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RESEARCH AND THEORY

Land use dynamics in a tropical protected area buffer zone: is the management plan helping?

Juliana Carmo de Souza[1] · Tatiana Sussel Gonçalves Mendes[1] · Rafael Beltrame Bignotto[2] · Enner Herenio de Alcântara[1] · Klécia Gili Massi[1]

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Abstract

Buffer zones, mandatory in the Brazilian protected area network as well as globally common in reserves, are essentially transitional areas within the core protected area (PA) that aim to downgrade the land-use intensity of the surrounding landscape from potentially damaging external influences. Buffer zones are regulated by the management plan and studies comparing these restrictions to land cover dynamics, and landscape configuration in buffer zones of protected areas are not common. Thus, we aimed to assess land use and land cover dynamics since 1995 in the buffer zone of Serra do Mar State Park (in Portuguese: Parque Estadual Serra do Mar: PESM), Southeast Brazil, and to compare them with restrictions imposed by its Management Plan. We hypothesized that, despite restrictions of the management plan, land use and land cover changes have intensified and increased in extent, in the nearest surroundings of PESM, with regards to deforestation, urban expansion, and forest discontinuity, which may further result in threatening conservation values of PESM. To evaluate land use and land cover dynamics in the study site, transition satellite imagery from 1995 to 2020 available at MapBiomas Project was used. We verified that (i) forest cover percentages in the whole area, in each municipality and in legal reserves inside private rural land in the PESM buffer zone did not alter, (ii) the rate at which urban areas expanded during the study period slowed over time, and (iii) the boundary between the protected area and the buffer zone was mostly deforested. Thus, the PESM Management plan and restrictions, together with other environmental policies not analyzed in this study, might be working to contain deforestation and urbanization, and, lately, to maintain conservation values of PESM. However, there is a need for alternatives to improve the implementation of regulations on the buffer zone management plan.

Keywords Atlantic forest · Conservation · Forest cover · Protected area · Urban expansion

Introduction

The Atlantic Forest biome, a biodiversity hotspot (Myers et al. 2000), was originally located in 17 Brazilian states, from Rio Grande do Sul to Rio Grande do Norte. The former distribution of the Atlantic Forest has now become heavily populated, with the overall area accounting for 70% of Brazil's Gross Domestic Product, GDP (MMA 2000: mma.gov.br). Currently, only a small proportion (12.4%) of the former forest cover remains (SOS Mata Atlântica & INPE 2019). This biome was the first one in Brazilian history to be degraded and deforested and the first to have a protected area (icmbio.gov.br) and a specific legislation (Law of the Atlantic Forest: Law 11.428/2006, Brasil 2006). Degradation processes in this biome are related to anthropogenic activity, especially commodities agriculture and urban settlements (Dean, 1996). The biome landscape is very fragmented (Ribeiro et al. 2009) and vegetation remnants are surrounded by agriculture areas (32% of the biome area is occupied by pastures: MAPBIOMAS 2021). One strategy to minimize anthropic pressures on Atlantic Forest sites is the creation of protected areas.

Protected areas (PA, in Portuguese: unidades de conservação: UC), instituted by Law 9985/2000 (SNUC, Brasil 2000), are "territorial spaces and its environmental

✉ Klécia Gili Massi
klecia.massi@unesp.br

[1] Institute of Science and Technology, Sao Paulo State University - Unesp, São José Dos Campos, São Paulo 12247-004, Brazil

[2] Instituto de Pesquisas Ambientais - Secretaria de Infraestrutura E Meio Ambiente, São Paulo, São Paulo 05459-900, Brazil

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resources, including jurisdictional waters, with relevant natural characteristics, legally established by the Government, with conservation objectives and defined limits, under a special administration regime, to which applies guarantees of adequate protection." Protected areas play an important role in biodiversity conservation, integrating elements of the landscape, allowing sustainable use of natural resources, ecosystem restoration, and provision of important ecosystem services (Silva et al. 2023). Protected areas and its surrounding land in Brazil (Moraes et al. 2017; Amaral et al. 2019) have been under agricultural pressures, which may affect biodiversity conservation (Parra-Sanchez & Banks-Leite 2020) and ecosystem resilience (Oliveira et al. 2020). In the Atlantic Forest biome, there are 131 federal, 443 state, 14 municipal, and 124 private protected areas that cover less than 2% of the biome (icmbio.gov.br).

Brazilian parks allow nature to be preserved and natural resources to be only indirectly used (Law 9985/2000, Brasil 2000). Among parks, the Serra do Mar State Park (in Portuguese: Parque Estadual Serra do Mar: PESM), created in 1977, represents the largest continuous preserved portion of the Atlantic Forest in Brazil, for the purpose of nature preservation, valuing local culture, scientific research, and environmental education (São Paulo 2021: infraestruturameioambiente.sp.gov.br/pesm/). The park covers 332,000 ha divided into ten management units (Itariru, Curucutu, Itutinga-Pilões, Bertioga, São Sebastião, Padre Dória, Caraguatatuba, Santa Virgínia, Picinguaba and Cunha), located in 25 municipalities in São Paulo state, southeast Brazil. Little is known about land use and land cover dynamics and anthropogenic pressures to PESM. In only one unit (Cunha), the park is under strong anthropogenic pressure, with urban areas expanding around it and land subdivision in the nearby rural land (Starzynski et al. 2018). In another unit (Santa Virgínia unit), the buffer zone is very fragmented (667 forest fragments of a maximum size of 30 ha: Villani 2007).

Buffer zones are globally important, but it is still unknown whether buffer zones are an extension of national parks or if its major role is to integrate parks and people (Martino 2001 in a literature review about buffer zones). According to the same author, most of worldwide buffer zones have failed to integrate conservation and development. In Brazil, buffer zones (in Portuguese: zonas de amortecimento: ZA) are mandatory, comprised of private land adjacent to the protected area boundary and aim to downgrade use intensity of surrounding landscape compared to the stricter restrictions within the core protected area, creating a gradient and avoiding edge effects at the PA, as zones have specific rules and restrictions for human activities (Law 9985/2000, Brasil 2000). These specific norms and restrictions are given by the Management Plan, which is the main instrument for the planning and management of natural resources of protected areas (Law 9985/2000, Brasil 2000). PESM management plan regulates, among other things, the creation of private protected areas, subdivision of land, urban expansion, native forest cover, exotic species use, and intensive agricultural practices in its buffer zone (São Paulo 2006). Buffer zones exist in reserves around the world and it is extremely important to assess land use and land cover dynamics and anthropogenic pressures under management plans on park buffer zones that are home to biodiversity hotspots (in this case, PESM in Brazilian Atlantic Forest), to identify how effective the implementation of this management plan is, and why some areas have better implementation than others, which could help guide the future creation of official buffer zones and remodeling of existing PAs and buffer zone management plans.

More recently, the assessment of land use and land cover dynamics in buffer zones of protected areas and the provision of scenarios for updating management plans have been more common in Brazil (Moraes et al. 2017; Amaral et al. 2019; Oliveira et al. 2020). However, using satellite imagery to calculate the relative success of management plan implementation in terms of preventing deforestation in buffer zones of protected areas have not been undertaken in a biodiversity hotspot (in this case, Brazilian Atlantic Forest), which is a novelty of this study. Therefore, this study aims to evaluate land use and land cover dynamics in the Serra do Mar State Park (PESM) buffer zone and compare them with restrictions imposed by its Management Plan. Specifically, we aimed to evaluate: (i) forest cover increase in legal reserves inside private rural land, (ii) urban expansion on the PESM buffer zone, and (iii) vegetation loss and connectivity loss between the buffer zone and PESM itself. We hypothesized that management plan restrictions have not been implemented successfully during the study period 1995–2020 in PESM. Conducting such a case study evaluation is very important for better understanding Atlantic Forest protected areas buffer zone management effectiveness more broadly, or even the global importance of using the available spatial data to identify where management plans are failing and find solutions.

Material and methods

Study site

The study area comprises Serra do Mar State Park buffer zone (in Portuguese: Parque Estadual Serra do Mar: PESM), located in a 10 km buffer of park limits (Resolution CONAMA 13/1990, Brasil, 1990), resulting in a total extension of 5666.84 km^2, belonging to mostly São Paulo and a small portion of Rio de Janeiro states (Fig. 1). PESM is in a wide area of the Atlantic Forest biome covered mainly by evergreen tropical forests (Dense Ombrophilous and Mixed

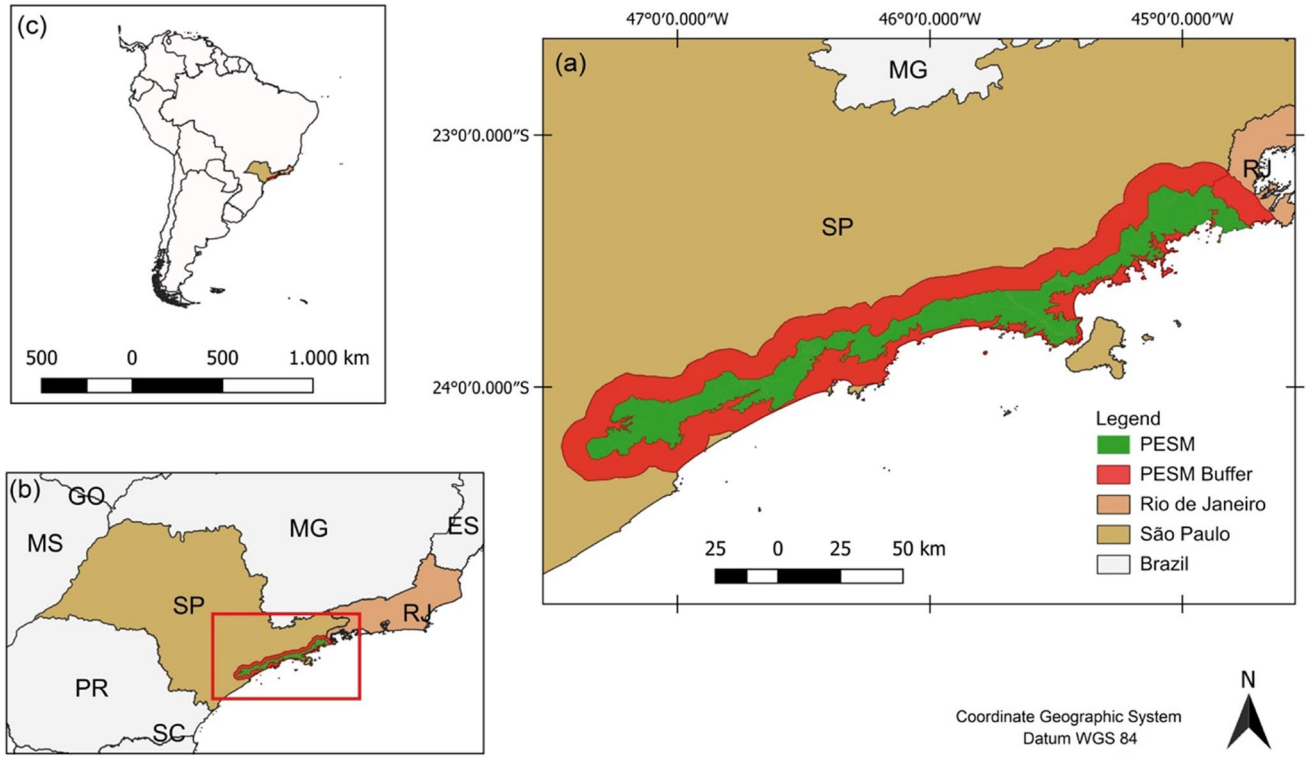

Fig. 1 Study area: **a** Serra do Mar State Park (PESM) buffer zone, **b** inside São Paulo state, **c** Brazil and South America. Limits of PESM and its buffer zone are approximate, as the park still has legal issues relating to state ownership regularization

Ombrophilous) and associated ecosystems (coastal grasslands, mangroves, and highland grasslands). Because of its high levels of biological diversity (1265 species of vascular plants and 1523 amphibians, reptiles, birds, and mammals: São Paulo 2006), PESM plays a key role in biodiversity conservation in southeast Atlantic Forest (Ayres et al. 2005), in addition to providing significant ecosystem services (Starzynski et al. 2018).

Although PESM was created in 1977 (Decree 10,251/1977, São Paulo 1977) and expanded in 2010 (Decree 56,572, São Paulo 2010), its first management plan was from 1997 to 1998 (considered an operational environmental management plan) and updated in 2006 (more strategic and complete: Deliberation Consema 34/2006, São Paulo 2006). It is managed and administered by the São Paulo State Forestry Foundation (*Fundação Florestal*) and it has ten units (each with a different park manager), located in 25 municipalities (São Paulo 2021: infraestruturameioambiente.sp.gov.br/pesm/). In some cases, the PESM covers less than 5% of the total municipality area (such as Mogi das Cruzes and Santo André), while in others, it occupies more than 75% of this area (such as Caraguatatuba and Ubatuba). Thus, different units of the PESM and its buffer zones, and municipalities where they are, are under different anthropogenic pressures and different pressure degrees. Before park creation, several areas inside PESM boundaries were farms (São Paulo 2006). In PESM, as in all Brazilian protected areas, the buffer zone is not officially considered part of it (thus, a park), but because it is located in its surroundings, has the function of protecting these limits, and some limitations on human activities apply.

The buffer zone of PESM is in 35 municipalities and is characterized by a wide diversity of socio-economic activities. The urbanization and industrialization in central-south portion (between the Metropolitan Region of São Paulo and Baixada Santista, Santos lowlands, especially in Cubatão) and real estate speculation and irregular land occupation in the north portion (Litoral Norte) are major anthropogenic pressures in PESM and its buffer zone (São Paulo 2006). Some highways such as BR-116, connecting São Paulo to Paraná state, BR-101, connecting Santos (in São Paulo state) and Rio de Janeiro (in Rio de Janeiro state), and SP 150/160, connecting São Paulo city and Santos lowlands are development ways, and resulting in deforestation and degradation, particularly for jussara palm extraction (São Paulo 2006). Tourism and unplanned occupation both threaten, especially, the north portion of the PESM landscape (São Paulo 2006). The south portion (Vale do Ribeira) of PESM is well conserved, while the northwest (Vale do Paraíba) is under agricultural and silvicultural (mainly *Eucalyptus* species) pressures (São

Paulo 2006). In addition, water pipes, gas ducts, and transmission lines also represent vectors of deforestation and urbanization in the region (São Paulo 2006).

All municipalities inside PESM and its buffer zones are projected to have increased its human population in recent times (the last projection when this study was performed was 2020: SEADE 2021). Ecological and economical zonings of São Paulo state (ZEE 2021, released in 2022: São Paulo 2022), of Santos lowlands (São Paulo 2013) and of the North Coast (2004), public policies to organize and manage environmental and socioeconomic actions in São Paulo state, have been and will likely change land use and land cover dynamics in these regions (https://www.infraestruturameioambiente.sp.gov.br/portalzee/). Other environmental projects, as Conexão Mata Atlântica (from 2015), a payment for ecosystem services program, are financing forest conservation and restoration in the buffer zone of PESM units Cunha, Itariru, and Santa Virgínia. Thus, it is not possible to disentangle different environmental policies from the efficient implementation of the management plan of PESM.

Some units of PESM and its buffer zones are located in common municipalities (for example, Cunha and Picinguaba units are in Ubatuba municipality), but they do not overlap in extension, and for this reason, data were analyzed and results will be presented per municipality.

Forest cover and urban sprawl assessment

To undertake analysis, the landscape historical series was obtained using images with a spatial resolution of 30 m available at MapBiomas Project—Collection 6 (Souza et al. 2020, from Annual Series of Land Use and Land Cover of Brazil, accessed on 11/20/2020, through mapbiomas.org) for the years 1995 (before the first management plan of PESM), 2000, 2005, 2010, 2015, and 2020. All images were merged in QGIS software (QGIS Development Team 2017). Boundaries of PESM were available at IBGE, Brazilian Institute of Geography and Statistics, website (IBGE 2021: ibge.gov.br).

To evaluate land use and land cover dynamics in the PESM buffer zone, time series imagery, that are 5-yearly change spatial layers (1995–2000, 2000–2005, 2005–2010, 2010–2015, and 2015–2020) summarized as forests that remained forest (1), other land uses that became forest (2), forests that became agricultural and urban expansion (3), available at MapBiomas Project were analyzed. For evaluating changes in vegetation cover within Legal Reserves (LR, in Portuguese: reserva legal, RL) present in private rural land located in the buffer zone, we assessed LR limits at the National System of Rural Environmental Registry (in Portuguese Cadastro Ambiental Rural, CAR 2021: car.gov.br) and vegetation cover from 1995 to 2020 available at Mapbiomas Project. Legal Reserves are an instrument of environmental conservation, as it determines a percentage of native vegetation that needs to be maintained in rural properties, which in São Paulo state is 20% of rural land size, and it guarantees the sustainable economic use of natural resources, assists in the rehabilitation of ecological processes, promotes the biodiversity conservation, and protects the native fauna and flora (Native Vegetation Protection Law, NVPL: Law 12.651/2012, Brasil 2012). According to NVPL, LR vegetation could form ecological corridors to connect protected.

Vegetation loss and connectivity

Connectivity was assessed for the years 1995 and 2020 (before the first management plan of PESM and the last collection of Mapbiomas, respectively) within the buffer zone by establishing ten buffers of 1 km each and observing the whole PESM buffer zone. The proximity index (PROX) metric was generated using the V-LATE 2.0 (Vector-based Landscape Analysis Tools Extension) (Tiede 2012) as an extension for ArcGIS 10.8 software (Environmental Systems Research Institute). The proximity index is the sum of the ratio between area and inter-patch (fragments) distance for all fragments within a predefined distance (radius) around a fragment. When the proximity index equals zero, the fragment has no neighbors within the specific search radius. The proximity index increases as the neighborhood (defined by the search radius) is increasingly occupied by patches/fragments (Cabral et al. 2018). Thus, the proximity index ranges from 0 to infinity.

Lastly, land use and land cover dynamics in the PESM buffer zone were compared to the Management Plan restrictions (the full plan has more than 400 pages in Portuguese, but we provide an Appendix 1 with a summary of buffer zone restrictions in the plan in English). The PESM buffer zone aims "to protect and recover springs, forest remnants and landscape integrity in the region surrounding PESM, to ensure the maintenance and recovery of biodiversity and its water resources" and among the recommendations of the management plan are: (i) to encourage the registration, conservation, and recovery of legal reserves, and (ii) to identify the areas of greatest pressure for urban settlement adjacent to PESM and articulate freezing of its expansion, and non-recommended uses, as (iii) cutting of vegetation in forests adjacent to the park (São Paulo 2006). Thus, we analyzed forest cover increase in legal reserves inside private rural land, urban expansion on the PESM buffer zone, and vegetation loss and connectivity loss between the buffer zone and PESM itself as responses of PESM Management Plan recommendations. To test for differences between land use and land cover classes before (1995) and in the last evaluation (2020), we used paired sample *t*-test. Analyzes were performed in R version 3.6.3 (R Central Development Team 2019).

Results

Forest cover and urban sprawl assessment

Land use and land cover mapping for the Serra do Mar State Park (in Portuguese: Parque Estadual Serra do Mar: PESM) buffer zone identified that forest area increased by 40.15 km^2 in the whole interval analyzed (Fig. 2 and Table 1), which was non-significant ($t = 0.015$, $P = 0.989$). In 1995–2000, forest area (remained and forest gain) represented 63.29% of the total buffer zone area, in 2000–2005, 63.57%, in 2005–2010, 64.39%, from 2010 to 2015, 64.05%, and from 2015 to 2020, 64.20%. In the same period (1985–2020), the native forest cover of the Atlantic Rainforest biome in Brazil decreased 1% (from 27 to 26% of the original cover), corresponding to 1.3 million ha (data available at Mapbiomas project).

This increase was unevenly distributed in the whole buffer zone area (Table 2) and non-significant when municipalities were considered ($t = -0.077$, $P = 0.939$). Most

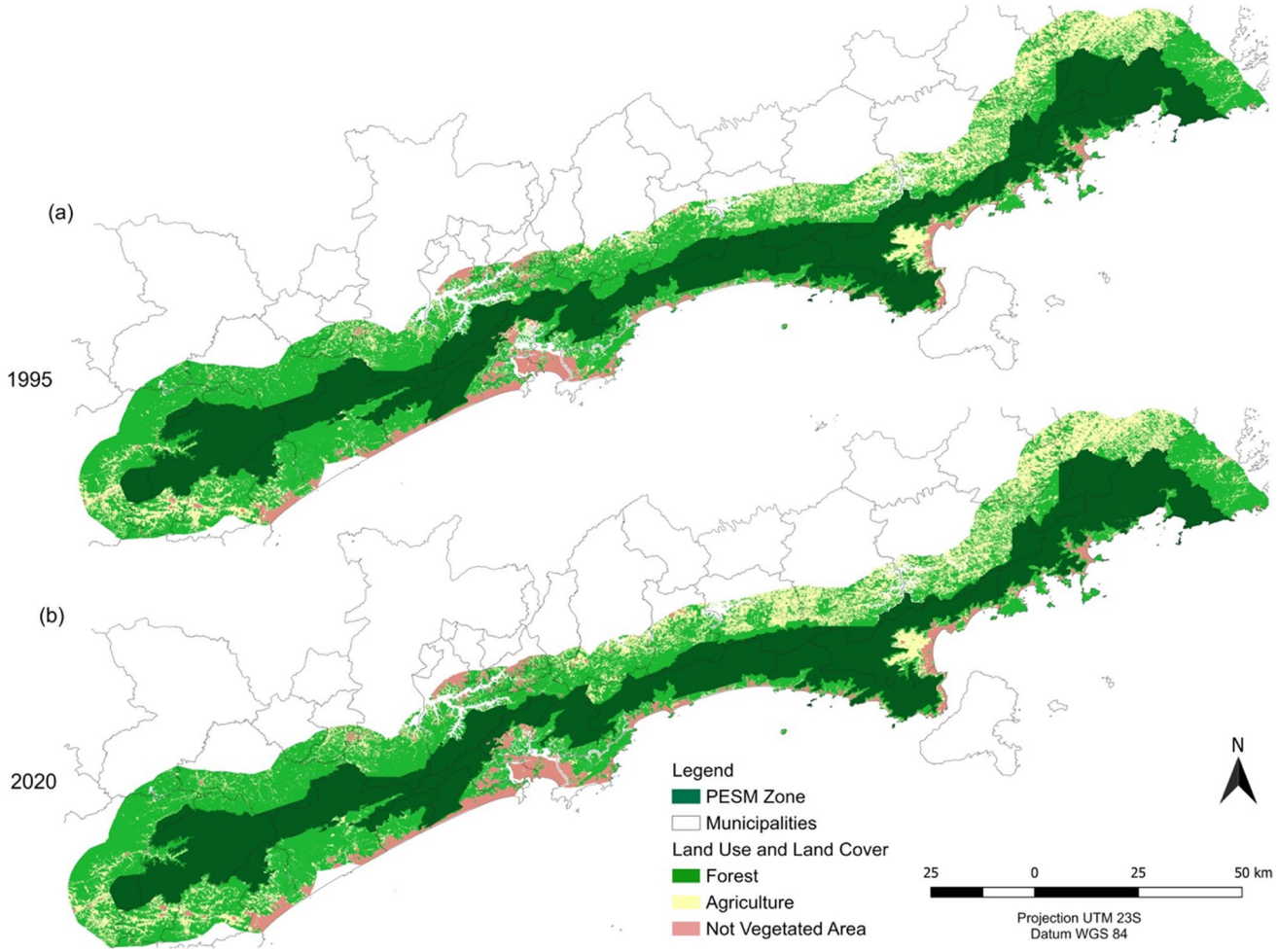

Fig. 2 Land use and land cover of the study area, Serra do Mar State Park (PESM) buffer zone, in **a** 1995 and **b** 2020

Table 1 Land use and land cover change classes evaluated during five-year intervals in Serra do Mar State Park (PESM) buffer zone

	Transitions classes area (km^2)/period				
	1995–2000	2000–2005	2005–2010	2010–2015	2015–2020
Other land use that became forest	92.35	144.13	145.00	114.96	103.98
Forest that remained forest	3483.42	3458.31	3492.07	3514.77	3523.57
Other land use that became urban	23.96	12.70	13.94	16.53	12.00
Forest that became agriculture	182.06	119.06	90.24	123.34	70.95

Table 2 Forest cover and urban expansion in the beginning (1995–2000) and end (2015–2020) of studied intervals in Serra do Mar state park (PESM) buffer zone per municipality, Brazil

Land uses (km^2)/year	Forest cover		Urban expansion	
Municipality	1995–2000	2015–2020	1995–2000	2015–2020
Bertioga	116.43	109.24	2.82	0.72
Biritiba Mirim	130.27	116.90	0.23	0.03
Caraguatatuba	48.12	54.63	2.22	1.65
Cubatão	24.39	32.19	1.11	1.17
Cunha	116.11	117.97	0.00	0.00
Embu-Guaçu	49.19	51.34	0.31	0.57
Guarujá	67.26	68.71	1.99	0.66
Ibiúna	42.59	44.20	0.00	0.00
Iguape	11.44	11.83	0.00	0.00
Itanhaém	244.70	241.10	1.90	0.67
Itariri	149.05	162.80	0.27	0.13
Juquitiba	258.07	260.76	0.05	0.10
Lagoinha	11.25	10.06	0.00	0.00
Miracatu	369.50	382.67	0.14	0.09
Mogi das Cruzes	134.28	126.11	0.20	0.24
Mongaguá	33.55	31.53	0.90	0.00
Natividade da Serra	177.35	196.86	0.01	0.03
Paraibuna	134.53	121.07	0.00	0.00
Paraty	230.28	234.52	0.34	0.17
Pedro de Toledo	153.28	168.21	0.15	0.05
Peruíbe	92.90	92.27	1.46	0.64
Praia Grande	24.24	25.12	2.06	0.30
Ribeirão Pires	28.21	28.68	0.42	0.26
Rio Grande da Serra	24.55	24.53	0.26	0.34
Salesópolis	122.51	105.54	0.00	0.00
Santo André	73.35	75.24	0.73	0.10
Santos	78.97	82.26	0.72	0.86
São Bernardo do Campo	104.38	107.23	1.41	0.34
São Lourenço da Serra	32.92	33.70	0.00	0.00
São Luiz do Paraitinga	94.60	94.71	0.00	0.00
São Paulo	162.51	169.70	0.27	0.46
São Sebastião	69.63	71.04	2.00	0.96
São Vicente	30.58	34.45	0.55	0.59
Suzano	19.51	19.40	0.04	0.07
Ubatuba	114.22	121.11	1.39	0.80

municipalities (23) slightly increased forest cover from 1995 to 2020 in the PESM buffer zone, except for Bertioga, Biritiba Mirim, Itanhaém, Lagoinha, Mogi das Cruzes, Mongaguá, Paraibuna, Peruíbe, Ribeirão Pires, Rio Grande da Serra, and Suzano that lost vegetation (Table 2).

We also found that urban expansion is still pressuring the PESM buffer zone (Fig. 2 and Table 1). However, this pressure has significantly decreased over the last 25 years evaluated ($t = 2.226$, $P = 0.031$), i.e., before the first management plan (of 1997) other land uses becoming urban were almost double the values of 2020. The decrease in urban expansion was seen in most municipalities of the PESM buffer zone (17) from 1995 to 2020, except for Cubatão, Embu-Guaçu, Juquitiba, Mogi das Cruzes, Natividade da Serra, Rio Grande da Serra, Santos, São Paulo, São Vicente, and Suzano.

Forest cover in legal reserves

Our analysis of forest cover in legal reserves inside private rural land of the PESM buffer zone (Fig. 3) found only an 0.82% increase in vegetation cover from 1995 (381.726 km^2) to 2020 (384.875 km^2), which was non-significant ($t = -0.029$, $P = 0.977$).

When we looked at individual municipalities, most of them (25) had small increases in vegetation cover in legal

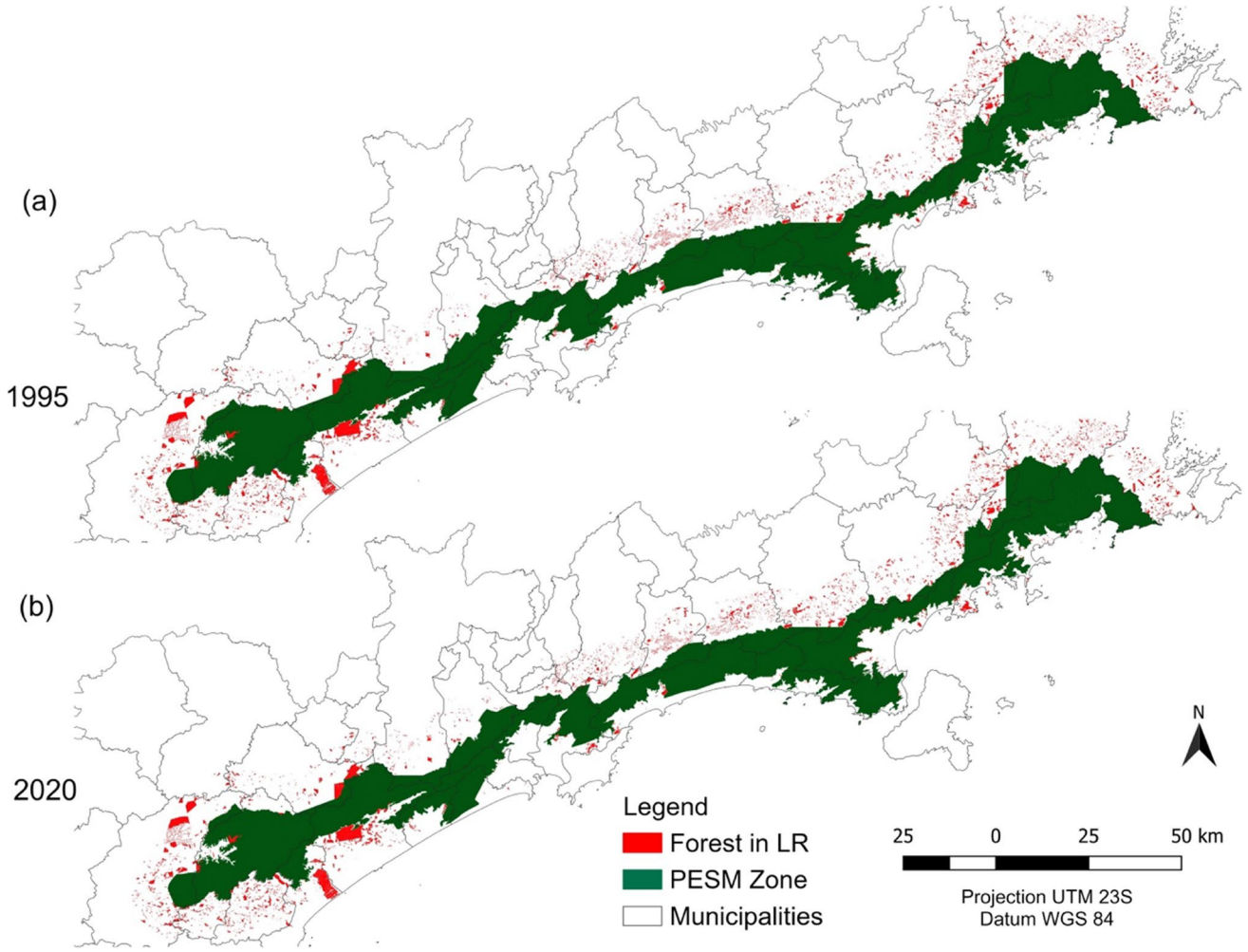

Fig. 3 Forest cover change in legal reserves (LR) inside private rural land of Serra do Mar state park (PESM) buffer zone in **a** 1995 and **b** 2020

reserves of rural land inside the PESM buffer zone, and some decreased (five: Bertioga, Biritiba Mirim, Mongaguá, São Paulo, and Salesópolis, this last one had the higher values of forest loss in LR) and five municipalities had the same amount, from 1995 to 2020 (Table 3).

Forest connectivity assessment

In relation to connectivity, we found that, in general, between 1995 and 2020, there was a decrease in mean and maximum proximity (thus, increased isolation) within the whole PESM buffer zone and 1 km-buffers inside the PESM buffer zone (Table 4). Between 3 and 4 km far from PESM, the highest decrease in connectivity was seen and between 8 and 9 km the highest increase in connectivity in the studied period was observed (1995–2020: Table 4). Most of 1 km-buffers and the whole PESM buffer zone had diminished number of isolated fragments yet this difference was non-significant (Table 4; $t = 0.038$, $P = 0.97$).

Discussion

In general, we observed that during the studied period changes in forest cover and inside legal reserves were not significant in Serra do Mar State Park (in Portuguese: Parque Estadual Serra do Mar: PESM) buffer zone. A net increase by only approximately 1% in forest cover was observed in the PESM buffer zone landscape within 1995 and 2020, representing 40.15 km^2. Native vegetation has been increasing, through natural regeneration and ecosystem restoration projects, in São Paulo state in the last years (Natural Vegetation Inventory, São Paulo, 2020), but our results confirm only a slight increase for the PESM buffer zone. Despite high forest cover (and low conversion to

Table 3 Forest cover area change in legal reserves (LR) inside private rural land of Serra do Mar state park (PESM) buffer zone per municipality, Brazil

		Forest cover area in LR (km^2)/year	
Municipality	State	1995	2020
Bertioga	SP	4.01	4.00
Biritiba Mirim	SP	12.53	11.52
Caraguatatuba	SP	6.38	6.57
Cubatão	SP	0.05	0.05
Cunha	SP	21.67	22.05
Embu-Guaçu	SP	1.31	1.38
Guarujá	SP	2.81	2.84
Ibiúna	SP	0.79	0.84
Iguape	SP	1.37	1.39
Itanhaém	SP	49.24	49.31
Itariri	SP	21.42	22.20
Juquitiba	SP	17.26	17.26
Lagoinha	SP	0.41	0.41
Miracatu	SP	50.88	51.95
Mogi da Cruzes	SP	12.88	12.89
Mongaguá	SP	2.26	2.18
Natividade da Serra	SP	22.33	22.83
Paraibuna	SP	19.94	20.07
Paraty	RJ	19.08	19.25
Pedro de Toledo	SP	14.49	15.33
Peruíbe	SP	27.32	28.07
Praia Grande	SP	0.31	0.31
Ribeirão Pires	SP	0.05	0.06
Rio Grande da Serra	SP	0.08	0.08
Salesópolis	SP	16.78	14.71
Santo André	SP	1.00	1.05
Santos	SP	6.14	6.30
São Bernardo do Campo	SP	2.59	2.66
São Lourenço da Serra	SP	1.95	1.96
São Luiz do Paraitinga	SP	23.66	24.30
São Paulo	SP	5.48	5.47
São Sebastião	SP	2.50	2.52
São Vicente	SP	0.33	0.34
Suzano	SP	3.00	3.04
Ubatuba	SP	9.44	9.69

agriculture, of 64% in the buffer zone), which is significantly higher than in the Atlantic Forest biome (12.4% according to SOS Mata Atlântica & INPE 2019, and 28%, according to Rezende et al. 2018), about 36% of the buffer zone had other land uses and covers, which might damage native vegetation conservation and ecosystem services provision of PESM (Metzger et al. 2019). PESM buffer zone landscape aims to protect and recover landscape integrity in the region surrounding the protected area (São Paulo 2006), and thus high standards of environmental quality are required. Municipalities having forest loss were found in Curucutu, Itutinga-Pilões, Padre Dória, and Santa Virgínia units and need environmental policies and special attention from public managers to stop deforestation in the PESM buffer zone.

The urban expansion rate has significantly decreased over the last 25 years, although urban expansion is still pressuring the PESM buffer zone. This urban expansion decrease was verified in most municipalities of the PESM buffer zone (17) from 1995 to 2020, except for Cubatão, Embu-Guaçu, Juquitiba, Mogi das Cruzes, Natividade da Serra, Rio Grande da Serra, Santos, São Paulo, São Vicente, and Suzano. These municipalities are in the Metropolitan region of São Paulo, where urban growth is still happening (Lima & Rueda 2018) and Santos Lowlands (except for Natividade da Serra, which is in the Santa Virginia unit). Thus, according to the PESM Management Plan, together with local stakeholders of these municipalities, public managers could act to freeze this sprawl, especially in the PESM buffer zone around São Paulo metropolitan area. In this case, the management plan of PESM might be working. Other studies performed in Brazil and worldwide have shown human populations still increasing in borders of protected areas (Wittemyer et al. 2008; Joppa et al. 2009; Amaral et al. 2019; Kubacka et al. 2022).

Our results indicate that command and control policies are likely to have suppressed urban expansion after the first management plan (verified by a decrease in urban uses from 1995–2000 to 2000–2005 period), but as time went by (from 2005 to 2015) and environmental policies and governments changed, urban pressure returned to increase. In addition, 2003 to 2014 was an expansion period in the Brazilian economy (Paula & Pires 2017), which may have promoted urban development and settlements in the PESM buffer zone. Lastly, the verticalization process, happening especially on the coast, replaces rural land with higher buildings. In the end, we cannot attribute this verified decrease in urban development degree, from 1995 to 2020, in the studied region to command-and-control policies or to economic dynamics, but it is a positive finding that urban pressures, despite still happening, have been decreasing its rate. Future studies could access that, for example, by using a specific regulation, as the Law of the Atlantic Forest (Law 11.428/2006, Brasil 2006), to evaluate since 2006 (its release year) of all protected areas within this biome and building modeling based on likely predictors like socioeconomic variables, as another study did for the Brazilian Native Vegetation Protection Law (Rezende et al. 2018).

Our analysis of forest cover in legal reserves inside private rural land of the PESM buffer zone found a non-significant and small increase in vegetation cover during the study

Table 4 Mean and maximum proximity and number of isolated fragments in 1 km-buffers and in the whole buffer zone of Serra do Mar state park (PESM), Brazil. Proximity varies from 0 to infinite and higher values mean higher connectivity

Buffers	Mean proximity		Number of fragments		Maximum proximity	
Distance to park	1995	2020	1995	2020	1995	2020
0 to 1 km	53,905,438.1	50,298,971.5	76	72	18,488,721,702.3	16,680,800,260.4
1 to 2 km	207,324,255.9	142,777,818.9	34	38	86,451,287,177.6	88,926,901,701.3
2 to 3 km	41,013,624.4	3,289,030.2	22	23	48,599,630,644.2	1,713,769,680.1
3 to 4 km	83,114,634.3	26,924,794.6	24	21	77,613,256,004.8	14,539,736,345.4
4 to 5 km	6,691,710.1	6,623,180.5	29	28	5,941,255,246.3	6,159,494,449.9
5 to 6 km	181,481,352.2	191,740,578.6	21	20	121,284,204,094.0	119,450,918,274.0
6 to 7 km	130,585,924.9	131,747,392.7	16	17	68,103,464,713.8	67,074,122,578.9
7 to 8 km	210,797.1	156,244.7	16	18	49,179,801.5	37,056,852.2
8 to 9 km	502,853.7	765,097.4	23	20	159,643,864.2	357,609,160.6
9 to 10 km	31,253,843.4	21,373,935.3	34	32	11,817,813,956.6	11,370,477,407.3
Whole PESM buffer zone	66,954,515.14	54,474,607.61	307	298	121,284,204,094.0	119,450,918,274.0

period. However, the buffer zone is mostly constituted of small farms, that according to NVPL, do not need to restore the LR; thus, reinforcing the importance of a management plan in revegetating even where legal requirements might not apply. Thus, it is important that public managers act to improve vegetation cover in the whole buffer zone, but units having forest loss in LR should be prioritized. These municipalities correspond to Bertioga and Curucutu (each with one municipality having forest loss in LR of its buffer zone) and Padre Dória (with three municipalities). The Padre Dória unit was the last one to be created (in 2014) and it might still be facing management issues in the territory.

PESM buffer zone is 5666.84 km^2, and according to NVPL legal requirements of 20% of forest cover in LR (Brasil 2012), we should have 1133.37 km^2 of native vegetation. Thus, the actual native vegetation cover in LR in the PESM buffer zone represents one-third (33.59%) of how much it should be. According to NVPL, native vegetation of LR can be compensated or allocated by restoring or regenerating the vegetation on the same property, or by restoring it in another rural property or by compensation from landowners with legal reserve surplus (Brasil 2012). In this case, to improve the environmental quality and connectivity of the PESM buffer zone to the protected area itself, legal reserves of private rural lands inserted in the buffer zone should be restored in the original location.

Legal Reserves recompositing do not impose only native species planting (Brasil 2012), but it enables mixed plantings with exotic species and agroforestry systems, and a recent state Resolution (Resolution 189/2020: São Paulo 2018) regulated sustainable use of native species in Legal Reserves; thus, we argue that the São Paulo state Forestry Foundation and Secretariat of Environment and Infra-structure could incentive legal reserves agroforestry restoration of the whole PESM buffer zone through sustainable use and incentive mechanisms, such as payment for ecosystem services project Conexão Mata Atlântica (Atlantic Forest Connection) does in the northwest portion (Vale do Paraíba) of PESM (conexaomataatlantica.mctic.gov.br/cma/), but with higher values.

In relation to connectivity, we found that there was a decrease in proximity (thus, increased isolation) within the whole PESM buffer zone. At the same time, most of 1 km-buffers and the whole PESM buffer zone did not change the number of isolated fragments. Landscape metrics cannot be analyzed separately: the same number of isolated fragments may indicate that natural regeneration of abandoned areas (verified by increase in forest cover) and the connection of small fragments, creating a large fragment, that is more distant (less proximate) to others is taking place in PESM buffer zone. In recent years, this has been verified in the northwest portion of the PESM buffer zone (in Vale do Paraíba: Silva et al. 2017; Rocha et al. 2020). So, our results suggest the improvement of environmental quality in the PESM buffer zone due to the regeneration and to management plan restrictions. In other Brazilian protected areas, vegetation fragments in the buffer zone have become smaller and the park has become isolated (de Moraes et al. 2017; Amaral et al. 2019).

Conclusions

The assessment of the buffer zone of Serra do Mar State Park in the Brazilian Southeast Atlantic Forest from 1995 to 2020 and comparing land use and land cover dynamics with restrictions imposed by the park management plan, showed: (i) unchanged forest cover in the whole area, in each municipality and in legal reserves inside private rural land, (ii) reduced urban expansion, and (iii) vegetation connectivity

loss between buffer zone and PESM itself, which should be analyzed together with other landscape metrics. Thus, the PESM Management plan and restrictions, together with other environmental policies, might be working to contain deforestation and urbanization, and, lately, to maintain conservation values of PESM. Despite that, restoration is still needed in some portions. As PESM and its buffer zone is one of the most important protected areas for the conservation of the Atlantic Forest (infraestruturameioambiente.sp.gov.br/pesm/), we argue that positive results of evaluated parameters are due to environmental concerns relating to this park, specifically, because this particular protected area is under high anthropogenic pressures and therefore vulnerable to degradation and deforestation. The relative success of the management plan within the 10-km official buffer zone over the study period 1995–2020 therefore indicates that buffer zones can achieve meaningful conservation outcomes even in difficult circumstances. This has implications for the Atlantic Forest biome, the Brazilian PA network, and the global approach to a spectrum of legal land-use restrictions for conservation purposes and to prevention of natural hazards, as landslides that have been occurring in the past few years. Thus, we recommend the assessment of PESM landscape integrity, promoted by the buffer zone, to be expanded in other conservation metrics (not only of the PESM management plan), and also the evaluation of land use and land cover changes of the buffer zone on species biodiversity inside PESM.

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Declarations

Competing Interests The authors declare no competing interests.

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