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RESEARCH ARTICLE

Utility of landscape mosaics and boundaries in forest conservation decision making in the Atlantic Forest of Brazil

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Abstract We evaluated changes in the Atlantic Forest landscape over the last 40 years based on changes in boundaries and mosaics, including the hypothetical landscape resulting from the application of Brazilian laws for forest protection. Mosaics were identified as sets of land-use patches with a similar pattern of boundaries. Landscapes of different years, therefore, can be distinguished by differences in mosaics. We developed a technique to identify boundaries between patches from land-use maps using ArcGis® and to build the patch x boundary matrix required for mosaic identification by means of a factorial and cluster analysis. The mosaics were characterized by some key uses as well as by their boundaries with other land uses. The mosaics were scored for forest conservation according to five issues: landscape permeability, cover, availability, quality, and fragmentation of forest. The values were based on land use and boundary patterns. Although Brazilian laws regarding forest protection have promoted conservation and the hypothetical legal landscape has presented the highest forest habitat availability, this expansion perpetuates a boundary pattern that complicates conservation and management, thus increasing the pressure on forest patches and favoring the further fragmentation of protected forest patches. These conclusions cannot be reached by simply recording changes in land uses.

Keywords Landscape management · Legal protection · Change vector · Landscape heterogeneity · Landscape metrics

Introduction

Establishing the conservation value of forest fragments depends on intrinsic natural characteristics as well as on the context in which these areas are inserted (Hersperger 2006). Understanding local landscape change, including its general geographical and ecological context and all its related dynamics, is crucial for appropriate decision-making, planning, and design of landscapes for the future (Antrop 2004), particularly for forest conservation.

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The patch–corridor–matrix approach (Forman 1995) describing the spatial structure of a landscape is an efficient model for the application of tools and methodologies to examine the influence of spatial patterns on ecological processes and their changes over time (Wiens 1995; Schröder and Seppelt 2006; Turner and Cardille 2007). However, this model is limited in its ability to detect landscape spatial heterogeneity (Gustafson 1998; McGarigal and Cushman 2005; Kent 2007), leading to errors in decision-making for landscape management. Landscape models should reflect the spatial heterogeneity in such a way that they clearly show the patterns of ecological interactions and landscape complexity. This can be done by studying landscape mosaics based on the analysis of the composition, context, and arrangement of patches and their boundaries (Lovett et al. 2005; Roldán-Martín et al. 2006).

Most studies have focused on the identification and characterization of homogeneous patches that distinguish land uses, but few have examined the interactions among patches (Roldán-Martín et al. 2003) connected by horizontal flows of materials and energy (Margalef 1963, 1979, 1996; Van Leeuwen 1966; Wiens et al. 1985; Turner and Chapin 2005).

Ecological interactions and flows in a landscape can be examined based on boundary identification between adjacent patches with different land uses (Cadenasso et al. 2003; Roldán-Martín et al. 2003). These boundaries are transition zones that act as resistance and retention "filters" that affect permeability (Forman 1995) and influence the direction of landscape movements (Cadenasso et al. 2003). From a historical perspective, Margalef (1963, 1979) and Wiens et al. (1985) suggested the need to examine boundary dynamics to understand landscape patterns and processes, while Noss (1983) considered the significance of boundary dynamics in the maintenance of biological diversity and the creation and management of protected areas.

The study of boundaries has become an important research goal in studies of landscape function (Rescia et al. 1995; Fortin et al. 2000; Kepner et al. 2000; Baudry and Bourel 2004; Zebisch et al. 2004), conservation planning, and land-use management (Fortin et al. 2000; Wiens 2005). The typology of boundaries, including their length, frequency, and arrangement in mosaics, responds to the spatial pattern of landscape heterogeneity (Metzger and Muller 1996) and is particularly sensitive to environmental changes (Fortin et al. 2000) and land use (Roldán-Martín et al. 2006).

A landscape mosaic can be defined as a set of patches with a pattern of boundaries (Roldán-Martín et al. 2003) and consequently with a pattern of ecological interactions (Cantwell and Forman 1993; Wiens 1995, 2005; Roldán-Martín et al. 2006). Mosaics integrate information on land uses and boundaries and are therefore the best descriptors of landscape changes (Roldán-Martín et al. 2006; De Pablo et al. 2012). Mosaics can be used as units of landscape organization (Wiens 1999; Hersperger 2006) to identify territories that differ in structure, function, and forest conservation status. The methods can vary depending on the approach used to interpret structural heterogeneity. In addition, implementing this concept is difficult in large territories (Roldán-Martín et al. 2003). These limitations may explain limited number of studies on the complexity of landscape interactions based on mosaics and their use in environmental planning and management (Hersperger 2006; Roldán-Martín et al. 2006).

In addition, there are no methods to relate landscape mosaics with their potential to provide support as a resource source or habitat. The quality of mosaics as forest habitats can be assessed based on forest patch size, quality, connectivity, and boundary configuration. These features are related to the biological conservation role of mosaics, including the likelihood of the persistence or disappearance of native species (Colli et al. 2003; Kuussaari et al. 2009), and have been used as indirect assessments of resource availability (Pulliam 1988; Hanski 2001). This assessment approach obviously does not replace the use of field data but is very important for making conservation decisions about large areas for which data are difficult to acquire (Landeiro et al. 2012).

This work studies changes that have occurred in the last 40 years in mosaics and boundaries that configure the Atlantic Forest landscape and assumes that changes in boundaries and mosaics in the landscape can be used to evaluate changes in the mosaics' forest conservation value. We also compare the historical landscapes with the legal scenario: the landscape that could exist if forest protection laws had been implemented in full in the study area. Thus, we seek to understand the changes in the heterogeneity of the historical landscapes and their distances from this legal expectation, using as reference the analysis of changes in boundaries and mosaics.

Materials and methods

Study area

The study area included 14.060 ha of the "Serra do Japi," a mountainous region in the southeastern region of Sao Paulo State, Brazil (Fig. 1). This area is surrounded by important access roads and encompasses 8.000 ha of conserved Atlantic Forest. A portion of the forest is protected as the Serra do Japi Biological Reserve, a Strict Nature Reserve (protected area type Ia), according to the International Union for Conservation of Nature (IUCN). Despite increasing urban pressure, the Biological Reserve is protected at all administrative levels: municipal, state, and federal. Currently, the main economic activity is forestry, particularly *Pinus* spp. and *Eucalyptus* spp. plantations, while in the past, the predominant cultivations were sugar cane, coffee, and viticulture (Hardt et al. 2012).

Characterization of land uses

Three historical land-use maps were created with ArcGis® 9.2 based on the photointerpretation of aerial orthophotos from 1962, 1994, and 2005 (scale 1:25,000) provided by the Agriculture State Administration (SAA-SP) and a private aerial photography company (Base Ltda). To define the land-use categories recognized in the orthophotos and to locate the control points used in georeferencing the maps, exhaustive field trips were conducted before, during and after the finalization of the maps between 2005 and 2008.

The land-use categories recognized in the three maps (Table 1) were defined according to the following specifications: (i) to make them comparable over the period studied; (ii) to ensure accuracy in their recognition in the photos; (iii) to ensure relevance according to the planning guidelines applicable to the study area.

The base map used was a topographic map (scale 1:10.000) provided by the Geographic and Cartographic Institute of São Paulo State (IGC). Geometric adjustments of the orthophotos (RMS $= 1.98$, 2.4 and 2.8 for 2005, 1994 and 1962, respectively) indicated a high fidelity with respect to the IGC topographic base map. The orthophotos were transferred to the geographic information system (GIS) with a pixel size of 0.5 m^2 and were observed on a scale of 1:1,000.

A legal scenario map of the Japi Forest was created to represent all legal protections focused on forest conservation (Hardt et al. 2012). This map illustrated all areas that, according to forest laws, should be forests, such as forests along streams (30 m), springs (50 m), dams (15–100 m), wetlands (50 m), and the upper-third of hillsides with slopes greater than 45° (Forest Law 4.771/1965). Based on the criteria established by the law, all areas that were forests in 1983 were maintained. In 1983, Serra do Japi was considered a natural asset (CONDEPHAT 11/1983). In addition, all Atlantic Forest areas that were in advanced stages of regeneration in 1993 were maintained as forests (Laws 750/1993 and 11.428/2006 on Protection of the Atlantic Forest). In areas without legal protection, the land uses recorded in 2005 were maintained.

Identification of boundaries and mosaics

As mentioned previously, a mosaic is a set of patches with a similar pattern of boundaries at a given scale of analysis. The landscape comprises the different mosaics recognized therein at a given time (Roldán-Martín et al. 2003). Therefore, changes in land-use patches over time modify the boundaries and, consequently, the mosaics and the landscape.

To identify mosaics and the changes therein over time, four matrices of patches x frequency of boundaries were generated, one for each land-use map, including the legal scenario map. Each patch was defined by its land use, and its boundaries were the limits between this patch and its neighboring patches with different land uses. We developed a new technique using ArcGis® to identify such boundaries and to automatically build the matrices of patches x frequency of boundaries. The procedure was applied to the land-use maps previously obtained. The method was based on previous studies by Rescia et al. (1994), Metzger and Muller (1996) and Roldán-Martín et al. (2003, 2006) and was basically the same as that of the two latter works but was improved by the automatic elaboration of the matrices of patches x boundaries.

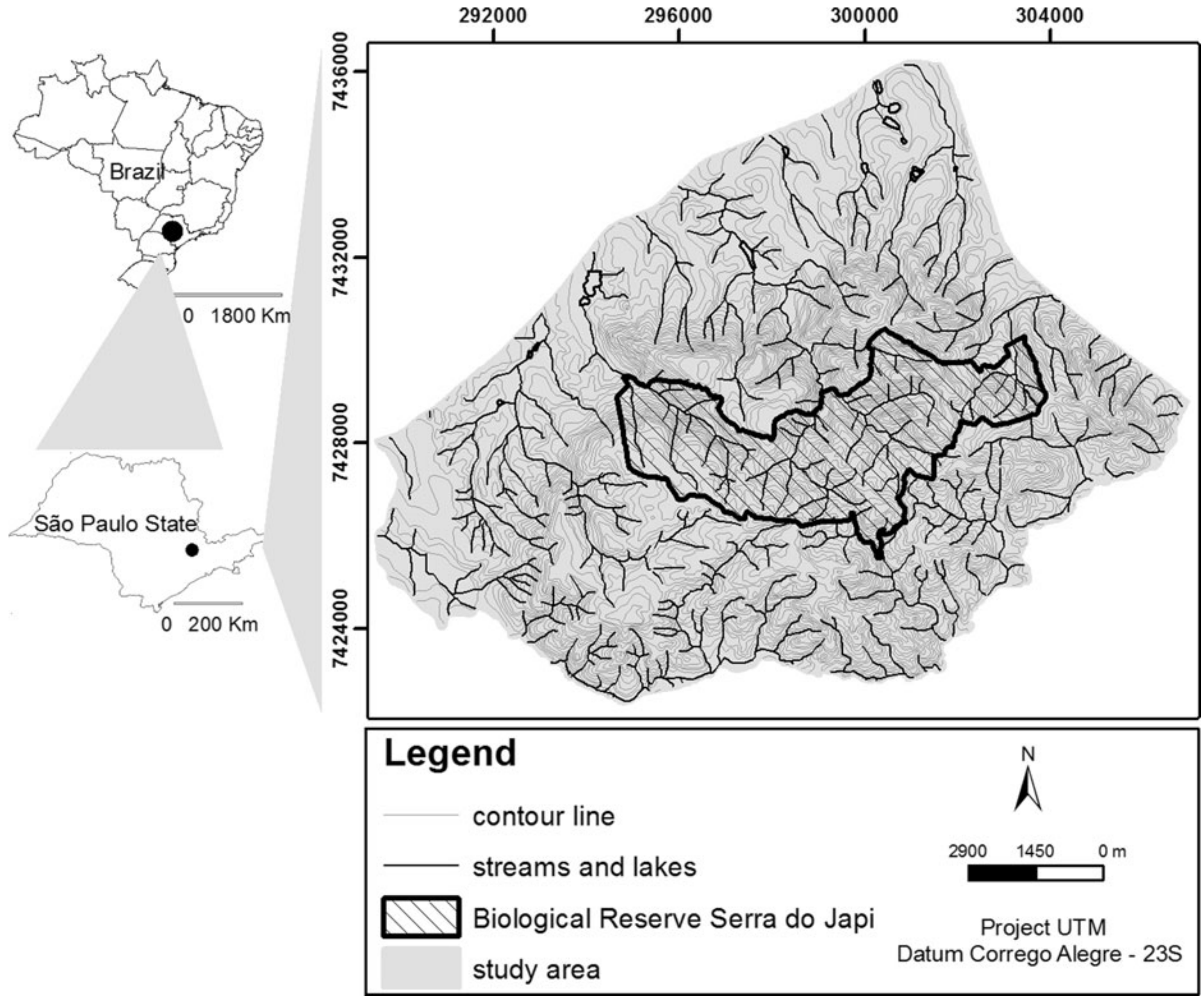

Fig. 1 Study area located in Serra do Japi, São Paulo, Brazil

Table 1 Description and codes of the categories of land use identified in Serra do Japi, Brazil

Category	Code	Criterion of classification
Cropland	CRO	Annual or perennial croplands
Field	FIE	Pasturelands, abandoned areas (old areas of agriculture and silviculture), yards, lawns, and wasteland or unused lands
Bare soil	BAR	Rural or urban areas without vegetation
Forest	FOR	Semi-deciduous seasonal forests
Lake	LAK	Natural lakes and reservoirs
Road	ROA	Trails, tracks, and roads
Reforestation	REF	Plantations of *Eucalyptus* spp., *Pinus* spp. or *Araucaria* spp.
Grouping of trees/shrub	GTS	Patches and corridors of trees and shrubs, natural or human-modified, without forest structure
Urban	URB	Urban nuclei and isolated residential, commercial or industrial buildings

Each matrix was submitted to multivariate ordination and clustering analysis, according to the methodology developed by Roldán-Martín et al. (2003, 2006). The ordination was conducted with a Detrended Correspondence Analysis DECORANA—DCA (Hill and Gauch 1980) with rescaling of the first three axes with the software PC-Ord®. Groups of patches with similar boundary patterns were recognized by hierarchical agglomerative clustering of their coordinates in the ordination axes. Ward's method was used as the amalgamation algorithm and the Euclidean distance as the measure of similarity using the software XlStat®. For each year and for the legal scenario, the final mosaics were defined by the boundary frequencies of the groups obtained at the chosen cut level in the dendrogram. To render comparable mosaics in historical and legal maps, all of the mosaics were arranged in a single matrix and subjected to ordination and clustering analysis. Mosaics of the same group were considered alike because they shared similar boundary patterns, regardless of the year (including the legal scenario). Based on the patch number register (ID), the class of mosaic was joined with the land-use map and incorporated into the ArcGis® database. This permitted the mapping of the mosaics.

Assessment of landscape mosaics

The spatial configuration of the Atlantic Forest remnants is relevant for species conservation (Pires et al. 2002; Pardini et al. 2009), and, because mosaics summarize the different patterns of the spatial configurations of patches that exist in the landscape, the assessment of their conservation value is useful. The assessment considered the cover, availability, quality, and fragmentation of forest patches, the permeability of different land-use patches and the boundaries comprising each type of mosaic (Table 2).

In the assessment of forest availability and landscape connectivity, we considered secondary data on a set of small mammals (marsupials and rodents) and whose habitats most favored the forest patches (Pires et al. 2002). These groups were chosen based on the availability of data on their biology and on their abundance and dispersal in heterogeneous landscapes similar to those studied previously (Barrett and Peles 1999; Pires et al. 2002; Pardini et al. 2009).

The indices were based on (i) the characteristics of the fragmentation process: changes in forest patch size and spatial configuration and, consequently, the availability and connectivity of habitat; (ii) the bibliographic information on the most significant characteristics of the forest patch quality as the habitat of these animals and the permeability of non-forest patches (Pires et al. 2002); and (iii) our ability to identify these forest habitat characteristics (size, shape, spatial configuration and successional stage) in aerial photographs.

Results

We identified ten land-use types (Fig. 2a) in the last 40 years in Serra do Japi; these types were combined into 37 types of boundaries (Fig. 2b) clustered in nine mosaic types (Fig. 2c).

The land-use changes demonstrated that Serra do Japi maintained large areas of forests during this period, although human interference increased with the expansion of silviculture, urban areas, and access roads (Fig. 2a), which were identified as historical changes that were important influences on habitat loss. The legal scenario proposes an increase in forest area and a decrease in anthropic uses. Although most legal requirements for forest protection have been met in the current landscape (2005), the 1960s was the period during which the forest cover was closest to the desirable conservation stage (Hardt et al. 2012).

The boundary analysis highlighted landscape changes that the land-use analysis did not identify. Despite the small area occupied by roads in 1962 compared with that in the subsequent years (Fig. 2a), the boundaries indicated that this particular year was the period with the highest frequency of boundaries between roads and other uses, mainly human-modified fields, agriculture, and groupings of trees and shrubs (Fig. 2b).

The nine types of mosaics were identified by considering the three historical land-use maps and the legal scenario (Fig. 2c). Each mosaic has a pattern of boundaries, with data on the richness, frequency, and dominance of the boundaries (Table 3). Two mosaics were identified as agricultural ($M1_{\mathrm{CRO–URB}}$ in all years and $M2_{\mathrm{CRO\text{-}all}}$ in 1994); two others were characterized by boundaries with lakes ($M3_{\mathrm{LAK\text{-}all}}$ in all years and $M4_{\mathrm{LAK–FOR}}$ in the legal scenario); and the other four mosaics were defined by bare soils ($M5_{\mathrm{BAR\text{-}all}}$ in 1994 and 2005), groupings of tree-shrubs ($M6_{\mathrm{GTS\text{-}all}}$), urban uses ($M7_{\mathrm{URB\text{-}all}}$), and reforestations ($M8_{\mathrm{REF\text{-}all}}$). Finally, one mosaic was highlighted by the highest

Table 2 Criteria for evaluating the conservation value of mosaics based on their potential as habitat for some small mammal species

Metric	Formula	Description
Forest ratio	$FR = \frac{FA}{MA}$	Area of forest cover (FA) per mosaic area (MA).
Forest size	$FS = \frac{\sum_{i=1}^{n}(A_i \cdot CS_i)}{FA \cdot CS_{max}}$	Quality of habitat based on forest patch sizes. A_i area of patch i, CS_i coefficient of patch size i, ranging from 0 to 3: 0 (<1 ha), 1 (1–50 ha), 2 (50–100 ha), and 3 (≥100 ha), constructed according to information in Bierregaard and Dale (1996) and Pardini et al. (2005).
Forest shape	FSh = 1 - EF	Proportion of core forest habitat, calculated as the inverse of the forest cover affected by the edge effect (EF); considering a 60 m edge width, based on filed edge data on the same area (Hardt et al. 2010).
Forest successional stage	$FSS = \frac{FA_{adv}}{FA}$	Proportion of forest in the most advanced successional stage (FA_{adv}); we identified two successional stages (initial and media/advanced) during field trips and mapped them on aerial photographs by their different roughness.
Optimum resource availability	$ORA = \frac{\sum_{i=1}^{n}(FSh_i \cdot CS_i \cdot FA_i)}{MA \cdot CS_{max} \cdot FA_{max}}$	Potential of landscape forest resource availability based on the forest core (FSh_i), its size (CS_i), and its successional stage (FA_i) in relation to the best condition of resources with maximum potential quality of the mosaic. FSh_i and CS_i range between 0 and 1; $FA_i = 2$ if the forest patch is in an advanced successional stage and 1 if in the initial stage.
Permeability	$P = 1 - \frac{\sum_{i=1}^{n}(A_i \cdot EI_i)}{MA \cdot EI_{max}}$	Capability of non-forest patches to facilitate biological flows measured by the effective isolation of the forest patch i. $EI_i = DI_i \times R_i$; DI_i distance (m) from the $patch_i$ to nearest forest patch; R_i resistance of $patch_i$ to the species flows (Metzger and Décamps 1997; Metzger 2004). R_i was based on the movement of small mammals (Pires et al. 2002).
Trend to forest fragmentation	$ED = \frac{\sum_{i=1}^{n} BLF}{FA}$	*ED*: Degree of forest fragmentation, calculated as the total boundaries length of forest patches (BLF) per forest area (FA) (Metzger 2004; Zeng and Ben Wu 2005).
	$ESD = \frac{\sum_{i=1}^{n} BFq}{FA} * 10^3$	*ESD*: Degree of interaction of forest with non-forest patches, measured as the number of boundary segments (BFq) per FA (Zeng and Ben Wu 2005).

Data standardized to 0–1 (except ED and ESD)

richness of interactions among forests and human-modified fields and road networks ($M9_{FIE–FOR–ROA}$).

The maps of the mosaics revealed changes characterized by contraction, expansion, and mobility in the territory over time (Fig. 3). The forest patches in 1962, for example, were included in two mosaics that had a high degree of richness and frequent boundaries (Table 3): the mosaic $M6_{GTS\text{-}all}$, in which interactions with groupings of trees/shrubs were predominant; and the mosaic $M9_{FIE–FOR–ROA}$, which was characterized by interactions with human-modified fields. The analysis also showed changes in the combination of boundaries in 1994, when large fragments (900 ha, approximately 12 % of the total forest area) were incorporated into the reforestation mosaic ($M8_{REF\text{-}all}$), increasing the frequency of these boundaries (Fig. 3).

The mosaic elements (land-use patches and boundaries) and their interactions demonstrate the complexity of the boundary patterns in each mosaic (Fig. 4). The principal forestry mosaic ($M9_{FIE–FOR–ROA}$) was the predominant and the most complex and was comprised of an intricate mesh of boundaries, with more intense interactions between human-modified fields and the road network, both of which are elements of the perforation of the forest (Fig. 4). In the years studied, $M9_{FIE–FOR–ROA}$ always occupied large territories, increasing its surface over time ($46 < 52 \ll 69 \ll 86$ % in the periods of 1962, 1994 and 2005 and in the legal scenario, respectively—Fig. 3). In this mosaic, the area of forestry fragments gradually increased ($25 \ll 88 < 99.2 < 99.8$ %) and became associated with most types of land use (between 50 and 70 %) and boundaries (between 60 and 80 %) with high frequency (Table 3; Fig. 4).

The conservation values for each mosaic (Table 4) showed that of the nine mosaics identified, only three ($M6_{GTS\text{-}all}$ in 1962, $M8_{REF\text{-}all}$ in 1994 and $M9_{FIE–FOR–ROA}$ in all years) contributed to the landscape optimum resource availability (ORA). In these years, high values of the ORA in $M6_{GTS\text{-}all}$ and

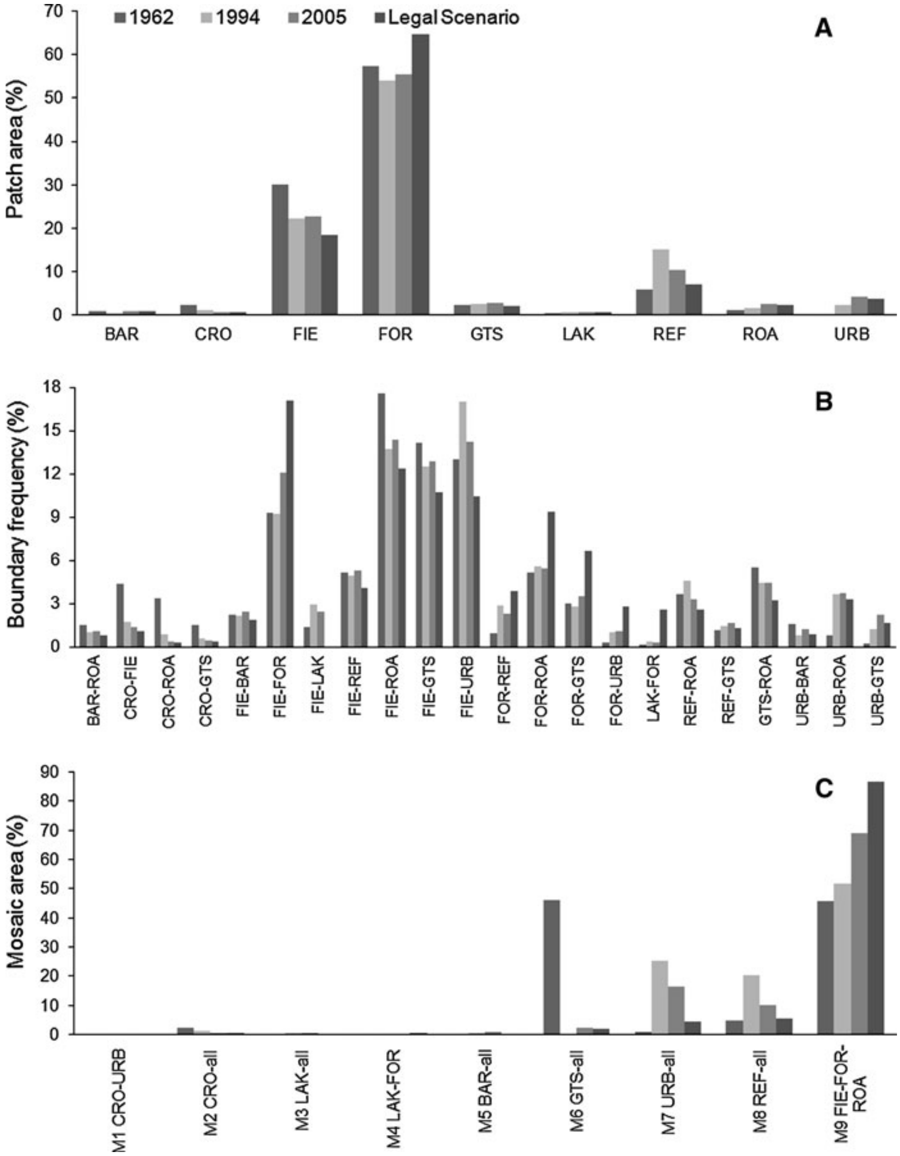

Fig. 2 Patch areas, boundaries frequency, and mosaic areas of Serra do Japi in 1962, 1994, and 2005 and in the legal scenario. *CRO* cropland, *BAR* bare soil, *FIE* field, *FOR* forest, *GTS* grouping of tree/shrub, *LAK* lake, *REF* reforestation, *ROA* road, *URB* urban

$M9_{FIE–FOR–ROA}$ were due to their large sizes (FS) and their advanced stages of succession (FSS), although with shapes (FSh) that promoted an edge-effect (Table 4).

From a historical perspective, the mosaics that contributed most to conservation were those showing the most significant changes over time: mosaics $M6_{GTS\text{-}all}$/$M9_{FIE–FOR–ROA}$ in 1962 became $M8_{REF\text{-}all}$/$M9_{FIE–FOR–ROA}$ in 1994 and $M9_{FIE–FOR–ROA}$ in 2005 (Fig. 3; Table 4). In 1962, the mosaic $M6_{GTS\text{-}all}$, in which groupings of trees/shrubs were predominant, had the highest permeability ($P = 1.00$) due to the interactions between both habitats. In the same year, this mosaic also had the highest ORA (ORA = 0.30, Table 4) but a low value of interactions (ESD = 9.9), and the risk of fragmentation was therefore low (ED = 5.5) (Table 4). In the following decades, $M9_{FIE–FOR–ROA}$ became the mosaic that contributed most to the optimal resource availability (ORA = 0.35 and 0.38 in 1994 and 2005, respectively), with a slight decrease in landscape permeability ($P = 0.99$ and 0.98 in those same years, respectively), and with more complex interactions among boundaries (ESD = 16.1 and 24.9 in the same years, respectively) (Table 4).

The legal scenario maintains the same historic mosaic with high richness and frequency of

Table 3 General characterization of mosaics according to their boundary patterns

Mosaic	BR	SB	BFq	Characteristic boundaries	Description
$M1_{CRO–URB}$	1	1	21	CRO–URB	Mosaic identified only in 1994, with boundaries between urban use (URB) and agriculture (CRO)
$M2_{CRO\text{-}all}$	9	5	562	CRO; FIE–URB	Mosaic of agricultural influence, with pattern of boundaries between CRO patches and other land uses; observed in all years and in the legal scenario
$M3_{LAK\text{-}all}$	9	5	304	LAK; FIE–GTS	Typically formed by boundaries between lakes (LAK) and other land uses, mainly human-modified fields (FIE) and groupings of trees/shrubs (GTS); observed in all years and in the legal scenario
$M4_{LAK–FOR}$	3	1	298	LAK–FOR	Predominance of interactions between LAK and riparian forests (FOR); only observed in the legal scenario
$M5_{BAR\text{-}all}$	13	6	485	BAR; FIE–URB	Mosaic with predominant boundaries between patches of bare soil (BAR) and other land uses; only observed in 1994 and 2005
$M6_{GTS\text{-}all}$	16	6	2,955	GTS	With the exception of 1994, this mosaic was observed in all years and in the legal scenario. High frequency of boundaries between GTS and other land uses, mainly URB and FIE
$M7_{URB\text{-}all}$	19	7	2,645	URB; FIE–URB	Mosaic of urban influence with high frequency of boundaries (URB) and other land uses, mainly FIE (FIE–URB); observed in all years and in the legal scenario
$M8_{REF\text{-}all}$	14	5	961	REF	Mosaic characterized by pattern of boundaries between reforestation (REF) and other land uses; observed in all years and in the legal scenario
$M9_{FIE–FOR–ROA}$	25	10	7,490	FIE–FOR; FOR–ROA; FIE–ROA	Mosaic with high richness and frequency of boundaries among forest (FOR), FIE, and road networks (ROA); observed in all years and in the legal scenario

BR boundary richness, *SB* significant boundaries (90 % 435 of the total), and *BFq* frequency of boundaries

boundaries (mosaic $M9_{FIE–FOR–ROA}$, Figs. 3, 4), but it is also the scenario in which this mosaic is more prone to fragmentation, given its values of trend toward fragmentation (level of fragmentation, $ED = 8.6$; pressure for land uses, $ESD = 44,3$; Table 4), which are mainly due to the increasing influence of the road network (Fig. 2a). By contrast, the high forestry cover ($FR = 0.65$) both in this scenario and in this mosaic favors a network of habitats with a higher ORA ($ORA = 0.42$) and, as consequence, a higher permeability of landscape ($P = 0.97$).

Discussion

Contributions of legal protection to landscape conservation

Our analyses demonstrated that a comparison of historical changes and legal scenarios can facilitate the determination that well-meaning laws are not achieving their desired effect. Although current Brazilian laws propose an increase in forest area and a decrease in anthropic uses (Fig. 2a), our analysis of mosaics shows conflicting relationships among these goals. The influence of all types of human interference on forest patches has increased, increasing the susceptibility of the landscape to fragmentation, mainly in the $M9_{FIE\text{-}FOR\text{-}ROA}$. These observations highlight the vulnerability of protected forest in Brazil. Brazilian law guarantees the right to access properties rather than a policy of reducing the effects of forest fragmentation promoted by the maintenance or creation of roads. The laws support an increase in forest areas without concern for achieving a goal of landscape conservation. This directly affects the management and conservation of the Biological Reserve, the main reason for the legal regulations of the Serra do Japi. The legal scenario broadens the conflict between the protected forests and human presence in the maintenance of access roads, increasing neighborhood pressures on protected areas.

Future scenarios focused on forest habitat conservation should spatially combine patches of different

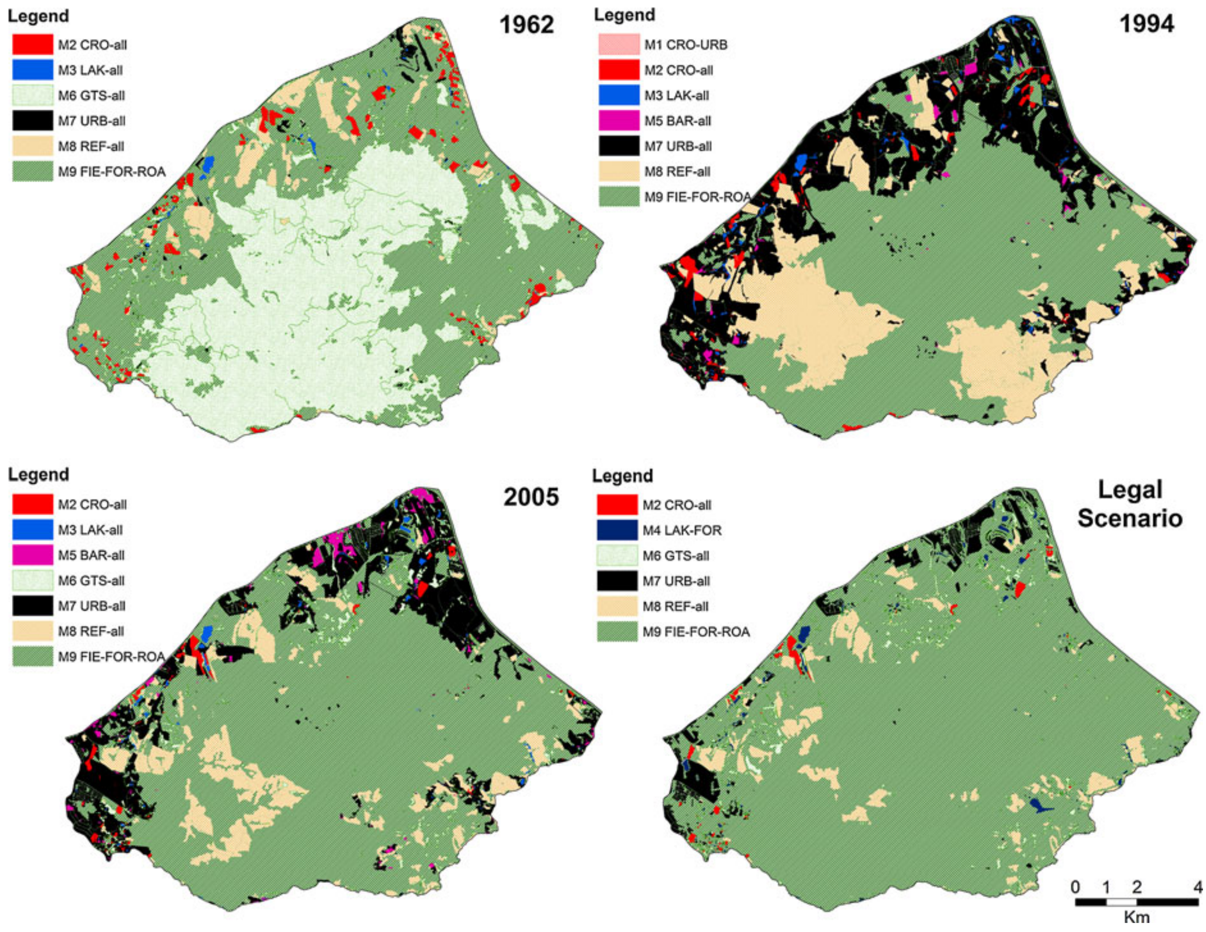

Fig. 3 Maps of mosaics in 1962, 1994, and 2005 and in the legal scenario in Serra do Japi

land uses to maximize ORA and *P* values. This maximization can be achieved with different mosaics depending on the ecological, social, and economic needs of the territory and with different levels of fragmentation. In contrast to current practice, protection laws should focus on mosaics and not only on individual patches.

As an example, a future scenario focusing on conservation should facilitate the management and conservation of forest landscapes. To that end, the creation of a mosaic with boundaries favoring forest recovery and with a low complexity of interactions (low values of richness, frequencies, length, and density of boundaries) is necessary. This mosaic should decrease the isolation of forest patches and increase their connectivity, thus strengthening some interactions among patches across their boundaries and weakening others, depending on the needs of the territory.

Driving forces and change vectors over time

Although Serra do Japi is a protected area, the analysis of the mosaics revealed an increase in urban uses as the main driving force of landscape change. The mosaics with human influence, mainly $M7_{\text{URB-all}}$ (Fig. 3), illustrated the concept of functional urban areas (Cheshire 1995), in which cities create extensions of their complex interactions, affecting large areas and reaching functionally different territories (Antrop 2005). If the analysis of urban influence had been conducted based on the predominance of patches (Fig. 2a), then the result would indicate a great urban advance in 2005. However, the analysis of the mosaics clearly demonstrated that 1994 was a period that was critical for urbanization (Figs. 2c—$M7_{\text{URB-all}}$, 3), as a consequence of the constant presence of isolated buildings. This period represented a turning point

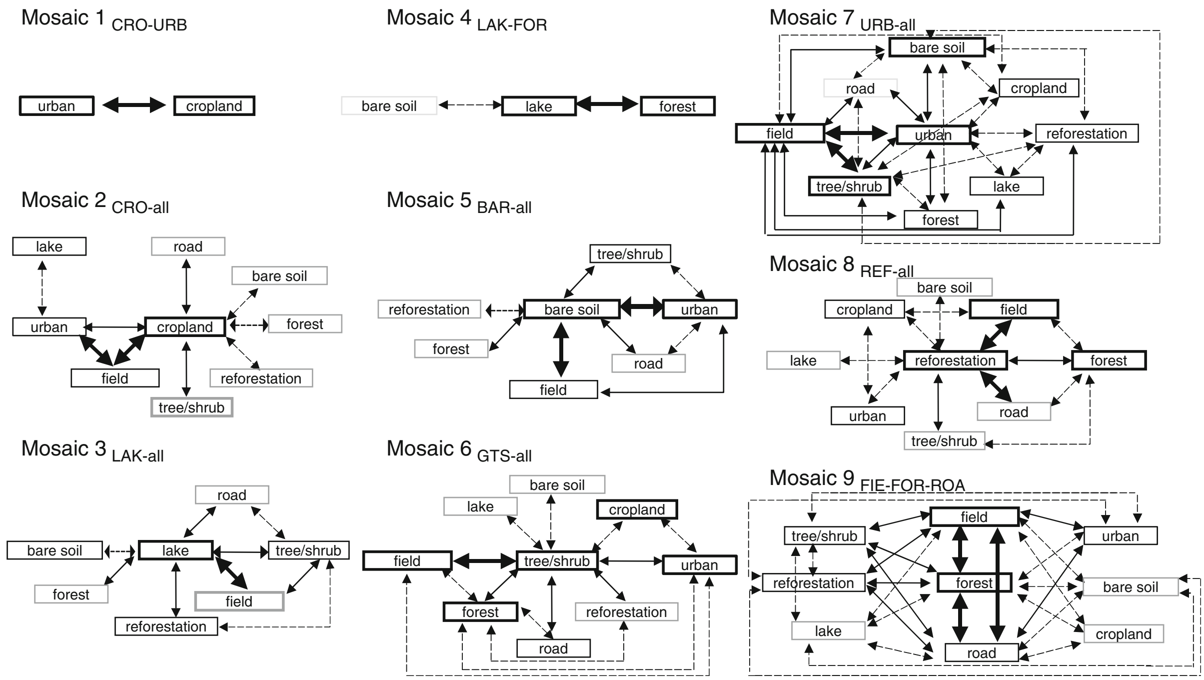

Fig. 4 Graphic representation of the complexity of land uses, the dominant element, and its interactions in each mosaic. The thicknesses of the *arrows* and the *boxes* indicate the frequency of the boundaries and land-use patches, respectively

between the typically rural mosaics of 1962 and those of urban uses, which only consolidated effectively in 2005 with an increase in urban clusters (Fig. 2a, b).

The high frequency of road boundaries in 1962 suggests that they might have been a driving force of change during this period. Roads can intensify negative effects on forests and modify the interactions among these and other types of land uses (Bürgi et al. 2004; Antrop 2005; Hawbaker et al. 2006).

Although the forests patches have always been included in one category of protected area under the same management plan (Fig. 2a), the analysis of the mosaics revealed important changes in the combination of boundaries with non-forest patches. Based on neighboring patches, the forest is organized in different types of mosaics. Other studies have already shown the relationship between the increase in the dominance and frequency of boundaries of a given type of land use and the landscape fragmentation (Van Apeldoorn et al. 1992; Rescia et al. 1994, 1995). We emphasize that mosaic recognition allows us differentiate every portion of the forest that has been influenced by a specific human activity, greatly facilitating the analysis of fragmentation trends.

Unlike the patch–corridor–matrix model, the identified mosaics integrated the information on land uses and boundaries, thus providing a more depth description of landscape heterogeneity. The overlap of patches from different years did not provide this information nor permit the delineation of human influence areas. These examples of landscape interpretation suggest that decision making on the delineation and management of conservation areas should also consider the information that boundaries and mosaics provide to the analysis of landscape patches.

The evaluation of the historical sequence of mosaic changes allowed us to better understand the dynamics and complexity of the interactions among patches based on the boundary information (Figs. 3, 4). As observed by Valverde et al. (2008), the study of mosaics facilitates the identification of the effects of management on a territory in addition to delimiting the areas of land-use influence and of interactions between uses. This reinforces the argument by Roldán-Martín et al. (2006) that mosaics are the landscape elements that best describe scenarios.

Table 4 Values of forest conservation in the historical landscapes and in the legal scenario of Serra do Japi and their mosaics

		Availability of forest resource					*P*	Forest fragmentation	
		FR	FS	FSh	FSS	ORA		ED	ESD
	1962	0.57	0.92	0.68	0.89	0.37	0.92	6.3	13
	1994	0.54	0.93	0.73	0.89	0.38	0.94	6.1	18
	2005	0.56	0.92	0.71	0.9	0.38	0.94	6.3	26
	Legal	0.65	0.89	0.66	1	0.42	0.97	8.9	45
M1$_{\text{CRO–URB}}$	1994	–	–	–	–	–	0.66	–	–
M2$_{\text{CRO-all}}$	1962	–	–	–	–	–	0.71	–	–
	1994	–	–	–	–	–	0.79	–	–
	2005	–	–	–	–	–	0.78	–	–
	Legal	–	–	–	–	–	0.89	–	–
M3$_{\text{LAK-all}}$	1962	–	–	–	–	–	0.39	–	–
	1994	–	–	–	–	–	0.7	–	–
	2005	–	–	–	–	–	0.66	–	–
M4$_{\text{LAK–FOR}}$	Legal	0.15	0.32	0.06	1	0	0.92	91	105
M5$_{\text{BAR-all}}$	1994	–	–	–	–	–	0.69	–	–
	2005	–	–	–	–	–	0.7	–	–
M6$_{\text{GTS-all}}$	1962	0.95	0.94	0.72	0.9	0.3	1	5.5	10
	2005	0.15	0.27	0	0.44	0	0.98	33.7	235
	Legal	0.01	0.26	0	1	0	0.98	54.1	367
M7$_{\text{URB-all}}$	1962	–	–	–	–	–	0.57	–	–
	1994	–	–	–	–	–	0.86	–	–
	2005	0.01	0.32	0.08	0.86	0	0.8	11.3	45
	Legal	–	–	–	–	–	0.74	–	–
M8$_{\text{REF-all}}$	1962	–	–	–	–	–	0.85	–	–
	1994	0.31	0.81	0.51	0.77	0.03	0.97	12.4	28
	2005	–	–	–	–	–	0.97	–	–
	Legal	–	–	–	–	–	0.98	–	–
M9$_{\text{FIE–FOR–ROA}}$	1962	0.29	0.83	0.57	0.86	0.07	0.87	9.1	23
	1994	0.92	0.94	0.76	0.91	0.35	0.99	5.2	16
	2005	0.8	0.92	0.72	0.9	0.38	0.98	6.1	25
	Legal	0.75	0.89	0.66	1	0.42	0.98	8.6	44

Dashes indicate mosaics without forest patches. See abbreviations in Tables 2 and 3

Complexity of interactions in landscape mosaics

The complexity of interactions between patches and their organization in landscape mosaics explains how the same set of patches and boundaries can participate in distinct mosaics, according to their frequency, predominance, and complexity of interactions (Fig. 4).

The historical persistence of boundaries between the forest and human-modified fields (M9$_{\text{FIE–FOR–ROA}}$) makes this type of use the strongest human influence on forest conservation. The configuration of these boundaries in the mosaic as an element of the perforation of forests represents a first stage in a sequence of changes in the landscape pattern, indicating that human-modified fields are key elements in the management and monitoring of the landscape in the study area. The management of the protected areas, which encompasses forests and the interactions between uses, is not a simple task because of the complexity of interactions among the forestry mosaics, which require management actions specific for each type of the neighboring patches of each fragment.

Among the mosaics with greater human intervention (agriculture—$M1_{CRO-URB}$ and $M2_{CRO\text{-}all}$/reforestation—$M8_{REF\text{-}all}$/urban use—$M5_{BAR\text{-}all}$ and $M7_{URB\text{-}all}$/ and artificial lakes—$M3_{LAK\text{-}all}$ and $M4_{LAK-FOR}$), the mosaic with predominantly urban use ($M7_{URB\text{-}all}$) had the most complex interactions based on the high richness (BR) and frequency (BFq) of boundaries, particularly with human-modified fields (Fig. 4; Table 3).

The knowledge of the dominant mosaic and the interactions in each mosaic (Fig. 4) allowed us to apply the concept of the matrix in a different way than that described and adopted by Forman (1995). The element of the mosaic with the greatest influence on landscape dynamics (e.g., forest in $M9_{FIE-FOR-ROA}$) as well as the elements of highest interaction (e.g., field and road network in $M9_{FIE-FOR-ROA}$) may contribute the most in the functional relationships between the "matrix-element" (forest patches) and the landscape. Therefore, spatial–temporal changes in the mosaics indicated substitutions in the "matrix-element" and also in its interactions over time (Figs. 3, 4). One example is the substitution of $M9_{FIE-FOR-ROA}$ for $M7_{URB\text{-}all}$ in the northern and northwestern regions of the study area between 1962 and 1994, when there was a change from forest to urban matrix (Fig. 3). This information is valuable for the planning of the protected area because the management of the matrix element must be different according to its neighboring patches and its location in the core or buffer zone of the protected area. There are complementary strategies for forest conservation (Lindenmayer and Fischer 2006). This approach seems to be particularly important in very structurally heterogeneous landscapes in which the presence of many interactions that make the identification of a matrix difficult, like most of Serra do Japi.

Contribution of mosaics to forest conservation

If, in 2005, the planning target of the study area had prioritized the most important mosaics for forest habitat conservation, mosaic $M9_{FIE-FOR-ROA}$ would have been the most valuable because of it displayed the highest ORA value, highest permeability, and lowest fragmentation. The two other mosaics with forest patches in 2005 were $M6_{GTS\text{-}all}$ and $M7_{URB\text{-}all}$. These mosaics were different from the forest conservation point of view: $M7_{URB\text{-}all}$ had the smallest forest area but contained forest patches of varying sizes in advanced successional stages, with the lowest permeability and less fragmentation; $M6_{GTS\text{-}all}$ had more forest surface and high permeability and fragmentation (Table 4), but all of its forest patches were small and in less advanced successional stages. $M7_{URB\text{-}all}$ would be more valuable for species with high core habitat requirements and less diverse surroundings, while M6 would be more valuable as forest habitat for species not requiring large fragments and less variable surroundings. In the legal scenario, $M9_{FIE-FOR-ROA}$ is also the most valuable mosaic and is very similar to $M9_{FIE-FOR-ROA}$ in 2005 but with higher fragmentation, as indicated by the greater ED and ESD values. $M6_{GTS\text{-}all}$ had less forest area but contained patches in more advanced successional stages than those in $M6_{GTS\text{-}all}$ in 2005. The mosaic $M4_{LAK-FOR}$ is similar but with more fragmentation than in $M9_{FIE-FOR-ROA}$.

In summary, mosaic $M9_{FIE-FOR-ROA}$ in 2005 and in the legal scenario is the most valuable from the perspective of forest habitat conservation. $M6_{GTS\text{-}all}$ in 2005 and in the legal scenario and $M4_{LAK-FOR}$ also had value for this purpose, but the low core area of their forest patches and their high permeability and fragmentation require management to improve their value. $M7_{URB\text{-}all}$ in 2005 had less permeability and fragmentation and larger forest patches, so in this case, permeability should be improved.

The mosaic with reforestation patches ($M8_{REF\text{-}all}$) should also be the focus of planning actions in the study area because it promotes landscape connectivity (P), despite its high anthropic influence, small-sized forests (FS), and unfavorable shape (FSh) for the maintenance of the integrity of forest cores (Table 4). Because the tree structure in reforested areas is similar to that in forests, these mosaics typify a soft matrix in the landscape, which facilitates organism dispersal (Franklin 1993; Lindenmayer and Fischer 2006).

In addition, the small forest patches may play an important role in "activating" the conservation potential of some mosaics. This is the case for $M7_{URB\text{-}all}$, the mosaic of urban influence, which, in 1994, reached a high permeability ($P = 0.86$) but had no conservation potential because of the lack of forest patches. This potential was achieved in 2005 when small forest patches ($HS = 0.08$) covering a small surface ($HR = 0.01$) permitted the permeability ($P = 0.80$) to be utilized by forest species (Turner and Corlett 1996; Crooks 2002).

These considerations suggest the importance of mosaics in identifying areas with different needs for conservation and defining priority areas for conservation and management actions that are more appropriate for the different patches according to the mosaics to which they belong.

For this case study, this approach was very useful in planning the use and occupation of the Biological Reserve surroundings. The changes in conservation values that have occurred in the last four decades demonstrated the socio-political-economic relationship that exists in the region. The mosaics highlighted historical trends and the possibility of evaluating different proposals for the future conservation of the protected area. The mosaics may also reveal the limitations of each choice as well as the essential sites and aspects to manage the landscape.

Conclusions

The analysis of landscape changes over time based on boundaries and mosaics provides additional information on overlapping patches of land use, revealing important aspects of changes in the conservation status of forest landscapes and the implications of these changes for forest management. Therefore, this analysis should be used as a management tool when decisions on the use of a territory depend on a knowledge of neighborhood relationships between land uses and their interactions.

The information about the attributes of the boundaries and mosaics provides essential guidelines to managers regarding landscape functionality. The mosaic analysis is useful for evaluating structural changes in the landscape by identifying its predominant elements, areas with higher potential of conservation, driving forces, vectors of change, and boundaries that conflict with the aims of forestry protection.

The application of this method to the legal scenario is important because it demonstrates that the enforcement of current forestry laws, despite favoring increases in forest area, also maintain a set of interactions in the landscape that confounds adequate management for conservation and increases the pressure in boundary zones, which facilitates increased fragmentation potential. Our case study suggests that laws can be improved if the government includes efforts to amend the design of access roads to properties. The roads should have a configuration that eases the impact on the forest, optimizing access and reducing circuit drawings. Such a configuration would improve boundary relations within the mosaic and its value in forest conservation.

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