EFFECTS OF URBAN SPRAWL ON FOREST CONSERVATION IN A METROPOLITAN WATER SOURCE AREA[1]

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ABSTRACT – The clearing of native vegetation in water source areas and its effects on water supply availability have become a major concern in large metropolises. This study examined the spatial and temporal changes in land use and cover and their effects on the conservation of Atlantic Forest in a water source area in the Metropolitan Region of São Paulo that is the second most densely populated territory in Brazil, the municipality of Diadema. Historical maps and trend scenarios were developed by applying the Markov chain in association with cellular automata. Forest conservation was assessed based on a set of landscape metrics of resource availability, fragment isolation, and trends of forest fragmentation. Our findings revealed an increase in urban growth of 37% in the last five decades directly associated to the clearing of 50% of forests in intermediate/advanced stages and 40% in early stages. The main drivers of landscape change were human-modified fields (41%) and net roads (54%). Optimal resource availability was drastically reduced (75%) while isolation increased (361.5%) among existing forest fragments. Therefore, future trends indicate that, without changes in the management of the area, deforestation may occur rapidly and continuously until 10% of forest remains, leading to potential adverse effects on water availability and quality of the Billings Reservoir and the local biodiversity.

Keywords: *Landscape metrics, Land use and cover, Billings reservoir.*

EFEITOS DA EXPANSÃO URBANA NA CONSERVAÇÃO DE FLORESTAS EM UMA ÁREA DE MANANCIAL METROPOLITANO

RESUMO – A supressão da cobertura vegetal em áreas de mananciais e seus efeitos sobre a disponibilidade de água para o abastecimento público têm se tornado cada vez mais uma preocupação das grandes metrópoles. Este estudo avaliou as mudanças espaço-temporais de uso e cobertura da terra e seus efeitos na conservação de florestas de Mata Atlântica em uma área de manancial de restrição hídrica para o abastecimento da Região Metropolitana de São Paulo, inserida na segunda maior densidade demográfica do Brasil, no município de Diadema. Foram elaborados mapas históricos e cenários de tendência futura por meio da aplicação da cadeia de Markov em associação com autômatos celulares. A conservação de florestas foi avaliada a partir de um conjunto de métricas da paisagem embasadas na disponibilidade de recursos, no isolamento e na tendência de fragmentação florestal. Os resultados confirmaram que houve incremento do uso urbano de 37% nas últimas cinco décadas, que está diretamente relacionado com o desmatamento de 50% de floresta em estágio médio/avançado e 40% em estágio inicial, sendo os campos antrópicos (41%) e as vias de acesso (54%) as principais forças motrizes de mudança da paisagem. Houve uma drástica redução na disponibilidade de recurso ótimo (75%) e no aumento do isolamento (361,5%) dos fragmentos florestais atuais. Como consequência, as tendências indicam que, se não houver mudanças na gestão da área, o desmatamento pode acontecer de forma acelerada e ininterrupta, restando apenas 10% de floresta o que pode, potencialmente, prejudicar a disponibilidade e qualidade hídrica do reservatório e a biodiversidade local.

Palavras-Chave: *Métrica da paisagem, Uso e ocupação da terra, Represa Billings.*

1. INTRODUCTION

Urban sprawls in water source areas in large cities, such as São Paulo, have caused concern regarding the availability and quality of public water supply, requiring increasingly farther sources (ANA, 2015; Alvim et al., 2015). Historically, the occupation of environmentally sensitive sites, such as water sources, occurs as a result of urban expansion from central areas to the outskirts of cities, where low-income populations settle in areas devoid of public services, often in a disorderly and irregular manner (Duarte and Malheiros, 2012). One of the main issues caused by these settlements is the clearing of the vegetation cover, which can result in siltation of rivers and reservoirs, hinder water infiltration into the soil and pollutant removal, compromising the water quality of the catchment area of water sources (Liu, 2015).

Given the effects of vegetation clearing, the quantity and quality of remaining forest fragments in water source areas are expected to reflect their environmental conservation status (Biao et al., 2010). According to principles of landscape ecology, the processes associated with environmental conservation can be inferred from patterns of vegetation composition and distribution and land uses (Turner et al., 2001). Based on this approach, structural patterns can be assessed by using landscape metrics or indexes (McGarigal and Marks, 1995), such as quality of the forests based on size, shape, isolation, succession stage, and anthropic boundaries (Zeng and Wu, 2005; Hardt et al., 2013a, 2014).

The current state of environmental conservation is also associated to land use history, which can be characterized based on the identification and understanding of the driving forces of changes observed over time (Bürgi et al., 2004; Plieninger et al., 2016). Understanding the dynamics of these changes can assist planning and assessing future conservation actions, such as the construction of trend scenarios to prevent or mitigate adverse impacts (Ferraz and Vettorazzi, 2003; Willis et al., 2007; Whitlock et al., 2017).

Given the increasing urban pressure of large metropolises, it is necessary to understand its effects on forest conservation. Therefore, studies are needed on the application of methods and techniques for the conservation of sensitive areas, such as water sources, in order to ensure the supply of water, especially in densely populated areas. In this sense, this study was aimed to evaluate the history and future trends of space-time changes in land use and cover and their effects on the conservation of the Atlantic Forest in an area of water scarcity, in the second most demographically dense area of Brazil, the municipality of Diadema. Our findings may be used as a framework for planning and managing water sources, as it reveals the consequences of urban sprawling on the remaining forest fragments based on changes in landscape structural patterns.

2. MATERIALS AND METHODS

2.1 Study area

This study was conducted in the southern area of the municipality of Diadema in the Metropolitan Region of São Paulo (SP), Southeastern Brazil. The population projection of the municipality for 2017 was 418 thousand inhabitants in a small territory of 30.7 km² - 13.1 hab./km² (IBGE, 2017). Of these, 7.2 km² are located over a water source protection area of the Billings Reservoir (São Paulo, 2009), where the population has increased considerably in recent decades and modified the native Atlantic Forest formed by remnants of Dense Ombrophilous Forest (São Paulo, 2010).

The study area encompasses 7.9 km² and consists of 12 micro-watersheds, tributaries of the Billings Reservoir. The limits of the area were determined with the software ArcGIS® (version 10.2.2), using the municipality limits to the south and the watershed delimitation to the north (Figure 1).

2.2 Land use and cover maps and scenarios

Historical maps and future scenarios of land use and cover were elaborated for the area of the Billings Reservoir in Diadema.

We mapped the historical changes in ArcGIS® using manual vectorization based on visual assessment of aerial orthophotos of 1962 and 2011, provided by the Municipality of Diadema, at a scale of 1:25,000 and 1:10,000, respectively. Twelve types of land use and cover were categorized based on region characteristics, using as criteria: pattern, shape, texture, granularity, and color tone of the photos.

Future scenarios were constructed from the projection of trends of land use and cover using the Markov chain, an empirical mathematical model that assumes that the relationship among present variables will be maintained in the future (Baker, 1989). According to this model,

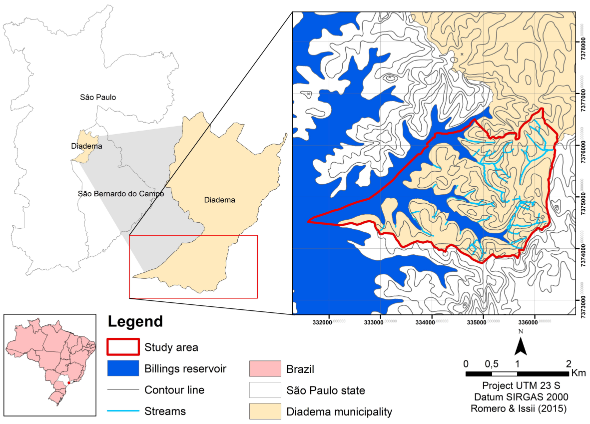


Figure 1 – Location and delimitation of the study site in the water source area of the Billings reservoir, in Diadema municipality, state of São Paulo – Brazil.
Figura 1 – *Localização e delimitação da área de estudo na região de manancial da represa Billings no município de Diadema, estado de São Paulo – Brasil.*

the condition of the system after time t+1 depends only on the state of the system at time t and those likely to occur, represented in transition matrices (Eastman, 2012). The future prediction was obtained using the software IDRISI® (Taiga version) based on the probability of transition between the years 1962 and 2011, with the application of the Markov chain with a proportional error of 0.15, considering that the precision of the maps of use and coverage was always higher than 85%. Predictions were made at 10-year intervals (2021 to 2060), until the maximum interval of the historical analysis (1962-2011), which was 49 years (2060). Since the product generated by the Markovian analysis does not provide a single image of the representation of the future probabilities, the cellular automata technique was used to create trend scenarios with the CA_Markov tool of the same software with neighborhood rules "5x5". In this application, also was used as criteria the number of iterations equal to the time interval of each scenario, ranging from 10 to 49 iterations, following Eastman (2012).

The historical and trend changes in land use and cover were calculated using IDRISI® by overlaying maps to create cross-tabulation (CROSSTAB tool). In order to facilitate the visualization and interpretation of these changes, graphs were generated in Excel® to show the percentage of losses and gains of a certain use/cover in relation to the other types.

2.3 Selection and application of landscape metrics

The different maps and scenarios were compared by selecting a set of landscape indexes or metrics to assess the conservation of forests. Thus, quantity and quality of forests were estimated considering the composition and configuration of landscape elements from a set of metrics based on: i) Optimal Resource Availability (ORA), calculated as a function of the Forest Ratio (FR), Size (FS) Shape (FSh), and Successional Stage (FSS); ii) analysis of landscape connectivity using the Euclidean Nearest Neighbor distance (ENN) and Proximity Index (PROX) measurements and; (iii) analysis of forest fragmentation trends, based on frequency, measured as the Edge Segments Density (ESD), and length, calculated as the Edge Density (ED) for the total boundaries between forest and the different types of human-related uses (Table 1).

3. RESULTS

In 49 years, more than half of the Atlantic Forest surrounding the Billings Reservoir was cleared in Diadema, totaling 182 ha (Figure 2). The increase in urban uses observed in 2011 was 37% and accounts for 50% of the clearing of forest in intermediate/advanced stages and 40% in early stages (Figure 3A). This change is concentrated in the northern part of the study area, where net roads (54%), grouping of trees (50%) and human-modified fields (41%) were also frequent changes observed in urban areas (Figures 2 and 3A).

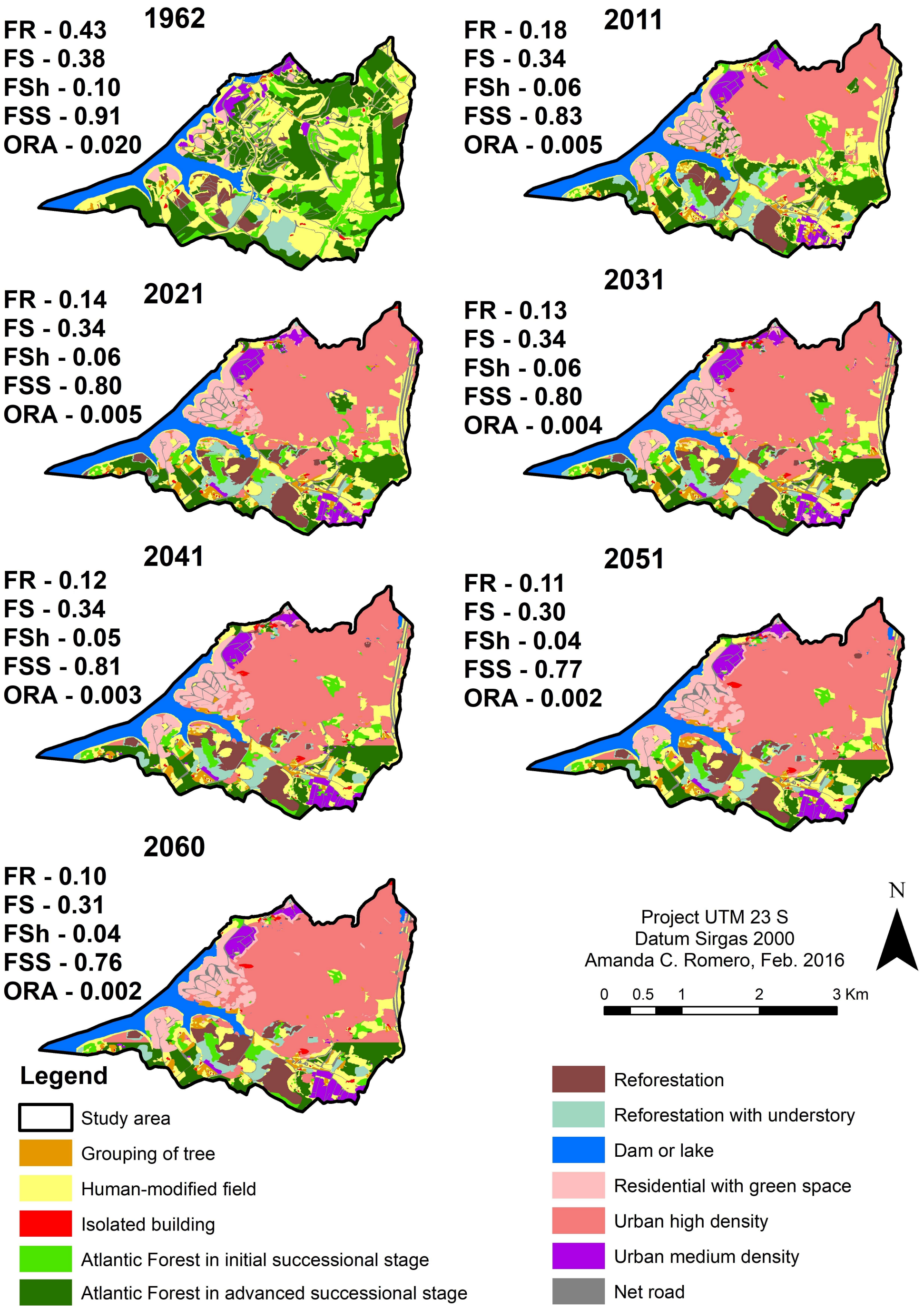
The future scenarios present a pessimistic perspective for the conservation of the region. Trends indicate an increase in forest loss, mainly as a result of urban sprawling to the north and west, towards the municipality's water source areas, in the southeast portion of the study area (Figure 2). By 2060, over half of the current native forest will potentially be replaced by a urban high density, from the same types of land use changes – human-modified fields (37%), grouping of trees (29%), and net roads (24%) (Figure 3B). Another important force driving deforestation may come from the expansion of *Eucalyptus* spp. or *Pinus* spp. reforestation with an increase in monoculture plantations to the detriment of understory crops.

Since 1962, human-modified fields and net roads have been the two types of land use most often observed bordering the forest, both in frequency and in length (Figure 4A). These boundaries predominate in 2011

Table 1 – Criteria used to assess the forest conservation in historic landscapes and future scenarios. Modified from Hardt et al. (2013a, 2014).
Tabela 1 – *Critérios de avaliação da conservação da floresta nas paisagens históricas e nos cenários futuros. Modificado de Hardt et al. (2013a, 2014).*

	Metric	Formula	Description	Software
Forest resource availability variable from 0 to 1	Forest Ratio - FR	$FR = \frac{FA}{TA}$	Forest cover area (FA) per total landscape area (TA)	ArcGIS®
	Forest Size - FS	$FS = \frac{\sum_{i=1}^{n}(A_i . CS_i)}{FA . CS_{max}}$	Patch forest area (A_i) weighted by coefficient of patch size (CS_i), ranging from 0 to 4: 0 (≤ 0,01 ha), 1 (≤ 10 ha), 2 (10 – 50 ha), 3 (50 e 4 (≥ 100 ha), in relation to the maximum size (CS_{max}), adapted from Hardt et al. (2014)	ArcGIS®
	Forest Shape - FSh	$FSh = \frac{\sum_{i=1}^{n}(CA_i)}{FA}$	Proportion of forest core area (CA_i), considering a 70 m edge width, based on data obtained by Hardt et al. (2013b) for Atlantic Forest fragments with urban boundary	ArcGIS® V-LATE extension
	Forest Successional Stage - FSS	$FSS = \frac{FA_{adv}}{FA}$	Proportion of forest in the most advanced successional stage (FA_{adv}), identified during the mapping based on aerial photographs differences roughness	ArcGIS®
	Optimal Resource Availability - ORA	$ORA = \frac{\sum_{i=1}(CA_i . CS_i . CSS_i)}{TA . CS_{max} . CSS_{max}}$	Forest quality, weighted by core area (CA_i), size coefficient (CS_i) and successional stages (CSS_i = 1 for initial stage and 2 for medium/ advanced stage) in relation to the maximum potential in the total area (TA)	ArcGIS®
Landscape connectivity (McGarigal and Marks, 1995)	Euclidean Nearest Neighbor distance - ENN	$ENN = h_{ij}$	Measure of focal $patch_i$ isolation by the shortest straight-line distance (h_{ij}) to nearest neighboring $patch_j$ of the same type, based on patch edge-to-edge distance	FRAGSTATS®
	Proximity Index - PROX	$PROX = \sum_{s=1}^{n} \frac{a_{ijs}}{h_{ijs}^2}$	Sum of patch forest area (a_{ijs}) divided by the nearest edge-to-edge distance squared (h_{ijs}) between the focal patch and all patches of the corresponding patch type whose edges are within 500 m from the focal patch	
Trends to forest fragmentation	Frequency/Edge Segments Density - ESD	$ESD = \sum_{k=1}^{n} s_{ik}$	Number of boundary segments (s_{ik}) between forest $patch_i$ and human-related neighboring $patch_k$ (Zeng and Wu, 2005), calculated by the sum for boundary type	ArcGIS®
	Length/Edge Density - ED	$ED = \sum_{k=1}^{m} e_{ik}$	Cumulative total boundaries length (ED) between the forest $patch_i$ and human-related neighboring $patch_k$, calculated in meters by the sum for boundary type (Mcgarigal and Marks, 1995; Zeng and Wu, 2005)	FRAGSTATS®

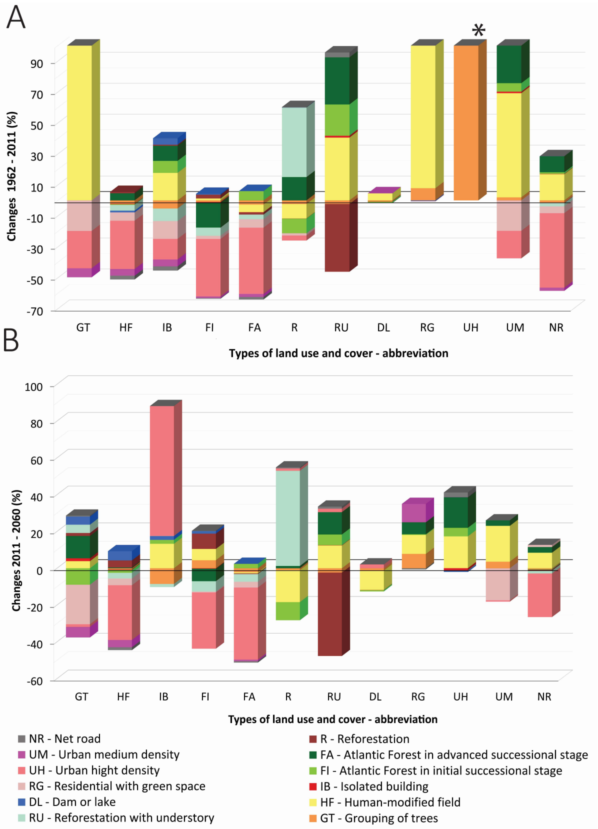
but with less intensity, as the forest begins change with other kinds of fragmentation pressures from new anthropogenic uses, such as reforestation with understory, residential with green spaces (residential areas with gardens and grouping of trees) and high-density urban areas. In future scenarios, the boundary between forest and human-altered field will continue to predominate, but as these fields are transformed into high-density urban areas (Figure 2 and 3B), the urban-forest boundary increases primarily in frequency and can further intensify beginning in 2041 (Figure 4A).



*Forest Ratio (FR), Size (FS) Shape (FSh), Successional Stage (FSS) and Optimal Resource Availability (ORA)

Figure 2 – Historic maps and trend scenarios of land use and cover in the water source area of the Billings reservoir in the municipality of Diadema - SP.

Figura 2 – *Mapas históricos e cenários de tendência de uso e cobertura da terra na região de manancial da represa Billings no município de Diadema-SP.*



* the gain of highly-density urban areas between 1962-2011 exceeds 7000%

Figure 3 – Percentage of change in land use and cover types in the water source area of the Billings reservoir in the municipality of Diadema-SP: **A** - between the years 1962 and 2011; **B** - between the years 2011 and 2060. Bars below and above the zero axis indicate, respectively, the losses and gains of land use indicated in the X-axis (acronym) for the other types of use.

Figura 3 – *Porcentagem de mudança nos tipos de uso e cobertura da terra na região de manancial da represa Billings no município de Diadema-SP: A - entre os anos de 1962 e 2011; B - entre os anos de 2011 e 2060. Barras abaixo e acima do eixo zero indicam, respectivamente, as perdas e os ganhos do uso indicado no eixo X (sigla) para os outros tipos de uso.*

Although in 1962 the forest covered nearly half (43%) of the study area, had high successional stage - FSS (0.91) and forest fragments were closer - PROX, the rural landscape of this decade had low optimal resources availability - ORA (0.02). This low ORA value was associated with the irregular shape - FSh (0.10) and size - FS (0.38) of forest fragments, most of them less than 10 ha. During the 49 years of analysis of historical changes (1962-2011), ORA further declined (0.005), representing a reduction of 75%, mostly as a result of the sharp decrease in the proportion of forest - FR (0.18), especially in fragments in more advanced successional stages - FSS (0.83). The distances from forest fragments - ENN increased dramatically (361%) between the years of 1962 and 2011 and will continue to increase until 2060. Another concerning situation for the maintenance of landscape connectivity are PROX values approaching zero in the 2021 scenario. Until this year, ORA values remain the same as those for 2011 (0.005) and then decline until 2051 (0.002). The expected future variations for ORA are explained by the further reductions in the proportion of forest - RF (0.14 to 0.10), successional stage - FSS (0.8 to 0.76) and size of fragments with areas less than 10 ha (Figure 2 and 4).

4. DISCUSSION

The urban high-density growth of Diadema occurred towards the outskirts of the city, mainly as a result of deforestation. Studies have shown that unplanned urban occupation is directly associated with clearing of the vegetation cover, and the processes of urbanization and deforestation are often simultaneous events in order to meet the demand for new spaces (Weber and Puissant, 2003; Atmis et al., 2007; Defries et al., 2010; Martins, 2011). In the case of Diadema, at the municipal and state levels, the protection of the water sources is regulated by the State Law 13.579/09 of APRM-B - Area of Protection and Recovery of water sources of the Billings Reservoir (São Paulo, 2009) and by the complementary Municipal Law 273/08 of the Master Plan (Diadema, 2008). According to the environmental zoning of these legal provisions, most of the areas cleared for urbanization was not officially intended for urban expansion and were occupied irregularly. In large Brazilian metropolises, the exponential increase of the urban population, unemployment, and real estate speculation do not provide adequate housing alternatives for the low-income population (Canettieri, 2015). As observed in the study area, this population tends to be restricted to the outskirts of cities, with lower-cost housing options, usually located in irregular lots in areas of environmental protection and water sources and devoid of urban infrastructure and environmental sanitation (Jacobi, 2004; Canettieri, 2015).

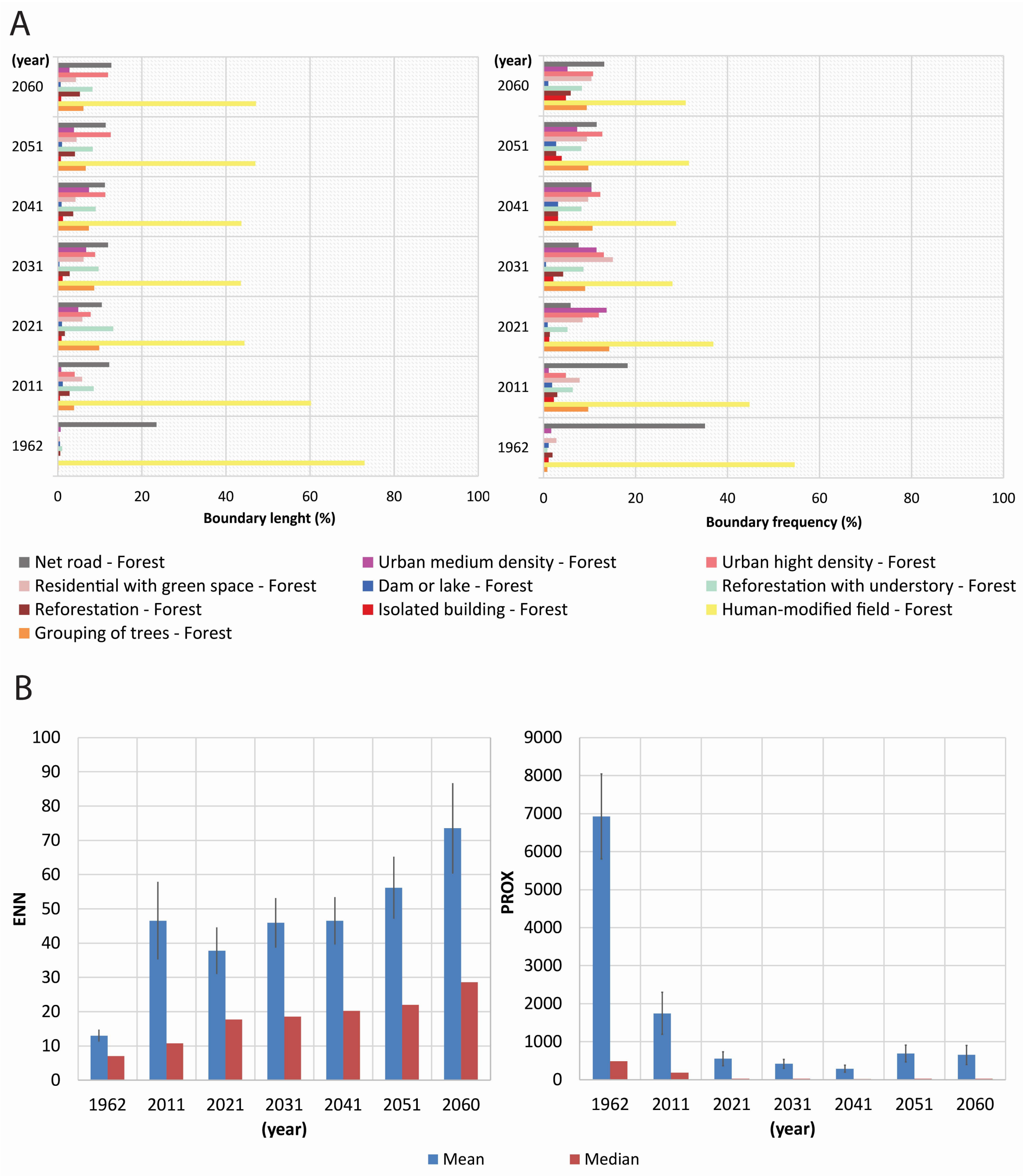


Figure 4 – Length and frequency of boundaries between forest patches and other land uses and cover (**A**) and isolation measurements, Proximity Index – PROX and Euclidean Nearest Neighbor distance – ENN, among the forest fragments (**B**) in the water source area of the Billings reservoir in the municipality of Diadema in the different years of examined in the study.

***Figura 4** – Comprimento e frequência de fronteiras entre as manchas de floresta e os outros usos e coberturas da terra (**A**) e medidas de isolamento, Índice de Proximidade – PROX e Distância Euclidiana do Vizinho mais Próximo – ENN, entre os fragmentos de floresta (**B**) da região de manancial da represa Billings no município de Diadema nos diferentes anos de estudo.*

The analysis of changes in land use and cover revealed the driving forces responsible for shifting the rural landscape from the 1960s to the recent urbanization (2011). The presence of grouping of trees, human-modified fields, and net roads facilitate the emergence of new residential and urban uses (Hardt et al., 2013a). Studies show that access to previously unoccupied areas allows new opportunities for economic activities that, in turn, generate income and become places of interest to live (Chomitz and Gray, 1996; Freitas et al., 2010; Barber et al., 2014). Our finding about how grouping of trees and human-modified fields function as drivers of urbanization is very relevant for the management of green spaces in large urban centers, such as São Paulo. It means that squares and gardens, represented by these uses, can be facilitators for the occupation of new irregular uses (Ferraz and Machado, 2014).

Future projections indicate that, without improvements in the environmental management of the area, continuous and rapid deforestation can occur. Therefore, management changes are a priority, as urban expansion continues toward the water source of the Billings Reservoir, an environmentally sensitive area of the municipality. Pollution generated by the direct dumping of sanitary effluents in the water body is a concern, as well as and the clearing of riparian forest, increasing soil vulnerability and the risks of landslides and floods (Jacobi, 2006; Anelli, 2015). Forests protect soils against erosion and rivers and reservoirs from silting, favoring infiltration and reducing runoff, which ensures the recharge of water sources and aquifers and helps regulate water flow during times of flood and drought (Neary et al., 2009; Liu, 2015). In addition, the conservation of riparian forests is able to filter the environmental pollutants, contributing to the maintenance of adequate conditions for aquatic biodiversity (Neary et al., 2009; Pereira-Silva et al., 2011). Thus, the trend of replacing the forest cover of water source areas for urban high-density uses and the lack of planning can adversely impact the maintenance of the water quality and quantity from the Billings Reservoir.

Boundary metrics are usually used as indicators of connectivity or landscape fragmentation (Metzger and Muller, 1996). Increases in frequency and length of edges between human-related activities and forest remnants promote landscape fragmentation (Zeng and Wu, 2005). Therefore, the dominance of forests boundaries with human-modified fields and net roads since 1962 supports the influence of these uses on the historical changes of forest loss and fragmentation and the emergence of the present urban area. A new contact zone between the forest and the urban matrix is created, increasing pressure on the forest due easier access and higher human circulation, such as trails, improper waste disposal, vandalism, and wood collecting (Matlack, 1993). The forest-urban contact zone also has the potential to increase the extent of the natural edge effect (Hardt et al., 2013b), which may result in changes in the composition and density of fauna and flora, as well as invasion or dominance of exotic species that are more competitive than less tolerant species (Fahrig, 2003; Ries et al., 2004; Villaseñor et al., 2014). As a result, urban areas become new agents of fragmentation and to a higher extent, responsible for the drastic reduction in the optimal resource availability -ORA observed in this study.

The results obtained for 1962 support the assumption that quantity of forest without habitat quality does not always promote environmental conservation (Fahrig, 2001; Pflüger and Balkenhol, 2014; Magura et al., 2017). Small, elongated, and irregularly shaped forest patches are the main limitations for the most demanding species that are restricted to the interior of forests because they are not able to survive under the environmental conditions at edge microclimates (Wiens et al. 1993; Fahrig, 2003; Kahilainen et al., 2014).

The current data (2011) show that the forest cover of the water source area of Diadema was considerably reduced, with dramatic qualitative changes. Future projection scenarios indicate that the process of landscape fragmentation will advance and as a result, forest fragments will become more disconnected and with lower environmental quality. The physical and functional reach between habitats, variable with home range, dispersal capacity, and species migration (Matos, et al., 2016; Pflüger and Balkenhol, 2014) represent another concerning factor for the survival of local species and ecologic groups.

Given the effects of conservation trends, the first improvement for the conservation of Diadema forests is an increase in forest cover in order to protect water sources and consequently the public water supply. However, our findings emphasize that special attention should be giving to the size and shape of fragments and the conduction of studies for the identification of priority areas for the restoration of the functional connectivity of the landscape and facilitation of the genetic flow of local species.

5. CONCLUSIONS

The analysis of the historical changes in land use and cover in the water source area of the Billings Reservoir in Diadema revealed that deforestation in the last five decades is directly associated to urban sprawling in the municipality, resulting in great damage to the local conservation of the Atlantic Forest. Consequently, there is a clear trend towards even further reductions in quantity, quality, and connectivity of forest fragments, which can have adverse effects on water availability and quality of the reservoir and be a potential threat to the survival of local native species. Reversing this scenario depends on changes in planning and management aimed at ensuring the maintenance of the remaining forest remnants, as well as incentives to viable alternatives for restoring the native vegetation.

The main scientific contribution of our study is to demonstrate the utility of assessment methods of forest conservation to understand the effects of the urban expansion densely populated in water source areas with irregular occupations, and their potential to be applied in landscape planning and management.

The main challenge of this methodological application, however, is the lack of historical geospatial data and in-depth studies about the effects of urbanization on the conservation of biological diversity, especially of the species and ecological groups that occur in this region.

6. ACKNOWLEDGMENTS

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