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Effects of roads, topography, and land use on forest cover dynamics in the Brazilian Atlantic Forest

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ABSTRACT

Roads and topography can determine patterns of land use and distribution of forest cover, particularly in tropical regions. We evaluated how road density, land use, and topography affected forest fragmentation, deforestation and forest regrowth in a Brazilian Atlantic Forest region near the city of São Paulo. We mapped roads and land use/land cover for three years (1962, 1981 and 2000) from historical aerial photographs, and summarized the distribution of roads, land use/land cover and topography within a grid of 94 non-overlapping 100 ha squares. We used generalized least squares regression models for data analysis. Our models showed that forest fragmentation and deforestation depended on topography, land use and road density, whereas forest regrowth depended primarily on land use. However, the relationships between these variables and forest dynamics changed in the two studied periods; land use and slope were the strongest predictors from 1962 to 1981, and past (1962) road density and land use were the strongest predictors for the following period (1981–2000). Roads had the strongest relationship with deforestation and forest fragmentation when the expansions of agriculture and buildings were limited to already deforested areas, and when there was a rapid expansion of development, under influence of São Paulo city. Furthermore, the past (1962) road network was more important than the recent road network (1981) when explaining forest dynamics between 1981 and 2000, suggesting a long-term effect of roads. Roads are permanent scars on the landscape and facilitate deforestation and forest fragmentation due to increased accessibility and land valorization, which control land-use and land-cover dynamics. Topography directly affected deforestation, agriculture and road expansion, mainly between 1962 and 1981. Forest are thus in peril where there are more roads, and long-term conservation strategies should consider ways to mitigate roads as permanent landscape features and drivers facilitators of deforestation and forest fragmentation.

1. Introduction

Roads can have many ecological impacts, affecting air quality, soil, vegetation, wildlife and humans near them (Forman and Alexander, 1998; Spellerberg and Morrison, 1998; Forman et al., 2003; Coffin, 2007). Road construction and improvement increase the accessibility of remote areas, allowing logging, hunting, and deforestation for new agricultural and pasture fields (Nagendra et al., 2003; Fearnside, 2007). Roads are thus considered agents of deforestation, accelerating forest fragmentation, reducing forest regrowth (Young, 1994; Laurance et al., 2002; Nagendra et al., 2003; Soares-Filho et al., 2004; Fearnside, 2007, 2008a), and thus threatening several tropical forests (Nepstad et al., 2001; Soares-Filho et al., 2004; Fearnside, 2007).

In the Atlantic Forest region, despite its high road density, there are few studies available in the international literature about the effects of roads. Most studies in neotropical regions have focused on the Amazon Forest (Nepstad et al., 2001; Mäki et al., 2001; Laurance et al., 2002; Soares-Filho et al., 2004; Fearnside, 2007, 2008a; Perz et al., 2007), and a direct comparison of road effects on these two areas is innappropriate. The Amazon forest and the Atlantic forest have distinct histories of human occupation and land use dynamics (Drummond, 2004). While only 1% of Brazilian Amazon rain forest had been deforested in 1970 (Drummond, 2004), the Brazilian Atlantic Forest has been degraded along the coastline by land use (mainly agriculture and cattle production) and natural resource exploitation (logging) since Portuguese

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colonization in the 16th century (Dean, 1997; Drummond, 2004). Since roads have been constructed in Brazil, especially after 1920s (Neto, 2001), native Atlantic forest was degraded first by land use then by roads, in contrast to Brazilian Amazon forest where roads were built by the government to promote occupation of the region (Pfaff, 1999).

Because the Brazilian Atlantic Forest has a long land use history, we consider that past patterns of land use also have an important role in cycles of deforestation, fragmentation, and reforestation (Geist and Lambin, 2002; Soares-Filho et al., 2004; Fearnside, 2007, 2008a). In addition, topography can also influence patterns of forest fragmentation and forest cover, as previously demonstrated in several regions, including the Brazilian Atlantic Forest region (Miller et al., 1996; Cabral and Fiszon, 2004; Silva et al., 2007; Cabral et al., 2007). Usually, areas with steep slopes or poor soils are less used and more likely to remain forested (Ranta et al., 1998; Resende et al., 2002; Silva et al., 2007).

Roads and land use play an important and coupled role in forest dynamics. Global, regional, and national demand for agricultural products create new land use demands and influence rates of deforestation (Armenteras et al., 2006; Killeen et al., 2007; Fearnside, 2008a). Roads can act as an attractor for a driving force likely to induce change, such as land use, because they are an easy route for activities causing deforestation and forest fragmentation occurrs concurrently with deforestion (Nagendra et al., 2003; Bürgi et al., 2004). Logging, agriculture or cattle grazing, are all land uses causing deforestation in tropical forests (Liu et al., 1993; Laurance, 1999; Laurance et al., 2002; Fearnside, 2008a). Elsewhere, high road densities have indicated intensive use of landscapes and road density was a strong predictor of cumulative forest loss and fragmentation also in New Zealand and the United States (Saunders et al., 2002; Bresee et al., 2004; Ewers et al., 2006). Because roads improve land access and allow new land uses to occurr, road metrics are often important variables in predictive models of deforestation (Mäki et al., 2001; Soares-Filho et al., 2004).

The relationships among roads, land use, deforestation, regrowth, and forest fragmentation may be heterogeneous in space and time as the economic drivers of land use and road change. These heterogeneities translate into the patterns we observe on the landscape. Using aerial photographs from three time spans (1962, 1981 and 2000), we evaluated the relationships of topography, land use, and roads with forest fragmentation, deforestation and forest regrowth in an Atlantic Forest region from southeastern Brazil. We expected to find higher deforestation and fragmentation, and lower forest regrowth in less declivous areas, where there are more roads, and more intensive land use. The heterogeneity and intense dynamics of the studied region allow examining a wide range of factors affecting forest cover dynamics (Teixeira et al., 2009). Understanding the relationships between roads and environment, including humans, provides information for landscape and transportation planners, environmentalists, politicians and other stakeholders who make decisions balancing economical, social, ecological and political issues (Dramstad et al., 1996; Forman et al., 2003; Forman, 2004).

2. Methods

2.1. Study area

This study was carried out in the Plateau of Ibiúna, a Pre-Cambrian formation situated 50 km from the city of São Paulo (23°41′S–23°47′S; 47°02′W–47°07′W), southeastern of Brazil (Fig. 1). The elevation ranges from 850 to 1100 m and the relief is characterized by denudation, convex hills, and inclinations of more than 15% (Ross and Moroz, 1997). The weather is warm and

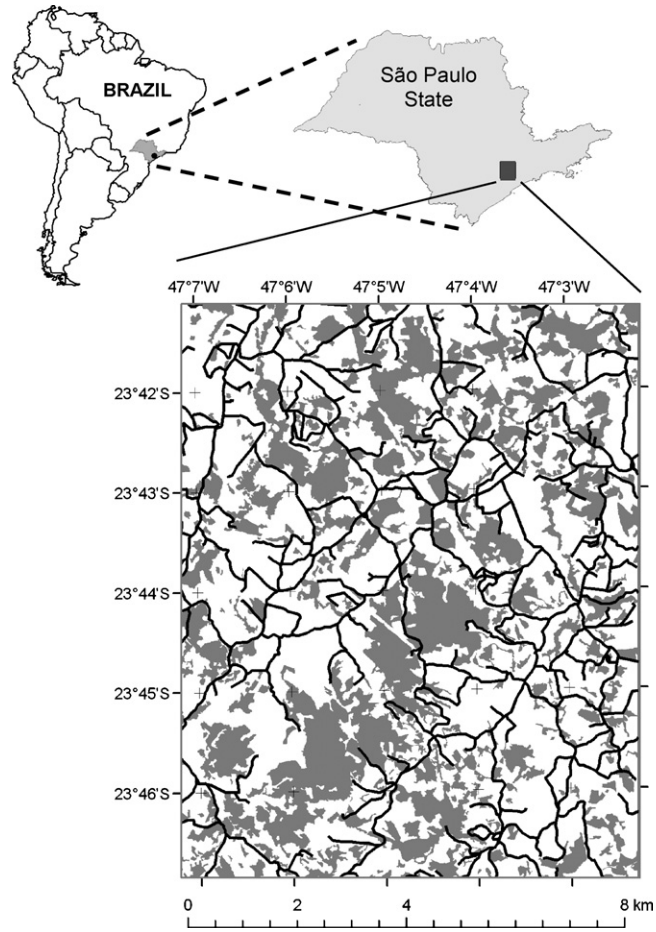

Fig. 1. Study area characterized by 31% of native forest (gray) embedded in a road network (black lines), in São Paulo State, southeastern Brazil (April 2000).

humid, with mean monthly temperature varying between 11 and 27 °C. The annual precipitation is about 1300–1400 mm and it is seasonally variable, with the driest and coldest months between April and August. The vegetation is a transition between the coastal Atlantic rain forest and the Atlantic semi-deciduous forest, being classified as "Lower Montane Atlantic Rain Forest" (Oliveira-Filho and Fontes, 2000). Floristic surveys in the region showed a high tree richness (362 species in the region with diameter at breast height >5 cm), with a dominance of Myrtaceae (79 species), Lauraceae (38) and Fabaceae (31) (Bernacci et al., 2006). The landscape is fragmented and dominated by agricultural fields (38%), native forest (31%) and rural buildings or urban areas (16%). There are also pine and eucalyptus plantations (7%) and vegetation in early stages of regrowth (8%).

Forest loss occurred in the 20th century through logging (timber production) and burning (charcoal production), essentially 50–80 years ago (Seabra, 1971; Brannstrom, 2002, 2005). Thus, the entire study area is composed of intermediate to old second-growth forest reestablished after this period (Seabra, 1971). Since 1920s, the main economic activity in the Plateau of Ibiúna region is agriculture and poultry farming (Seabra, 1971). Between 1960s and 1980s, charcoal production and agriculture declined, which was followed by an increase in forest cover. However, between 1980s and 2000s, expanding towns caused a shift from farms to country houses (Teixeira et al., 2009).

The Plateau of Ibiúna is well connected to São Paulo city trough large motorways, however, the studied region has only secondary roads, some paved and a large amount of unimproved roads, used mostly for local traffic and transport of agricultural products to the city of São Paulo.

2.2. Sample design and data sources

Maps of roads, land use and land cover were obtained from aerial photographs from 1962 (1:25,000; 12 photos), 1981 (1:35,000; 5 photos) and 2000 (1:10,000; 61 photos). Those photographs were chosen based on the data availability and the interval between each set (19 years). Differences in scale between aerial photographs were minimized by differences in the resolution of digitalization (Teixeira et al., 2009). The aerial photographs were georeferenced and mosaiced, using the year of 2000 as reference (georeferencing mean error was less than 5 m, UTM, SAD 1969, 23-S; Teixeira et al., 2009).

Road and the land-use/land-cover maps were generated by visual photo interpretation using the original aerial photographs with a stereoscopic device (Teixeira et al., 2009). We mapped three land-use/land-cover classes which were easily observed even in the worst resolution (from 1981): agriculture (agricultural and abandoned fields); forest (native secondary forest in intermediate and late stages of regrowth); and buildings (urban areas or rural areas where buildings, such as houses are located). Map accuracy was checked in the field for the year of 2000 and was above 88% (Silva et al., 2007).

Slope maps were generated from topographic maps (1:10,000) produced by Instituto Geográfico e Cartográfico do Estado de São Paulo (IGC) in 1979. Elevation curves (5 m resolution) were digitized to generated an elevation model and then to calculate slope (Teixeira et al., 2009). We used slope to represent topography because slope orientation causes small changes in vegetation and altitude is highly correlated to slope (Silva et al., 2007).

The studied landscape was divided into 94 non-overlapping squares of 100 ha forming a grid. Adjacent and equivalent in time, the squares should capture landscape modifications caused by historic and socio-economic factors occurred in the region. In each square and in each year, measures representing road distribution, land-use and land-cover proportions, forest fragmentation, slope variation, and distance from the city of São Paulo were taken. Road distribution was represented by road density (road length/square area, km/km^2). Land-use and land-cover proportions (class area/square area) were measured for each of the three classes (agriculture, forest, and buildings). We used slope standard deviation to represent the relief variation.

Forest dynamics were evaluated through three variables: forest fragmentation, deforestation, and forest regrowth. Forest fragmentation was represented by forest patch density, which was the number of forest patches in each square. Patch density is a useful measurement to describe forest sub-division or fragmentation (Riitters et al., 1995) and has a clear ecological significance (Neel et al., 2004). Path density was trasformed to a normal distribution using logarithm transformation to meet the required assumptions of regression analysis (Zar, 1996). Changes in forest patch density (hereafter fragmentation), deforestation, and forest regrowth were measured for the two time spans (1962–1981 and 1981–2000). Agriculture and buildings changes were evaluated for the two time periods as well.

2.3. Model development and validation

We used generalized least squares regression models (Pinheiro and Bates, 2004) to explore the relationships between the three forest variables (fragmentation, deforestation and regrowth) and the five independent variables (road density, agriculture cover, buildings cover, standard deviation of slope, and distance from the city of São Paulo) (Table 1). Similar models were built to explore the change of agriculture, buildings, and roads (dependent variables) explained by road density (except for road models), forest cover (except for road models), agriculture (except for agriculture model), buildings (except for buildings models), standard deviation of slope, and distance from the city of São Paulo (independent variables) (Table 1). All variables with 60% or more of correlation were not included in models. The independent variables were from the initial time period. Thus, for models evaluating changes between 1962 and 1981, the independent variables were from 1962, and for models for the 1981–2000 period, the independent variables were from 1981 (Table 1). To evaluate long-term responses, we included also predictor variables from 1962 in changes observed between 1981 and 2000 (Table 1). All regression analyses were done using R software, version 2.9.2 (Hornik, 2009).

Since we assumed that all independent variables would have an equal chance of affecting forest variables, we started with all variables in models and removed variables coefficient p-values greater than 0.05 using a backwards elimination procedure. Backwards elimination has significant advantages over forward and stepwise selection schemes (Mantel, 1970). Model improvement was measured using Bayesian Information Criterion (BIC) values, which is more conservative than Akaike's Information Criterion (AIC) (Burnham and Anderson, 2002). We calculated BIC weight (wi) and evidence, which provide ways to compare the selected model with the others, and then evaluate its performance (Burnham and Anderson, 2002). The evidence ratio (wi_max/wi_i) was used to visualize differences between models (Burnham and Anderson, 2002). Once variable selection was complete, we examined model residuals to validate the assumptions of least squares models: normally distributed errors, constant variance, and independent observations (Legendre and Legendre, 1998). However, ecological phenomena are not spatially and temporally independent (Fortin and Dale, 2005). Thus, we tested for spatial autocorrelation in

Table 1
The initial generalized least squares (GLS) regression models used to evaluate the landscape dynamics during two time periods.

Time period	Dependent variable	Independent variables
1962–1981	Fragmentation	Road62, agriculture62, buildings62, SPdist and slope
	Deforestation	
	Regrowth	
	Agriculture expansion	Road62, forest62, buildings62, SPdist and slope
	buildings expansion	Road62, forest62, agriculture62, SPdist and slope
	road expansion	agriculture62, buildings62, SPdist and slope
1981–2000	Fragmentation	Road62, road81, agriculture62, agriculture81, buildings62, buildings81, SPdist and slope
	Deforestation	
	Regrowth	
	Agriculture expansion	Road62, road81, forest62, forest81, buildings62, buildings81, SPdist and slope
	Buildings expansion	Road62, road81, forest62, forest81, agriculture62, agriculture81, SPdist and slope
	Road expansion	Agriculture62, agriculture81, buildings62, buildings81, SPdist and slope

model residuals using a variogram fitting procedure (Pinheiro and Bates, 2004). If spatial autocorrelation was detected, we built additional models with the same variables, but including correlation structures that account for spatial autocorrelation in the model errors (Pinheiro and Bates, 2004; Hawbaker et al., 2005, 2006). The significance of the spatial correlation on model improvement was tested using an ANOVA procedure between the two models (Pinheiro and Bates, 2004). By including spatial autocorrelation structures in the final models, the aim was to nullify the effects of spatial autocorrelation on the significance of regression coefficients and reduce the chance of Type I errors (incorrect rejection of null hypotheses). Thus, regression models should be more robust, increasing their predictability power, especially models on ecological phenomena that are spatially and temporally dependent (Fortin and Dale, 2005).

3. Results

Agriculture and native forest were the dominant land use/land covers in the Plateau of Ibiúna region (Fig. 2). The forest dynamics were characterized by a higher forest regrowth rate in the first time period (1962–1981) than in the second time period (1981–2000) (Table 2). In both time periods, most deforestation was caused by agriculture: about 853 ha of forests were converted in agriculture in 1981 and about 635 ha in 2000 (Table 2). However in the second time span, buildings also contributed to deforestation (395 ha; Table 2). In the second time period, occurred an expansion of rural buildings and urban areas in 1020%, covering 15% of the entire landscape in 2000 (Fig. 2, Table 2). Most of forest regrowth came from agricultural fields and vegetation in early stages of regrowth in both time periods (Table 2).

Road density increased through time in the whole landscape from 1.55 km/km^2 in 1962, to 1.85 km/km^2 in 1981, and to 2.30 km/km^2 in 2000. In other words, road density increased by 0.30 km/km^2 (19%) during the first time period, 0.45 km/km^2 (24%) during the second one, and 0.75 km/km^2 (48%) during both time periods. An analysis of road density in the 94 studied grids showed not only an increase of mean road density (1962: 1.53; 1981: 1.88; 2000: 2.29) but also an increase in standard deviation of road density (1962: 0.865; 1981: 0.965; 2000: 1.122) indicating a more

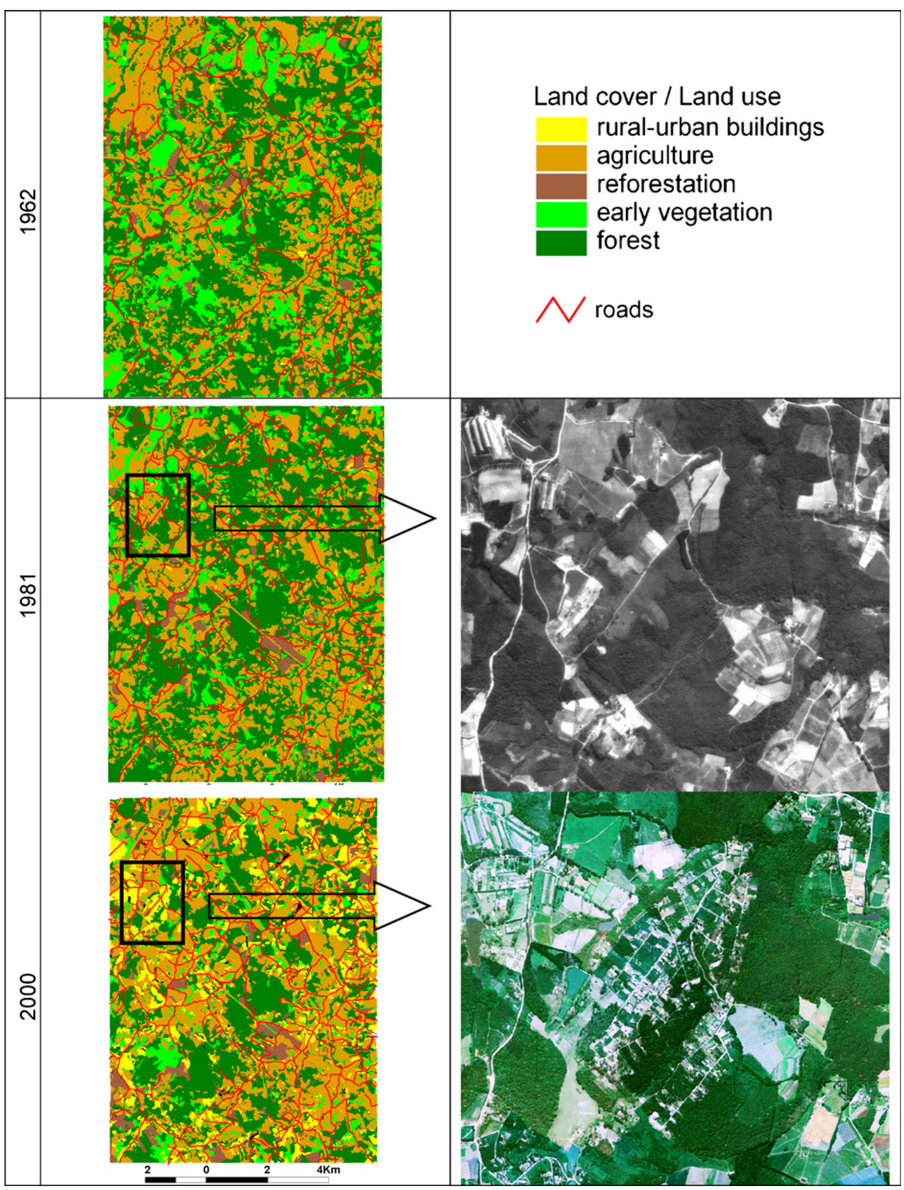

Fig. 2. Land use/land cover and roads in three periods (1962, 1981 and 2000) of Ibiúna Plateau. In detail, we point out the increase of urban buildings in aerial photographs of 1981 and 2000.

Table 2
Transition matrix showing changes of land use and land cover between: (A) 1962 and 1981; (B) 1981 and 2000 (values in ha).

		1981					
		Rural buildings or urban areas	Agricultural fields	Pine and eucalyptus plantations	Vegetation in early stages of regrowth	Native forest	Total
(A)							
1962	Rural buildings or urban areas	5.13	20.92	0.85	6.39	11.61	44.90
	Agricultural fields	64.71	1500.46	66.87	337.36	734.22	2703.62
	Pine and eucalyptus plantations	0.58	47.41	22.09	11.07	84.33	165.48
	Vegetation in early stages of regrowth	12.42	393.70	21.04	117.40	735.77	1280.33
	Native forest	27.47	852.82	113.38	238.81	2034.45	3266.93
	Total	110.31	2815.31	224.23	711.00	3600.38	7461.00

		2000					
		Rural buildings or urban areas	Agricultural fields	Pine and eucalyptus plantations	Vegetation in early stages of regrowth	Native forest	Total
(B)							
1981	Rural buildings or urban areas	80.35	20.27	3.08	2.05	4.57	110.32
	Agricultural fields	602.35	1702.01	185.31	112.18	213.46	2815.31
	Pine and eucalyptus plantations	27.63	56.65	120.15	6.50	13.30	224.23
	Vegetation in early stages of regrowth	129.98	258.10	41.69	87.95	193.32	711.04
	Native forest	395.26	635.49	153.85	359.1	2056.68	3600.38
	Total	1235.57	2672.52	504.08	567.78	2481.33	7461.00

heterogeneous distribution of road density in 2000. Most of the road network already existed in 1962 and new roads were primarily extensions of the existing roads controlled by slope (Fig. 3, Table 3). The studied landscape was also characterized by high slopes, with less than 14% of the landscape presenting slopes below 5° (mean = 7.8°, standard deviation = 2.6°), but 20% presented steeper slopes up to 10°.

In the time span between 1962 and 1981, the past buildings and slope variation were the main factor affecting forest cover dynamics (Table 3). Buildings were positively related with fragmentation, and negatively related with forest regrowth. Slope

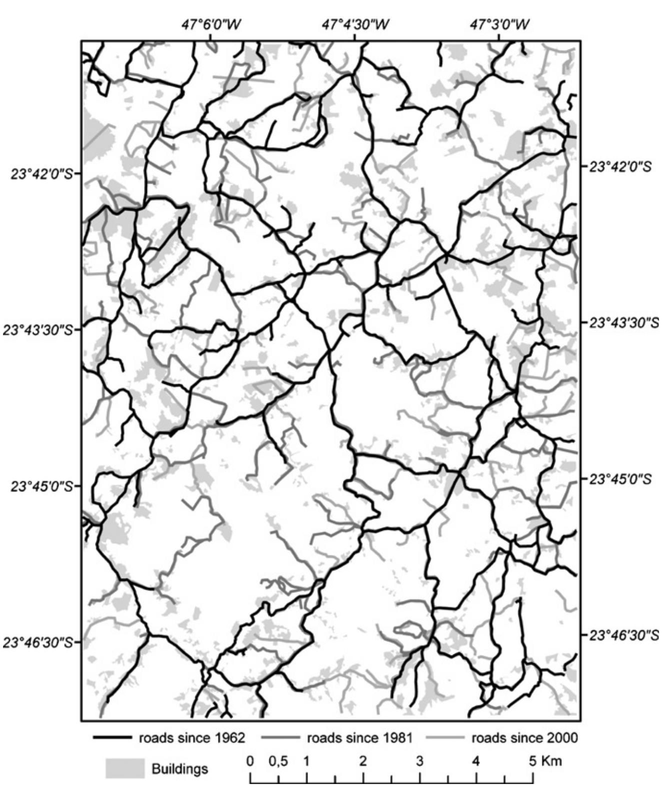

Fig. 3. Road network of each time period and buildings of 2000.

variation was positively related with deforestation. More deforestation occurred in sinuous relief, fragmentation occurred where buildings were predominant in 1962, while regrowth occurred more frequently in areas distant from these human constructions (Table 3). In this time span, we did not find any evidence of road density effects for forest dynamics. Agriculture expanded in more sinuous relief, while buildings expanded where agriculture occurred before, and road density increased on sinuous relief (Table 3).

Between 1981 and 2000, forest dynamics were strongly affected by 1962 road density (Table 3). Past road density (1962) was positively related to fragmentation and deforestation. Past (1962) agriculture was strongly related to forest regrowth, and distance from São Paulo city contributed in some way. This means that deforestation and fragmentation occurred essentially in sites with more existing roads, while regrowth occurred in sites with less agriculture and more distant from São Paulo city. Agriculture expanded in areas with less forest in 1962 and nearer to São Paulo city. Buildings expanded also in areas with less forest in 1962, but sites with more existing roads where relevant too. Road density expanded in sites nearer to São Paulo city.

4. Discussion

Our results demonstrated that legacies of road development and land use have played a substantial role in determining patterns of deforestation, fragmentation, and forest regrowth in the Plateau of Ibiúna. Road density was one of the strongest predictors of forest cover dynamics, but the influence of road density was observed only after a time-lag, after agricultural expansion stabilized. Slope variation and land use also played an important role determining spatial variability in forest dynamics.

Roads and topography are not the actual drivers of deforestation, but they act as attractors of land-use change and deforestation, and thus play a role in forest dynamics. The real drivers of deforestation then are the broad-scale socio-economic conditions that provide demand for agricultural and forest products (Verburg et al., 2002; Sohl and Sayler, 2008). Those demands and how they influence land-use and land-cover change are translated to a local level by individual land-owner decisions, and certainly land accessibility provided by existing roads or the potential to build

Table 3
Generalized least squares (GLS) regression models with evidence <3.0 relating forest dynamic variables (fragmentation, deforestation and regrowth), land use dynamic variables (road, agriculture and buildings expansion) and independent variables (road density, land use, slope and distance from the city of São Paulo) using Bayesian Information Criterion (BIC), after backwards elimination of variables. RSE: residual standard error.

Time period	Dependent variable	Independent variables	BIC	Weight	Evidence	RSE
1962–1981	Fragmentation	+Buildings62	126.89	0.926	1.0	0.433
	Deforestation	+Slope	274.20	0.969	1.0	0.941
	Regrowth	−Buildings62	142.62	0.996	1.0	0.472
	Agriculture expansion	+Slope	198.35	0.995	1.0	0.623
	Buildings expansion	+Agricult62	503.83	0.825	1.0	3.211
	Road expansion	+Slope	238.04	0.990	1.0	0.773
1981–2000	Fragmentation	+Road62	86.47	0.965	1.0	0.343
	Deforestation	+Road62	273.49	0.963	1.0	0.947
	Regrowth	−Agricult62	233.81	0.548	1.0	0.740
		−Agricult62 +DistSP	234.74	0.344	1.6	0.709
	Agriculture expansion	−Forest62 −DistSP	190.30	0.912	1.0	0.556
	Buildings expansion	−Forest62	289.30	0.676	1.0	1.001
		−Forest62 +Road62	290.84	0.313	2.2	0.978
	Road expansion	−DistSP	244.75	0.968	1.0	0.801

roads new roads can influence those decisions (Wear and Bolstad, 1998). However, roads can be considered a driver of deforestation when they focus land use actions in a local or regional socio-economic context, showing a stronger relationship with forest dynamics than land use.

The most important predictors of forest dynamics changed in the two studied periods, being essentially land use and slope variation from 1962 to 1981, and past (1962) road density and land use for the following period (1981–2000). Roads were strongly related to deforestation and forest regrowth when the expansion of agriculture was limited to already deforested areas, and when the landscape experienced a rapid expansion of developed areas. In the first time period (1962–1981), deforestation, roads, and agriculture expanded on sinuous relief, while fragmentation and regrowth were affected primarily by buildings. In the second time period (1981–2000), deforestation and fragmentation occurred where there were more existing roads, while regrowth occurred more in sites with less agriculture in the past (1962) and farther from the major city in the area (São Paulo). In these cases, the higher density of roads was a primary predictor of forest fragmentation and deforestation as proximity to roads provided accessibility for homes (Nagendra et al., 2003).

Roads have long-term effects on forest cover dynamics and established roads were more important predictors of deforestation and fragmentation than new roads. In Ibiúna, new roads were mainly extensions of old, existing roads inside farms or connecting small secondary roads, thus the oldest road network dominanated the landscape, which may explain their importance for landscape dynamics. In addition, the density of established roads (1.55 km/km^2) was already relatively high at the begining of our study period. For comparison, road density in densily populated regions of USA and Europe range between 1.10 and 3.50 km/km^2 (e.g. 1.10 km/km^2 in Northern Great Lakes (USA), 1.50 km/km^2 in southern Illinois (USA), 3.37 km/km^2 in Netherlands and 3.50 km/km^2 in northern Wisconsin (USA); Saunders et al., 2002; Lin, 2006; McDonald et al., 2008). Thus, besides the instant impact of roads when they are constructed inside or near forests, roads threaten forests when land uses do not directly impact forest dynamics, even after many decades. Roads are relatively permanent elements of the landscape. They facilitate deforestation due to increased accessibility, and do not stimulate forest regrowth due to land valorization (Nagendra et al., 2003). Even when roads do not directly influence deforestation, roads represent a long-term latent driver of deforestation, especially in landscapes with a long history of human occupation.

The latent impact of roads on forests may be especially important for regions where there is a longer history of human settlements, such as the Brazilian Atlantic Forest. In the Amazon or other less populated tropical forests, a new road causes considerable landscape changes (Soares-Filho et al., 2004; Fearnside, 2007). However, even in tropical forest with low population densities, roads practically represent a guarantee of deforestation in the future particularly when agriculture is not the main driver. Roads compound the ecological impact of land-use change because new land uses after initial road development will demand new transportation resources which will further fragmented the remaining forest.

Roads have a strong influence on forest dynamics in the Brazilian Atlantic Forest. On the other hand, land use as expansion of mechanized agriculture and cattle farms has been the main deforestation drivers in the Amazon Forest during the last decades (Armenteras et al., 2006; Killeen et al., 2007; Fearnside, 2008a). Hawbaker et al. (2006) discussed the circular nature of road development showing that roads both affect and are affected by land use development. In regions where land use has occured for centuries, for example Southeastern Brazil and Northern Wisconsin (USA), it is difficult to assign a direct causality (Hawbaker et al., 2006). Nevertheless, remote areas in the North of Brazil could be used to evaluate the landscape changes caused by a new road. In the Amazon Forest, there is a "fishbone" deforestation pattern, which deforestation caused by clearing for small farms begins at roadsides leaving remnant forest strips between them (Arima et al., 2005; Ferraz et al., 2005; Oliveira-Filho and Metzger, 2006). That deforestation pattern indicates that roads attract human settlement and then initiate new land-use changes (Mäki et al., 2001; Fearnside, 2007). In Brazil, highways have been constructed by the federal government to encourage migration to strategic economic areas or for connecting economic markets to reduce transport costs and product prices; that is the placement of the road network is exogenous to agricultural land use (Chomitz and Gray, 1996; Mäki et al., 2001; Geist and Lambin, 2002; Laurance et al., 2002; Fearnside, 2007). Roads increase accessibility for new migrants and new land uses (Liu et al., 1993; Mäki et al., 2001; Laurance et al., 2002; Nagendra et al., 2003; Fearnside, 2005; Porter-Bolland et al., 2007). When initial land use begins, a positive-feedback road-land use relationship starts (Geist and Lambin, 2002; Hawbaker et al., 2006). In some cases, land users need to transport their products and connect land properties and unofficial roads are constructed, that is the placement of the road network is endogenous to agricultural land use (Chomitz and Gray, 1996; Arima et al., 2005; Perz et al., 2007). In the Brazilian Atlantic Forest, there is a circular relationship between roads and land use, however roads become especially relevant for forest dynamics when the expansion of new land uses into undeveloped areas is reduced. Thus roads are permanent landscape elements which represent a latent threat for forests.

Land use dynamics were explained by different factors in the two periods of our study. From 1962 to 1981, road and agriculture expanded in sinuous relief and buildings expanded where agriculture occurred before. From 1981 to 2000, proximity from São Paulo city was a relevant variable explaining road and agriculture expansions. Moreover, agriculture and buildings expanded where forest were less common in the previous time period (1962). The influence of the major city (São Paulo) on this region increased, as São Paulo expanded and more highways were built. From 1981 to 2000, the buildings expansion of 1020% shows a urbanization tendency for that region, and the influence of São Paulo on land use dynamics become relevant. The rate of deforestation was even higher than the regional rates due to the close proximity to the city of São Paulo, thus reflecting a land speculation process trigged by the establishment of country houses and condominiums (Teixeira et al., 2009). Road and agriculture expanded more in sites nearer São Paulo city. The Plateau of Ibiúna region is one of the primary sources of food products (agriculture and poultry) for São Paulo city. The urbanization of villages near major cities, associated with increased transportation connectivity, has been observed in many regions of Europe and the United States (Antrop, 2004; Lepczyk et al., 2007). That urbanization and the resulting dense network of roads is a threat to forests (Fearnside, 2008b).

Topography affected land use and forest dynamics. Deforestation, agriculture and road expansion, from 1962 to 1981 occurred in sinuous relief. In the first time period, sites presenting a sinuous relief – sites with many valleys and hills – were more occupied by roads and agriculture, and thus deforestation. Sinuous relief does not consider elevation or if the slope is high or low, as other studies do (e.g. Teixeira et al., 2009). In Atlantic Forest region, usually forest was commonly found on steep slopes and near streams, where it is difficult to grow crops and accessibility was limited (Teixeira et al., 2009). However, sinuous relief provides favorable sites to crops, as valleys. Thus, topography determines were roads and land use expand, which then impacts forest cover. Topography has been considered as a relevant factor to explain forest cover and diversity in Atlantic Forest region, mainly because steep terrain and inaccessibility usually limit land-use change, and then tropical forests are in most cases located in sites where access is difficult (Cabral and Fiszon, 2004; Cabral et al., 2007; Munroe et al., 2007; Silva et al., 2007, 2008; Teixeira et al., 2009). In our study region, slope variation was relevant to road and agriculture expansion in the first time period. In that time, roads expanded in more sinuous slopes, probably allowing an expansion of agriculture, and thus causing deforestation. In the second time period, slope was not relevant, but proximity of São Paulo city was positively related to road and agriculture expansion.

In conclusion, the Atlantic forest dynamics in the studied region were directly related to past road density, past land use (buildings and agriculture expansion), and slope variation. Furthermore, the effects of roads have long-term effects on these dynamics, acting as attractors of landscape change. Thus, where densely distributed roads are present, forests are in peril. In contrast, forests far from land use (buildings and agriculture) and major cities are more likely to be preserved and to regenerate. Effective conservation and restoration strategies would be well served to consider how roads are distributed and potential land-use changes could affect future forest dynamics.

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