Biodivers Conserv (2015) 24:2255–2272
DOI 10.1007/s10531-015-0980-y

ORIGINAL PAPER

Atlantic Forest spontaneous regeneration at landscape scale

Camila Linhares de Rezende[1,2,3] · Alexandre Uezu[4] · Fabio Rubio Scarano[1,2] · Dorothy Sue Dunn Araujo[1,5]

Received: 15 February 2015 / Revised: 4 August 2015 / Accepted: 10 August 2015 / Published online: 19 August 2015

Abstract The Atlantic Forest suffered five centuries of continuous deforestation related to successive economic cycles, and is now reduced to 11.7 % of its original cover. The Atlantic Forest Restoration Pact was launched in 2009 and aims to restore 15 million hectares until 2050. Natural regeneration can play an important role in meeting this target, however little attention has been paid to this process and there is a gap in the knowledge about its driving factors at the landscape scale. We mapped forest cover of an Atlantic Forest municipality in Southeastern Brazil, in five timeslots between years 1978 and 2014,

Communicated by Jefferson Prado, Pedro V. Eisenlohr and Ary T. de Oliveira-Filho.

Electronic supplementary material The online version of this article (doi:10.1007/s10531-015-0980-y) contains supplementary material, which is available to authorized users.

✉ Camila Linhares de Rezende
clrezende@biologia.ufrj.br

Alexandre Uezu
aleuezu@ipe.org.br

Fabio Rubio Scarano
fscarano@fbds.org.br

Dorothy Sue Dunn Araujo
dorothy@jbrj.gov.br

1 Departamento de Ecologia, Universidade Federal do Rio de Janeiro, Caixa Postal 68020, Rio de Janeiro, RJ CEP 21941-970, Brazil

2 Fundação Brasileira para o Desenvolvimento Sustentável, Rua Engenheiro Álvaro Niemeyer, 76, São Conrado, Rio de Janeiro, RJ CEP 22610-180, Brazil

3 Instituto Estadual do Ambiente, Av. Venezuela, 110, Saúde, Rio de Janeiro, RJ CEP 20081-312, Brazil

4 Instituto de Pesquisas Ecológicas, Caixa Postal 47, Rod. Dom Pedro I, km 47, Nazaré Paulista, SP CEP 12960-000, Brazil

5 Instituto de Pesquisas Jardim Botânico do Rio de Janeiro, Rua Pacheco Leão, 2040, Solar da Imperatriz, Rio de Janeiro, RJ CEP 22460-036, Brazil

and used the weights of evidence method for modeling its spatial dynamics, in order to understand where natural regeneration is occurring and which are the main factors related to this phenomenon. In 36 years, forest cover increased 3,020 hectares (15.3 %), related to the decreasing of both rural population ($R^2 = 0.9794$, $p = 0.0013$) and cropland cover ($R^2 = 0.8679$, $p = 0.0212$). Landscape metrics shows the increment of number of fragments and structural connectivity among them. The main spatial variables influencing forest cover dynamics were topographic position, slope, solar radiation, soil type and distance to forest, urban areas and roads. Secondary forests provide ecosystem services that can turn into economic benefits, and natural regeneration can reduce restoration costs to the municipality. The cost of active restoration of the same area would have meant a total expense of U$ 15.1 million (U$ 419 k/year). We show here that spontaneous regeneration must be accounted for and incorporated into the spatial planning of Atlantic Forest restoration.

Keywords Natural regeneration · Forest restoration · Landscape dynamics · Spatial modeling

Introduction

The Brazilian Atlantic Forest is one of the 35 biodiversity hotspots of the planet, which are regions with high levels of biodiversity and endemism, but highly threatened by human activities (Zachos and Habel 2011; Myers et al. 2000). After five centuries of continuous deforestation due to successive economic cycles, the natural cover of this biome is now reduced to 11.7 % of its original size, of which 80 % are distributed in small fragments of 50 ha or less (Ribeiro et al. 2009, 2011). Thus, the Atlantic Forest is one of the most endangered forests in the planet (Mittermeier et al. 2005) and one of the three biodiversity hotspots most vulnerable to climate change (Bellard et al. 2014).

The consequent habitat loss affects fluxes of ecosystem services to the extent that the >100,000,000 people living within this biome (>60 % of the Brazilian population) face challenging times related, for instance, to shortage in water supply (Joly et al. 2014). In parallel, most of the threatened species listed in the Brazilian redlists of fauna and flora belong to this biome (Machado et al. 2010; Martinelli and Moraes 2013).

This situation has prompted a variety of stakeholders to launch in 2009 the Atlantic Forest Restoration Pact. This initiative established the target to restore 15 million hectares until 2050, which would practically double the current remaining vegetation cover of the biome (Melo et al. 2013). Six years later, only 58,000 hectares (or 0.03 % of the goal) are under the umbrella of the Pact (http://www.pactomataatlantica.org.br), which clearly indicates the need for scaling-up the restoration of this biome.

Restoration costs are obviously limiting, despite some recent optimism derived from its comparison to the Brazilian annual GDP (Banks-Leite et al. 2014). Brancalion et al. (2012) estimated an average cost of U$ 5000.00 per hectare of Atlantic Forest recovered by active restoration. In this context, to optimize the use of resources devoted to restoration is critical to achieve the ambitious targets set for the biome, and natural regeneration can play an important role in reducing restoration costs (Holl and Aide 2011).

Secondary forests emerging in human-impacted landscapes will not match the original old-growth forests in species composition (Hobbs et al. 2006). However, the natural recovery of forest cover can restore components of the original biodiversity and several ecosystem functions, such as carbon storage and water supply (Chazdon 2008). Moreover, if natural regeneration is combined with manmade species enrichment, it can maximize diversity at reduced costs (Holl and Aide 2011).

A drastic example of large scale ecological restoration through natural regeneration occurred in Puerto Rico, where socioeconomic changes related to the development of urban-industrial activities led to an intense rural exodus. As a result of the abandonment of fields, forest cover increased from 18 % in 1951 to 45 % in 2000, equivalent to an annual growth rate of 1.89 % (Helmer et al. 2008). In Brazil, Neef et al. (2006) modeled forest cover dynamics in the Amazon and estimated that the area occupied by secondary forests increased by over 500 % during the period of 1978–2002.

Although old and recent evidence point out for the relative resilience of the Atlantic Forest (Freitas et al. 2006; Uezu 2006; Piotto et al. 2009), little is known about the driving factors of spontaneous recovery at landscape scale. It is essential to understand this phenomenon with a spatially explicit approach, as well as to identify areas with greatest potential for natural regeneration, in order to guide restoration strategies to be adopted in broad scale.

This paper provides evidence that natural, spontaneous regeneration of the Atlantic Forest can be a significant factor to promote biome restoration at lower costs and that, therefore, needs to be incorporated to restoration spatial planning. This conclusion is based on evidence collected at the municipality of Trajano de Moraes, located in the State of Rio de Janeiro, Southeast Brazil, and we argue that it can be applicable to other parts of the biome.

This region has undergone important socioeconomic changes during the last century, related to an intense occupation for coffee production, followed by land abandonment in recent decades (Pinheiro 1993; Linhares 2004). Those changes led to a decrease in land occupation pressure, making this municipality a good model for understanding how different vectors of human pressure affect spatial dynamics of the Atlantic Forest. We aimed to (i) map the spatial dynamics of forest cover in this municipality; (ii) model, quantify and characterize the influence of environmental and anthropogenic spatial variables on this dynamic; (iii) simulate forest cover distribution for the year 2050; and (iv) determine variation of landscape parameters over time.

Methods

Study area

The Atlantic Forest is the second largest rainforest biome in South America, extending over a wide latitudinal gradient (3°S to 30°S) along the Brazilian coast, under conditions of high environmental heterogeneity. Besides evergreen, semideciduous and deciduous forests, this complex biome also comprises areas of mangroves, swamps, *restingas*, inselbergs, high altitude grasslands and mixed forests of Araucaria pine (Scarano 2009; Ribeiro et al. 2011). Its environmental complexity is reflected in high levels of diversity and endemism: the biome is home to over 2328 species of vertebrates, of which 732 are endemic, and more than 20,000 plant species, of which 8000 are endemic. Such indices, associated with its high proportion of habitat lost, defines the Atlantic Forest as one of the main hotspots of global biodiversity (Mittermeier et al. 2005).

Historically, deforestation began in the lowlands to open areas for agriculture, housing and for harvesting the Brazilwood (*Caesalpinia echinata*). Later, in the eighteenth and nineteenth centuries, it extended to hillside areas, especially during the coffee cycle (Dean 1996). However, some areas of this biome recently started to show the opposite process, and presented an increase in forest cover (SOS Mata Atlântica and INPE 2013, 2014). For instance, Uezu (2006) mapped forest cover dynamics in Pontal do Paranapanema, Southeastern Brazil, and found an annual net gain of 0.3 % in forest cover, result of natural regeneration, between years 1984 and 2003.

The municipality of Trajano de Moraes (42°3′41″W; 22°3′47″S) covers an area of $\sim$600 km^2 located in the State of Rio de Janeiro, Southeastern Brazil, within the area of the Serra do Mar Ridge, which holds the highest level of endemism for several taxonomic groups in the whole Atlantic Forest biome (Jenkins et al. 2013). The ridge divides the municipality in two main hillsides: the northwest side—facing the continent—and the southeast side, facing the ocean and the elevation ranges from 80 to 1830 m above sea level, representing a large environmental variability. Approximately 60 % of its area is classified as Evergreen Dense Forest, while the other 40 % is considered Seasonal Semideciduous Forest (Projeto RADAMBRASIL 1983).

The colonization of this region began in the late eighteenth century, with the arrival of prospectors and miners in search of gold. With the rapid depletion of mining, this economic activity was replaced by coffee plantations, with the first coffee seedlings arriving in the region in 1817 (Linhares 2004). In the late nineteenth century, the Rio de Janeiro coffee economy fell into decay. In Trajano de Moraes this process was gradual, extending over the entire first half of the twentieth century. In addition to the plantation decay, this period is characterized by progressive isolation of the city, resulting in the formation of an impoverished peasant community, composed by small landowners and former slaves (Pinheiro 1993). Because of this process, the latest census points out Trajano de Moraes as the second least densely populated municipality in the state of Rio de Janeiro (17.44 inhabitants/km^2). The estimated population is 10,348 inhabitants, and gross domestic product (GDP) per capita is $ 4,454.00 USD.

Forest cover mapping and census data

We mapped forest cover in the years of 2014, 2006, 1999, 1988 and 1978 by visual interpretation of orthophotos (year 2006) and satellite imagery - LANDSAT 1 MSS (year 1978), LANDSAT 5 TM (years 1988 and 1999) and LANDSAT 8 OLI (year 2014). Forest was defined as all native arboreal vegetation with continuous canopy, usually >5 m height. Interpretation started by the orthophotos, in the scale of visualization of 1:5,000. This first mapping in a finer scale was used to define the pattern of reflectance of forest class in satellite imagery. It was superposed to the imagery of the years 2014 and 1999, and vectors were reshaped according to the changes occurred between years in a scale of visualization of 1:20,000. The same process was repeated subsequently to the years 1988 and 1978, always using the polygons of the most recent mapping as a baseline to the next one. A single person performed imagery interpretation, in order to maintain the pattern of interpretation. We checked 71 field points distributed throughout the municipality, which corresponded to areas of doubt in visual interpretation. Those points were photographed in the field and related to the visual pattern of the satellite image. These data allowed a better separation between patches of Atlantic Forest and other vegetation types (rupicolous vegetation, shrubs and eucalyptus). Map validation for years 2010 and 2014 was made through 100 randomized checkpoints for each year, which were compared to high resolution satellite imagery from Google Earth, similarly to Cohen et al. (2010), and reached an accuracy of over 95 % for both time periods.

Vector data from forest cover mapping of each year was converted to raster matrices containing classes “Atlantic Forest” and “matrix”, with a pixel size of 30 m. Landscape evolution was evaluated through the following landscape metrics, calculated in FRAGSTATS (McGarigal et al. 2002): percentage of landscape covered by forest, number of fragments, area of the largest fragment and average distance to nearest fragment. Percentage of forest cover is the main explanatory variable that can regulate species diversity in a landscape (Andren 1994; Fahrig 2001, 2003), while patch size is particularly important in landscapes with low connectivity, especially for sensitive species (Hanski and Gilpin 1997; Ferraz et al. 2007; Martensen et al. 2008; Uezu and Metzger 2011). The number of fragments represents how segmented a landscape is, and the mean nearest neighbor indicates how isolated patches are in a landscape (Hanski and Gilpin 1997).

In order to evaluate the influence of socioeconomic conjuncture of the municipality on the dynamics of its landscape, we used linear regression for testing the relationship between forest cover and census data on the size of rural and cropland area, produced by the Brazilian Institute of Geography and Statistics (IBGE)[1] (http://www.ibge.gov.br). Some of the years selected for forest mapping lacked census data. In this case, we interpolated data of the two nearest censuses by linear regression in order to obtain an estimate of these parameters in each mapped year.

Spatial modeling

We used the method of weights of evidence (WoE) for modeling forest cover dynamics and quantifying the influence of environmental and anthropogenic spatial variables on the probability of regeneration and deforestation. WoE constitute a Bayesian method, originally used in Geology (Bonham-Carter 1994), which offers the advantage of not being restricted by the classical assumptions of parametric statistical methods, which spatial data often violate. The calculation of each variable effect does not depend of a joint solution, with the premise that the input variables must be spatially independent (Soares-Filho et al. 2003). Calculations were performed in Dinamica EGO software (Soares-Filho et al. 2014), using the simulation model developed by Soares-Filho et al. (2006).

The choice of explanatory variables (Table 1) considered the pattern of occupation and land use of the Atlantic Forest, which is highly related to the relief and vectors of occupation, tending to prioritize lowland areas nearer to urban centers and roads (Dean 1996; Teixeira et al. 2009). The use of fire was also considered, as it tends to propagate in drier areas, in sites with higher intensities of solar radiation (Rothermel et al. 1986; Chuvieco et al. 2002). Likewise, environmental variables associated to secondary forest succession (Guariguata and Ostertag 2001), such as soil type, temperature, precipitation, solar radiation and distance to forest, were also included in the analysis. As WoE may only be applied to categorical data, it was necessary to categorize continuous variables. To do this, we used an adaptation of the method of categorization Agterberg et al. (1993), proposed by Soares-Filho et al. (2009).

We calculated WoE values for each of the timeslots mapped between 1978 and 2014 (1978–1988; 1988–1999; 1999–2006 and 2006–2014), and also for the entire period (1978–2014). For each variable, the WoE values of different timeslots were plotted against

[1] Census data until year 1991 was acquired online (http://cod.ibge.gov.br/23gqk, accessed in May 08, 2014) while older census data was acquired at the Library of IBGE.

Table 1 Data used for calculating spatial variables employed for modeling the Atlantic Forest cover dynamics in Trajano de Moraes, Brazil

Data	Variable
Forest cover mapping	Distance to forest (m)[a]
	Distance to matrix (m)[a]
Municipal seats (SEA/IBGE 2006)	Distance to municipal seats (m)[a]
Villages (SEA/IBGE 2006)	Distance to villages (m)[a]
Municipal seats and villages (SEA/IBGE 2006)	Distance to urban areas (m)[a]
Rivers (SEA/IBGE 2006)	Distance to rivers (m)[a]
Roads (SEA/IBGE 2006)	Distance to roads (m)[a]
Digital Elevation Model (SEA/IBGE 2006)	Elevation (m)
	Slope (degrees)[a]
	Solar radiation (kWh/m^2)[a]
	Topographic Position Index (m)[b]
Soil map (SEA/INEA 2011)	Soil class
WorldClim (Hijmans et al. 2005)	Average monthly precipitation (mm)
	Average annual temperature (°C)

[a] Calculated in ArcGIS (ESRI 2013)

[b] Calculated according to the methodology proposed by Weiss (2001) and adapted by Jenness (2006). The raster data are available online at http://dx.doi.org/10.6084/m9.figshare.1436095

the categories of values in order to identify which variables presented consistent patterns of influence on regeneration and deforestation. Those with consistent patterns were tested for correlation through Crammer tests and contingency, and subsequently included in the model.

We simulated forest cover changes for the next interval of 36 years subsequent to the analyzed period (2014–2050), calibrating the model with the transition matrix and the WoE of selected variables calculated for the period 1978–2014. The model was validated using the method proposed by Hagen (2003) and adapted by Almeida et al. (2008) for Dinamica EGO (Soares-Filho et al. 2014). Therefore, the actual transition matrix range from 1978 to 2014 was compared to the transition matrix designed for this same time-frame, taking into consideration only the areas converted from one class to another. This evaluation was carried out at different scales through the multiple windows decay function, with window sizes ranging from 1 to 35 pixels (0.09–110.25 ha). As Dinamica EGO transition functions use a stochastic mechanism of cell selection, each model execution results in a unique landscape. To mitigate this effect on the landscape metrics projected for the year 2050, we worked with the average landscape metrics calculated for 5 replicas generated by the execution of the model, similarly to Castro et al. (2005) and Teixeira et al. (2009).

Results

Forest cover mapping and census data

All analyzed timeslots from 1978 to the present had net forest gain. In 36 years, forest cover in Trajano de Moraes increased 3020 hectares (15.3 %), from 19,787 hectares in 1978 to 22,807 hectares in 2014, equivalent to a growth rate of 0.4 % per year (Fig. 1).

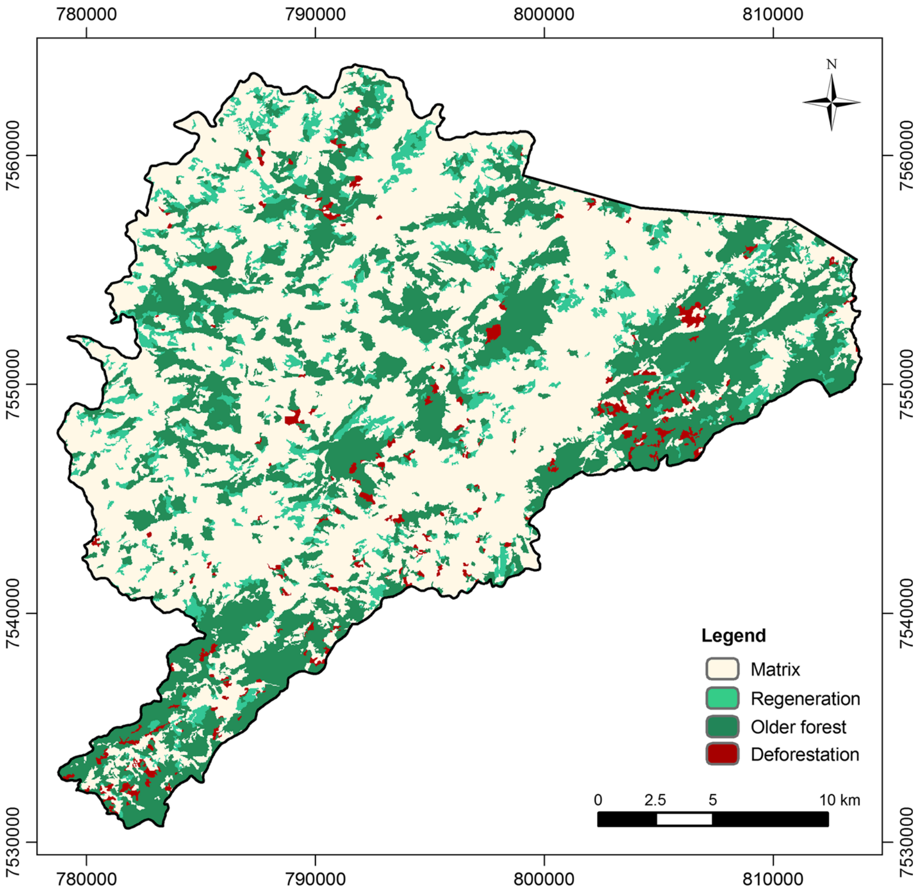

Fig. 1 Forest cover dynamics between years 1978 and 2014 in Trajano de Moraes, Brazil. Datum WGS84, UTM Zone 23S. The raster data are available online at http://dx.doi.org/10.6084/m9.figshare.1436095

During this same period, the municipality had major changes in its population size and composition. The predominance of rural over urban population decreased from 74.0 to 53.5 %, and total population decreased by 13.8 %, from 12,006 to 10,348 people. Those demographic trends also reflect in land use pattern, with cropland area being reduced by 7.7 % (Fig. 2). The gain of forest cover was significantly related to this dynamic, especially to the reduction of the rural population ($R^2 = 0.9794$, $p = 0.0013$) and cropland cover ($R^2 = 0.8679$, $p = 0.0212$) (see electronic supplementary material, Fig. S1).

Spatial modeling

Spatial variables influencing regeneration with consistent patterns were, in order of importance (WoE range in parenthesis): topographic position (3.3); solar radiation (2.8); distance to urban areas (2.1); slope (1.8); soil type (1.7); distance to forest (1.5); distance to all roads (1.2) and distance to main rivers (0.9) (Fig. 3).

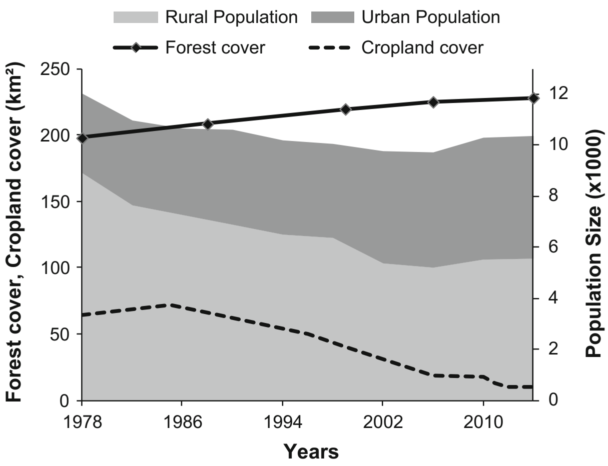

Fig. 2 Forest cover and census data for rural and urban population sizes and cropland area in Trajano de Moraes, Brazil, between years 1978 and 2014. Total population sizes, represented in the secondary y-axis, correspond to the superposition of the urban population (*dark gray*) and the rural population (*light gray*)

Variables related to the relief had great influence on regeneration. Topographic position index (TPI) had the highest values of WoE, starting in −120 m and decreasing to approach zero around −50 m. TPI represents topographic position in a continuum, in which negative values correspond to depressions and valleys, while values near zero represents flatter areas and positive values are linked to the hilltops and ridgetops. Therefore, regeneration was favored in the areas of depressions and hillsides, and disadvantaged in plains and ridges (Fig. 3a). Slope also presented a consistent pattern, in which regeneration is diminished in flatter areas, gradually being favored in areas with increasing slope up to the limit threshold of around 30°, when the weight of evidence stabilizes (Fig. 3b). Solar radiation also presented a consistent pattern of influence in all timeslots. Extreme values of radiation disfavored regeneration, while intermediate values around 1200 kWh/m^2 had the highest values of WoE (Fig. 3c).

Regarding the distance to urban areas, the most consistent pattern appeared when villages and municipal seats were analyzed together. In all timeslots, regeneration was disfavored near urban areas, including therein villages and municipal seats, and this effect tended to stabilize at a distance of 5 km (Fig. 3d). The same pattern was observed to the distance of all roads and main rivers, which tended to stabilize at the distances of 700 m and 1 km, respectively (Fig. 3e, f).

During all timeslots, the type of soil more favorable to regeneration was the Eutrophic Red-Yellow Argisol and the less favorable was the Dystrophic Oxisol. Dystrophic Haplic Cambisol had low positive values of WoE and Dystrophic Red-Yellow Latosol had low negative values of WoE during all timeslots (Fig. 3g). Regeneration also tended to occur near forest edges, with this influence decreasing as the distance increases, until a threshold of approximately 600 m where the WoE values stabilize (Fig. 3h).

Spatial variables influencing deforestation with consistent patterns were, in order of importance (WoE range in parenthesis): slope (4.1); distance to all roads (3.2); solar radiation (2.9); distance to main rivers (1.5) and distance to matrix (0.4) (Fig. 4).

Deforestation tended to occur in more plain areas, being favored between 0° to 23° of slope (Fig. 4a). It also occurred nearer roads and main rivers, with this influence decreasing until stabilization around 1200 and 800 m away respectively (Fig. 4b, c). Areas with higher solar incidence were more prone to deforestation (Fig. 4d), which also had a slight

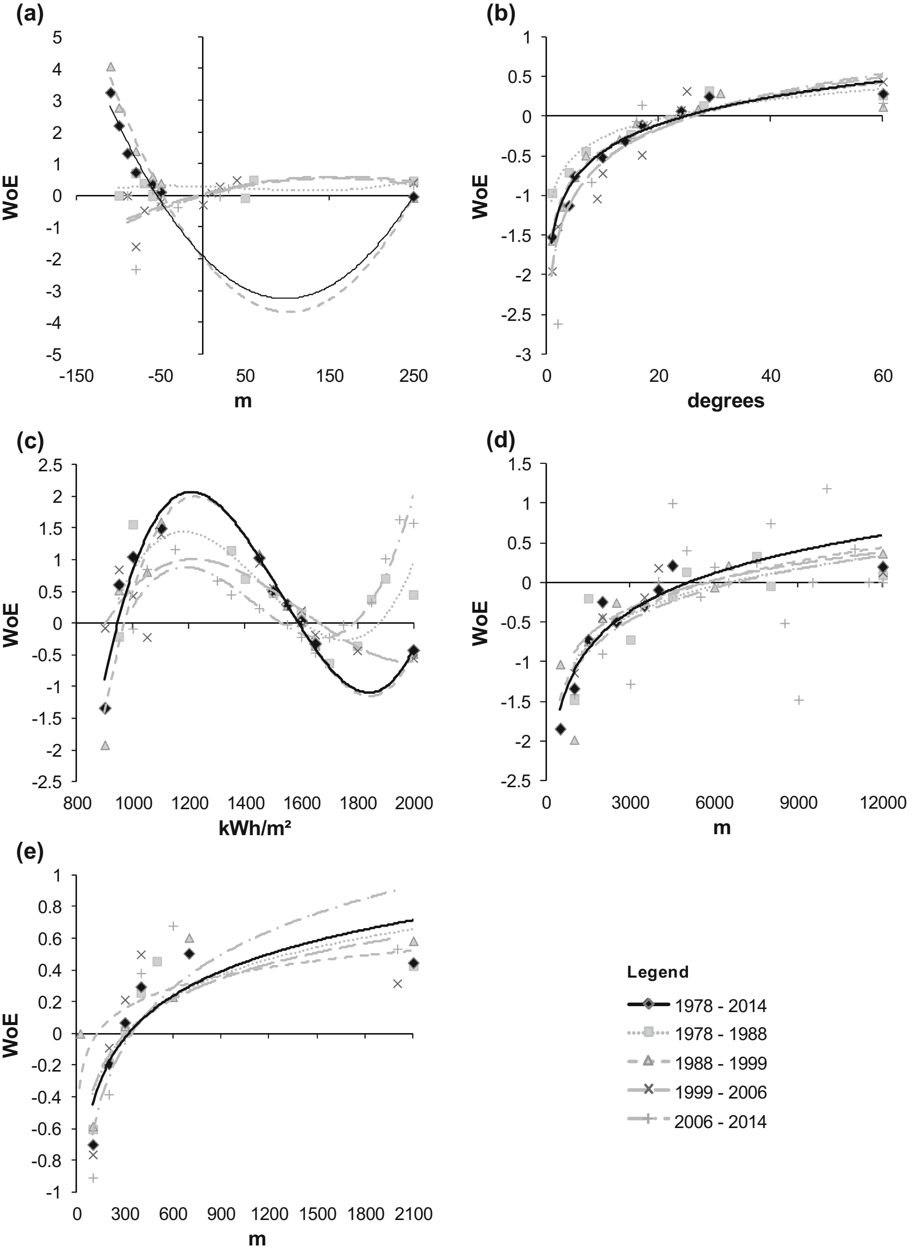

Fig. 3 Weights of Evidence (WoE) of explanatory spatial variables for regeneration modeling in Trajano de Moraes, Brazil, between years 1978 and 2014. **a** Topographic position index (TPI); **b** slope; **c** solar radiation; **d** distance to urban areas; **e** distance to all roads; **f** distance to main rivers; **g** soil type (CXbd = Dystrophic Haplic Cambisol; LVAd = Dystrophic Red-Yellow Latosol; PVAd = Dystrophic Red-Yellow Argisol; PVAe = Eutrophic Red-Yellow Argisol); **h** distance to forest

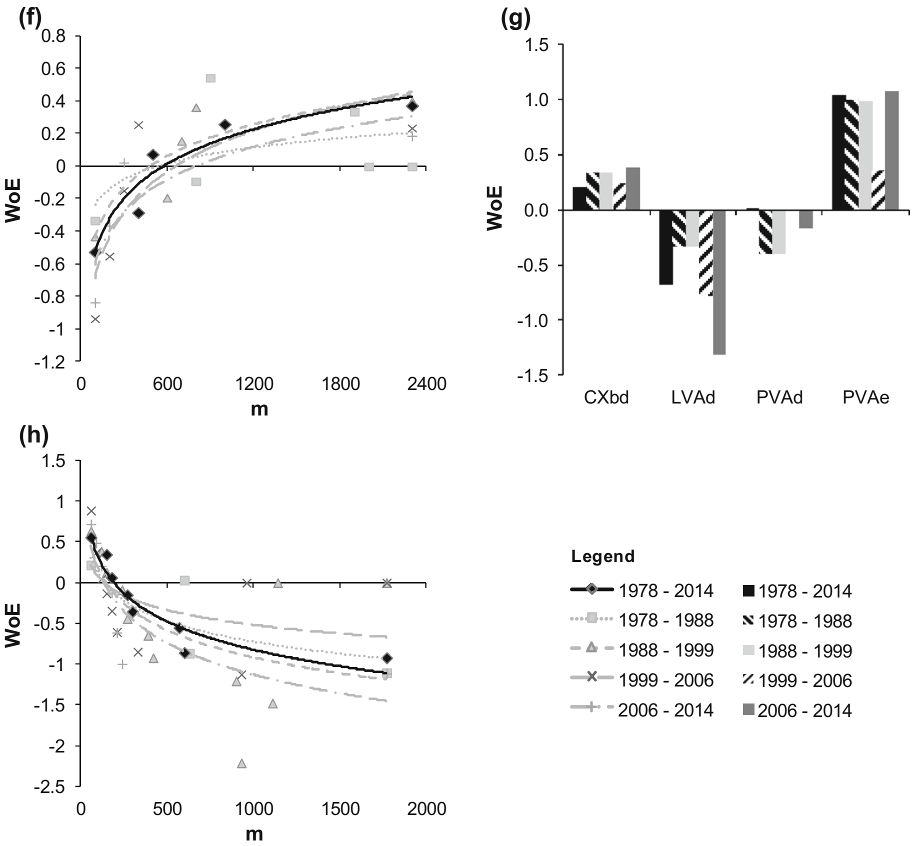

Fig. 3 continued

tendency to occur in the border of fragments, at a maximum distance of 300 m from the matrix (Fig. 4e).

Simulation

The results for contingency and Crammer tests indicate that the variables selected for forest cover modeling are independent (see electronic supplementary material, Tables S1, S2). The comparison between mapped and projected transition areas for the period 1978–2014 had a minimum similarity of 24 % for the window size of 0.09 ha (i.e. the model had little efficiency in determining the fate of a pixel in a very local scale), and 78 % for the window size of 110.25 ha (i.e. the model was highly efficient to forecast the fate of a pixel in a larger area).

Landscape metrics showed the increase of land cover (PLAND) and area of the largest fragment (AREA_LF), which tends to remain in the simulation for year 2050. Following this trend, it is also forecasted an increase in the number of fragments (NP) and the structural connection, represented by the average distance to nearest fragment (ENN_MN) (Fig. 5).

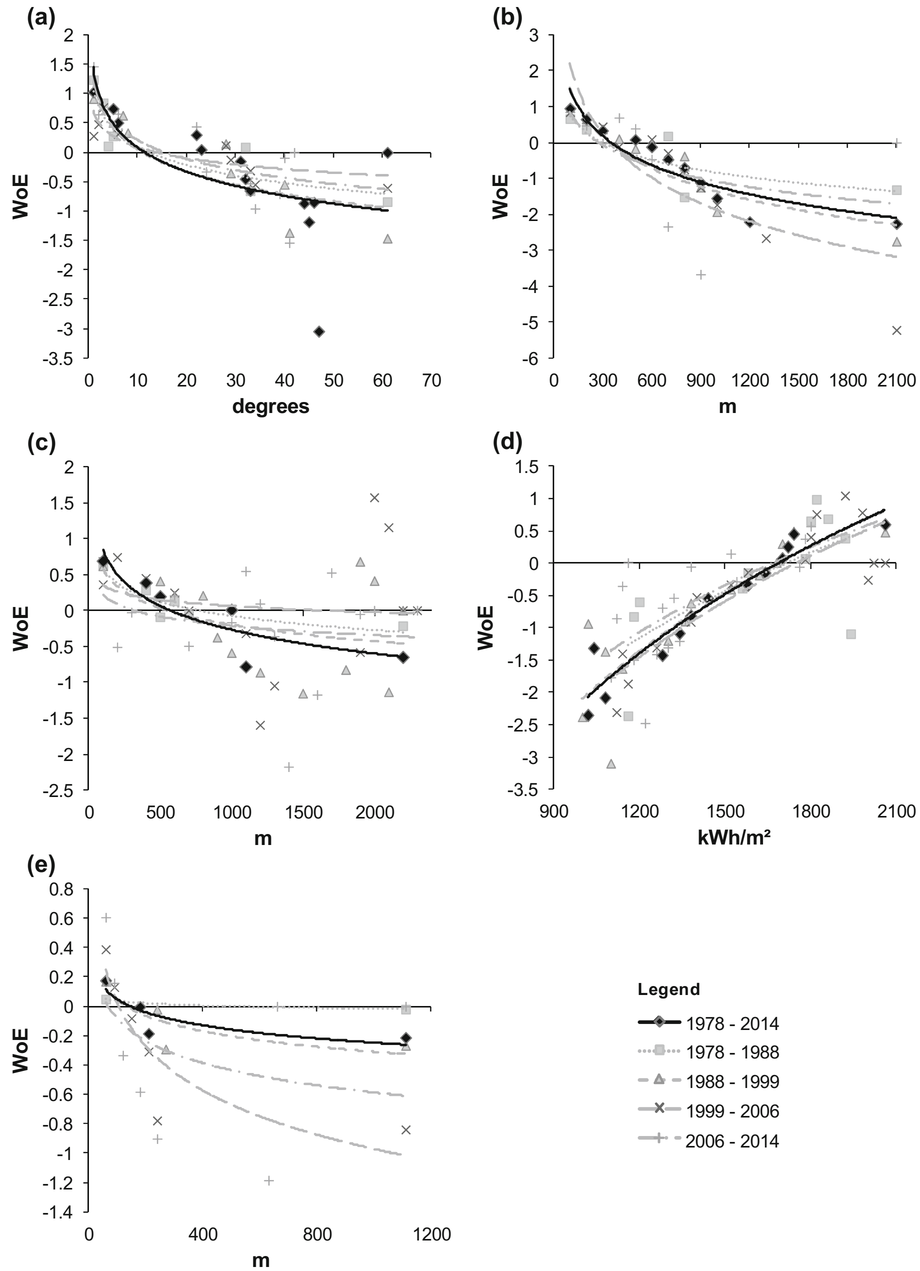

Fig. 4 Weights of Evidence (WoE) of explanatory spatial variables for deforestation modeling in Trajano de Moraes, Brazil, between years 1978 and 2014. **a** Slope; **b** distance to all roads; **c** distance to main rivers; **d** solar radiation; **e** distance to matrix

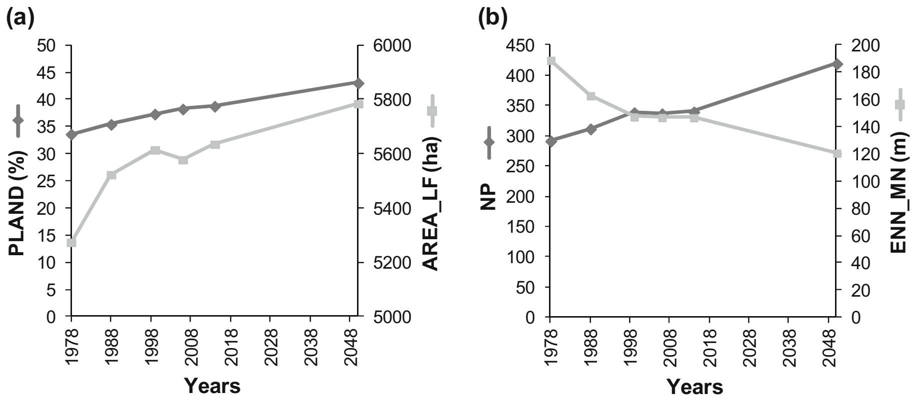

Fig. 5 Landscapes metrics mapped (period 1978–2014) and projected (period 2014–2050) in Trajano de Moraes, Brazil. *PLAND* percentage forest cover, *AREA_LF* area of the largest fragment, *NP* number of fragments, *ENN_MN* average distance to nearest fragment

Discussion

Forest cover dynamics

The municipality presented a significant forest gain, strongly related to its socio-economic dynamics in the last four decades. Regression analysis suggests that the rural exodus, which started after the economic decline of coffee, reduced the intensity of land use and allowed the advance of the succession process in abandoned areas. Contradicting the general trend of reduction in tropical forests cover (FAO 2010), the regeneration of secondary forests due to the abandonment of land has been observed in some regions of Brazil (Buschbacher et al. 1988; Neeff et al. 2006; Piotto et al. 2009) and other Latin American countries such as Costa Rica (Holl 1999), Puerto Rico (Helmer et al. 2008), Argentina (Ramadori et al. 1997) and Colombia (Etter et al. 2005).

The pattern of forest cover increase observed in the municipality of Trajano de Moraes differs considerably of the one shown by the whole State of Rio de Janeiro in recent decades. While the state had an annual reduction of more than 0.21 % of its forest component in the period 1995–2013 (SOS Mata Atlântica and INPE 2002, 2014), the municipality of Trajano de Moraes presented an annual increase of 0.25 % of forest cover between 1999 and 2014. Considering the period of 1978–2014, this discrepancy is even greater, since the municipality reached a forest cover growth rate of 0.4 % per year. The rate of forest gain in Trajano de Moraes was also higher than the value found for another area of the Atlantic Forest located in the State of São Paulo, which presented an annual forest gain of 0.28 % between 1984 and 2003 (Uezu 2006).

Influence of spatial variables

Variables associated to the distribution of human occupation and land use had a great influence on the occurrence of both regeneration and deforestation. However, the patterns of influence of the spatial variables were more consistent in the analysis of regeneration, given the greater number of events of this phenomenon, as compared to deforestation.

Regeneration tended to occur in more pronounced depressions, with higher slopes. Due to its rugged conditions, those areas are not favorable to the occupation and to agricultural production and therefore tend to suffer less pressure of use. Inversely, deforestation tended to occur in little steep slopes and flat areas, where transport and mechanization of crops for commercial purposes are facilitated, following a pattern described to other areas of the Atlantic Forest (Silva et al. 2007; Teixeira et al. 2009; Freitas et al. 2010).

Likewise, urban areas, rivers and roads acted as vectors of human occupation, favoring deforestation and inhibiting regeneration in its surrounding areas, a trend observed in several regions of South America (Etter et al. 2006; Soares-Filho et al. 2006; Teixeira et al. 2009). This trend must be carefully considered during road planning in the Atlantic Forest, since this biome is characterized as a conflict zone for road construction because it concentrates both high environmental and agricultural values (Laurance et al. 2014).

As land use pressure in Trajano de Moraes decreased in the last decades, spatial variables related to environmental conditions had a great influence on the municipality's landscape dynamics. Regeneration tended to occur in areas with intermediate values of solar radiation, possibly due the trade-off between light availability and moisture, both limiting factors for seedling establishment during the process of secondary succession (Guariguata and Ostertag 2001). Areas with higher solar incidence are also more prone to burning, which is considered by the Brazilian Ministry of Environment as one of the biggest threats to this region (Ministério do Meio Ambiente 2007).

Distance to forest fragments and soil fertility were also important factors determining regeneration in the municipality. Forest growth tended to occur in the first 180 meters of distance from older fragments. This threshold is similar to that found in another study in the Atlantic Forest (Teixeira 2005), and confirms the importance of the presence of remaining forests as sources of propagules, promoting increased species richness, number of individuals and biomass of regenerating areas (Guariguata and Ostertag 2001). Regeneration was highly favored in areas of Red-Yellow Argisol, which is the only eutrophic soil occurring in the study area. At the same time, distrophic soils presented low or negative values of WoE for regeneration, corroborating several studies that points low soil fertility as a major barrier to regeneration (Buschbacher et al. 1988; Aide and Cavelier 1994; Holl 1999).

Benefits of forest gain

Landscape parameters for forest cover in the municipality presented a substantial improvement in the last 40 years. Forest cover reached 38.8 % of the total area of the municipality in 2014, almost twice the proportion of forest cover of the State of Rio de Janeiro in 2013 (20.3 %) and almost three times higher than the proportion for the whole Atlantic Forest biome (15 %) (SOS Mata Atlântica, INPE 2014). This is an important change as some studies revealed a threshold for species extinction varying from 30 % to 50 % of habitat amount (Andren 1994; Pardini et al. 2010; Martensen et al. 2012). If the trends presented by the municipality remain in the coming decades, there will be a higher chance that this number will be above the threshold in the future, with the municipality reaching 43.0 % of forest cover in 2050 by means of natural regeneration. For this reason, it is possible that this natural process may guarantee the permanence of most of the biodiversity in the study area or will create condition to receive species that were already lost locally before the studied period (Lira et al. 2012).

Furthermore, forest gain led to the improvement of structural connection and the increase of the largest fragment size and of the number of fragments. Mean distance among patches had a considerable decrease from 189 m in 1978 to 146 m in 2014. This occurred especially due the increase in the number of forest patches in the landscape. This reduction in patch isolation can favor the mobility for many species able to cross open areas and use small fragments, favoring gene flow (Uezu et al. 2005; Vieira et al. 2009). Those improvements could possibly stop extinction processes initiated more than a century ago, considering the time-lag in response to extinction, which may take up to 200 years for plants (Vellend et al. 2006), 100 years for birds (Brooks et al. 1999) and 50 years for primates (Cowlishaw 1999). However, for species more averse to cross open areas, these distances are still large enough to isolate them in separate patches (Uezu et al. 2005; Awade and Metzger 2008). In this context, a planned forest restoration in this area could stimulate natural regeneration by reducing disturbances on priority sites, in order to create corridors and increase connectivity among fragments.

Despite the legacy of past uses, such as the presence of exotic species and floristic homogenization (Grau et al. 2003), the conservation value of regenerating forests has been increasingly recognized in recent years (Chazdon 2008; Edwards et al. 2011). Data collected in the Atlantic Forest indicates that the gain of forest cover is followed by an increase in plant diversity, compared to previous sucessional stages and other land uses (Piotto et al. 2009). Regenerating forests also provide a number of ecosystem services (Chazdon 2008) that can be reversed into economic benefits, such as water production, carbon sequestration, fire control, biodiversity and aesthetic quality (Balvanera et al. 2012).

From an economic perspective, natural regeneration can play an important role in reducing restoration costs. If the 3020 ha of forest gained between 1978 and 2014 in Trajano de Moraes were recovered by active restoration, the municipality would have spent an amount of U$ 15.1 million, considering an average active forest restoration cost U$ 5000.00 per hectare (Brancalion et al., 2012).

The processes that lead to land abandonment should also receive attention. Although the economic downturn may contribute substantially to the regeneration of natural ecosystems, the decline in agricultural production brings the need to implement new production models that promote improvement of social conditions linked to the more efficient use of natural resources. The history of devastation of the Atlantic Forest is closely related to the poorly planned agriculture until the early twentieth century (Dean 1996). However, nowadays there are plenty alternative ways of farming that can reconcile agricultural production and the maintenance of biodiversity, such as agroforestry and organic farming (Hole et al. 2005; Bhagwat et al. 2008). Those production systems can also be associated to economic mechanisms that reward actors who conserve or restore the ecosystem services (Magrin et al. 2014).

Projections indicate that losses in environmental services will affect some social groups more than others, with negative impacts especially for the poorest population (Magrin et al. 2014). Therefore, the decision to promote natural regeneration, to restore and to protect ecosystems, ensuring the provision of environmental services, is also an ethical and social justice choice.

Acknowledgments We would like to thank M.L. Lorini for her contributions to this study; F. Brasil, S. Teixeira, M. Gonçalves, J. Fernandes and V. Medeiros for field support; and the State Institute for the Environment of Rio de Janeiro (INEA) for supporting this research. We are very grateful to the Society for Conservation GIS (SCGIS) and ESRI Conservation Program, for providing a scholarship to C.L. Rezende and sponsoring the presentation of this study at the 13th Annual SCGIS Conference and 30th Annual ESRI International User Conference. We also thank CAPES for granting a Master's degree fellowship to C.L. Rezende.

References

Agterberg F, Bonham Carter G, Cheng Q, Wright D (1993) Weights of evidence modeling and weighted logistic regression for mineral potential mapping. Computers in Geology, 25 Years of Progress 13–32

Aide TM, Cavelier J (1994) Barriers to lowland tropical forest restoration in the Sierra Nevada de Santa Marta, Colombia. Restor Ecol 2:219–229. doi:10.1111/j.1526-100X.1994.tb00054.x

Almeida C, Gleriani J, Castejon E, Soares-Filho B (2008) Using neural networks and cellular automata for modelling intra-urban land-use dynamics. Int J Geogr Inf Sci 22:943–964

Andren H (1994) Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. Oikos 71(3):355–366

Awade M, Metzger JP (2008) Using gap-crossing capacity to evaluate functional connectivity of two Atlantic rainforest birds and their response to fragmentation. Austral Ecol 33:863–871. doi:10.1111/j.1442-9993.2008.01857.x

Balvanera P, Uriarte M, Almeida-Leñero L et al (2012) Ecosystem services research in Latin America: the state of the art. Ecosystem Services 2:56–70. doi:10.1016/j.ecoser.2012.09.006

Banks-Leite C, Pardini R, Tambosi LR et al (2014) Using ecological thresholds to evaluate the costs and benefits of set-asides in a biodiversity hotspot. Science 345:1041–1045. doi:10.1126/science.1255768

Bellard C, Leclerc C, Leroy B et al (2014) Vulnerability of biodiversity hotspots to global change. Glob Ecol Biogeogr 23:1376–1386. doi:10.1111/geb.12228

Bhagwat SA, Willis KJ, Birks HJB, Whittaker RJ (2008) Agroforestry: a refuge for tropical biodiversity? Trends Ecol Evol 23:261–267. doi:10.1016/j.tree.2008.01.005

Bonham-Carter G (1994) Geographic information systems for geoscientists: modelling with GIS. Pergamon Press, Oxford

Brancalion PHS, Viani RAG, Strassburg BBN, Rodrigues RR (2012) Finding the money for tropical forest restoration. Unasylva 63:239

Brooks TM, Pimm SL, Oyugi JO (1999) Time lag between deforestation and bird extinction in tropical forest fragments. Conserv Biol 13:1140–1150. doi:10.2307/2260567

Buschbacher R, Uhl C, Serrao EAS (1988) Abandoned pastures in eastern Amazonia. II. Nutrient stocks in the soil and vegetation. J Ecol 76:682–699. doi:10.2307/2260567

Castro CL, Pielke RA, Leoncini G (2005) Dynamical downscaling: assessment of value retained and added using the Regional Atmospheric Modeling System (RAMS). J Geophys Res 110:D05108. doi:10.1029/2004JD004721

Chazdon RL (2008) Beyond deforestation: restoring forests and ecosystem services on degraded lands. Science 320:1458–1460. doi:10.1126/science.1155365

Chuvieco E, Riaño D, Aguado I, Cocero D (2002) Estimation of fuel moisture content from multitemporal analysis of Landsat Thematic Mapper reflectance data: applications in fire danger assessment. Int J Remote Sens 23:2145–2162. doi:10.1080/01431160110069818

Cohen WB, Yang Z, Kennedy R (2010) Detecting trends in forest disturbance and recovery using yearly Landsat time series: 2. TimeSync—Tools for calibration and validation. Remote Sens Environ 114:2911–2924. doi:10.1016/j.rse.2010.07.010

Cowlishaw G (1999) Predicting the pattern of decline of African primate diversity: an extinction debt from historical deforestation. Conserv Biol 13:1183–1193

Dean W (1996) A ferro e fogo: a história e a devastação da Mata Atlântica brasileira. Editora Companhia das Letras, São Paulo

Edwards DP, Larsen TH, Docherty TDS et al (2011) Degraded lands worth protecting: the biological importance of Southeast Asia's repeatedly logged forests. Proc R Soc Lond B Biol Sci 278:82–90. doi:10.1098/rspb.2010.1062

ESRI (2013) ArcGIS Desktop. Environmental Systems Research Institute, Redlands

Etter A, McAlpine C, Pullar D, Possingham H (2005) Modeling the age of tropical moist forest fragments in heavily-cleared lowland landscapes of Colombia. For Ecol Manag 208:249–260. doi:10.1016/j.foreco.2004.12.008

Etter A, McAlpine C, Pullar D, Possingham H (2006) Modelling the conversion of Colombian lowland ecosystems since 1940: drivers, patterns and rates. J Environ Manag 79:74–87. doi:10.1016/j.jenvman.2005.05.017

Fahrig L (2001) How much habitat is enough? Biol Conserv 100:65–74. doi:10.1016/S0006-3207(00)00208-1

Fahrig L (2003) Effects of habitat fragmentation on biodiversity. Annu Rev Ecol Evol Syst 34:487–515

FAO (2010) Global forest resources assessment 2010: main report. Food and Agriculture Organization of the United Nations, Rome

Ferraz G, Nichols JD, Hines JE et al (2007) A large-scale deforestation experiment: effects of patch area and isolation on Amazon birds. Science 315:238–241. doi:10.1126/science.1133097

Freitas SR, Neves CL, Chernicharo P (2006) Tijuca National Park: two pioneering restorationist initiatives in Atlantic forest in southeastern Brazil. Braz J Biol 66:975–982. doi:10.1590/S1519-69842006000600004

Freitas SR, Hawbaker TJ, Metzger JP (2010) Effects of roads, topography, and land use on forest cover dynamics in the Brazilian Atlantic Forest. For Ecol Manag 259:410–417. doi:10.1016/j.foreco.2009.10.036

Grau HR, Aide TM, Zimmerman JK et al (2003) The ecological consequences of socioeconomic and land-use changes in post agriculture Puerto Rico. Bioscience 53:1159–1168

Guariguata M, Ostertag R (2001) Neotropical secondary forest succession: changes in structural and functional characteristics. For Ecol Manag 148:185–206. doi:10.1016/S0378-1127(00)00535-1

Hagen A (2003) Fuzzy set approach to assessing similarity of categorical maps. Int J Geogr Inf Sci 17:235–249. doi:10.1080/13658810210157822

Hanski I, Gilpin ME (eds) (1997) Metapopulation biology: ecology, genetics, and evolution. Academic Press, San Diego

Helmer EH, Brandeis TJ, Lugo AE, Kennaway T (2008) Factors influencing spatial pattern in tropical forest clearance and stand age: implications for carbon storage and species diversity. J Geophys Res 113(14):2008. doi:10.1029/2007JG000568

Hijmans RJ, Cameron SE, Parra JL et al (2005) Very high resolution interpolated climate surfaces for global land areas. Int J Climatol 25:1965–1978

Hobbs RJ, Arico S, Aronson J et al (2006) Novel ecosystems: theoretical and management aspects of the new ecological world order. Glob Ecol Biogeogr 15:1–7. doi:10.1111/j.1466-822X.2006.00212.x

Hole DG, Perkins AJ, Wilson JD et al (2005) Does organic farming benefit biodiversity? Biol Conserv 122:113–130. doi:10.1016/j.biocon.2004.07.018

Holl KD (1999) Factors limiting tropical rain forest regeneration in abandoned pasture: seed rain, seed germination, microclimate, and soil. Biotropica 31:229–242. doi:10.1111/j.1744-7429.1999.tb00135.x

Holl KD, Aide TM (2011) When and where to actively restore ecosystems? For Ecol Manage 261:1558–1563. doi:10.1016/j.foreco.2010.07.004

Jenkins CN, Pimm SL, Joppa LN (2013) Global patterns of terrestrial vertebrate diversity and conservation. PNAS 110:E2602–E2610. doi:10.1073/pnas.1302251110

Jenness J (2006) Topographic Position Index. Jenness Enterprises, Flagstaff

Joly CA, Metzger JP, Tabarelli M (2014) Experiences from the Brazilian Atlantic Forest: ecological findings and conservation initiatives. New Phytol 204:459–473. doi:10.1111/nph.12989

Laurance WF, Clements GR, Sloan S et al (2014) A global strategy for road building. Nature 513:229–232. doi:10.1038/nature13717

Linhares EF (2004) Entre escravos e anjos: condições e significados da infância em um assentamento rural fluminense. Universidade Federal do Rio de Janeiro, Tese de Doutorado

Lira PK, Ewers RM, Banks-Leite C et al (2012) Evaluating the legacy of landscape history: extinction debt and species credit in bird and small mammal assemblages in the Brazilian Atlantic Forest. J Appl Ecol 49:1325–1333. doi:10.1111/j.1365-2664.2012.02214.x

Machado ABM, Drummond GM, Paglia AP (eds) (2010) Livro vermelho da fauna brasileira ameaçada de extinção. Ministério do Meio Ambiente, Ministério da Educação, Brasília

Magrin GO, Marengo JA, Boulanger J-P et al (2014) Central and South America. In: Barros VR, Field CB, Dokken DJ et al (eds) Climate change 2014: impacts, adaptation, and vulnerability. Part B: Regional aspects. contribution of working Group II to the fifth assessment report of the intergovernmental panel of climate change. Cambridge University Press, Cambridge, pp 1499–1566

Martensen AC, Pimentel RG, Metzger JP (2008) Relative effects of fragment size and connectivity on bird community in the Atlantic Rain Forest: implications for conservation. Biol Conserv 141:2184–2192. doi:10.1016/j.biocon.2008.06.008

Martensen AC, Ribeiro MC, Banks-Leite C et al (2012) Associations of forest cover, fragment area, and connectivity with neotropical understory bird species richness and abundance. Conserv Biol 26:1100–1111. doi:10.1111/j.1523-1739.2012.01940.x

Martinelli G, Moraes MA (eds) (2013) Livro vermelho da flora do Brasil. Centro Nacional de Conservação da Flora, Rio de Janeiro

McGarigal K, Cushman S, Neel M, Ene E (2002) FRAGSTATS: Spatial Pattern Analysis Program for Categorical Maps. Department of Environmental Conservation, University of Massachusetts, Amherst

Melo FPL, Pinto SRR, Brancalion PHS et al (2013) Priority setting for scaling-up tropical forest restoration projects: early lessons from the Atlantic Forest Restoration Pact. Environ Sci Policy 33:395–404. doi:10.1016/j.envsci.2013.07.013

Ministério do Meio Ambiente (2007) Áreas Prioritárias para Conservação, Uso Sustentável e Repartição dos Benefícios da Biodiversidade Brasileira
Mittermeier RA, Gil PR, Hoffman M et al (2005) Hotspots revisited: earth's biologically richest and most endangered terrestrial ecoregions. Cemex, Mexico City
Myers N, Mittermeier RA, Mittermeier CG et al (2000) Biodiversity hotspots for conservation priorities. Nature 403:853–858. doi:10.1038/35002501
Neeff T, Lucas RM, Santos JR et al (2006) Area and age of secondary forests in Brazilian Amazonia 1978–2002: an empirical estimate. Ecosystems 9:609–623
Pardini R, de Bueno A, Gardner TA et al (2010) Beyond the fragmentation threshold hypothesis: regime shifts in biodiversity across fragmented landscapes. PLoS ONE 5:e13666. doi:10.1371/journal.pone.0013666
Pinheiro D (1993) Sindicatos e Associações em Trajano de Moraes - Rio de Janeiro: um Estudo sobre a Diferenciação da Representação Política dos Pequenos Produtores nos Anos 80. Dissertação de mestrado, Curso de Pós-Graduação em Desenvolvimento, Agricultura e Sociedade; Universidade Federal Rural do Rio de Janeiro, Rio de Janeiro
Piotto D, Montagnini F, Thomas W et al (2009) Forest recovery after swidden cultivation across a 40-year chronosequence in the Atlantic forest of southern Bahia, Brazil. Plant Ecol 205:261–272. doi:10.1007/s11258-009-9615-2
Projeto RADAMBRASIL (1983) Regiões Fitoecológicas do Estado do Rio de Janeiro
Ramadori D, Brown AD, Liberman M, Baied C (1997) Agricultura migratoria y sucesión secundaria en bosques nublados del noroeste de Argentina. Desarrollo sostenible en ecosistemas de montaña: Manejo de areas frágiles en los Andes La Paz (Bolivia): Universidad de las Naciones Unidas 113–127
Ribeiro M, Metzger JP, Martensen AC et al (2009) The Brazilian Atlantic forest: how much is left, and how is the remaining forest distributed? Implications for conservation. Biol Conserv 142:1141–1153. doi:10.1016/j.biocon.2009.02.021
Ribeiro MC, Martensen AC, Metzger JP et al (2011) The Brazilian Atlantic forest: a shrinking biodiversity hotspot. In: Zachos FE, Habel JC (eds) Biodiversity hotspots. Springer, Berlin, pp 405–434
Rothermel RC, Wilson RA, Morris GA, Sackett SS (1986) Modeling moisture content of fine dead wildland fuels: Input to the BEHAVE fire prediction system
Scarano FR (2009) Plant communities at the periphery of the Atlantic rain forest: rare-species bias and its risks for conservation. Biol Conserv 142:1201–1208. doi:10.1016/j.biocon.2009.02.027
SEA/IBGE (2006) Restituição das ortofotos do Estado do Rio de Janeiro na escala 1:25.000. Secretaria Estadual do Ambiente, Rio de Janeiro
SEA/INEA (2011) Mapeamento de Solos do Estado do Rio de Janeiro na escala 1:100.000. Secretaria Estadual do Ambiente, Instituto Estadual do Ambiente, Rio de Janeiro
Silva W, Metzger J, Simões S, Simonetti C (2007) Relief influence on the spatial distribution of the Atlantic Forest cover on the Ibiúna Plateau, SPInfluência do relevo na distribuição espacial da Mata Atlântica no Planalto de Ibiúna, SP. Braz J Biol 67:403–411
Soares-Filho B, Cerqueira GC, Araújo WL (2003) Modelagem de dinâmica de paisagem: concepção e potencial de aplicação de modelos de simulação baseados em autômato celular. In: Albernaz AL, Silva JMC, Valeriano D (eds) Ferramentas para modelagem da distribuição de espécies em ambientes tropicais, 1st edn. Museu Paraense Emílio Goeldi, Belém, p 100
Soares-Filho BS, Nepstad DC, Curran LM et al (2006) Modelling conservation in the Amazon basin. Nature 440:520–523. doi:10.1038/nature04389
Soares-Filho BS, Rodrigues HO, Costa WLS (2009) Modelagem de Dinâmica Ambiental com Dinamica EGO. Centro de Sensoriamento Remoto/Universidade Federal de Minas Gerais, Belo Horizonte
Soares-Filho BS, Rodrigues HO, de Costa WLS et al (2014) Dinamica EGO. Version 2.4.1. Universidade Federal de Minas Gerais, Belo Horizonte, Brasil. http://www.csr.ufmg.br/dinamica
SOS Mata Atlântica, INPE (2002) Atlas dos remanescentes florestais da Mata Atlântica: período 1995–2000. SOS Mata Atlântica, São Paulo
SOS Mata Atlântica, INPE (2013) Atlas dos remanescentes florestais da Mata Atlântica: período 2011–2012. SOS Mata Atlântica, São Paulo
SOS Mata Atlântica, INPE (2014) Atlas dos remanescentes florestais da Mata Atlântica: período 2012–2013. SOS Mata Atlântica, São Paulo
Teixeira AMG (2005) Modelagem da dinâmica de uma paisagem do Planalto de Ibiúa (1962–2000) e inferências sobre a sua estrutura futura (2019). Master's dissertation, Universidade de São Paulo, São Paulo
Teixeira AMG, Soares-Filho BS, Freitas SR, Metzger JP (2009) Modeling landscape dynamics in an Atlantic Rainforest region: implications for conservation. For Ecol Manage 257:1219–1230. doi:10.1016/j.foreco.2008.10.011

Uezu A (2006) Composição e estrutura da comunidade de aves na paisagem fragmentada do Pontal do Paranapanema. Doctoral thesis, Instituto de Biociências da Universidade de São Paulo, São Paulo

Uezu A, Metzger JP (2011) Vanishing bird species in the Atlantic Forest: relative importance of landscape configuration, forest structure and species characteristics. Biodivers Conserv 20:3627–3643. doi:10.1007/s10531-011-0154-5

Uezu A, Metzger JP, Vielliard JME (2005) Effects of structural and functional connectivity and patch size on the abundance of seven Atlantic Forest bird species. Biol Conserv 123:507–519. doi:10.1016/j.biocon.2005.01.001

Vellend M, Verheyen K, Jacquemyn H et al (2006) Extinction debt of forest plants persists for more then a century following habitat fragmentation. Ecology 87:542–548. doi:10.1890/05-1182

Vieira MV, Olifiers N, Delciellos AC et al (2009) Land use vs. fragment size and isolation as determinants of small mammal composition and richness in Atlantic Forest remnants. Biol Conserv 142:1191–1200

Weiss A (2001) Topographic position and landforms analysis. In: ESRI user conference. San Diego, pp 200–200

Zachos FE, Habel JC (eds) (2011) Biodiversity hotspots: distribution and protection of conservation priority areas. Springer, Heidelberg