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Three decades of land-use and land-cover change in mountain regions of the Brazilian Atlantic Forest

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ABSTRACT

Mountain regions are key hotspots for biodiversity conservation and for provisioning ecosystem services. Containing fragile ecosystems and home to millions of inhabitants, mountains are also places of great value for tourism, cultural practices and endemic species. In this paper, we developed the first multitemporal land-use and land-cover assessment of mountain regions within the Brazilian Atlantic Forest (BAF), the most endangered Brazilian tropical biome. The study used spatial thematic mapping for 1985, 2001, and 2018 to understand changes in landscape composition, patterns of change in patch metrics of natural vegetation cover, and correlations between human population and natural vegetation. Change detection techniques, landscape metrics and statistical tests (e.g., Kruskal-Wallis) were applied. We found that landscape composition did not change at significant levels over the 34 years (1985–2018), but that intense exchange between natural vegetation and agriculture creates a shifting mosaic steady-state. Additionally, natural vegetation loss was 13-fold lower within mountains than in other areas of the BAF biome, which indicates lower human-induced change in mountain regions. Urban and rural population (number of inhabitants) showed positive correlation with natural vegetation at municipality level indicating higher presence of population in municipalities with large extents of natural vegetation. Analysis demonstrated that the study region was under lower population pressure and urban growth compared to other areas and had kept large extents of natural vegetation within large patches, different to what is observed at biome level. However, telecoupling processes may result in indirect land changes in mountain regions of the BAF biome. Our results indicate that mountains play a key role in conserving the remnants of the BAF.

1. Introduction

The United Nations declared 2002 the International Year of Mountains, calling attention to a particularly important part of the Earth system for supplying freshwater, supporting biological diversity, providing high-value destinations for tourists, and serving as homes for around 12% of the human population (UN (United Nations), 2009). Considered a fragile environment (Ledo, Condés, & Alberdi, 2012), and important to ensure ecosystem services provision, such as freshwater to supply distant populations, mountainous landscapes and their associated socio-ecological systems are in constant change due to thriving human settlements (Rescia, Pons, Lomba, Esteban, & Dover, 2008; Spies, 2018; Tovar, Seijmonsbergen, & Duivenvoorden, 2013; Bhatta, Shrestha, Neupane, Jodha, & Wu, 2019), urban and infrastructure growth (Grocke & McKay, 2018), and resource exploitation (Sati, 2004). These changes sometimes make mountains more fragile and prone to natural disasters (Ding, Cheng, & Wang, 2014; Alcántara-Ayala & Moreno, 2016), severe erosion processes (Alewell, Meusburger, Brodbeck, & Bänninger, 2008), biodiversity and agrobiodiversity loss (Saxena, Maikhuri, & Rao, 2005; Bhattarai, Maren, & Subedi, 2014), and compromising the maintenance of ecosystem services (Sauter, Kienast, Bolliger, Winter, & Pazúr, 2019; Callisto et al., 2019). Globally, but excluding Antarctica, only 16.9% of mountain regions are located within protected areas (Rodríguez-Rodríguez, Bomhard, Butchart, &

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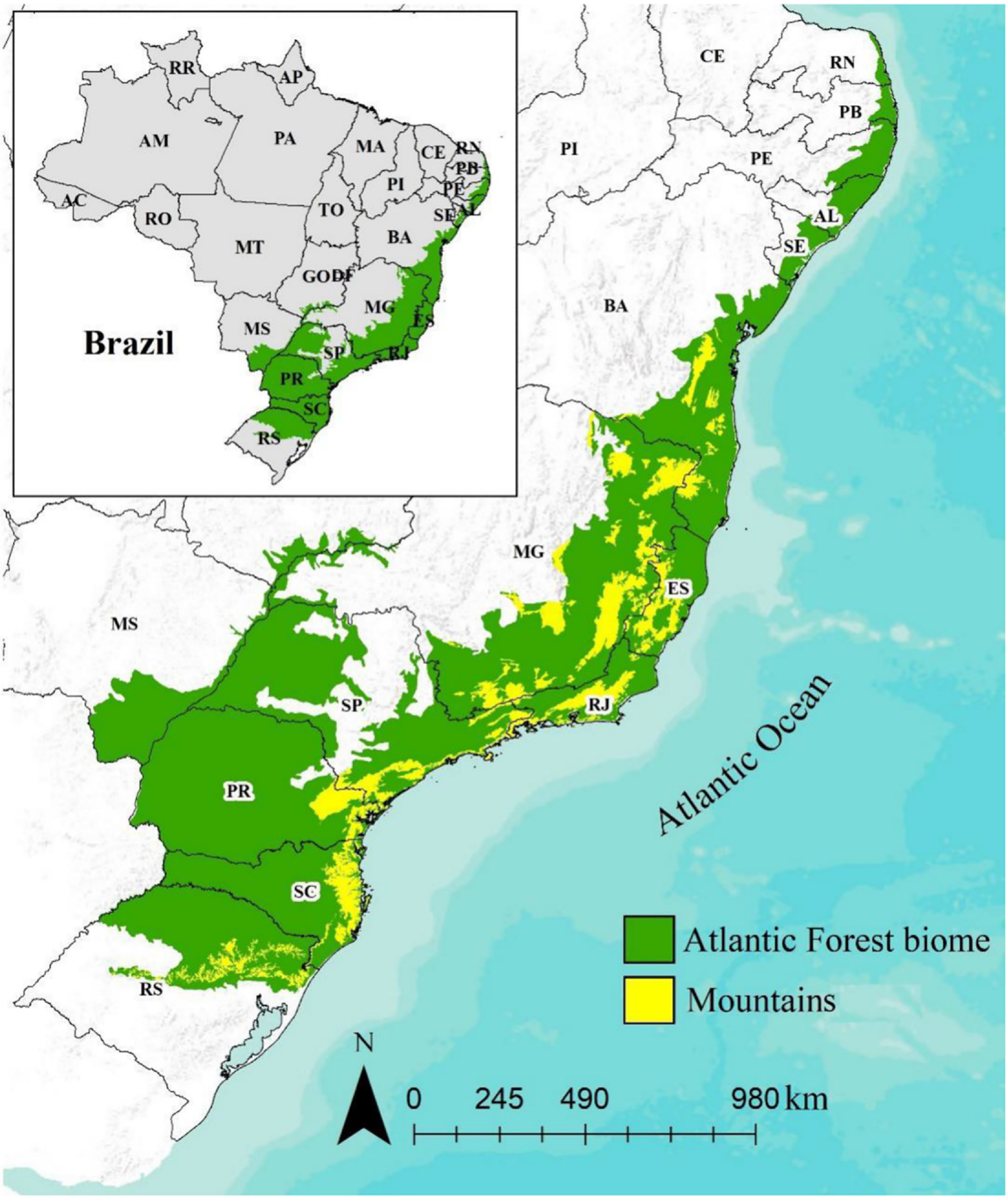

Fig. 1. The study area comprises the Atlantic Forest biome with focus on the mountain regions within the biome, highlighted in yellow. The definition of mountain regions follows the IBGE systematic geomorphologic mapping system (IBGE (Brazilian Institute of Geography and Statistics). (2009), 2009). Ocean and terrain features are from the "World Reference Overlay" and "World Ocean Base". (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Foster, 2011) despite previous studies demonstrating protected area effectiveness for biodiversity and forest conservation in mountains (Jones, Hawes, Norton, & Hawkins, 2019).

Mountains occupy about 25% of the Earth's land surface (Rodríguez-Rodríguez et al., 2011), and Brazil, a large country, is among the twenty countries with the largest territories covered by mountains (Netto & Assis, 2015) including key hotspots of tropical biodiversity (Silveira et al., 2019). Although Brazil's highest peak lies within the Amazon biome (i.e., *Neblina Peak*-2,994 m a.s.l.), the largest mountain regions are located in the Eastern coastal zone of the country, predominantly within the Atlantic Forest biome (Ab'Saber, 2003).

In Brazil, the Atlantic Forest biome has been the most deforested and degraded (over 70% of the biome) since European colonization (Silva, Batistella, & Moran, 2016). Vegetation in the biome is fragmented, with patches of natural vegetation remnants smaller than 50 ha on average (Pardini, Bueno, Gardner, Prado, & Metzger, 2010). A recent study found that the entire biome has 28% of natural vegetation cover left, of which only a fraction is considered in good conservation status while the majority of the mapped natural vegetation is most likely confined in edge-affected patches or secondary vegetation, disconnected and isolated (Rezende et al., 2018). A global hotspot of biodiversity (Zachos & Habel, 2011), the Atlantic Forest is also the most densely populated biome in Brazil, with about 125 million inhabitants and a region responsible for almost70% of the national gross domestic product (GDP) (Martinelli et al., 2013; Scarano & Ceotto, 2015). In recent decades, the forest transition process-in which native forest cover increases following a period of high deforestation rates-has been observed in some parts of the biome. Silva et al. (2016); Silva, Batistella, Moran, and Lu (2017)) found consistent rates of forest regrowth in a region of São Paulo State between 1985 and 2011, while

Baptista (2008) and Rezende, Uezu, Scarano, and Araujo (2015) observed the transition in the Southern State of Santa Catarina from 1970 to 2005, and in Rio de Janeiro State from 1978 to 2014, respectively.

Despite the expanse of mountains in Brazil, along with their considerable importance for biodiversity and key ecosystem services (e.g., freshwater provisioning), there are no current public policies addressing sustainable development and conservation in these specific regions (Netto & Assis, 2015; Callisto et al., 2019). Additionally, few studies have addressed biodiversity in the mountain regions of Brazil (Santos, José, Vianna Filho, & Neto, 2016; Oliveira et al., 2015; Meireles & Shepherd, 2015; Brum, Teodoro, Abrahão, & Oliveira, 2017; Silveira et al., 2019) and none have dealt with land-use and land-cover (LULC) or with human population dynamics.

In this paper, we present analysis of changes in natural vegetation cover in the mountain regions within the Brazilian Atlantic Forest (BAF, hereafter) biome over a period of 34 years (from 1985 to 2018). Specifically, we examine changes in landscape metrics and identify major drivers of land-cover change, human population dynamics, and stability in landscape composition. This study sheds light on the role of mountain regions in conserving the Brazilian Atlantic Forest and brings insights for policy making to protect these ecoregions by examining the following questions: Are mountain regions within the BAF facing LULC change driven by urbanization and agricultural expansion? If this is the case, we would expect to see a growing trend of urban and agricultural land-use classes replacing natural vegetation classes and fostering natural vegetation fragmentation. What are the major land changes in mountain regions of the BAF biome? If these mountain regions are undergoing land-change processes, we expect to detect high rates of change and low stability of LULC classes through landscape metric analysis. Are mountain regions facing similar natural vegetation and population dynamics as the areas outside mountains within the BAF biome? If not, can we affirm that mountain regions play a key role in conserving the remnants of the BAF biome? Here, we expect to see different changes in urban and rural population dynamics between mountain populations compared to the rest of the biome as an indicator of such differences. Additionally, if mountains are undergoing different LULC changes compared to the rest of the biome, we should expect to see lower rates of natural vegetation loss. As previous studies on LULC change have not focused on mountain regions in the BAF biome, there is no existing empirical evidence of how and at what scale, these regions are responding to human-induced changes over time.

2. Material and methods

2.1. Study area

Within Brazil, the Atlantic Forest biome spans mainly across the coastal zone, over seventeen States and with a total area of 1,110,182 km^2 (Fig. 1). According to the Brazilian Institute of Geography and Statistics (IBGE, 2009), the mountain regions (named according to the IBGE classification system: *Serras*) within the biome-and which form our study region-reach their highest elevation at 2,892 m a.s.l. at the *Bandeira Peak* in Espírito Santo State. The definition of mountain regions follows the IBGE systematic geomorphologic mapping system (IBGE, 2009). The mountain regions span over eight States (Bahia, Espírito Santo, Rio de Janeiro, Minas Gerais, São Paulo, Paraná, Santa Catarina, and Rio Grande do Sul) and within the bounding coordinates 12^{0}80′6″ S, 39^{0}51′8″ W in the northeast and 29^{0}80′6″ S, 54^{0}97′7″ W in the southwest.

2.2. Data

We conducted a spatiotemporal analysis of LULC, focused on changes in natural vegetation cover over a period of 34 years (1985 to 2018). LULC data are derived from MapBiomas *v4.0*, a freely available dataset developed by a consortium of Brazilian and international research institutes, universities, private organizations, and NGOs aiming to generate national coverage of LULC information (a complete description of the project can be found at http://mapbiomas.org). The global accuracy of LULC classifications in *v4.0* is 89% and with a total of 27 LULC classes and raster products at 30-m spatial resolution (derived from Landsat data).

To address the aims of the study, the 27 classes of LULC were reclassified (supplementary material 1) into classes of (1) natural vegetation-all types of natural vegetation including forest, shrubs and natural grasses; (2) planted forests-forest areas covered by commercial three species, mainly eucalyptus; (3) agriculture-which includes pastures and crop fields; (4) built-up area-urban areas, infrastructure and mining; (5) water bodies-rivers, streams and dams, and (6) other-miscellaneous pixels such as cloud cover. The mountain regions (rugged reliefs, composed of diverse geology, forming peaks and ridges or steep edges of plateaus) were delimited by the IBGE through the systematic geomorphologic mapping initiated by the RADAMBRASIL project in 1971 and updated by the Natural Resources Survey for the 21th century (Botelho & Pelech, 2019). The freely available (*Banco de Dados de Informações Ambientais: Geomorfologia*) shapefile of geomorphology (including the topographic compartment named as "Serras", a synonymous of mountains in Portuguese) was used to extract LULC for 1985, 2001, 2010 and 2018 within the mountain regions of the BAF. This approach delimits our study area into areas inside *vs.* outside the mountain regions of the BAF and is important to allow comparisons of LULC changes between mountain and non-mountain regions. Additionally, freely available topographic information (i.e., elevation and slope) from TOPODATA developed by the National Institute for Space Research (INPE) was used to analyze the influence of topography on LULC spatial patterns. TOPODATA is a national coverage geomorphometric dataset developed from the Shuttle Radar Topographic Mission (SRTM) data, to provide a 30-m resolution Digital Elevation Model (DEM) (Valeriano, 2008). A municipality grid vector file (IBGE, 2015) provided by the IBGE was also overlaid to identify the municipalities within the study area. Population statistics are also provided by IBGE on a regular decadal basis at the municipality level (IBGE, 1990, 2010). The population census of 2010 was used to evaluate population dynamics of urban and rural areas within the mountains. To identify only the urban areas, a vector file of urban settlements developed in 2015 by the Brazilian Agricultural Research Corporation (Embrapa), was overlaid with the study area (Embrapa, 2015).

We used a shapefile of Conservation Areas of Total Protection (i.e., direct use or exploitation of natural resources are not allowed within those areas), to explore the extent of mountain regions in the Atlantic Forest under current total protection. Information on protected areas are provided by the Brazilian Ministry of Environment, through the interactive WebGIS portal *i3Geo MMA*. The list with all public available data and sources used in the study is provided in supplementary material 2.

2.3. Data analysis

2.3.1. Land-use and land-cover change

The thematic maps of 1985, 2001 and 2018 were submitted to change detection procedures to trace LULC transitions and exchanges during the period of study, and the percentage of landscape occupied by each class (landscape composition) was determined. The percentages of landscape for all LULC classes in 1985 and 2018 were compared using a *paired T-test* to evaluate if the landscape was in a stable state (i.e., testing the Null Hypothesis that over the 34 years, the proportions occupied by each LULC class have not changed significantly). To implement change detection, we used the method of post-classification comparison that uses separate multi-temporal classified images to compare changes pixel-by-pixel (Lu, Mausel, Brondízio, & Moran, 2004). The exchange component of the change detection procedure measures the proportion of transitions from class *a* to class *b* at a given location (pixels) occurring simultaneously with class *b* transitioning to class *a* in other locations (pixels), in a similar approach proposed by Pontius and Santacruz (2014).

The biophysical feature of slope, derived from the DEM-TOPODATA was classified in six categories according to the Brazilian Agricultural Research Corporation (Embrapa) system to define agricultural suitability: (*i*) 0–3%, (*ii*) 3–8%; (*iii*) 8–20%; (*iv*) 20–45%; (*v*) 45–75%; and (*vi*) greater than 75%, ranging from (*i*) very suitable to (*vi*) unsuitable (Embrapa, 1999). The reclassified raster was used to analyze the occurrence of natural vegetation according to the slope classes of suitability. With regards to urban areas, the slope data were reclassified into two classes to represent landslide risk for urbanization: (*low*) 0–30%; and (*high*) greater than 30% (Sato et al., 2011). To understand the distribution of natural vegetation due to elevation, four other categories were created, based on IBGE (2012) definitions of *Atlantic lowland forest* (0–30 m a.s.l.), *Atlantic lower montane forest* (30–400 m a.s.l.), *Atlantic montane forest* (400–1000 m a.s.l.), and *Atlantic upper montane forest* (greater than1000 m a.s.l.). In Brazil, Atlantic Forest natural vegetation is distributed among these four different types according to their elevation. Studies have shown diverse vegetation types and species composition associated to the elevational sections of mountain zones in the biome, indicating negative correlation with species richness and elevation, but greater endemism in higher elevations (Meireles & Shepherd, 2015; Caglioni et al., 2018; Silveira et al., 2019; Sauter et al., 2019). The urban areas were also overlaid against elevation to assess their distributions.

Based on the municipality grid vector file, we selected only the municipalities with total or partial area within the mountain regions using a GIS intersection operation. The resulting new vector file was used to identify the municipalities with urban area within the mountains. A Spearman's rank-order correlation was used to verify if rural population of 2010 was correlated with natural vegetation cover (in 2010) at the municipality level. The Shapiro-Wilk test rejected the null hypothesis (H_0) of data normal distribution (i.e., natural vegetation in 2010) leading us to choose the Spearman's correlation. The same correlation analysis was applied to test natural vegetation in 2010 with the urban population of 2010, at municipality level.

Some land changes (e.g., deforestation) are analyzed for the entire biome to allow comparisons between mountain and non-mountain regions with regard to landscape spatiotemporal patterns. This approach provides a comparative analysis to verify if mountains play an important role for the spatiotemporal dynamics of natural vegetation cover and landscape structure.

2.3.2. Landscape metrics

Landscape metrics were calculated for 1985, 2001 and 2018 to allow analysis of changes in landscape patterns. In this study, we generated landscape metrics of composition and spatial configuration (Table 1) (Turner, Gardner, & O'Neill, 2001). Patch-based analyses of individual cover types provide reliable measures for temporal analysis (Turner et al., 2001; Pelorosso, Chiesa, Tappeiner, Leone, & Rocchini, 2011). Therefore, patch-level spatial configuration metrics are applied to the natural vegetation LULC class. The natural vegetation patches were also grouped in patch size classes of greater than 200 ha, 200–150 ha, 150–100 ha, 50–100 ha, 10–50 ha, and < 10 ha to allow analysis of landscape composition addressing discrete classes of patch size, a useful approach to provide comparisons between years and to understand fragmentation patterns (Silva, Batistella, Palmieri, Dou, & Millington, 2019). The shape index is a measure of complexity that expresses how regular or irregular a given patch is. Greater shape index values indicate a greater number of borders of a patch, which potentially affects the patch suitability for sensitive species and increases the exposure for edge effects. The patch metric analysis also elucidates if the landscape is under a steady state of landscape composition but with a shifting mosaic-i.e. shifting steady-state mosaic, when the landscape is represented by different patch classes with the total fraction of any class remaining relatively constant over time despite significant changes in particular patches (Chambers et al., 2013). A similar dynamic is the proposed meta-stable state of equilibrium where human-induced land change (e.g., agriculture, urbanization) is balanced with regeneration of natural vegetation (Pelorosso et al., 2011).

A Kruskal-Wallis (KW) non-parametric test was applied to landscape metrics to assess significant differences in shape index, area and edge values of patch size classes of natural vegetation. The null hypothesis (H_0) assumes that no differences are expected in the mean ranks of shape index, area and edge in each pair of patch size class (i.e., the same class in both years). A post-hoc test by the Bonferroni method (Bland & Altman, 1995) was applied to measure differences by each pair of patch size class. An overview of the methodological steps are is illustrated systematically in Fig. 2.

3. Results

3.1. Land change and population dynamics

The mountain regions occupy around 12% (14 Mha) of the entire BAF biome. LULC change in the period was not significant (not rejecting H_0 in a *paired T-test*). The Percentage of Landscape (PL) showed the distribution for all LULC classes in the study area in a steady state between 1985, 2001, and 2018 (Fig. 3b). It was observed the emergence of planted forests, mainly with Eucalyptus species, from < 1% in 1985 to 3% (413,000 ha, Fig. 3a) in 2018. The relatively stable LULC composition over the analyzed period highlights the natural vegetation class as the dominant land cover in the study area ranging from 50.9% (7.8 Mha) in 1985, 50.4% in 2001 (7.7 Mha) to 49.6% (7.5 Mha) in 2018, with 92% and 91% of persistence between 1985 and 2001 and 2001–2018, respectively (i.e., number of pixels assigned to a given class in one year remaining the same in the next year). In 2018, the natural vegetation in mountain regions represented around 26% of the total natural vegetation in the entire BAF. Interestingly, we observe that while the native vegetation cover decreased 2.7% (212,000 ha) during the period of 34 years (19852018) within the study area, the entire

Table 1
Metrics of landscape ecology for the entire landscape, patches, LULC class and for patch size classes of native vegetation. The metrics are described according to McGarigal (2015).

Metrics	Description
Patch Area	The area of each patch comprising a landscape mosaic
Mean Patch Size	A measure of central tendency of patch area of a given LULC class across the landscape
Mean Shape Index	A measure of central tendency of patch complexity of a given LULC class across the landscape
Average Weight Mean Shape Index	A landscape-centric perspective of patch complexity of a given LULC class across the landscape that reflects a random condition of a pixel chosen randomly
Percentage of Landscape	The proportional abundance of each LULC class (patch type) in the landscape
Number of Patches	A simple measure of the extent of subdivision or fragmentation of a given LULC class (patch type)
Largest Patch Index	A measure of dominance the quantifies the percentage of total landscape occupied by the largest patch
Total Edge	The absolute measure of total edge length of a particular LULC class (patch type)

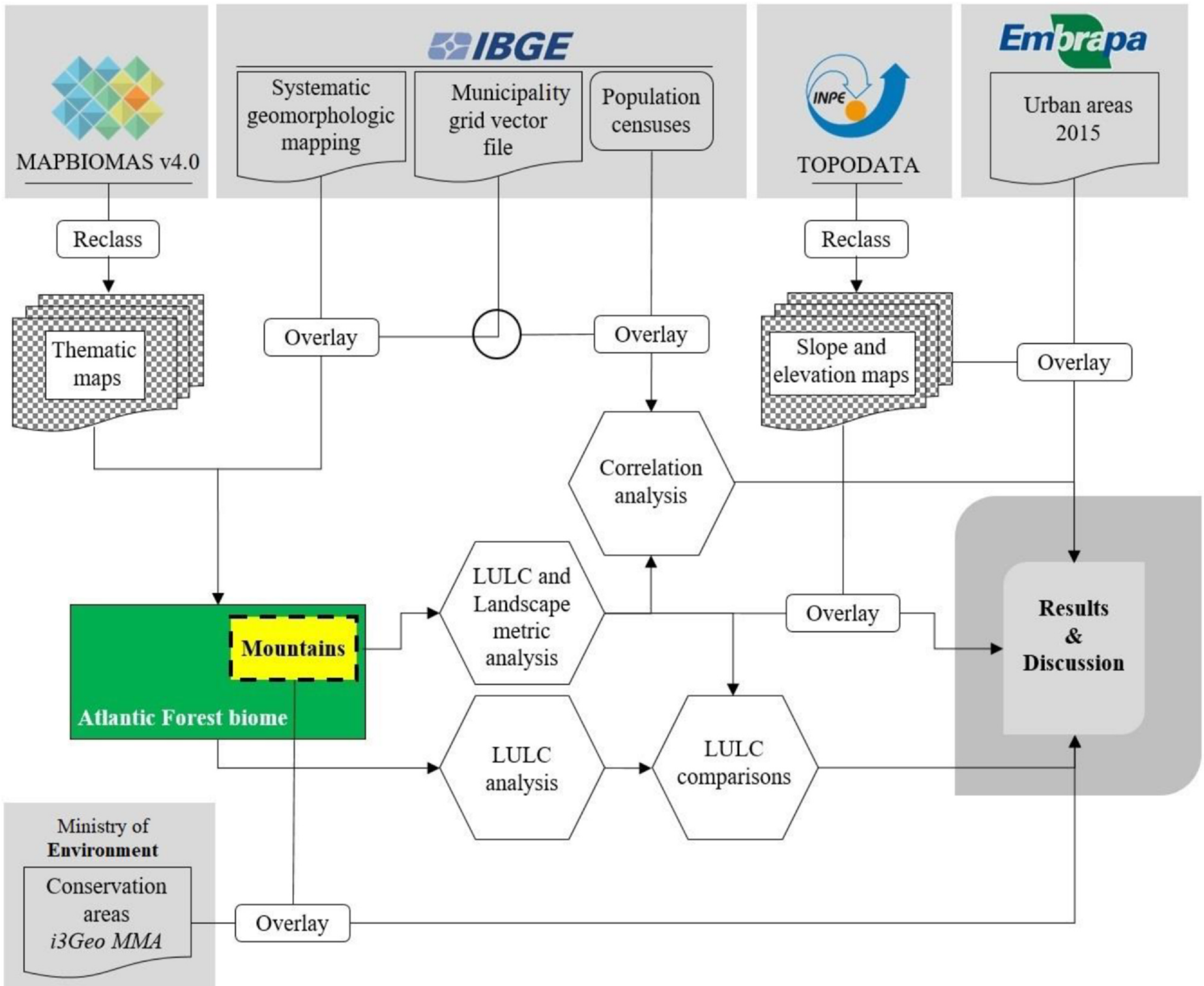

Fig. 2. Flow chart of methodological steps conducted by the study.

biome lost 8.5% (2.9 Mha), which implies a higher deforestation rate in non-mountain regions (i.e., 10.2% natural vegetation cover loss outside the mountains, 2.7 Mha). Between 1985 and 2001, natural vegetation loss within the study area was lower at 1.04% (81,000 ha) than the 1.7% (131,000 ha) decrease between 2001 and 2018.

The natural vegetation class in 2018 was found predominantly (83% or 5.9 Mha) on slopes greater than 20% indicating a higher spatial correlation between this LULC class and unsuitable lands for agricultural use or to urban and infrastructure development. According to our results, the flat and gentle slopes (0–3% and 3–8%, respectively) represent only 4% of the mountain regions and with the lower share of natural vegetation cover (< 2%). Thus, the mountains of the BAF are predominantly steep. Across the elevational gradient, 51% (3.7 Mha) of the natural vegetation was observed within the *Atlantic montane forest* (400–1000 m a.s.l.) followed by the *Atlantic lower montane forest* (30–400 m a.s.l.) with 32% (2.3 Mha). With regards to LULC class composition (percentage of the landscape) in non-mountain regions, significant changes were not observed (not rejecting H_0 in a *paired T-test*) during the period, indicating a similar steady state in the proportions of each class between 1985 and 2018. However, when compared to the LULC class proportions in mountain regions, in non-mountain regions, different proportions of LULC classes were observed in 2018 with natural vegetation occupying only 26.6% (Fig. 3d), planted forest 4.3%, agriculture 64.7%, built-up areas 1.6%, water 2%, and others 0.8%.

Taking the LULC change patterns in Fig. 3a and b, a steady state of classes between years was observed but with higher exchanges between natural vegetation and agriculture at 489,000 ha from each other between 1985 and 2001, accounting for a total 6.4% of the total study area (978,000 ha). Between 2001 and 2018, a 459,000 ha exchange was observed from each other, accounting for 6% (918,000 ha) of the mountains. Additionally, between 1985 and 2001, there was a loss of natural vegetation (i.e., without exchange) of 4,500 ha (0.05% of the LULC class in 1985) to agriculture. In the same period, planted forest replaced 50,000 ha of natural vegetation (0.6% of the LULC class in 1985) without equivalent transition. Between 2001 and 2018, planted forest continued as the major driver replacing natural vegetation without equivalent exchange to offset the loss of natural vegetation, replacing 153,000 ha of natural vegetation (1.9% of the LULC class in 2001). Planted forest was the LULC class with the most unbalanced exchange with natural vegetation, taking over many cells of natural vegetation, becoming the major driver of natural vegetation net loss over the 34 years. However, the observed land changes, with a general steady state of land composition over time, is characteristic of what Pelorosso et al. (2011) defined as meta-stable state of equilibrium.

We found that 490 municipalities have their urban area within the mountains while 875 (including those 490) are partially of totally within the region (including urban and rural areas). Therefore, the urban population living in the study area increased from around 21 million inhabitants in 1990 to 28 million in 2010, a 33% increase

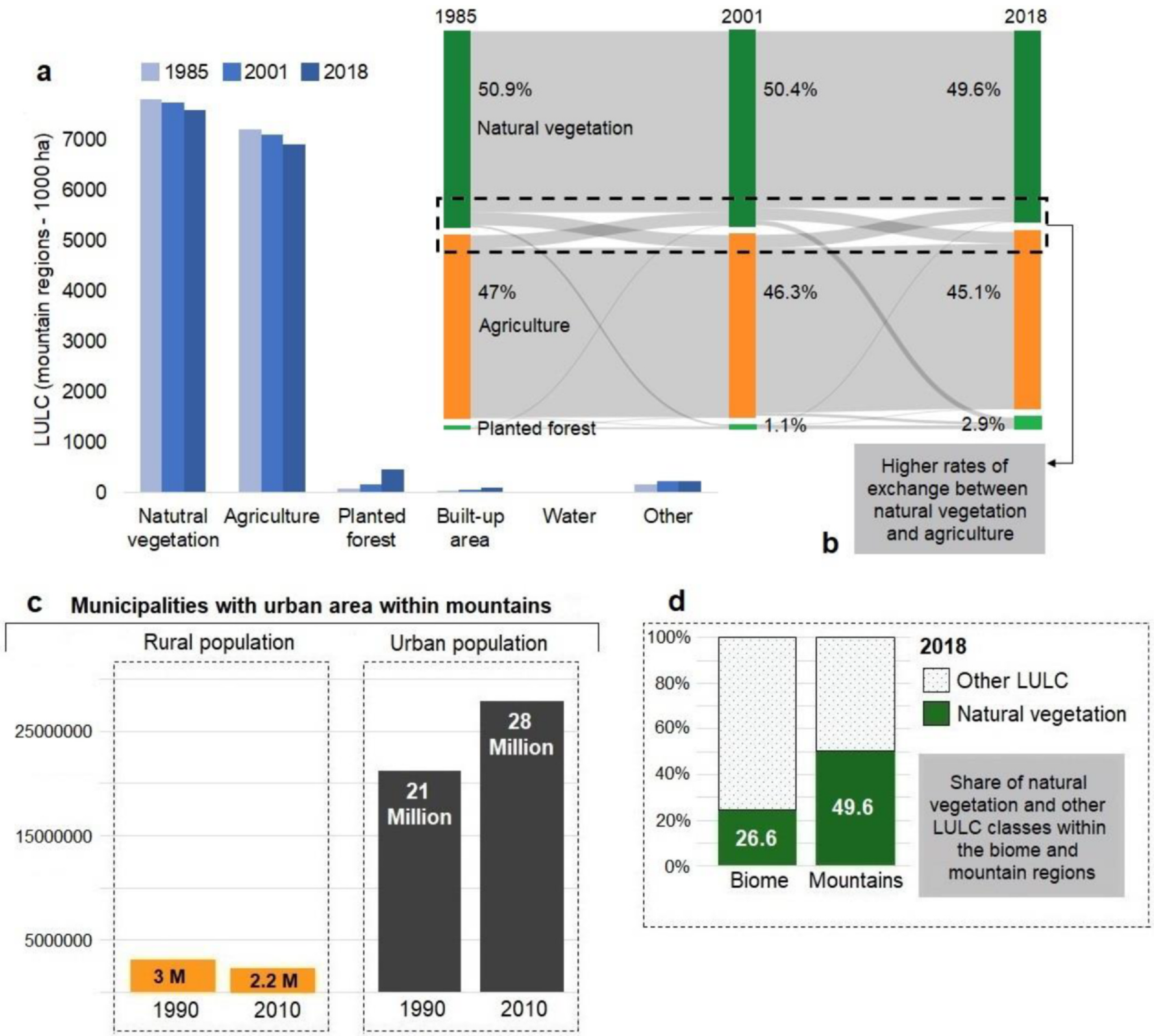

Fig. 3. The (a) bar plots present the area occupied by each LULC class observed within mountain regions. The (b) Sankey diagram displays the share of three major classes of LULC and highlights the exchange rate between classes of natural vegetation and agriculture among two periods 1985–2001 and 2001–2018, the major transition from natural vegetation to planted forest (2001–2018), and the persistence of each class along the period within the mountain regions. (c) Population dynamics in mountain regions of the Atlantic Forest biome. (d) Stacked bar charts represent the percentage of natural vegetation cover for the biome and the mountain regions in 2018.

(Fig. 3c). During the same period (1990–2010), the Brazilian urban population increased 45%, which indicates a slower pace of urban population growth in mountain regions of the Atlantic Forest.

Considering the LULC changes, the built-up area increased at a much higher rate than the respective urban population. From 1985 to 2018, the built-area increased around 171% but still representing < 1% of the entire mountain regions in 2018. Despite the greater urbanization, we found a positive significant correlation (*p-value* < 0.01) between natural vegetation cover area and urban population in 2010 with a Spearman's coefficient at 0.236. Although a low coefficient, this result suggests that higher urban population is likely to be associated with greater natural vegetation cover areas, at the municipality level. Additionally, a positive Spearman's coefficient of 0.302 was found between natural vegetation cover area and rural population in 2010 (significant correlation at *p-value* < 0.01). This result indicates that areas with higher rural population are also likely to be found in municipalities with larger natural vegetation areas.

We found 80% of urban areas within mountain regions between *Atlantic lower montane forest* (30–400 m a.s.l.) with 46% (52,000 ha) and *Atlantic montane forest* (400–1000 m a.s.l.) with 34% (39,000 ha). This indicates a higher concentration of people living in the most vegetated elevational gradients, a result that reinforces the positive Spearman's correlation between urban population and natural vegetation cover. With regards to slope, it was observed that 27% (31,000 ha) of urban areas occur on terrain greater than 30%.

With the largest LULC class represented by natural vegetation, the mountains' landscape composition differs from that observed outside mountains (i.e., with dominance of agricultural areas) and accounts for 26% of the biome's natural vegetation cover in 2018. However, only 8.7% are within Conservation Areas of Total Protection, critical for the conservation of the Atlantic Forest biome.

3.2. Patch and landscape level metrics

Although changes in landscape composition (i.e., Percentage of landscape occupied for each LULC class) were not significant over the period analyzed, changes were observed in landscape metrics giving evidence to the landscape meta-stable state of equilibrium. Based on patch level metrics (applied to each patch size for the class of natural vegetation for the three dates), the results indicate decreased fragmentation between 1985 and 2001 but then increasing between 2001 and 2018. Patch level analysis has been complementary to the understanding of landscape structure, function, and change, particularly in LULC assessments in forest biomes (Batistella, Robeson, & Moran, 2003). Four different but complementary metrics to evaluate the state of habitat quality and stability of the natural vegetation – Total Edge (TE), Average Weight Mean Shape Index (AWMSI), Number of Patches (NP), and Mean Shape Size (MSS) – provided insights to understand fragmentation patterns that occurred over the period analyzed. Between 1985 and 2001, the number of patches decreased 7% (17,690 patches), but then increased 14% between 2001 and 2018 (31,772 new patches added to the landscape). A general increase in mean patch size (MPS) was observed between 1985 and 2001 from 29 ha to 30 ha, but back to 26.5 ha in 2018. The class metric for shape complexity, the AWMSI, revealed a decrease of complexity from 54.75 in 1985 to 53.6721 in 2001 but increasing to 55.47 in 2018. Additionally, the total edge (TE) changed from 494,000 km in 1985 to 472,000 ha in 2001, reaching 497,000 ha in 2018. These results indicate a tendency of higher fragmentation and increased exposure to edge effects for natural vegetation from 2001 to 2018.

In Fig. 4, landscape metrics are presented according to patch size classes and results of KW tests at significant level are identified by markers (asterisks *p-value < 0.05, **p-value < 0.01) in the respective class group where significant changes were observed in the two periods of change.

New patches were observed from 2001 to 2018 and concentrated within the patch size class $<$ 10 ha (98.5%), while the other class sizes lost patches and underwent decreases in total class area in both periods (Fig. 4). Edge effects increased in both periods, but more predominantly between 2001 and 2018. Based on landscape change analysis, we found that agriculture contributed with 84% of total changes in natural vegetation class between 1985 and 2001 and with 70% from 2001 to 2018. Therefore, taking into account the exchanges between classes of agriculture and natural vegetation (*subsection 3.1*) and the results from Fig. 4, we have agriculture as the major driver of changes in the natural vegetation landscape mosaic, significantly affecting the dynamics of small patch size class ($<$ 10 ha, Fig. 4).

Regarding the natural vegetation class, we found the largest patch of the study area was in this class, with 1.97 Mha (27% of the class) in 1985, a Largest Patch Index (LPI) of 14 (i.e., a single patch covering 14% of the study area). This single largest patch spanned over São Paulo (SP), Paraná (PR) and Santa Catarina (SC) States and represented 18% of the largest continuous area with natural vegetation cover of the entire biome in 1985-i.e. the largest continuous area with natural vegetation spans over mountain and non-mountain regions. This patch underwent 130,000 ha (6.5% of the original patch in 1985) of deforestation during the analyzed period, pushed by the increases of planted forests. Nevertheless, it remained the largest patch within mountain regions in 2018 (1.84 Mha or 25% of the class-LPI of 13) and increased its importance as part of the largest continuous area with natural vegetation at the biome level-40%. In that regard, the patch analysis revealed that the largest continuous area of natural vegetation of the entire biome decreased 58% between 1985 and 2018, i.e., with the largest patch in 1985 dissolving into many patches and becoming fragmented. Up to 90% of the natural remnants of vegetation within the mountains are concentrated within fragments of over 50 ha in 2018.

4. Discussion

4.1. Human dimensions of landscape change

Over 34 years, the mountain areas of the Atlantic Forest biome presented a steady state of landscape composition in LULC classes in 1985, 2001, and 2018 (Fig. 3a and b). Changes were observed at the patch-level with more intense changes (significant level-KW test p-value < 0.01, Fig. 4) in small fragments of natural vegetation and in exchange with agricultural areas (Fig. 5). Pelorosso et al. (2011) have demonstrated a meta-stable state of equilibrium between agricultural areas and natural vegetation in a mountain city of Italy. There, the authors found that intense rates of exchange between transitions to new areas for agriculture were balanced with abandonment of previous ones that underwent secondary succession. We found a similar dynamic in our study area, where exchange rates between the two classes were observed in both periods of analysis. The planted forest was the class with greatest transition from natural vegetation (without exchange with natural vegetation in other locations) and the class with greatest rate of increase in the study period.

Given the hilly topography of the mountains and the greatest changes observed in small patches of natural vegetation cover indicate association of human activities restricted to small land parcels with no trend of large agribusiness systems (other than planted forests that are more suitable for the hilly terrains of the Atlantic Forest; Silva et al.,

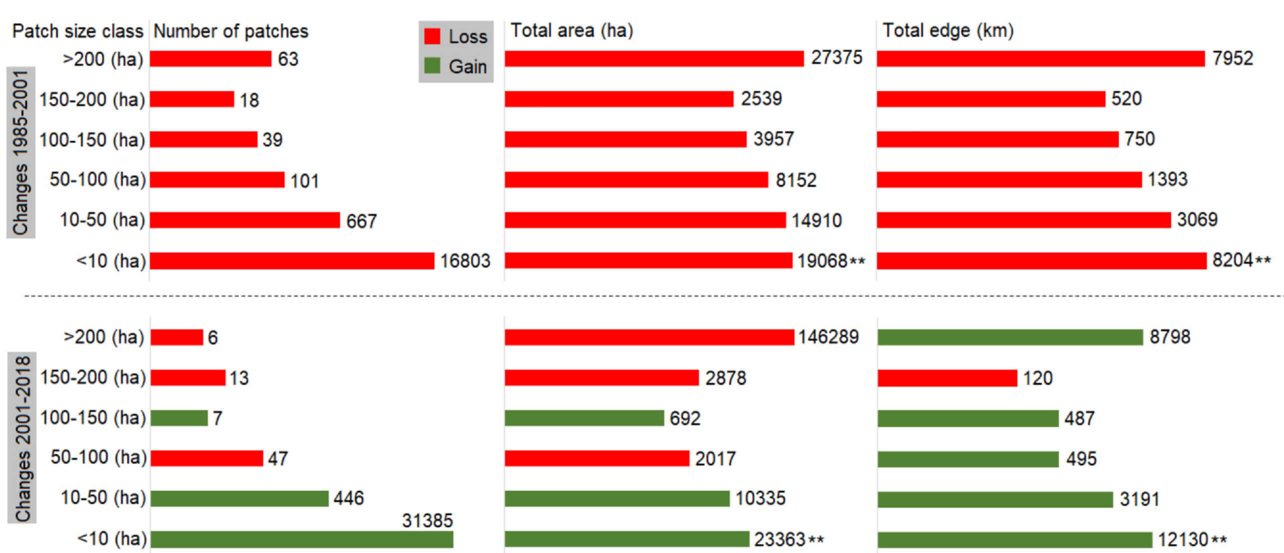

Fig. 4. Natural vegetation cover changes according to patch size classes between 1985 and 2001 and between 2001 and 2018 within the mountain regions of the Atlantic Forest biome. The horizontal bar charts display loss and gain in number of patches, total area and edge, per size class in each period. Asterisks are pointing out where statically significant changes where observed: **p-value < 0.01.

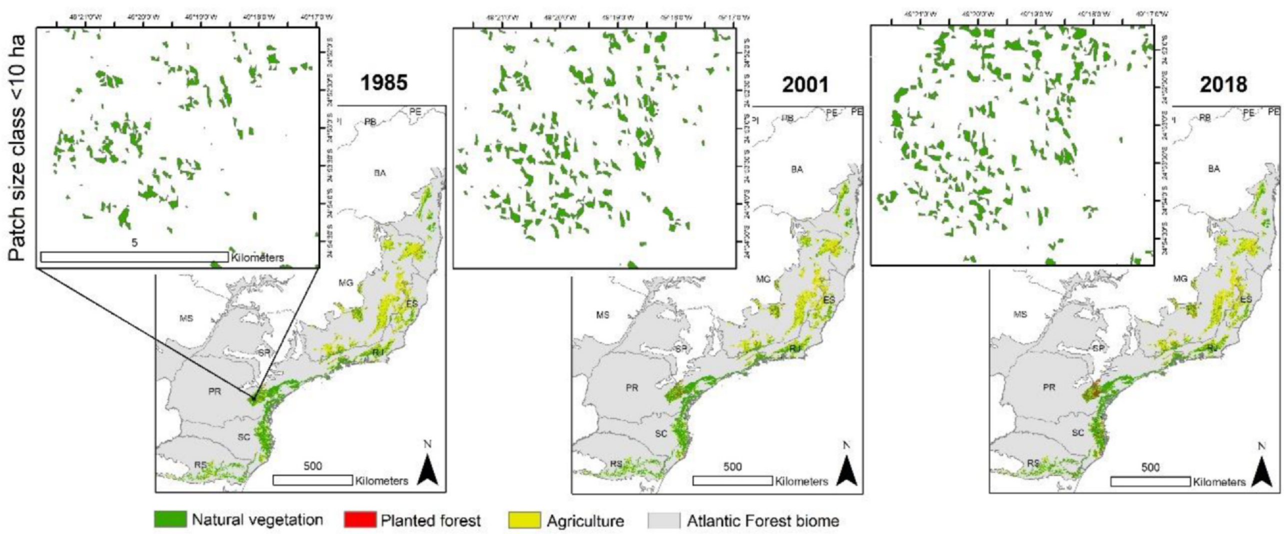

Fig. 5. The thematic maps highlight the major LULC classes found in mountain regions of the Atlantic Forest biome. The magnified boxes on the top displays only natural vegetation patches of size class < 10 ha, the group of vegetation fragments that underwent significant changes along the analyzed period.

2016). In that regard, we understand that the typical slope of the study area contributes to restricting large-scale human-induced changes, such as that observed in agribusiness (e.g., soybean) frontiers of Brazil where land is flatter (Dou, Silva, Yang, & Liu, 2018; Chen et al., 2018). Previous studies in local areas with hilly topography in the Atlantic Forest biome have demonstrated that local agribusiness activities are small-scale producers of dairy, horticulture and coffee (Souza, de Graaff, & Pulleman, 2012; Silva, Batistella, & Moran, 2018; Teixeira, Vermue, Cardoso, Peña Carlos, & Bianchi, 2018), and in most cases related to local and short supply chains arranged in coupled rural–urban systems (Silva, Rodrigues, Vieira, Batistella, & Farinaci, 2017).

Our study reveals that urban and rural populations are associated with higher natural vegetation cover areas, which indicates that densely populated areas do not necessarily result in widespread deforestation in mountain regions. We also found that 80% of urban areas are located at elevations with greater presence of natural vegetation, the same elevations with greatest species richness (Caglioni et al., 2018; Silveira et al., 2019), a similar situation observed in African mountains, i.e. higher densely populated areas associated with higher biological diversity (Burgess et al., 2007). A telecoupled systems approach (i.e., distant and connected coupled human-natural systems, Liu et al., 2013) has already shown the effects of tourism in environmental conservation in regions of higher ecological value (Wang & Liu, 2016; Liu et al., 2016; Chung, Dietz, & Liu, 2018) and here we hypothesize that ecological tourism connecting urban and distant populations to the mountain regions foster conservation, but also develop settlements in those regions with a majority relying on ecotourism and leisure activities. Additionally, as noted by previous studies, local communities are prone to conserve natural ecosystems in situations where they directly benefit from activities promoted by ecotourism (Sekhar, 2003; Moswete, Thapa, & Darley, 2020).

The development of tourism in rural and costal zones of the Brazilian Atlantic Forest is a trend already observed in many parts of the biome (Abrahão & Tomazzoni, 2018). Silva et al. (2018) found that landowners' conservation values in their searching for a second home (whether for leisure or to develop rural tourism), increased the likelihood of forest conservation practices in their properties. Tourism development in southern Brazil is a major economic and cultural off-farm activity (Graziano da Silva & Del Grossi, 2001; Neleman & Castro, 2016). Therefore, the high scenic, touristic and cultural values of the mountain regions of the Atlantic Forest (Souza & Medina, 2011; Conti & Irving, 2014) suggest that tourism and second home in the mountains, where forest cover is one of the most attractive features plays a key role for the maintenance of the observed steady state of the landscape. The positive correlation of local population with larger natural vegetation areas is also explained by the fact that these areas attract tourists while developing local economies and fostering changes in local small-scale agro-extractivism to join ecotourism business (Giatti & Rocha, 2001; Gomes, Bianchi, & Cardoso, 2020). Nevertheless, the growing forestry industry in Brazil, which supplies human demand for many forest-based products (e.g., charcoal, wood, cellulose pulp), indirectly induced the observed increase in planted forests, mainly at the expense of natural vegetation areas in the case of the mountain regions of the BAF.

Eucalyptus cellulose pulp production in the BAF has been shown to be an example of a forest-based telecoupled system with positive effects over natural vegetation, due to the adoption of international eco-certifications (e.g., Forest Stewardship Council) (Silva et al., 2019). However, little is known about forest plantations with products destined for local and regional uses (to supply charcoal, firewood, wood for tools and construction), overlooked by certification systems or robust public surveillance. Telecoupling processes connecting mountains with other systems remain understudied (Kapsar et al., 2019), but further research may uncover the underlying drivers of land exchange between agriculture and natural vegetation and other dynamics in the case of the Atlantic Forest.

We observed a 2.7% net loss of natural vegetation cover within the mountain regions in the 34 years, thirteen-fold lower than what has been observed in areas outside mountains. This result suggests lower human pressure over natural remnants of Atlantic Forest within the study area, therefore increasing the importance of the mountains as keystones for the biome's biological conservation.

4.1.1. Urban areas and development in mountains

It is alarming that 27% of the urban areas in mountain regions (although < 0.5% of the analyzed territory) lie on terrain with slopes greater than 30%. Terrain with slopes greater than 30% are not recommended for urbanization as the risk of landslides increases considerably, but also challenges urban planning-infrastructure development such as the construction of landfills and rainwater drainage systems (Sato et al., 2011). Therefore, this scenario is particularly critical in tropical mountain regions, susceptible to intense rainfall events potentially damaging infrastructures, threatening human lives and housing (Furian, Barbiéro, & Boulet, 1999; Rosa Filho & Cortez, 2010; Iwama, Batistella, & Ferreira, 2014). Between 1928 and 2005 in Brazil, Rosa Filho and Cortez (2010) found 3522 records of death caused by landslides in settlements on steep slopes. Despite the decline in rural population and the lower growth rate of the mountain urban population compared to the national rate, in the last decades cities in mountains faced a 33% increase of inhabitants pushed urban area to growth by 170% (reaching 0.6% of the study area in 2018). This will potentially exacerbate the tensions between human settlements and related drivers of environmental degradation (e.g., constructions in steep slopes increasing the likelihood of landslides and erosion processes; Sandholz, Lange, & Nehren, 2018) with the mountain ecosystem. Rosa Filho and Cortez (2010) and Sandholz et al. (2018) noted that housing on steep slopes increasingly affects poor people given the high frequency of *favelas* (i.e., unregulated low-income type of slum neighborhood) in those zones. In addition, trash production must be considered, as landfills in steep slopes are highly exposed to the risk of landslides and runoff (Sato et al., 2011; Sandholz et al., 2018), and in mountain regions these infrastructures are usually placed in peri-urban areas of low land market value associated with geological risks (Rosa Filho & Cortez, 2010).

4.2. Landscape change, biodiversity and ecosystem services

A previous study in the Atlantic Forest revealed that 80% of the biome's natural vegetation is concentrated in fragments smaller than 50 ha (Ribeiro et al., 2009). We found a different scenario in mountain landscapes, with 90% of the natural vegetation area within fragments larger than 50 ha, in 1985, 2001, and 2018. The landscape structure, in this case, shows a higher likelihood of concentration of larger fragments in mountain regions compared to non-mountains. The size of fragments has a great impact on species richness, core area and on human influence (e.g., poaching and logging) (Scariot et al., 2003; Oliveira, Grillo, & Tabarelli, 2004). A positive correlation of species richness with the size of forest fragments has been observed in the Atlantic Forest, pointing out that the greater the richness, the larger is the fragment (Vieira et al., 2003). Highly fragmented forest landscapes increase human accessibility to forest edges and core areas, increasing the likelihood of poaching and illegal logging with great impacts on biodiversity and to local ecological process (Vieira et al., 2003; Scariot et al., 2003). A study in the Andean Montane Cloud Forest has shown that inner areas in large patches of natural vegetation, with low or no influence of human pressure have the highest biodiversity values (Ledo et al., 2012). A similar result was observed in the Atlantic Forest, where inner areas of large forest fragments presented significantly higher number of tree species compared to the edges (Oliveira et al., 2004).

Despite increases in edge and shape complexity (Total Edge and Average Weighted Mean Shape Index patch metrics) from 1985 to 2018, significant changes were not observed in patch size classes greater than 10 ha. In this regard, the results reveal a significant stability of large fragments across time, which are vital for maintaining biodiversity as they are less likely to have the core areas affected by human activities.

The largest patch of natural vegetation within the study area, the same in 1985 and 2018, represented 18% of the largest continuous area of the biome in 1985 compared to 40% in 2018. Thus, despite decreasing in total area during the study period, this largest patch increased its importance in landscape structure. This is key to sustaining habitat-sensitive species, such as the *Sclerurus scansor*, a neotropical forest bird species found in the Atlantic Forest, that refuses to leave forest habitats even in highly fragmented landscapes, which makes it restricted to larger patches of forest (Hansbauer, Storch, Pimentel, & Metzger, 2008). Additionally, the large patches in the Atlantic Forest have greater importance in time-lag effects such as on bird functional-group richness, given its capacity to support sensitive species for longer periods, therefore key to support endangered populations (Uezu & Metzger, 2016).

4.2.1. Small patches matter for biodiversity and ecosystem services

Despite larger patches of natural vegetation exerting a higher positive effect on biodiversity conservation, small fragments also play an important role in ecological processes and ecosystem services. The patch size class of < 10 ha, the only with significant changes, is the most vulnerable to human-induced actions in mountain regions of the Atlantic Forest. However, in the Atlantic Forest of Minas Gerais State, Santos, Silva, Souza, Morel, and Santos (2018) found high tree species richness (around 150 species) in fragments up to 10 ha and with low species similarity between them (both located in the same study region), revealing the potential of small patches to conserve biodiversity. In the *Poço das Antas* Natural Reserve (Conservation Area of Total Protection), in the Atlantic Forest of Rio de Janeiro State, the abundance of almost all small mammal species are ten-fold higher in small forest patches than observed in large continuous fragments (Scariot et al., 2003).

Beyond the importance in conserving species, small patches of natural vegetation provide seedlings for local ecological restoration projects, soil conservation, erosion control, local climate regulation, and in maintaining the hydrological cycle in watersheds, an indispensable ecosystem service for freshwater provision and quality (e.g., filtering rainwater from higher slopes before entering water bodies carrying sediments or residual agricultural inputs). Silva et al. (2016) have also demonstrated that forest remnants are the most important landscape element driving forest transition through natural succession in the Atlantic Forest. Therefore, even small patches have great importance for maintaining key ecosystem services as well as supporting habitat for a variety of species, and a reservoir for plant diversity, key for the ongoing forest landscape transitions.

5. Conclusions

The limited LULC changes from the perspective of overall landscape composition may conceal important dynamics at the patch level, such as patterns of fragmentation, increased edge effects, higher exchange rates, and reduction in mean patch area of important continuous areas. Thus, the approach used in this study has proven to be effective for analyzing long-term landscape change in tropical mountain ecosystems under human influence.

With regards to natural vegetation cover and population dynamics, our study provided some important conclusions. First, the total loss of natural vegetation within mountain regions, thirteen-fold lower than outside, revealed that natural vegetation in mountains is under less pressure. Additionally, the fact that 90% of natural vegetation areas occur in patches larger than 50 ha indicates that the mountain regions are playing a vital role to conserve habitat-sensitive species in the Brazilian Atlantic Forest biome. Second, human population has posed less direct threat for natural vegetation in mountains, but 27% of built-up areas on slopes over 30% and with an urban area growth of 170% in 34 years, poses a high risk for human populations and a challenge for landscape and urban planning to (a) conserve key ecosystem services, such as freshwater provision, and (b) to develop urban infrastructure. However, the low proportion of mountains under total protection (only 8.7%) raises an alert as these key landscapes require specific public polices for planning and management-which are currently lacking. Particularly, we envision potential approaches to inform policy makers: i) The largest patch identified in this study can be the focus of a joint conservation initiative by the three states where it belongs; ii) landscape mosaics should be taken into account when examining particular ecological processes affected by fragmentation and the datasets produced are available for such analyses (e.g., MapBiomas); iii) specific patches of natural vegetation cover can also be extremely important for biodiversity depending on their species richness as well as occurrence of endangered and endemic species; iv) as the planted forests were major drivers for removal of natural forest in the mountains, this forestry-based sector should be strictly regulated (by public authorities and eco-certification protocols) to ensure compliance with environmental regulations.

Finally, our work highlights the importance of questioning straightforward assumptions about the influence of topography on human activity. It might be assumed that steep slopes would hinder human access to mountain regions, therefore lowering human pressure on those environments providing considerable protection or avoiding urbanization over unsuitable/higher risk areas. However, as we show here and as demonstrated by previous empirical findings (Moran, 2005), the topography of mountains may provide only a necessary but not sufficient protection. Therefore, institutions (e.g., rules in use, policies) play a key role working in combination with the biophysical features to ensure that conservation strategies and urban planning in these fragile landscapes provide real environmental protection and well-being for human populations.

CRediT authorship contribution statement

Ramon Felipe Bicudo Silva: Conceptualization, Methodology, Software, Investigation, Formal analysis, Writing - original draft, Writing - review & editing. **James D.A. Millington:** Methodology, Investigation, Writing - review & editing. **Emilio F. Moran:** Investigation, Writing - review & editing. **Mateus Batistella:** Investigation, Writing - review & editing. **Jianguo Liu:** Investigation, Writing - review & editing.

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