest intensification of pasture, increasing from 58,249 sq km in 1996 to 90,433 sq km in 2006 (IBGE, 1996, 2006). Some factors help to explain the continued predominance of pasture in land use changes in the Brazilian Amazon. For example, the expansion of the cattle herd shows that extensive cattle ranching is profitable in parts of the Brazilian Amazon (Margulis, 2004). Also, higher stocking rates are more common found in most deforested areas, which suggests an intensification of pasture use (Alves, Morton, Batistella, Roberts, & Souza Jr., 2009; Alves, Morton, Batistella, Roberts, & Souza, 2009).

In Mato Grosso the area under temporary agriculture increased from 27,824 sq km in 1996 to 57,344 sq km in 2006 (IBGE, 1996, 2006).The forest conversion to cropland in Mato Grosso is of particular interest because of the state's specific socio-demographic, economic, and bioclimatic conditions, which increase the probability that a different land use system will be established. Such growth in croplands is due to massive investments by commercial soybean farmers as well as to the success of farming systems and crop breeding research. Despite that, the main driver of forest loss in that state is large-scale cattle farming, even though the direct conversion of forest to cropland contributed substantially to the number of large deforested areas. The deforestation in Mato Grosso is much more mechanized than in the other two states. This mechanization makes it more likely that forest will be cleared and accelerates the deforestation.

With regard to the spatial dependence of our determinant variables, we know that land use tends to be spatially correlated, i.e. that land use change in one area tends to be correlated with that in adjacent or nearby areas. In this paper, we interpreted the differences between standardized regression coefficients for 1996/1997 and 2006/2007 as temporal changes in the influence of factors on deforestation and agricultural uses. A more detailed study should be done to find out to what extent this change can be attributed to temporal changes in dependent or independent variables, or both. In our study we made a number of simplifying assumptions, including: (i) a linear response between dependent (log cells proportion of deforestation or agricultural land uses) and the independent (partly log-transformed) factors; (ii) absence of interactions between the factors and dependent variable; (iii) absence of temporal correlation between the dependent variables for 1997 and 2007; and (iv) independent and identically distributed regression residuals. As our data were not derived from a controlled experiment, the results —notably the linear regression coefficients and their confidence intervals — should be interpreted with care, and be seen as an approximation. Using spatial lag regression modeling as an extension to linear regression is a first step towards exploring spatio-temporal data more thoroughly by regression modeling.

In this paper we integrated information from agriculture censuses with satellite data to provide additional information. This combination enabled us to analyze the spatial patterns of deforestation and agricultural uses within the Brazilian Amazon. We have shown that the extent and the rates of land use changes among the three states studied are largely driven by a set of conditions. Our mapped land uses time series and regression models show the distribution and proportion of major agricultural land uses, and also how these are influenced by several potential determinant factors.

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Appendix. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.apgeog.2011.04.003.

References

Achard, F., Eva, H. D., Stibig, H.-J., Mayaux, P., Gallego, J., Richards, T., et al. (2002). Determination of deforestation rates of the world's humid tropical forests. *Science, 297*(5583), 999–1002.

Aguiar, A. P. D. (2006). *Modeling land use change in the Brazilian Amazon: Exploring intra-regional heterogeneity*. São José dos Campos: National Institute for Space Research (INPE).

Aguiar, A. P. D., Câmara, G., & Escada, M. I. S. (2007). Spatial statistical analysis of land-use determinants in the Brazilian Amazonia: exploring intra-regional heterogeneity. *Ecological Modelling, 209*(2–4), 169–188.

Alves, D. S. (2002). Space-time dynamics of deforestation in Brazilian Amazonia. *International Journal of Remote Sensing, 23*(14), 2903–2908.

Alves, D. S., Morton, D. C., Batistella, M., Roberts, D. A., & Souza, C., Jr. (2009). The changing rates and patterns of deforestation and land use in Brazilian Amazonia. In *Amazonia and global change*. *Geophysical Monograpf Series, Vol. 186*.

Alves, D. S., Morton, D. C., Batistella, M., Roberts, D. A., & Souza, C. (2009). The changing rates and patterns of deforestation and land use in Brazilian Amazonia. In *Amazonia and global change*. *Geophysical Monograph Series, Vol. 186*.

Andersen, L. E., & Reis, E. J. (1997). *Deforestation, development, and government policy in the Brazilian Amazo: An econometric analysis*. Brasília, Brazil: IPEA.

Becker, B. (2005). Geopolítica da Amazônia. *Journal of the Institute of Advanced Studies of the University of Sao Paulo, 19*, 71–86.

Bivand, R. S., Pebesma, E. J., & Gómez-Rubio, V. (2008). *Applied spatial data analysis with R*. New York: Springer.

Cardille, J. A., & Foley, J. A. (2003). Agricultural land-use change in Brazilian Amazônia between 1980 and 1995: evidence from integrated satellite and census data. *Remote Sensing of Environment, 87*(4), 551–562.

Chambers, J. Q., Asner, G. P., Morton, D. C., Anderson, L. O., Saatchi, S. S., Espírito-Santo, F. D. B., et al. (2007). Regional ecosystem structure and function: ecological insights from remote sensing of tropical forests. *Trends in Ecology & Evolution, 22*(8), 414–423.

Dietz, T., Ostrom, E., & Stern, P. C. (2003). *The Struggle to Govern the Commons Science, 302*(5652), 1907–1912.

Fearnside, P. M. (1990). The rate and extent of deforestation in Brazilian Amazonia. *Environmental Conservation, 17*, 213–226.

Fearnside, P. M. (1996). Amazonian deforestation and global warming: carbon stocks in vegetation replacing Brazil's Amazon forest. *Forest Ecology and Management, 80*, 21–34.

Fearnside, P. M., Tardin, A. T., & Filho, L. G. M. (1990). In *Deforestation rate in Brazilian Amazonia*. São José dos Campos, Brazil: Instituto Nacional de Pesquisas Espaciais.

Geist, H. J., & Lambin, E. F. (2001). pp. 136p*What drives tropical deforestation?, Vol. 37*. LUCC Report Series No. 4.

Geist, H. J., McConnell, W., Lambin, E. F., Moran, E., Alves, D., & Rudel, T. (2006). Causes and trajectories of land-use/cover change. In E. F. Lambin, & H. Geist (Eds.), *Land-use and land-cover change, local process and global impacts*. Berlin Heidelberg: Springer.

Gibson, C., McKean, M. A., & Ostrom, E. (2000). *People and forests*. Cambridge and London: Communities, Institutions and Governance.

IBGE. (1996). In *Censo Agropecuário 1996* Insituto Brasileiro de Geografia e Estatística.

IBGE. (2006). In *Censo Agropecuário 2006* Insituto Brasileiro de Geografia e Estatística.

IBGE. (2008). In *Population Count 2007* Rio de Janeiro: IBGE. Available on-line at. http://www.ibge.gov.br/home/estatistica/populacao/contagem2007/.

INPE. (2010). In *PRODES - Amazon deforestation database* São Jose dos Campos: INPE. Available online at. www.obt.inpe.br/prodes.

IPCC. (2007a). Climate change 2007: synthesis report. In *An assessment of the Intergovernmental Panel on climate change* Intergovernmental Panel on climate change.

IPCC. (2007b). Summary for Policymakers. In B. Metz, O. R. Davidson, P. R. Bosch, R. Dave, & L. A. Meyer (Eds.), *Climate change 2007: Mitigation*. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. Contribution of working group III to the Fourth assessment Report of the Intergovernmental Panel on climate change.

Lambin, E. F. (1994). Modelling deforestation processes: a review. In *Research Report 1*. Brussels: European Commission.

Laurance, W. F., Albernaz, A. K. M., Fearnside, P. M., Vasconcelos, H. L., & Ferreira, L. V. (2004). Deforestation in Amazonia. *Science, 304*(5674), 1109–1111.

Laurance, W. F., Albernaz, A. K. M., Schroth, G.t., Fearnside, P. M., Bergen, S., Venticinque, E. M., et al. (2002). Predictors of deforestation in the Brazilian Amazon. *Journal of Biogeography, 29*, 737–748.

Leite, C. C., Costa, M. H., Lima, C. A., d., Ribeiro, C. A. A. S., & Sediyama, G. C. (2010). Historical reconstruction of land use in the Brazilian Amazon (1940–1995). *Journal of Land Use Science*1–20.

Margulis, S. (2004). Causes of deforestation of the Brazilian Amazon. In *W. B. w. paper. World Bank working paper, Vol. 22*.

Moran, E. F., Brondízio, E. S., & VanWey, L. K. (2005). Population and environment in Amazônia: landscape and household dynamics. In N. R. Council (Ed.), *Population, land use, and environment*.

Morton, D. C., DeFries, R., & Shimabukuro, Y. E. (2009). Cropland expansion in cerrado and transition forest ecosystems: quantifying habitat loss from satellite-based vegetation phenology. In R. S. D. C. Klink, & R. Cavalcanti (Eds.), *Cerrado land-use and Conservation: Assessing Trade-off's between human and Ecological Needs*. Washington D. C.

Nepstad, D., Soares-Filho, B. S., Merry, F., Lima, A., Moutinho, P., Carter, J., et al. (2009). The end of deforestation in the Brazilian Amazon. *Science, 326*(5958), 1350–1351.

Nobre, A. C., Sebestyen, G. N., Gitelman, D. R., Mesulam, M. M., Frackowiak, R. S., & Frith, C. D. (1997). Functional localization of the system for visuospatial attention using positron emission tomography. *Brain, 120*(3), 515–533.

Payton, M. E., Greenstone, M. H., & Schenker, N. (2003). Overlapping confidence intervals or standard error intervals: what do they mean in terms of statistical significance? *Journal of Insect Science, 3*(34).

Perz, S. G., & Skole, D. L. (2003). Social determinants of secondary forests in the Brazilian Amazon. *Social Science Research, 32*(1), 25–60.

Pfaff, A. S. P. (1996). *What drives deforestation in the Brazilian Amazon? Evidence from satellite and socioeconomic data*. New York: The World Bank, Policy Research Department.

Piribauer, T. (2010). *Land-use change modeling in the Brazilian Amazon - Exploring the impact of environmental factors*. Vienna: Vienna University of Technology.

Quéré, C. L., Raupach, M. R., Canadell, J. G., Marland, G., Bopp, L., Ciais, P., et al. (2009). Trends in the sources and sinks of carbon dioxide. *Nature Geoscience, Vol. 2*.

R-Team, R. D. C. (2005). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing.

Reis, E. J., & Guzmán, R. M. (1992). *An econometric model of Amazon deforestation*. Brazil: IPEA, Brasília.

Rylands, A. B., & Brandon, K. (2005). Brazilian protected areas. *Conservation Biology, 19*(3), 612–618.

Salazar, L. F., Nobre, C. A., & Oyama, M. D. (2007). Climate change consequences on the biome distribution in tropical South America. *Geophysical Research Letters, 43*, 6.

Shukla, J., Nobre, C. A., & Sellers, P. (1990). Amazon deforestation and climate change. *Science, 247*(4948), 1322–1325.

Skole, D., & Tucker, C. (1993). Tropical deforestation and habitat Fragmentation in the Amazon: satellite data from 1978 to 1988. *Science, 260*(5116), 1905–1910.

Soares-Filho, B., Moutinho, P., Nepstad, D., Anderson, A., Rodrigues, H., Garcia, R., et al. (2010). Role of Brazilian Amazon protected areas in climate change mitigation. *Proceedings of the National Academy of Sciences, 107*(24), 10821–10826.

Soares-Filho, B., Nepstad, D., Curran, L., Cerqueira, G., Garcia, R., Ramos, C. A., et al. (2006). Modelling conservation in the Amazon basin. *Nature, 440*(7083), 520–523.

Soler, L.d. S., & Verburg, P. H. (2010). Combining remote sensing and household level data for regional scale analysis of land cover change in the Brazilian Amazon. *Regional Environmental Change*. doi:10.1007/s10113-009-0107-7.