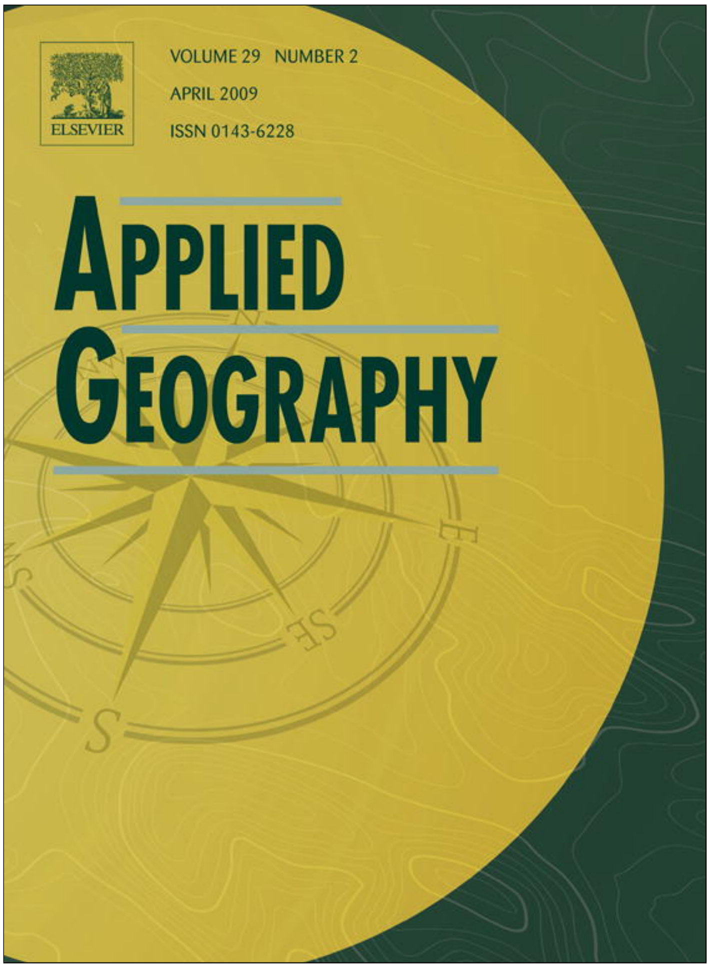
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Quantifying deforestation and secondary forest determinants for different spatial extents in an Amazonian colonization frontier (Rondonia)

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A B S T R A C T

Spatial patterns of deforested areas and secondary forest are analyzed in terms of the spatial variation in location factors at different spatial extents. The spatial extents considered are old and new agrarian colonization projects and the administrative units of two different municipalities in Rondonia: Vale do Anari and Machadinho d'Oeste. A grid database was constructed including land cover and potential location factors based on biophysical, accessibility, socioeconomic and policy data. Results of the spatial analyses confirmed the hypothesis that different extents yield different relationships between land use/cover patterns and their location factors, particularly between old and new agrarian colonization projects. It emphasizes that current patterns of forest, secondary forest and pasture/agriculture can only be understood with a combination of policy, accessibility, biophysical and socioeconomic factors while accounting for the historical pathways of change. Because we are dealing with different trajectories of land use/cover change, static analysis of the spatial pattern without acknowledging these trajectories will lead to erroneous interpretations of the current and future land use/cover dynamics.

Introduction

During the last decades human colonization has caused the loss of 17% of the forest in the Brazilian Amazonia. Rondonia State is now the fourth most deforested state in the region with deforestation rates fluctuating from 1110 to 4730 km^2/year between 1988 and 2007 (INPE, 2007). Known impacts of such land cover changes are losses in biodiversity, increases of carbon release and changes in the water cycle and regional climate, potentially affecting local communities and indigenous people (Millikan, 1992; Miranda & Mattos, 1992; Southworth, Dale, & Oneill, 1991; Werth & Avissar, 2004). In order to assess these impacts, several analyses of the determinants of deforestation have been done for the Brazilian Amazonia at different scales (Dale, Oneill, Southworth, & Pedlowski, 1994; Soares-Filho, Assuncao, & Pantuzzo, 2001; Soares-Filho et al., 2006). These studies confirm that the spatial variability of location factors as proximate drivers strongly affect the patterns of deforestation in the Brazilian Amazonia (Aguiar, Câmara, & Escada, 2007; Arima, Walker, Perz, & Caldas, 2005; Soares-Filho et al., 2006). However, the results of the analysis of land use/cover patterns and their determinants are dependent on the spatial extent and the spatial resolution of analysis (Gibson, Ostrom, & Ahn, 2000).

Amazonian spatial variability, as exemplified by different land cover patterns within the same region, appears to be associated with differences in colonization history, actors, economic activities, public policies and sometimes with

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biophysical aspects (Batistella, 2001; Cochrane & Cochrane, 2006; Escada, 2003; Fearnside, 2005). At the Amazonian scale different deforestation patterns appear to be linked to geopolitical frontiers with locally diverse ecological, socioeconomic, political and accessibility conditions (Aguiar et al., 2007; Becker, 2004). Although significant, these results are not directly applicable to regional and local scale studies due to scale effects related to extent and resolution (Overmars & Verburg, 2006). Furthermore, a more local analysis requires the distinction of more land cover categories, such as secondary forest, allowing more direct links to land use/cover and local actors. A main topic in the Brazilian Amazonia is the analysis of secondary forest patches inside colonized areas, once that might give insights in aspects of land management and actors' decisions (Alves, Escada, Pereira, & Linhares, 2003). Beyond the relevance of secondary forest to carbon budgets, climate change and biodiversity (Dale, Pearson, Offerman, & Oneill, 1994; Hughes, Kauffman, & Cummings, 2000), from the human dimension point of view, secondary forest dynamics potentially yield valuable information about household decisions (Perz & Skole, 2003). The link to household decision making is especially important in areas where small landholders predominate such as Rondonia State (Fearnside, 1993).

Rondonia is predominantly occupied by small landholders as a result of colonization projects created along the major roads in the 70s (Becker, 1997). The constant flux of migrants demanded colonization of new areas far from the major roads such as Machadinho d'Oeste and Vale do Anari municipalities, created in the 80s. They present similar biophysical characteristics and lot sizes, but with significant differences in their spatial configurations and planning (Batistella, 2001). Within these municipalities there are two different generations of agrarian colonization projects, old projects created between 1980 and 1990 and new ones created between 1990 and 2000. Agrarian colonization projects in Vale do Anari are typically drawing-table plans characterized by the well known fishbone patterns, while Machadinho's agrarian colonization projects were better planned taking local biophysical conditions into account leading to dendritical deforestation patterns. This offers us the possibility to investigate how spatial variability of proximate land cover change drivers contributed to the different deforested area and secondary forest patterns over different spatial extents.

Many different methods have been used to identify location factors of land cover (Briassoulis, 2000; Koomen, Stillwell, Bakema, & Scholten, 2007) with statistical models being one of the most common techniques to quantify the contribution of land use/cover determinants at various levels of analysis (Aguiar et al., 2007; Overmars & Verburg, 2005). Particularly, logistic regression is often used because the resulting probability maps can directly be used in land use/cover change models (Lesschen, Verburg, & Staal, 2005; Mertens & Lambin, 1997). Statistical analysis using field observations together with remote sensing and census data can reveal the driving factors acting from the household level to higher levels of organization (Perz & Skole, 2003; Rindfuss, Walsh, Turner, Fox, & Mishra, 2004). As a result, statistical land cover models of deforestation and secondary forest patterns at local scales can provide insights into the underlying processes of land cover change. Such insights might help governmental and non-governmental organizations to target more effective deforestation policies. (Fujisaka, Bell, Thomas, Hurtado, & Crawford, 1996; Verburg, 2006). The present study aims to identify differences in location factors of current deforested areas and secondary forest patterns over different spatial extents in Machadinho d'Oeste and Vale do Anari municipalities using logistic regression analysis.

First, the land use/cover history in the study area is described, followed by a short review of existing land use/cover studies which relate directly to the study area. Subsequently the study area and all collected data are described including the statistical methods employed. The results are presented for different spatial extents. The final section discusses the general outcomes of the present study.

Land use/cover processes in Rondonia

The colonization of Rondonia began during the 70s with the establishment of agrarian projects along the main road BR 364 (see Fig. 1a). Colonization was stimulated with easy credit for housing and subsistence agriculture (Becker, 1997). The National Institute of Land Reform (INCRA) built secondary roads to connect the agrarian projects to urban nucleus as part of the governmental support to the migrants. However, rural support, health, education and transport were usually incipient (Coy, 1987). During the 80s and 90s INCRA established new agrarian projects with smaller lot sizes to allocate a larger number of families. In this context, Machadinho d'Oeste and Vale do Anari settlements were established in 1982 in the northeast of Rondonia State with initial areas of 2129 and 1246 km^2, respectively. Until 2000, INCRA created 14 more agrarian projects in the vicinities of the initial settlements. Continuous migration pushed the government to split the area into two municipalities in 1997, whose names were taken from the very first settlements Machadinho d'Oeste and Vale do Anari. Today, the area of these new municipalities encloses the initial and subsequent agrarian projects, including conservation reserves and claimed or unclaimed lands in the neighboring areas (Fig. 1b).

As can be observed from Fig. 1a, the old agrarian projects are more deforested than the new ones. Another aspect is that the pattern of deforestation in Vale do Anari municipality has a typical fishbone pattern, while in Machadinho municipality the patterns are dendritic. This difference can be explained by the different ways of planning. The Anari settlement was planned two years earlier and this was done behind a drawing-table without taking the local topography into account. Machadinho was planned with roads following the watershed topography. Although different, both patterns follow the design of the roads and the proportional amount of deforestation between them has been quite similar along the years of colonization (INPE, 2007). However, the dendritic patterns in Machadinho appear to result in less fragmented forest, what is reinforced by several conservation reserves spread within the agrarian projects of this municipality.

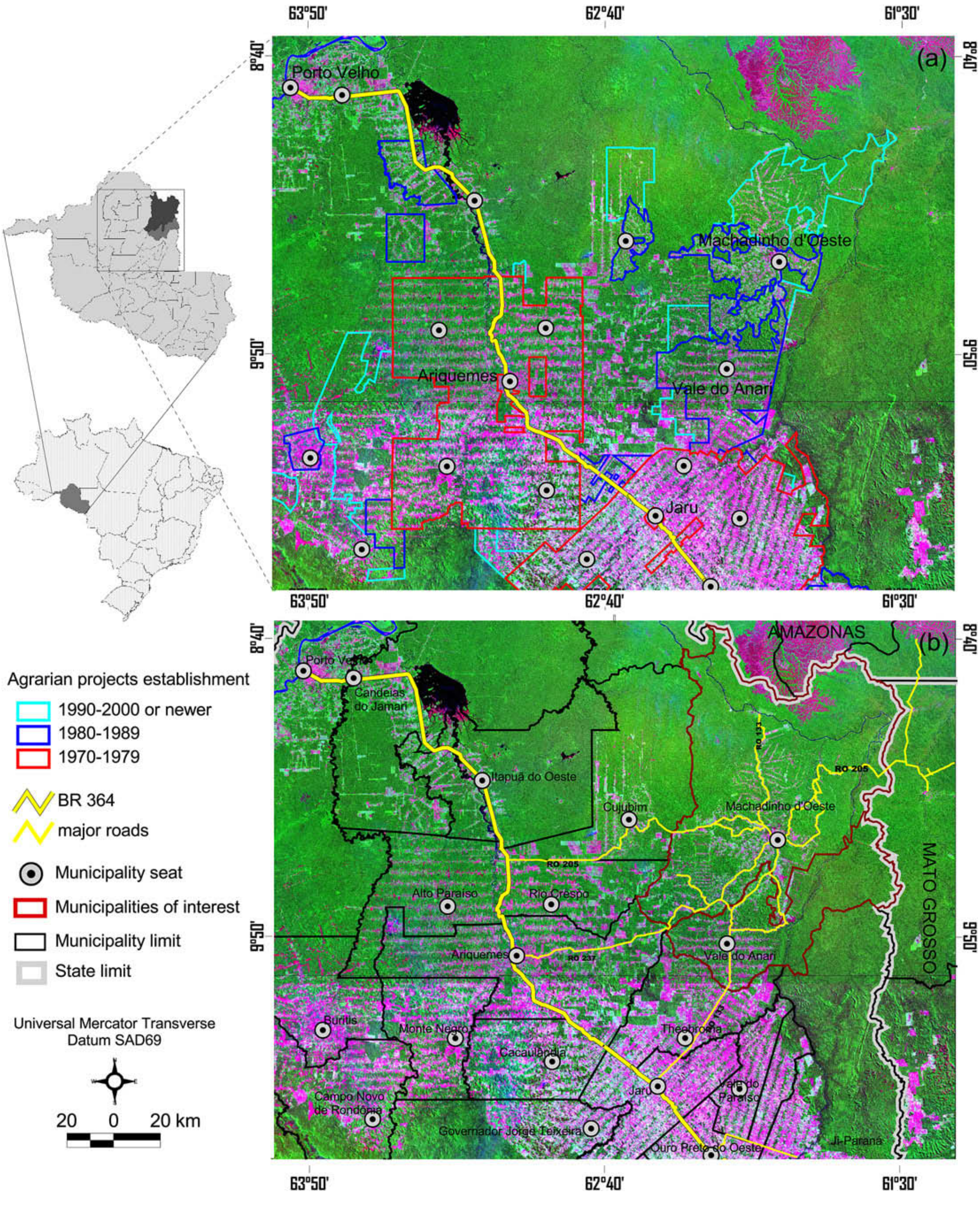


Fig. 1. (a) Agrarian projects created in the study area until 2000 (b) Political borders of study area highlighting Machadinho d'Oeste and Vale do Anari municipalities and the main roads. Both backgrounds show a Landsat TM mosaic from 2000 with the channels near-infrared, red and green associated to the colors red, green and blue, respectively. Forested areas are represented by dark green, secondary forest in light green and agriculture, bare soil and urban areas form a mosaic of magenta, light blue and/or white.

There is still an ongoing debate at the Amazonian scale what the contribution of different land owner categories is to deforestation. Fearnside (1993) showed that deforestation occurs mostly in medium (100–1000 ha) and large farms (>1000 ha) in the Brazilian Amazonia. However, in the northeast of Rondonia, originally occupied by small landholders, most of the deforestation between 1991 and 1997 was due to clearings between 50 and 100 ha (Alves, 2002), indicating that cattle ranchers bought up the smaller holdings and combined them to larger farms. Similar indications that small landholders have been selling their farms to cattle ranchers are observed in Rondonia (Mello & Alves, 2005; Pereira, Escada, & Rennó, 2007). In Para State where cattle raising activities are increasing among small landholders (Walker, Moran, & Anselin, 2000), an increase in overall deforestation can be observed during 2006–2007 (Souza & Verissimo, 2007).

Secondary forest plays an important role in smallholder farm management and related decisions. Due to law enforcement concerning forest remnants, high cost of deforestation and poor soil fertility most small landholders tend to slash and burn young secondary forest every 2–3 years. Slash and burn is a common practice to increase the soil fertility, to reduce weeds and to renew pasture (Dale, Oneill, et al., 1994; Pedlowski & Dale, 1992; Pedlowski, Dale, Matricardi, & da Silva, 1997). In extreme cases, these landholders either abandon their lands resulting in secondary forest growth, or they sell off their land in a process of land concentration leading to land use intensification. This intensification occurs mainly in older settlements, as a result of family aging, unsteady profit margins of agricultural products, decrease in land productivity, decrease of labor availability and diseases (Escada, 2003; Millikan, 1992). Land concentration processes are also found in other areas in Rondonia (Pedlowski & Dale, 1992; Pedlowski et al., 1997) and in Para State (Mertens, Poccard-Chapuis, Piketty, Lacques, & Venturieri, 2002; Perz, 2001).

Drivers of land use/cover change in the study area

An overview of previous land use/cover change studies in Rondonia state including the study area is summarized in Table 1. Alves, Pereira, De Sousa, Soares, & Yamaguchi (1999) showed that between 1985 and 1995 deforestation expanded to new areas in Machadinho and Anari municipalities near the major roads RO 133 and RO 205, adjacent to BR 364 (Fig. 1b). The percentage of deforestation within 12.5 km from these roads, where pioneer settlements were started, increased from 14% to 21% between 1985 and 1995. Cardille and Foley (2003) demonstrated by correlating land cover maps and census data of Rondonia, that planted pastures increased 500% in recently deforested areas between 1980 and 1995. This process was mostly happening near the urban areas Ji-Paraná and Ariquemes. Alves et al. (2003) observed that land intensification trends are mostly due to pasture expansion in already mostly deforested areas at the cost of secondary forest. Highly deforested areas increased between 1985 and 1995 occupying large areas adjacent to BR 364. Conversely, the areas of secondary forest occurred mostly at the edges of the forest, where new settlements are located.

Escada (2003) developed a method to construct maps of occupation based on farm size. These maps demonstrated a continuous expansion of pasture in the area of Machadinho at the expense of forest cover during 1991 to 2000. This analysis demonstrated that areas occupied by large, medium and small farms contributed equally to local deforestation processes. Combined with image interpretation and fieldwork, it was demonstrated that the process of land concentration was occurring in Vale do Anari.

Batistella (2001) developed a land use/cover change analysis for both Machadinho and Anari settlements using remote sensing data and household level interviews between 1988 and 1998. The analysis showed for Anari that pasture conversion and land abandonment of crop and pasture areas were the most dominant changes. In Machadinho a different result was found with an almost equal occurrence of pasture and agricultural fields. Small landholders used secondary forest for cattle grazing. According to local landholders, crop productivity was better in Machadinho, what was also indicated by land evaluation data from a previous census (IBGE, 2000).

It is expected that the spatial analysis of land cover patterns will result in similar location factors as reported in this review. It is also expected that by using different spatial extents a more in-depth understanding of the observed patterns is achieved. In order to test these hypotheses the whole study area was analyzed, followed by a stratification into the two municipalities

Table 1
Overview of previous land use/cover change studies in Rondonia state enclosing the study area.

Author	Objective	Method	Land use/cover determinants identified
Alves et al. (1999)	Spatial–temporal analysis of deforestation processes under occupation	Multitemporal analysis of deforestation from 1985 and 1995 by image classification and map-intersection	Distance to major roads, areas of pioneer settlements
Alves et al. (2003)	Estimate spatial–temporal distribution and evaluate the interdependence of deforestation and abandoned land	Multitemporal analysis of deforestation from 1985 and 1995 by image classification, fieldwork and map-intersection of deforestation and land abandonment	Land use intensification, pasture expansion near roads over forested and secondary forest areas, secondary forest concentration at forest fringes in new agrarian projects
Cardille and Foley (2003)	Examine changes in broad-scale patterns of agricultural land-use practices in part of the Brazilian Amazonia	Multitemporal image classification from 1980 and 1995 correlated with census data	Distance to urban areas, pasture expansion for cattle raising over forested areas
Escada (2003)	Spatial–temporal analysis of changes in land use/cover patterns and their associated actors in the centre-north of Rondonia	Multitemporal image classification and interpretation from 1985 to 2000 of deforestation and secondary forest patterns and fieldwork	Road infrastructure along time, pioneer settlements, agrarian structure and land concentration along time, spatial variability of patterns and actors
Batistella (2001)	Analyze distinct land use/cover patterns and institutional support impacts on deforestation and socioeconomic aspects	Multitemporal image classification from 1988 to 1998, landscape metrics, ANOVA and fieldwork	Settlement design, institutional support, conversion of cropped land to pasture, land abandonment, biophysical properties (soil fertility, water supply, slope)

(see Fig. 1b red boundaries) and a stratification by old and new agrarian colonization projects (see Fig. 1a, blue and cyan boundaries).

Materials and methods

Study area characterization

The study area consists of the municipalities Machadinho d'Oeste and Vale do Anari, both located in the northeast of Rondonia (Fig. 1b). Their total areas are 8509 and 3135 km^2, respectively, which corresponds to 5% of Rondonia State and 0.3% of the Brazilian Amazonia. They are situated about 400 km from the capital Porto Velho and are accessible by roads while river transport can be particularly useful during the wet season. Dense tropical rain forest is the predominant natural vegetation, but patches of savannah are found in the north (Radambrasil, 1978). The regional climate is classified as tropical rainy, according to the Köppen classification, with a dry season from June to September and a rainy season from October to May (Rondonia, 2004). The predominant soils are Feralsols, Aerenosols, Planosols and Gleysols, according to the FAO classification (Rondonia, 2000). Slopes are predominantly flat (0–3%), but undulating terrain (8–20%) is observed near river valleys. Conservation reserves are planned throughout the whole area and have various degrees of protection depending on the level of human intervention. The area has no indigenous reserves.

In 2000, the population of Machadinho consisted of 22,739 inhabitants, with 51% living in rural areas while Anari had 7737 inhabitants, with 76% in rural areas. The average population growth between 1991 and 2000 was 3.4% in Machadinho and 0.7% in Anari (IBGE, 2000). In 2007, the total population in Machadinho and Anari was estimated to be 29,548 and 8751, respectively (IBGE, 2007b). Another heterogeneous aspect between the two areas is that Machadinho has a more structured economy with better commercial and public infrastructure than Anari (IBGE, 2000, 2007a). The main economic activities of small landholders are self-sustaining agriculture and cattle raising to provide milk for local and regional markets. Medium and big farmers produce beef for local to international markets (SIF, 2006). Land selling or abandonment by small landholders is related to lack of subsidies, aging and offspring migration. In both municipalities, land management such as manure application, irrigation or crop/pasture rotation is hardly observed (EMATER-RO, 2006). Overgrazing is a common practice leading to pasture degradation and plagues (IDARON, 2006). Wood extraction has decreased in many agrarian projects due to extinction of commercial species and law enforcement, but fieldwork observations indicated a migration of illegal wood extraction to the northeast of Machadinho d'Oeste, into Colniza municipality in Mato Grosso State.

Building the database of potential location factors

Potential land use/cover proximate drivers and location factors were selected based on the review of previous land use studies, fieldwork information from 2001 and 2006 and data availability. The selected variables include biophysical, accessibility and socioeconomic aspects, as well as public policies. The first exploratory models included 55 variables, but only 38 had significant contributions in the final models (see Table 2). Classes of the categorical variables geomorphology, lithology and soil types are counted each as a unique variable. The grid database was built at a spatial resolution of 250×250 m, the highest resolution possible with the available data. This resolution is an exact multiplier of the average size of lots in the agrarian projects (2000×500 m). The original scale and resolution of the variables selected were quite different; especially biophysical variables have a different spatial variability than socioeconomic data and the accessibility measures. This suggests that some loss of information took place during the data aggregation process. In a preliminary test all data were aggregated to 500 m resolution. Initial analysis demonstrated similar patterns and correlation between deforested areas, secondary forest and location factors indicating limited loss of information. These results are consistent with other studies at multiple scales (Veldkamp & Fresco, 1997; Walsh, Evans, Welsh, Entwisle, & Rindfuss, 1999). Therefore, it was decided not to change the data resolution and use only the 250 m resolution data.

The land use/cover map used in this research was constructed from a series of 1985–2000 Landsat/TM images. The agrarian structure was obtained from as existing 2000 database containing the limits of properties and their classification per size (Escada, 2003). Only two land use/cover types were included in the analysis: pasture and agriculture (mapped as deforested area) and land abandonment or vegetation regrowth (i.e. secondary forest land cover).

Monthly precipitation data from 1970 to 2000 with a resolution of 0.25° were aggregated for the period from April to September and October to March, according to the seasonality in the region. Deforested area might have a significant correlation to dry season rainfall because precipitation is generally lower in deforested areas (Sombroek, 2001). As a result of low precipitation, colonists tend to burn their pasture and secondary regrowth in the dry season, thus a positive correlation of fires with dry precipitation is expected in secondary forest models. Slope, geomorphology, lithology and soil types describe the biophysical location factors used in this analysis.

Accessibility measures were calculated using cost distance algorithms (Geurs & Ritsema van Eck, 2001; Verburg, Overmars, & Witte, 2004). Differences in average speed of transportation for the road network according to seasonality of rainfall were taken into account. The average speed of transportation by roads, rivers and paths was estimated based on field measurements; interviews with landholders and local inhabitants (see estimates in Table 3). In order to evaluate the importance of roads in local deforestation processes, alternative models were tested using Euclidean distance to the destinations and cost distances disregarding the road network as opposed to the accessibility measures that include the road network.

Table 2
Variables representing the potential determinants of land use/cover selected for the analyses.

Variables	Description	Source
Biophysical		
Slope	Slope (%) derived from elevation data SRTM at 90 m	NASA/USGS (2000)
Geomorphology		
Flat	Flat areas with fluvial deposits, at risk of floods	CPRM (2004)
Floodplain	Sandy and muddy areas at risk or not of floods	
F_Terrace	Fluvial deposits with flat shapes and smooth inclination	
Differential_1	Crystalline rocks with medium drainage density, flat to smooth slope	
Differential_2	Crystalline or sedimentary rocks with convex peaks, medium drainage density, smooth slope	
Differential_3	Crystalline or sedimentary rocks with convex peaks, high drainage density, smooth slope	
Differential _4	Sedimentary rocks tabular smoothly ramped peaks, coarse drainage density, smooth slope	
Differential _5	Sedimentary rocks tabular smoothly ramped peaks, medium drainage density, smooth slope	
Lithology		
Sand_Silt	Alluvium, sand, clay, lignite, turf, gravel	CPRM (2004)
Sand	Sand and gravel	
Conglomerate	Sandstones and conglomerates	
Gneiss	Amphibolite, marbles, gneisses, migmatites	
Gabbro	Mafic and ultra-mafic crystalline rocks	
Granite	Granites and granodiorites	
Trachyte	Trachyte and other potassium feldspar rich rocks	
Soil type		
Quartz_Soil	Soil type: quartz psamments	SEDAM ZEE/RO
D_Y_Latosols	Soil type: dystrophic yellow latosols (FAO: Ferralsol)	(Rondonia, 2000)
D_RY_Latosols	Soil type: dystrophic red-yellow latosols (FAO: Ferralsol)	
E_RY_Latosols	Soil type: eutrophic red-yellow latosols (FAO: Acrisol)	
E_DR_Latosols	Soil type: eutrophic dark-red latosols (FAO: Nitisol)	
Plansoils	Soil type: dystrophic plansoils (FAO: Planosol)	
Gleysoils	Soil type: dystrophic gleysoils (FAO: Gleysol)	
Precip_W	Average of monthly precipitation in the wet season – October to March, 1970–2000	INPE/CPTEC (2005)
Precip_D	Average of monthly precipitation in the dry season – April to September, 1970–2000	
Fires	Euclidean distance to fire spots in 2000 obtained from AVHRR sensors	
Accessibility measures		
CD_Town_R	Cost distance to towns using only map of rivers	IBGE (2000)
CD_Town_W	Cost distance to towns in the wet season	
CD_Town_D	Cost distance to towns in the dry season	
ED_Sawmills	Euclidean distance to sawmills	MMA[a] fieldwork
CD_SFarms_R	Cost distance to small farms using only map of rivers	INCRA (2006);
CD_SFarms_W	Cost distance to small farms in the wet season	Escada (2003)
ED_BFarms	Euclidean distance to big farms	
CD_BFarms_W	Cost distance to big farms in the wet season	
Socioeconomic		
Pop_Density	Population density at district level	IBGE (2000)
Income_Pcap	Income *per capita* at district level	
Num_People	Number of people per district at district level	
Public policies		
Cons_Reserve	Conservation reserves at 1:1,000,000	IBAMA (2005)

[a] MMA – Brazilian Ministry of Environment, IBAMA – Brazilian Institute for Environment and Natural Resources Conservation.

Table 3
Estimates of the average speed of transportation per type of access in the dry and wet seasons.

Measure	Average speed (km/h)	
Access	Dry season	Wet season
Forested areas	3.0	3.0
Secondary rivers	11.5	11.5
Main rivers	23.0	23.0
Vicinal roads	30.0	15.0
Major roads	70.0	35.0
Highway BR 364	110.0	80.0

Socioeconomic data were selected from census data (IBGE, 2000). The year 2000 was chosen as the baseline for statistical analysis. Finally, conservation reserves were included in the analysis as a public policy aspect. Initially the conservation reserves were stratified according to the level of intervention allowed, but this yielded no significant differences, consequently all the reserves were considered equally.

Statistical methods

Statistical procedures were used to find coherent explanatory models of the deforested and secondary forest areas. Based on the earlier mentioned stratification, logistic regression analysis was performed at three different spatial extents: A) the whole study area; B) Machadinho d'Oeste and Vale do Anari municipalities separately; C) old and new agrarian projects established in the 80s and 90s separately. Samples of deforested areas and secondary forest areas were produced using a balanced, random sampling method avoiding adjacent cells to reduce the possible bias of spatial autocorrelation on the regression results (Overmars, de Koning, & Veldkamp, 2003).

Multicollinearity among variables was investigated using Pearson's correlation. The accessibility measures turned out to be the most inter-correlated variables. From the variables with inter-correlation coefficients $\geq$0.80, only the one most related to the land use/cover was retained in the analysis. This cut-off value is usually adopted in logistic regression models (Menard, 2001). After the correlation analysis, a more refined variable selection was done comparing the odds and the standardized regression coefficients of the independent variables, which were calculated following Menard (2001). Eventually, variables for which modeled relationships could not be explained by a causal explanation were excluded. Goodness-of-fit values were evaluated between initial and final models using the area under the ROC curve (relative operating characteristic) (Pontius & Schneider, 2001). Values for this statistics vary from 0.5 to 1.0. Logistic land use/cover models with ROC value higher than 0.7 are considered acceptable and values higher than 0.8 indicate a good model fit (Lesschen et al., 2005).

Results and discussion

Extent A: Machadinho d'Oeste and Vale do Anari as a whole

Table 4 presents the regression coefficients for the whole study area for models with accessibility measures based on the road network and for accessibility measures disregarding the road network. It is clear that regression coefficients for accessibility measures considering the road network are higher than in the models without the roads. As a result, the increase in the ROC values for models including road network indicates the importance of roads in determining land use/cover patterns in the region. Socioeconomic and public policy variables have a similar contribution for both sets of models, demonstrating their independent contribution to the pattern of deforested and secondary forest areas.

In models that include the road network the variables cost distance to towns in the wet and in the dry season showed significant contribution in explaining the variability of deforested and secondary forest areas, respectively. A similar importance of cost distance to main urban areas has been identified by other studies at different scales of analysis (Aguiar et al., 2007; Soares-Filho et al., 2001). Accessibility measures during the wet season were more important in explaining the deforested area because some locations are hardly accessible during the wet season. Similarly, cost distance to big farms in the wet season contributed significantly to the deforested area model. In the dry season the cost distance to towns determines the secondary forest area distribution, which is an indication that secondary forest occurs mostly at the forest fringes, as stated by Alves et al. (2003).

Extent B: Machadinho d'Oeste and Vale do Anari independently

Results of the models for deforested and secondary forest areas for each municipality are shown in Figs. 2 and 3. The main contributing variables for deforested areas in both municipalities were precipitation during the dry season, fires, cost distance to towns and to big farms during the wet season, and the occurrence of conservation reserves (see Fig. 2). The significant coefficients of biophysical variables in the deforested area in Machadinho appear to confirm that the planning of roads was done according to biophysical conditions.

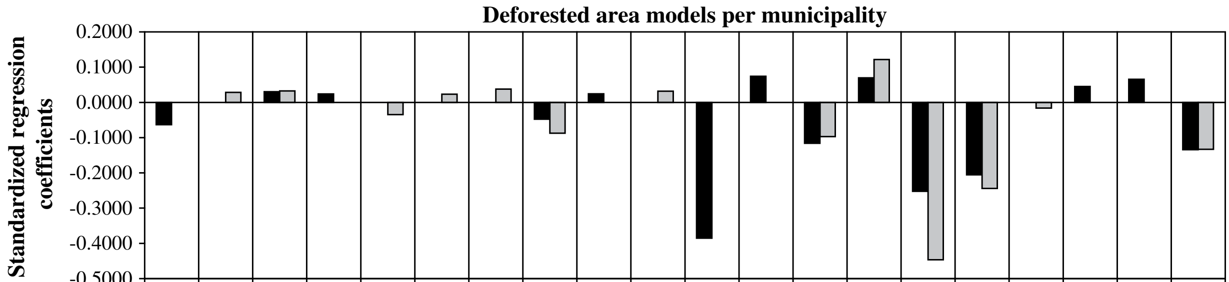
Cost distance to towns during the wet season is more important for Anari municipality, most likely because of Anari's proximity to larger towns. Machadinho municipality is relatively independent in terms of commercial, health and public services. This independence was confirmed by interviews with landholders. This difference is also related to a higher spatial correlation between roads and fishbone patterns in Vale do Anari than the dendritic patterns in Machadinho. The spatial variability between the municipalities was also captured by the socioeconomic variables income per capita and number of people that explained the spatial variation in deforested area only in Machadinho. Population density had a negative contribution to deforested area in Anari. These results reflect the higher and more spatially concentrated population in Machadinho compared with the less densely distributed population in Anari during the last decade (IBGE, 1991, 2000). The higher population density in Machadinho combined with better economic conditions has apparently attracted an additional influx of in-migration and stimulated more deforestation.

The main explaining variables for both secondary forest area models were sandy lithology, income per capita and conservation reserves (see Fig. 3). In general lithology and geomorphology contribute more to secondary forest models in Machadinho, while soils were more important in Vale do Anari models. The variable 'conglomerate', cemented gravel

Table 4
Results for the models with and without road network for the whole area of Machadinho d'Oeste and Vale do Anari, showing standardized regression coefficients and ROC values.

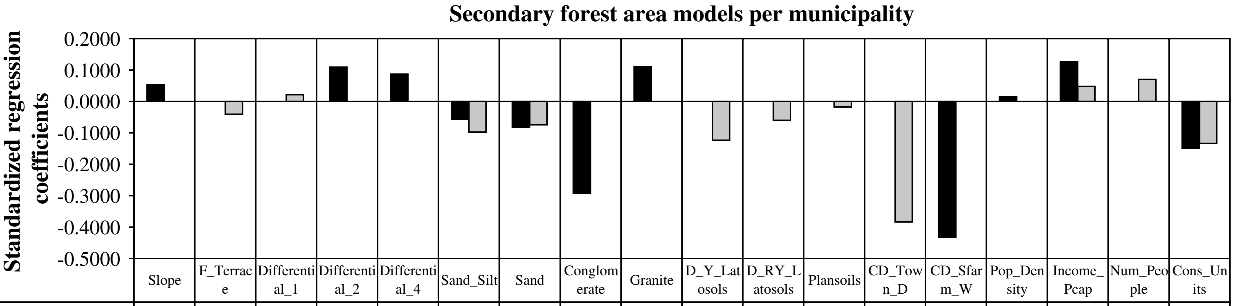
Machadinho and Anari	Models without road network		Models with road network	
Land use/cover	Deforested area	Sec_Forest area	Deforested area	Secondary forest area
ROC	0.8800	0.7990	0.8960	0.8070
Slope	–	–	–	0.0400
Flat	–	–	–	−0.0474
Floodplain	–	−0.3586	–	–
F_Terrace	−0.0490	−0.0196	–	–
Differential_1	0.0117	0.0241	0.0234	–
Differential_2	–	0.0661	–	–
Differential_4	0.0373	0.0468	–	–
Differential_5	–	–	–	−0.1128
Sand_Silt	−0.0587	−0.0796	–	−0.0868
Sand	−0.0822	−0.0738	–	−0.1009
Conglomerate	−0.1071	−0.2418	–	−0.2950
Gabbro	–	−0.0672	–	–
Trachyte	0.0142	–	0.0202	–
Quartz_Soil	0.0419	–	−0.0134	−0.0593
D_Y_Latosols	–	–	−0.0680	–
D_RY_Latosols	0.0783	–	–	–
E_RY_Latosols	0.0347	–	–	–
E_DR_Latosols	0.0490	0.0261	–	0.0353
Plansoils	0.0461	−0.0124	–	−0.0363
Gleysoils	−0.4138	–	−0.3828	–
Precip_W	–	0.1151	0.0915	0.0707
Precip_D	–	–	−0.1127	–
Fires	–	–	0.1419	0.1531
CD_Town_R	−0.0473	−0.0314	Not included	
ED_Sawmills	−0.0620	–		
CD_SFarms_R	−0.1795	−0.1877		
ED_BFarms	−0.0852	–		
CD_Town_W	Not included		−0.3491	–
CD_Town_D				−0.4394
CD_BFarms_W			−0.2038	–
Income_Pcap	0.0539	0.0865	–	0.0775
Num_People	0.0522	–	0.1063	–
Cons_Reserve	−0.1587	−0.1500	−0.1395	−0.1830

pointing to flat relative fertile areas, had a negative influence in the secondary forest model for Machadinho likely because these areas are favored for agriculture or because they still present considerable forest remnants. Cost distance to small farms in the wet season was only important in the Machadinho secondary forest area model. This relationship can be attributed to the high density of small farms in Machadinho (INCRA, 2006). In Vale do Anari cost distance to towns in the dry season was a significant contributor for similar reasons as stated for the models for the whole area.



	F_Terrace	Differential_1	Differential_2	Differential_4	Sand	Gneiss	Gabbro	D_Y_Latosols	E_RY_Latosol	E_DR_Latosol	Gleysoils	Precip_W	Precip_D	Fires	CD_Town_W	CD_BFarms_	Pop_Density	Income_Pcap	Num_People	Cons_Units
■ Machadinho d'Oeste - ROC 0.902	-0.0633		0.0302	0.0238				-0.0476	0.0245		-0.3854	0.0741	-0.1161	0.0698	-0.2522	-0.2055		0.0453	0.0657	-0.1341
□ Vale do Anari - ROC 0.802		0.0286	0.0327		-0.0346	0.0231	0.0377	-0.0876		0.0318			-0.0969	0.1217	-0.4467	-0.2442	-0.0160			-0.1332

Fig. 2. Graphic comparison of individual deforested area models for Machadinho d'Oeste and Vale do Anari municipalities.



	Slope	F_Terrace	Differential_1	Differential_2	Differential_4	Sand_Silt	Sand	Conglomerate	Granite	D_Y_Latosols	D_RY_Latosols	Plansoils	CD_Town_D	CD_Sfarm_W	Pop_Density	Income_Pcap	Num_People	Cons_Units
■ Machadinho d'Oeste - ROC 0.899	0.0531			0.1092	0.0868	-0.0572	-0.0823	-0.2928	0.1103					-0.4329	0.0157	0.1262		-0.1486
□ Vale do Anari - ROC 0.829		-0.0408	0.0215			-0.0975	-0.0744			-0.1236	-0.0599	-0.0175	-0.3836			0.0480	0.0700	-0.1336

Fig. 3. Graphic comparison of individual secondary forest models for Machadinho d'Oeste and Vale do Anari municipalities.

Extent C: old and new Agrarian colonization projects

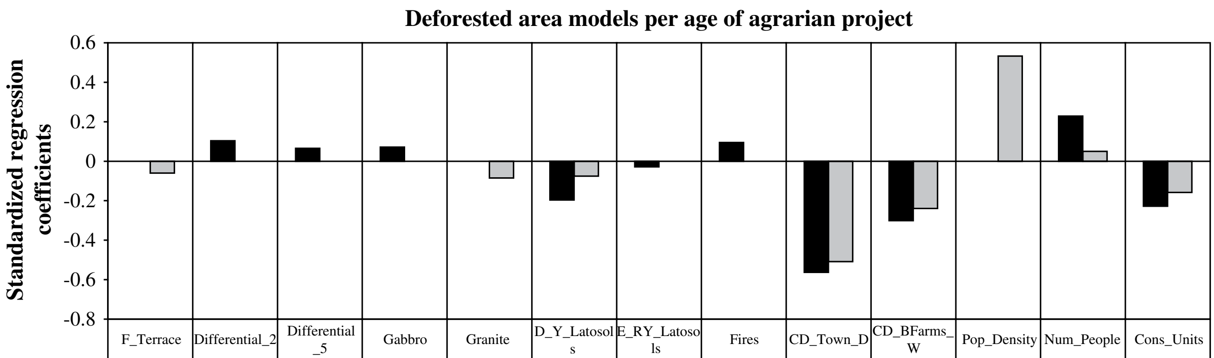
The deforested area and secondary forest area models for the old (1980–1990) and new (1990–2000) agrarian projects are shown in Figs. 4 and 5 respectively. The most important variables for both deforested area models were cost distance relations to towns and to big farms during the wet season, soil types, number of people and conservation reserves. In general, the low spatial variability in biophysical variables within this stratification is reflected by their minor importance in explaining the deforested areas. There appears to be a higher influence of number of people on deforested area in the older frontier (agrarian projects) and of population density in the new frontier. Although these variables look similar, these differences indicate land use intensification in the older frontiers. New frontiers have a low number of people, but a relatively high population density due to smaller lot sizes with dispersed deforested area patterns. These results confirm previous studies that show deforestation in old settlements linked to land use intensification and aggregated lots resulting from land concentration processes (Alves et al., 1999; Escada, 2003; Mertens et al., 2002; Millikan, 1992).

For the secondary forest area models the relevant variables were lithology, precipitation, cost distance to towns in the dry season and conservation reserves. The secondary forest variability was captured by lithology, soil types and income per capita. As expected, the models demonstrate that very poor soil types predominate in new agrarian projects, while in old ones small patches of better soils can be found, what affects secondary forest growth. The divergent responses of lithological categories within the two groups of settlements reflect that new projects are closer to the main river and present a higher occurrence of secondary forest patches, which are scarce in the old projects where land use intensification driven by high income per capita is significant, so secondary forest occurs in a few areas in the back of lots near the watershed and at steeper slopes (Alves et al., 2003; Soares-Filho et al., 2001). This can explain why the positive contribution of precipitation in the dry season is higher in new projects areas, because less rainfall is expected in highly deforested areas (Sombroek, 2001).

General outcomes for all spatial stratification

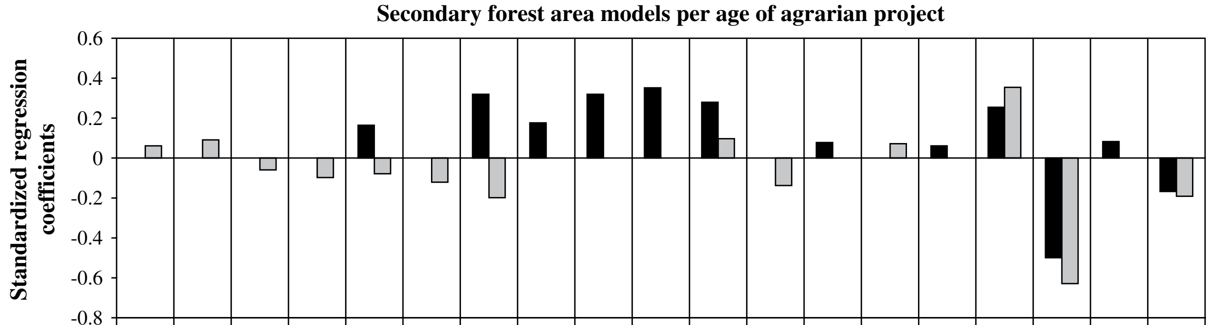
Accessibility measures

It is clear that accessibility measures adopting the road network determine deforested and secondary forest areas for all studied extents. Accessibility is more significant in explaining differences between the old and new agrarian projects, indicating that the agrarian projects as such predominantly determine land use/cover patterns together with road network. The most relevant accessibility measures were cost distances to towns and to big farms for deforested area, and cost distances



	F_Terrace	Differential_2	Differential_5	Gabbro	Granite	D_Y_Latosols	E_RY_Latosols	Fires	CD_Town_D	CD_BFarms_W	Pop_Density	Num_People	Cons_Units
■ Old agrarian projects - ROC 0.773		0.1041	0.0656	0.0715		-0.1964	-0.0284	0.0948	-0.563	-0.301		0.2288	-0.2281
□ New agrarian projects - ROC 0.831	-0.0602				-0.0852	-0.0755			-0.5088	-0.2390	0.5328	0.0499	-0.1580

Fig. 4. Graphic comparison of individual deforested area models for old (1980–1990) and new agrarian projects (1990–2000).



	Slope	F_Terrace	Differential_3	Differential _5	Sand_Silt	Sand	Conglomerate	Gneiss	Gabbro	Granite	Trachyte	D_Y_Latosols	D_RY_Latosols	E_DR_Latosols	E_DR_Latosols	Precip_D	CD_Town_D	Income_Pcap	Cons_Units
■ Old agrarian projects - ROC 0.804					0.1641		0.3193	0.1764	0.3193	0.3517	0.2796		0.078		0.0613	0.2547	-0.4992	0.0824	-0.1673
□ New agrarian projects - ROC 0.732	0.061	0.0907	-0.0596	-0.0975	-0.0784	-0.121	-0.1986				0.0972	-0.1377		0.0718		0.3541	-0.6287		-0.1912

Fig. 5. Graphic comparison of individual secondary forest models for agrarian projects established within 1980–1990 and within 1990–2000.

to towns and to small farms for secondary forest area. This dependence of land use/cover variability on agrarian structure and urban areas was also observed by recent modeling studies in the Brazilian Amazonia at broader regional scales (Aguiar et al., 2007; Soares Filho et al., 2001), but they cannot be considered as the sole determinants of deforested area given our results. It is essential to use a combination of accessibility, biophysical, socioeconomic and public policies considering the variability of actors and previous land use planning (Geist & Lambin, 2001; Verburg, 2006).

Biophysical variables

The biophysical variables, soils, geomorphology and lithology had a more significant influence on secondary forest than in deforested area models. Sandy lithology was negatively related to secondary forest area in Machadinho and in the old agrarian projects. It demonstrates that soil quality in these areas influences secondary forest dynamics. Similar interpretations based on household survey were found in other areas of the Brazilian Amazonia (Moran et al. (2000)). Precipitation during the dry season was more significant in explaining deforested area variability, most likely because the amount of rain is generally limited in deforested areas (Sombroek, 2001).

Socioeconomic variables and conservation reserves

The variables number of people and population density contributed positively to most deforested area models, while income per capita contributed best to secondary forest area models. In addition, income per capita was highly correlated to deforestation in Machadinho and in old agrarian projects, confirming the hypothesis that higher income causes land use intensification in old frontiers. Finally, it was observed that conservation reserves were significant in all the models with negative relationships. This demonstrates the importance of public policies to reduce deforestation in designated areas, which is also noted by other authors (Nepstad et al., 2006).

Conclusions

In the present study land use/cover patterns of deforested area and secondary forest in Rondonia State were related to potential location factors by means of logistic regression modeling at 250 m resolution. As potential location factors socioeconomic, political and biophysical variables were analyzed. Different spatial extents were used in order to evaluate the explanatory power of location factors over different spatial units. Our study confirmed earlier findings based on both coarser scale analyses of the whole Brazilian Amazonia (Aguiar et al., 2007; Soares Filho et al., 2006), as well as findings based on detailed and elaborate local studies (Alves et al., 2003).

The accessibility measures used in the analysis turned out to be significant land use/cover determinants at all different spatial extents. Accessibility measures were more important at the extent of the agrarian projects from which we conclude that deforestation tends to be closer to roads and pioneer areas as also stated by other authors (Aguiar et al., 2007; Alves, 2002), but also that the diffusive patterns of deforested areas are correlated to the spatial configuration of the agrarian projects as identified in the same area by Batistella (2001). Similar dynamics have occurred in the north of Mato Grosso and south of Para states, where economic conditions are the main attractors and the easy access by roads influence, but do not determine the process (Soares Filho et al., 2004).

Our multiple stratification approach, i.e., separate analyses by different municipalities and by old and new agrarian colonization projects, yielded many new insights in the land use/cover system dynamics. It was demonstrated how location factors play out differently in explaining deforested and secondary forest area patterns within different extents in Rondonia.

Most new insights for the study area were obtained by comparing old and new agrarian colonization projects. Indications were found that land use intensification (clearing of forest/secondary forest remnants) takes place in the old agrarian projects, characterized by a relatively large population and high income per capita (Alves et al., 2003). Land abandonment in the old agrarian projects happened in the more remote parts and on steeper slopes. In the new agrarian projects secondary forest patches were associated with the forest fringes. These results led us to conclude that we are dealing with land use/cover trajectories in time. Therefore static spatial pattern analysis without acknowledging these trajectories will lead to erroneous interpretations of the current and future land use/cover dynamics.

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