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Urban expansion and forest reserves: Drivers of change and persistence on the coast of São Paulo State (Brazil)

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ABSTRACT

Landscapes changes are a result of a wide range of interactions between actors and driving forces (DFs). In this study, we quantify the contribution of different types of DFs to processes of land change in the Northern Coast of São Paulo State (NCSP), Brazil, an important region for tourism and the energy sector. We analysed the relationship between DFs and the processes of land change from 1985 to 2000 and from 2000 to 2015 with partial least squares path modelling. The political and technological DFs were the most important groups of drivers for explaining the observed processes, especially the most dominant ones: policies on land use and environment (political DF), distances to the main transportation infrastructure (technological DF), and the presence of steep slopes in Serra do Mar (natural DF) influenced forest persistence and were also determinants for urban settlement distribution. The State Parks and the zones for nature conservation (political DF) were important for the maintenance of forest cover and overall the importance of political DF increased after 2000. In general, the DFs in NCSP were similar to those observed in other coastal and tourist regions, but surprisingly, despite a rapid population increase, demography did not explain urban and peri-urban growth. Urban growth was happening foremost in the zones for urban development and was accompanied by increases in water provision services and waste collection, whereas peri-urban sprawl was concentrated in conservation and agricultural zones, without investments in basic services. We conclude that an increasing demand for housing must be considered in future policies in NCSP, instead of solely focussing on economic interests in tourism and the energy sectors.

1. Introduction

Landscape change results from the interaction of actors and driving forces of varying importance (Antrop, 2005, 2000; Dansereau, 1975; Geist and Lambin, 2002; Klijn, 2004; Pedroli et al., 2010; Plieninger et al., 2016). Brandt et al. (1999) distinguish between five groups of driving forces: socio-economic, political, technological, natural and cultural. The systematic study of driving forces from these five groups can lead to a deeper understanding of the processes shaping landscape changes and provide a powerful basis for land-use planning (Antrop, 2005; Klijn, 2004).

A growing body of literature has focused on understanding the drivers of land changes through descriptive and quantitative approaches (Bürgi et al., 2017). Specifically, socio-ecological models can provide realistic and useful results, and facilitate communication between scientists, decisions makers and local stakeholders (Verburg et al., 2016, 2015). Quantitative models have frequently been applied to explain the drivers of land change at different spatial and temporal scales (Van Asselen and Verburg, 2013; Verburg et al., 2015). While most quantitative land-use models focus on land change prediction (Bolliger et al., 2017) and scenario-based modelling (Verburg et al., 2008), quantifying the contribution of different driving forces on land change in explanatory models received less attention. The Partial least squares path modelling (PLS-PM) is a powerful multivariate method to estimate

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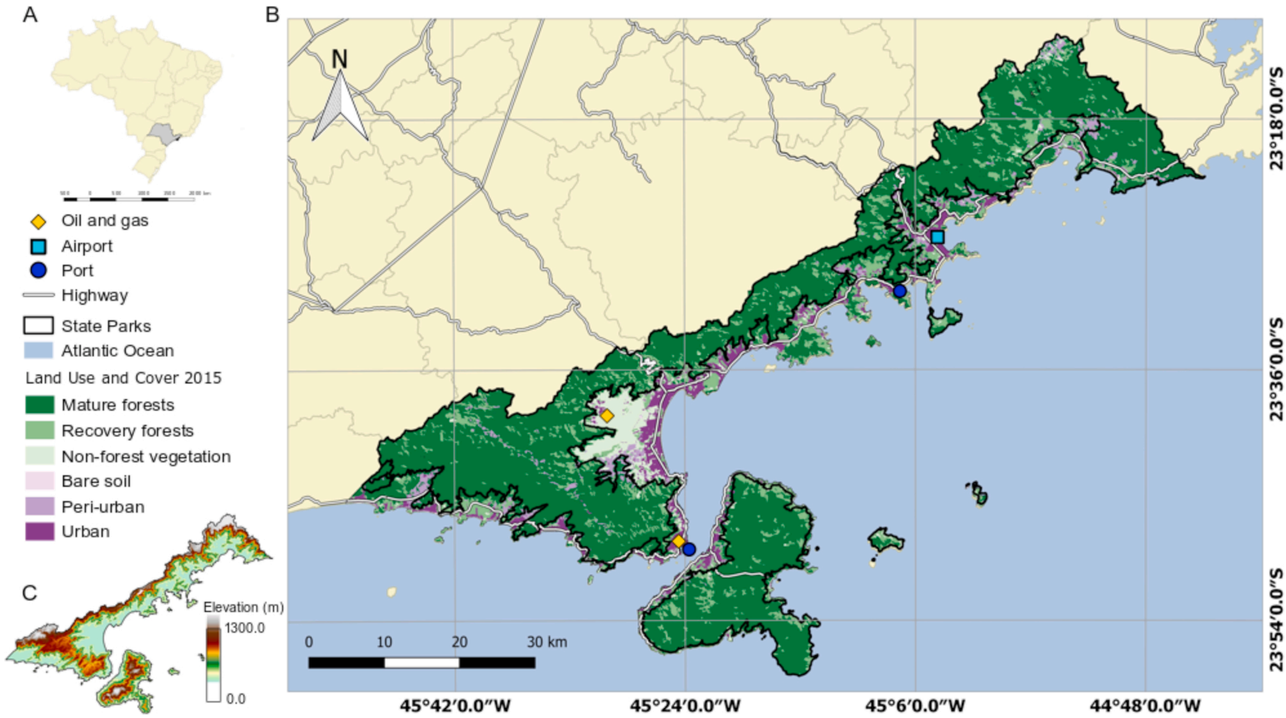

Fig. 1. A) Map of Brazil showing the location of São Paulo State. B) Northern Coast of São Paulo State (NCSP) showing the location of State Parks, main highways, oil and gas infrastructure, major ports and airports, and land use and cover (Pierri Daunt and Silva, 2019). C) Digital Elevation Model from NCSP (ALOS World3D, https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm).

complex cause–effect relationships (Sanchez, 2013) that has been traditionally applied in social science and business studies (Latan and Noonan, 2017), and more recently in environmental science (Fan et al., 2016; Sanches Fernandes et al., 2018) and land-change science (Fan et al., 2017). Since PLS-PM is less restrictive in the combination and use of different variables (Latan and Noonan, 2017; Nitzl and Chin, 2017) it is expected to be especially suited to quantify the contribution of driving forces to observed land-change processes.

As in many other parts of the world, the Northern Coast of São Paulo State (NCSP) experiences rapid urban growth encroaching into the natural and cultural landscapes. This process occurs since the late 20th century, foremost as a result of rapid population growth and investments in the tourist and energy industry sectors (Ab'Sáber, 1986; Ribeiro et al., 2009; Teixeira, 2013). At the same time, three State Parks have been established in the region to protect its rich biodiversity, resulting in more than 70 % of NCSP territory being designated for nature and biodiversity conservation. By coupling ecological and economic dimensions, an Ecological-Economic Zoning (EEZ) was introduced by the state government in 2005 and since became one of the main instruments to regulate land-use change at NCSP. Yet, it is unclear whether the designation of State Parks and the land-use policies have had the intended effect on land-use change and nature conservation.

We present results from a study analysing the relationship among driving forces and processes of land change in NCSP from 1985 to 2015, using PLS-PM. We use the term "process" in this paper, as suggested by Bürgi et al. (2017), as a way to synthesize land-use and cover (LULC) conversion or stability. An earlier study on LULC changes in NCSP has revealed a decrease in rates of urban growth and deforestation around the year 2000 (Pierri Daunt and Silva, 2019). Consequently, we split the study period into two 15-year periods to ask the following questions: 1) what were the main LULC change processes observed in each period? 2) What was the relative contribution of each driver of change to LULC processes in each period? 3) What impact did land-use policies and the designation of protected State Parks have on LULC dynamics?

By answering these questions, we contribute to a better understanding of the role of land-use policies in driving LULC change, which is still a knowledge gap in Brazil, as pointed out by Schielein and Börner (2018).

2. Material and methods

2.1. Study area: the Northern Coast of São Paulo State

NCSP is an administrative unit including four municipalities: Caraguatatuba, Ilhabela, São Sebastião and Ubatuba (Fig. 1), covering an area of 1,948 km^2. NCSP includes a portion of the Serra do Mar mountain range and is characterized by steep slopes rising from sea level to 1,300 m, most of which are high-risk areas for flooding and mudslides and thus unfit for human habitation (Ab'Sáber, 2007; Rossi and Queiroz Neto, 2001). The region is located within the Atlantic Forest biome and holds some of the largest and best-preserved Atlantic Forest remnants in Brazil (Instituto Nacional de Pesquisas Espaciais, 2016; Ribeiro et al., 2009). Presently, around 80 % of NCSP territory is covered by Atlantic Forest, and most of this forest area is located in three protected State Parks (Pierri Daunt and Silva, 2019).

The history of human settlement and land changes started after the European arrival in the early 1500s, but the rate and intensity of land changes increased strongly in the second half of the 20th century, when NCSP became a touristic hotspot. Tourism and the presence of the biggest Brazilian oil and gas company, Petrobras, created strong pressure to expand settlements and transportation networks (Comitê de Bacias Hidrográficas do Litoral Norte (CBHLN), 2016; IBGE, 2010; Pierri Daunt and Silva, 2019). After the construction of the major Brazilian highway BR101 along the coast by the end of the 1970s, NCSP population rapidly rose from 87,800 inhabitants in 1980 to 223,900 in 2000 and 281,800 in 2010 (Instituto Brasileiro de Geografia e Estatística, 1980, 1991, 2000, 2010), mostly as a result of immigration (do Carmo et al., 2012; Cunha, 2003; Comitê de Bacias Hidrográficas do Litoral Norte (CBHLN), 2016. Urban land use thus grew by 167 % from 1985 to 2015, through both peri-urban sprawl and densification of urban centres

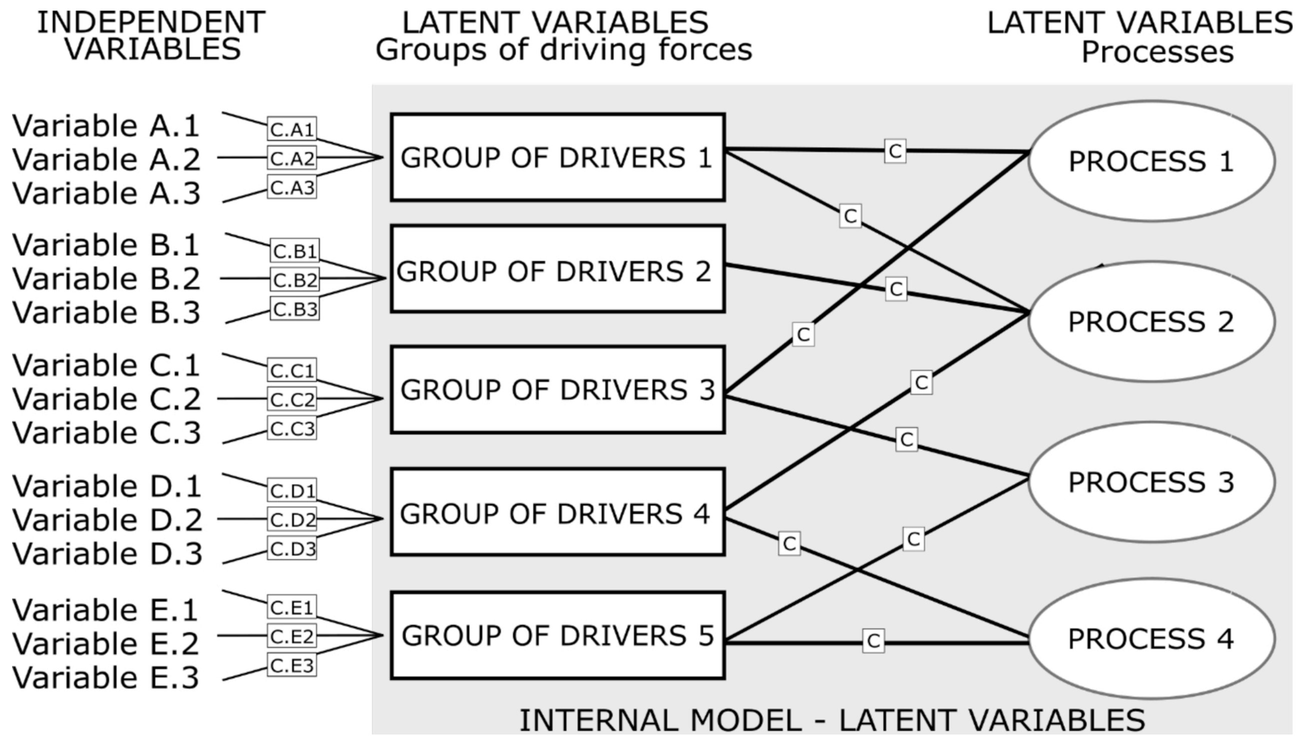

Fig. 2. Theoretical model structure using partial least squares path modelling (PLS-PM), following Sanchez (2013). C (coefficient of contribution) refers to the contributions of the groups of drivers to processes of change. C.A1 –C.E.3 refer to the contributions of independent variables to each group of drivers.

(Pierri Daunt and Silva, 2019).

Several policies were enacted during the end of 20th and early 21st century to control this development. In 1977, the three State Parks - "Serra do Mar", "Ilhabela" and "Ilha Anchieta" - were created to protect the Atlantic Forest biome. The Brazilian Protected Areas act of 2000 is the current standing policy regulating Brazilian protected areas. It prohibits any human settlement within designated State Parks, and restricts park uses to nature conservation, research and ecotourism. Presently, 70 % of NCSP lies within these three State Parks, and while over 90 % of the State Park area was covered by mature forest in 2015, more than 100 km^2 (8%) have changed from mature to recovery forest between 1985 and 2015 (Pierri Daunt and Silva, 2019). The Ecological-Economic Zoning (EEZ) State Decree 49.215 (2004) issued by the São Paulo State Government is currently one of the main instruments of regional environmental policy, including land-use policy.

2.2. Modelling driving forces and processes of change

We analysed the relationship between driving forces and processes using PLS-PM, as implemented in the "plspm" package (Sanchez et al., 2017) of the R programming language, version 3.6 (R Core Team, 2020). PLS-PM is often applied to estimate complex cause–effect relationships (Sanchez, 2013), and it was originally developed by Herman Wold (1966). It is a powerful multivariate method for analysing multiple relationships between a set of blocks of variables representing complex, multicausal processes, designated as "latent variables". In our model, the measured (or manifest) variables were organized into two types of latent variables, "groups of drivers" and "processes" of land change (Fig. 2). We considered that all "groups of drivers" can possibly effect all "processes" of land change.

The contribution of each independent variable to the respective group of drivers and to all processes, as well as the contribution of each group of drivers to each process, was analysed based on the coefficient of contribution. The first step to evaluate the quality of a PLS model is to assess the unidimensionality of the variables, which means that the measured variables must be in a geometrical space of one dimension, or, in other words, within a group the sign of the variables should be the same. Sanchez (2013) suggests inverting variables scales by multiplying the values by "-1", if necessary. We applied such correction to the variables "State Parks", "EEZ 1", "EEZ 2", "HDI" and "population density", for models from 2000 to 2015.

The model R^2 value indicates the proportion of process variance explained by the drivers. Following Sanchez (2013), R^2 can be interpreted as *high* ($R^2 > 0.5$), *moderate* ($0.2 < R^2 < 0.5$) or *low* ($R^2 < 0.2$).

PLS-PM models are rather sensitive to dominant processes; as State Parks cover 70 % of the study area and this value has been relatively stable over time, we built two separate models, one for the entire study area and one excluding the State Park area. This setup allowed us to get a better understanding of the relationship between drivers and processes outside the State Park boundaries.

2.3. LULC change data: dependent variable

Data on LULC change for NCSP between 1985 and 2015 was derived from maps produced by Pierri Daunt and Silva (2019) for NCSP (data publicly available at https://zenodo.org/record/2648783). We reclassified the LULC data into relevant processes of change from 1985 to 2000 and from 2000 to 2015 (Supplementary Material A). Different land cover conversions can sum up to the same process; for instance the process "urban growth" consists of conversions from various LC types into the "urban" class; "peri-urban growth" consists of conversions from various cover types into the "peri-urban" class; "forest persistence" consists of no changes in "mature" and "recovery" forest classes; and "deforestation" consists of conversions from both forest classes to any other cover type (Bürgi et al., 2017). We created binary rasters for each process of change from 1985 to 2000 and from 2000 to 2015, and this data was considered the dependent variable in our models.

2.4. Driving forces: independent variables

Driving forces were classified as natural, cultural, socio-economic, political and technological (Brandt et al., 1999, Table 1). The

Table 1
Independent variables used to model the processes of land use and land cover change in the Northern Coast of São Paulo State, Brazil. DF = driving forces. Sources: Brazilian Institute of Geography and Statistics (IBGE); Forestry Foundation from São Paulo State (FF-SP); National Department of Transportation and Infrastructure (DNIT); São Paulo State Environment Plan Division (CPLA-SP); U. S. Geological Survey (USGS). *All data from the IBGE National Census is referenced to permanent inhabitants and permanent housing. **The information is the same for 1985-2000 and 2000-2015.

Independent variable	Information/ description	Source/data origin	Time range (years)
Political DF			
State Parks	Serra do Mar, Ilhabela and Ilha Anchieta State Parks limits	FF-SP	before and after 2010
Ecological-Economic Zoning (EEZ)	EE Zones	CPLA - SP	2005
Waste service	Waste collection service in % per census sector (change per year)	Federal census (BIGS) *	1991, 2000, 2010
Sanitation service	Sanitation services in % per census sector (change per year)	Federal census (BIGS) *	1991, 2000, 2010
Water service	Clean water provision service in % per census sector (change per year)	Federal census (BIGS) *	1991, 2000, 2010
Socio-economic DF			
Basic education	Basic education in % per census sector (change per year)	Federal census (BIGS) *	1991, 2000, 2010
HDI	Human Development Index (HDI) per municipality (change per year)	Federal census (BIGS) *	1991, 2000, 2010
Mean income	Mean income in Reais (R$) per census sector (change per year)	Federal census (BIGS) *	1991, 2000, 2010
Population density	Population density per pixel (change per year)	Federal census (BIGS) *	1991, 2000, 2010
Permanent housing density	Density of permanent housing per pixel (change per year)	Federal census (BIGS) *	1991, 2000, 2010
Natural DF			
Distance to high-risk areas	Cumulative cost distance from areas with a high risk of flooding and mudslides	Geological Institute (GI)	Data for 1985-2000 and -2000−2015**
Slope	Slope °	ALOS 30 m	Data for 1985-2000 and -2000−2015**
Topography	Topography position index (TPI)	ALOS 30 m	Data for 1985−2000 and 2000−2015**
Technological DF and landscape access			
Distance to highways	Cumulative cost distance from principal highways	DNIT	Data for 1985−2000 and 2000−2015**
Distance to industrial infrastructure (oil and gas industry)	Cumulative cost distance from O&G industrial infrastructure	Visual identification	Before and after 2007
Distance to seaports and airport	Cumulative cost distance from ports and Ubatuba airport	Visual identification	Data for 1985−2000 and 2000−2015**

Table 1 (*continued*)

Independent variable	Information/ description	Source/data origin	Time range (years)
Cultural DF			
Distance to traditional communities	Cumulative cost distance from Native people presence	Watershed Committee -NCSP	Data for 1985−2000 and 2000−2015**

background information from the literature on the driving forces is available in Supplementary Material B. All input data was transformed to a raster with 30 × 30 m pixel size. Supplementary Material C Figure C shows the mapped values for each variable.

2.4.1. *Political driving forces*

The three State Parks were already established in 1977, before the start of our study period, and they were included in the model as a binary raster.

The 2004 EEZ (Fig. 3) represents the legally established land-use zones: Zone 1 is designated for forest conservation and allows a maximum of 10 % of built-up areas (192.36 km^2), and Z1EAP refers to the State Parks (1410.92 km^2). Zones 2 (108.14 km^2) and 3 (86.61 km^2) were created to promote agroforestry and sustainable ecotourism, and Zones 4 (89.01 km^2), 4OS (34.12 km^2) and 5 are reserved for urban and industrial uses (23.65 km^2).

The percentage of households receiving waste collection, sanitation and water provision services, called basic services in the context of this study, was derived from the Brazilian National Census data from 1991, 2000 and 2010. Annual rates of change for 1985 to 2000 and for 2000 to 2015 were estimated to allow comparability between LULC periods, since the Brazilian National Census occurs only every 10 years (1991, 2000 and 2010). Therefore, we calculated the difference between values and divided it by the number of years.

2.4.2. *Socio-economic driving forces*

Socio-economic data for NCSP was derived from the Brazilian National Census data (IBGE, 1991, 2000 and 2010). First, population density, permanent housing density, mean income and basic education percentages were calculated per 30 m pixel. Second, annual rates of change were calculated for 1985–2000 and 2000–2015 to allow comparability between LULC periods.

The Human Development Index (HDI) characterizes overall social situation, and it “should be the ultimate criteria for assessing the development of a country” (ONUP, 2019). HDI tends to be higher in urban areas. We used HDI per municipality as available in the Federal census data from the Brazilian Institute of Geography and Statistics (IBGE, 1991, 2000 and 2010) and annual rates of change were calculated for 1985–2000 and 2000–2015.

2.4.3. *Natural driving forces*

Slope and the topography position index (TPI) were derived from the ALOS World 3D 30 m digital elevation model, produced by the Japanese Aerospace Exploration Agency (JAXA) by downsampling 5 m resolution to 30 m resolution data (https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm), and were considered to be constant during the study period. The TPI is defined as the difference between the elevation of a central pixel and the mean of its surrounding cells, and it is frequently applied for landforms characterization (Weiss, 2001). Slope and TPI determine areas suitable for intensive land use, such as dense settlements, however, in Brazil urban sprawl often occurs in the surroundings of areas exposed to high environmental risks (Maricato, 2003). To address this aspect, the cumulative cost distance from areas with high flood and mudslide risk (São Paulo, 2014) were considered to be constant from 1985 to 2015.

The cumulative cost distance data provides the cumulative cost

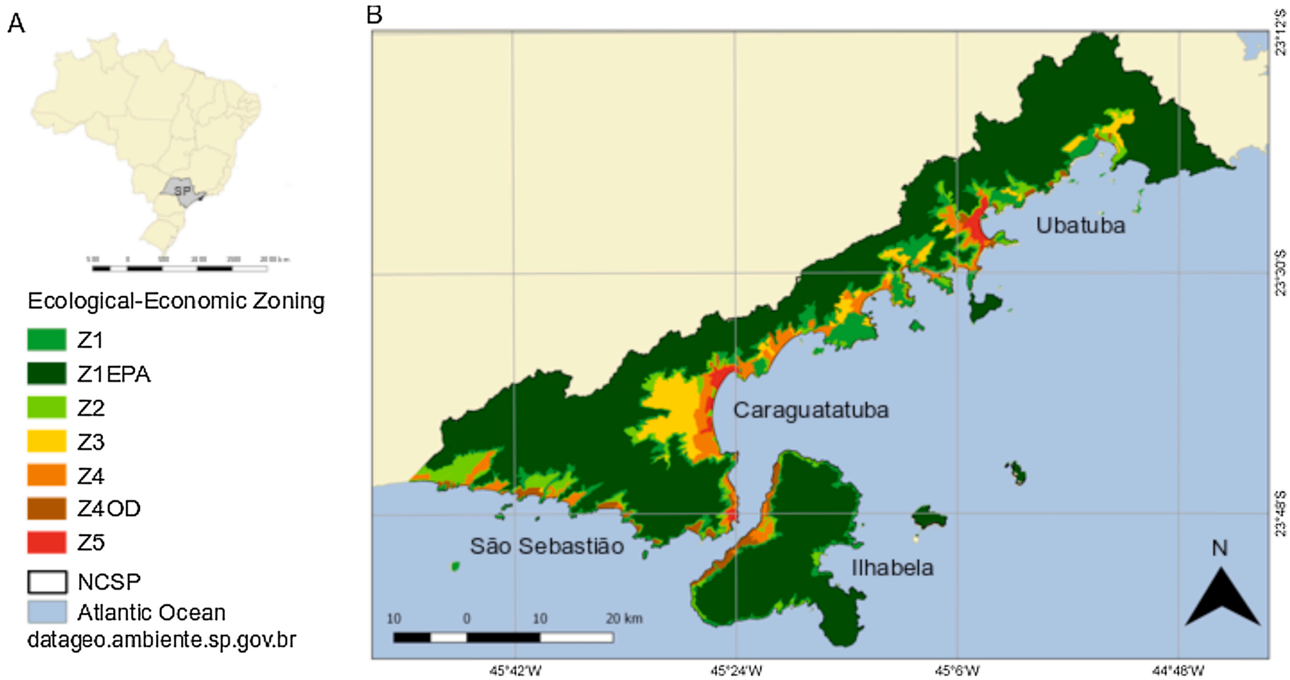

Fig. 3. A) São Paulo State location. B) Ecological Economic Zoning (EEZ) within the Northern Coast of São Paulo State (NCSP), implemented in 2004. Z1: forest and ecosystem conservation; Z1EPA: State Parks; Z2: natural resources and ecosystem conservation, water provision service, and landscape heritage conservation; Z3: agricultural use, rural villages, and multifunctional land use; Z4: dense urban development; Z4OD: urban development with low impact; Z5: industrial and urban services. Source: CPLASP.

distance for each cell to the nearest source over a cost surface (Environmental Systems Research Institute, 2016). To calculate the cumulative cost distance from areas with a high risk of flood and mudslides, we produced a multi-criteria cost surface raster by combining the topography dataset with the LULC categories dataset (Environmental Systems Research Institute (ESRI, 2016). Finally, we created cumulative cost distance raster maps (one for each time step) in the GRASS 7 environment accessed from QGIS 3.1 software.

2.4.4. Technological driving forces and landscape access

Distances from the main highways, seaports, Ubatuba airport and industrial infrastructure were assumed to be drivers of settlement growth (both urban and peri-urban), forest disturbance and deforestation processes, with areas closer to these infrastructures being more susceptible to change. Therefore, the cumulative cost distances to the principal highways, the two seaports, the Ubatuba airport, and the industrial infrastructure were calculated using GRASS and QGIS.

2.4.5. Cultural driving forces

The NCSP hosts several Guarani (indigenous people), Caiçara (traditional coastal peoples) and Quilombola (former escaped African and Afro-Brazilian slave settlements) territories (São Paulo, 2006, 2016). These traditional communities contribute to landscape and natural resource conservation, mainly through their small-scale agroecological family farming and use of fallow land, and for this reason were assumed as drivers of forest persistence. The NCSP Watershed Committee has provided the locations of the native settlements within these territories, from which we calculated the cumulative cost distances using GRASS and QGIS.

2.5. Pre-processing – cell analyses and normalization

Considering the diversity of data sources and spatial scales of input data, all variables were aggregated into 500 × 500 m cells (Coucelis, 1985). This procedure was performed using the "dplyr" package in R (R Core Team; Wickham et al., 2020). For quantitative variables, average values were calculated per cell, while for binary data such as EEZ and State Parks the percentage of each zone or park area within the cell was calculated and for land-use change, the percentages of each type of conversion within the cell were calculated. To deal with differences in measurement units, including indices, proportions and densities per unit area, all explanatory variables were normalized from -2 to +2 using the "norm" function in the package "scales" in R (Wickham and Seidel, 2019). To avoid multicollinearity, we tested for each model the correlation between pairs of independent variables described in Table 1, using the "corr" function in R (R Core Team, 2020), that returns a simple correlation matrix, and selected only variables with a correlation coefficient of less than 0.7. As our study is exploratory in nature, we did not aim for establishing the most accurate or parsimonious model to predict land change, but rather to quantify the relationship (i.e. estimate coefficients) between drivers and processes. Some technological driver variables (i.e. distances to seaports, airport and industrial infrastructure) were often correlated due to their aggregated spatial distribution, close to city centres. We therefore selected for each model the variable with the greatest estimated contribution. Population and housing density were correlated in all models, so we opted for including only population density in all models.

3. Results

3.1. What were the main LULC change processes observed in each period?

In NCSP, around 90 % of the State Parks persisted as forest (Fig. 4a). Outside the State Parks, the urban area increased by 98 % between 1985 and 2000, and by 35 % between 2000 and 2015 (Fig. 4b).

Therefore, urban growth outside State Parks and forest persistence

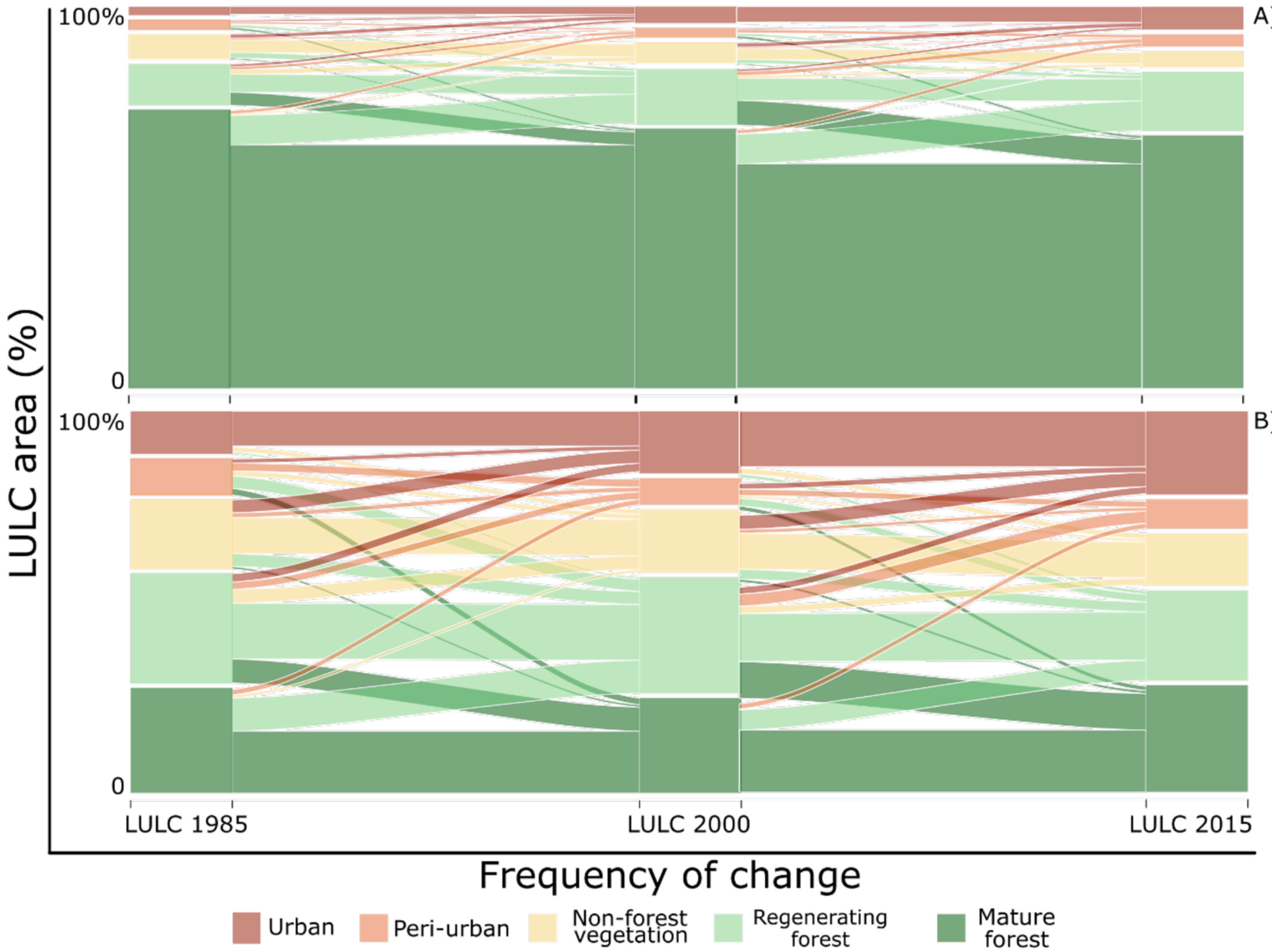

Fig. 4. Land-Use and Cover (LULC) change from 1985 to 2000 and from 2000 to 2015. Adapted from Pierri Daunt and Silva (2019). A) Entire Northern Coast of São Paulo State (NCSP); B) NCSP areas outside State Park limits. The alluvial graph allows to highlight the amount of area/pixels that continued to be forested inside park limits (in green), the conversion from forest to other LULC types, and the urban and peri-urban growth (in red and orange) outside the parks limits (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.).

within the Parks were the dominant processes, followed by deforestation and peri-urban growth (Supplementary Material A).

3.2. Driving forces of LULC from 1985 to 2000 in NCSP

Following Sanchez (2013), the R^2 for forest persistence (0.39) was considered moderate, but the R^2 for urban growth (0.16), deforestation (0.13) and peri-urban growth (0.07) were low (Fig. 5).

For the entire NCSP and the whole study period, political driving forces were most important, followed by technological, cultural and natural driving forces. Forest persistence was positively affected by political (coefficient of contribution C = 0.44) and technological driving forces (C = 0.45), i.e. forest persistence was explained by State Park limits (C = 0.64) and by the distance from highways (C = 0.41), and from seaports and airports (C = 0.39; Fig. 5). Forest persistence was negatively affected by the distance from traditional communities (C = -0.38), i.e. forests closer to these communities were more persistent. Regarding natural driving forces, forest persistence was explained by slope (C = 0.42) and distance to high-risk areas (C = 0.4). Socio-economic driving forces were not important as a group of drivers, but forest persistence was positively affected by increase of basic education percentage (C = 0.26; Table 2).

Deforestation was explained by political, natural and technological driving forces (Fig. 5), with negative contributions from the States Parks (C = -0.38), slope (C = -0.27), distance to high-risk areas (C = -0.21), and distance from highways (C = -0.21), seaports and the airport (C = -0.20; Table 2). Urban growth was mainly explained by natural (C = -0.27) and political drivers (C = -0.15), i.e. by the State Parks (C = -0.44), slope (C = -0.33), and distance to high-risk areas (C = -0.26). Surprisingly, urban growth was not explained by the increase in population density or by the percentage of households receiving basic services. Peri-urban growth was positively influenced by cultural driving forces (C = 0.3), but negatively by political (C = -0.23) and technological driving forces (C = -0.27; Fig. 5). Peri-urban growth was also negatively affected by the State Parks (C = -0.25), water service (C = -0.22) and waste collection service (C = -0.18; Table 2).

3.3. Driving forces of LULC from 1985 to 2000 outside State Parks

When considering only areas outside the State Parks for the period 1985 to 2000, R^2 was lower, i.e. < 0.2 for all LULC processes (Fig. 6). Forest persistence was positively influenced by socioeconomic driving forces (0.39) and by slope and distance to high-risk areas (Table 3). Deforestation was explained by distance to high-risk areas (C = 0.29),

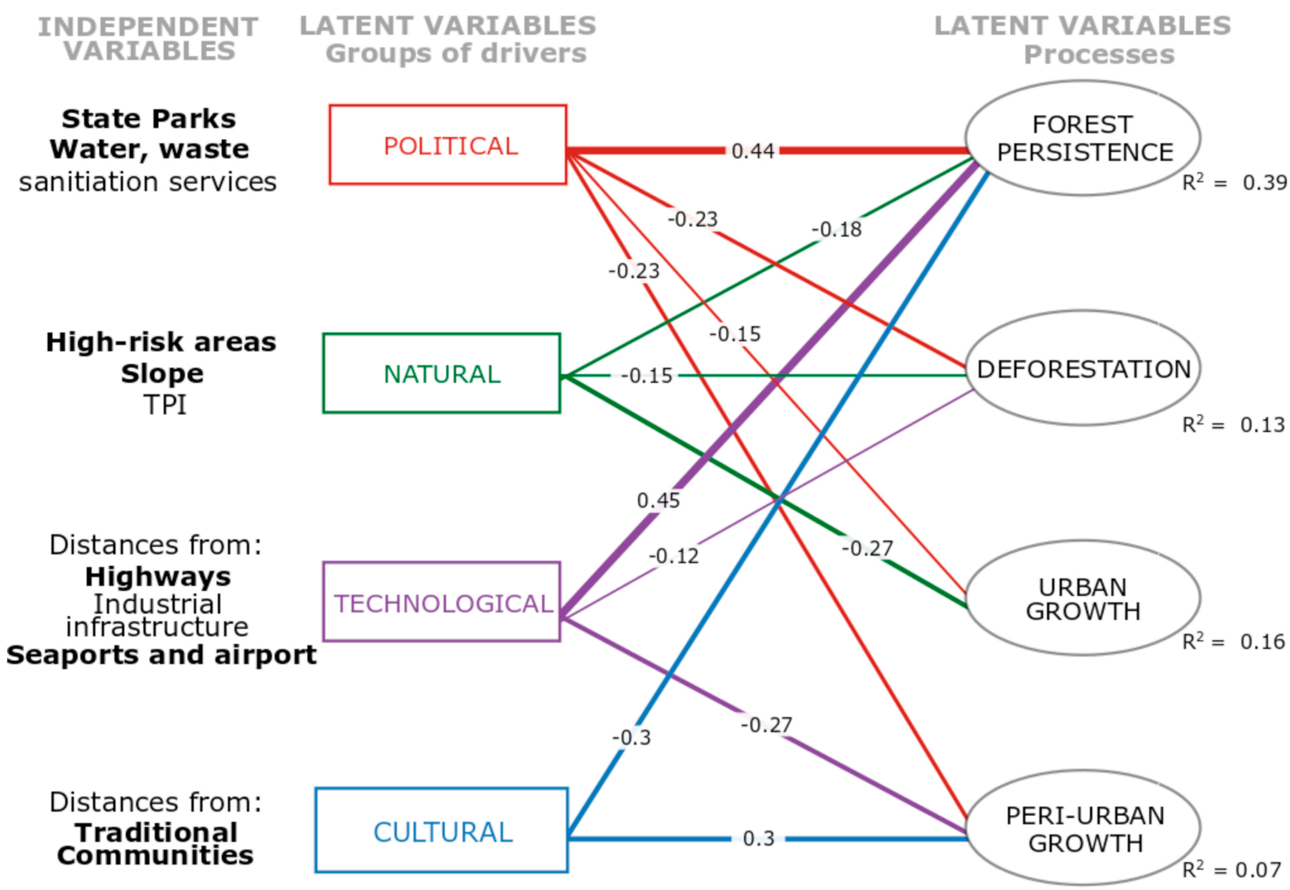

Fig. 5. Model for the entire study area for 1985 to 2000. In **Bold**: Independent variables with effect >0.7 and weight >0.5. Coefficient of contribution (C) values with an absolute value >0.1 are displayed.

Table 2
Coefficient of contribution (C) between drivers (independent variables) and processes: model for the entire study area for the period 1985 to 2000.

Driving forces (explanatory variables)	Forest persistence	Deforestation	Urban growth	Peri-urban growth
Political				
State Parks	0.64	−0.38	−0.44	−0.25
Waste collection service	0.31	−0.19	−0.16	−0.18
Sanitation services	0.11	−0.06	0.05	−0.10
Water service	0.34	−0.21	−0.11	−0.22
Socio-economic				
Basic education	0.26	−0.16	−0.16	−0.13
HDI	0.00	−0.01	−0.06	0.03
Mean income	0.08	−0.03	−0.06	−0.05
Population density	0.03	−0.12	−0.13	−0.03
Natural				
Distance to high-risk areas	0.40	−0.21	−0.26	−0.11
Slope	0.42	−0.27	−0.33	−0.17
Topography	0.06	−0.06	−0.06	−0.07
Technological				
Distance to highways	0.41	−0.21	−0.25	−0.12
Distance to seaports and airport	0.39	−0.20	−0.25	−0.10
Cultural				
Distance to traditional communities	0.38	−0.20	−0.25	−0.10

cultural driving forces (C = 0.27), and technological driving forces such as distance to highways (C = 0.29) and seaports (C = 0.27; Table 3).

Urban growth was negatively affected by distance to highways (C = -0.21), seaports and the airport (C= -0.24), and to high-risk areas (C = -0.24) and traditional communities (C = -0.24; Table 3). In contrast, the percentage of households receiving basic services was positively correlated with urban growth (Table 3). Peri-urban growth was most strongly influenced by cultural driving forces, followed by negative effects of technological and political drivers (Fig. 6). The percentage of households receiving basic services was negatively correlated with peri-urban growth (Table 3).

3.4. *Driving forces of LULC for 2000–2015 in NCSP*

After 2000, political driving forces became even more important than in the first study period for the entire NCSP area, followed by the technological driving forces and then cultural driving forces (Fig. 7). R^2 values for forest persistence and urban growth were moderate, whereas values for deforestation and peri-urban growth were low.

Forest persistence was positively affected by the State Parks (0.62) and by the distance from highways (C = 0.43), and was negatively influenced by all of the EEZ zones (Table 4). Distance from traditional communities was negatively correlated with forest persistence (C = -0.16). Conversely, deforestation was negatively influenced by the State Parks (C = -0.38) and positively by EEZ 4 (C = 0.21), EEZ 4OD (C = 0.19) and EEZ 3 (C = 0.18). Urban growth was affected by the State Parks (C = -0.44), EEZ 4 (C = 0.43), EEZ 4OD (C = 0.25) and EEZ 2 (C = 0.18). Peri-urban growth was negatively influenced by the State Parks (C = -0.25), and positively by EEZ 2 (C = 0.14) and EEZ 3 (C = 0.15), i.e. zones that regulate environmental conservation and rural development.

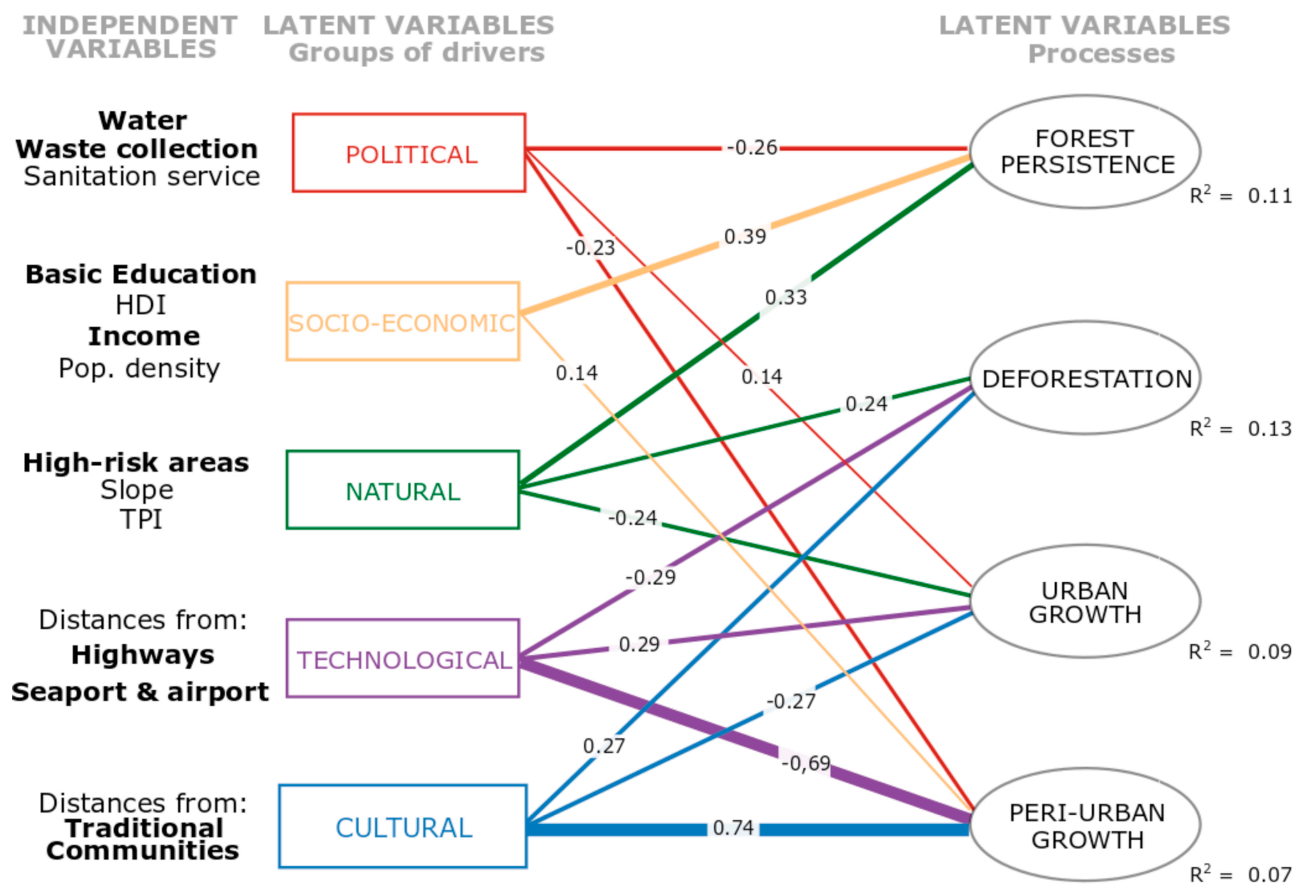

Fig. 6. Model for the area outside State Park limits for 1985 to 2000. In **Bold**: Independent variables with effect >0.7 and weight >0.5. Coefficient of contribution (C) values with an absolute value >0.1 are displayed.

Table 3
Coefficient of contribution (C) between drivers (independent variables) and processes: model for the area outside State Park limits for the period 1985 to 2000.

Driving forces (explanatory variables)	Forest persistence	Deforestation	Urban growth	Peri-urban growth
Political				
Waste collection service	0.02	−0.26	0.14	−0.13
Sanitation services	−0.12	−0.12	0.17	−0.11
Water provision	−0.05	−0.30	0.21	−0.17
Socio-economic				
Basic education	0.08	−0.23	0.10	−0.09
HDI	0.14	−0.04	−0.06	0.06
Mean income	−0.02	−0.26	0.21	−0.11
Population density	−0.02	−0.11	0.15	0.01
Natural				
Distance to high-risk areas	0.17	0.29	−0.24	0.15
Slope	0.20	0.10	−0.09	0.07
TPI 300	0.07	0.03	−0.09	−0.07
Technological				
Distance to highways	0.15	0.27	−0.21	0.11
Distance to seaports and airport	0.18	0.29	−0.24	0.18
Cultural				
Distance to traditional communities	0.17	0.29	−0.24	0.18

EEZ 5 negatively affected forest persistence but did not influence any other process, as this zone has been covered by dense urban use for a long time, and is designates for urban and industrial uses (Table 4).

3.5. *Driving forces of LULC for 2000–2015 outside State Parks*

In the model for 2000 to 2015 outside State Parks, R^2 was moderate for forest persistence (>0.2) and urban growth (0.19), while values for deforestation and peri-urban growth were low (Fig. 8).

Political driving forces were the strongest drivers from 2000 to 2015 outside State Park limits (Fig. 8). Forest persistence was positively influenced by EEZ 1 (C = 0.54), but negatively affected by EEZ 3 (C = -0.27) and EEZ 4 (C = -0.32) (Table 5). The waste collection service (C = -0.44), sanitation service (C = -0.24) and water service (C = -0.34) negatively impacted forest persistence (Table 5).

Deforestation was explained by technological driving forces, followed by socio-economic and natural driving forces (Fig. 8), i.e. deforestation was explained by distance from highways (C = 0.25) and high-risk areas (C = 0.28), and was positively influenced by HDI (C = 0.4) and negatively by the basic education (C = -0.45; Table 5). We must note that deforestation can only happen in areas that were forested before the studied time step, which explains the positive relationship with technological driving forces.

Urban growth was explained by political driving forces (Fig. 8), as it was positively influenced by the urban zones EEZ 4 (C = 0.34) and EEZ 4OD (C = 0.15) and negatively affected by EEZ 1 (C = -0.25), designated for forest conservation. Moreover, urban growth was explained by the percentage of households receiving clean water (C = 0.15), waste collection (C = 0.2) and sanitation services (C = 0.19). Urban growth was negatively influenced by the distance to highways (C = -0.18) and to the industrial infrastructure (C = -0.23), and by the socio-economic driving forces (Fig. 8 and Table 5). Peri-urban growth was positively affected by the distance to traditional communities (C = 0.69) and to industrial infrastructure (C = 0.15).

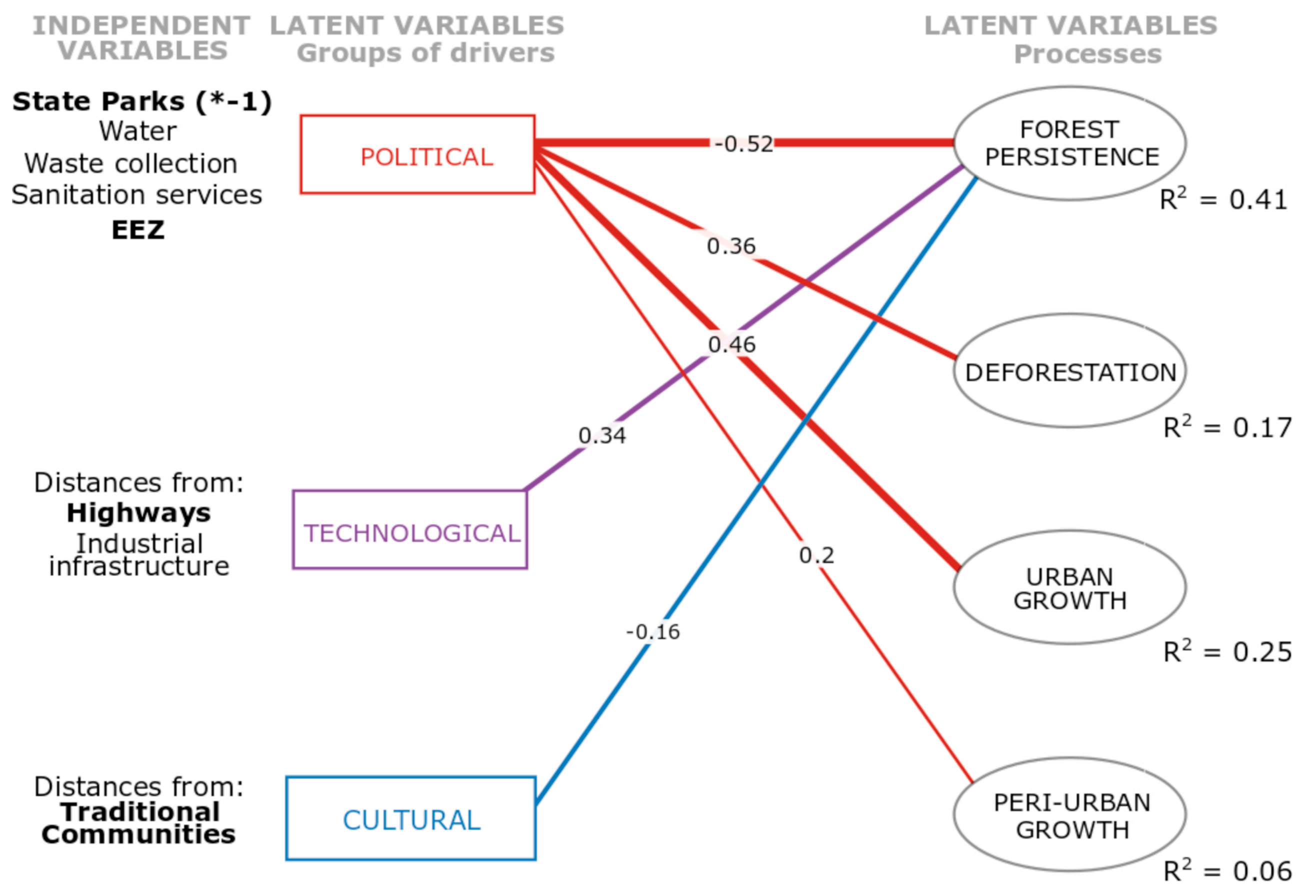

Fig. 7. Model for the entire study area for 2000 to 2015. In **Bold**: Independent variables with effect >0.7 and weight >0.5. Coefficient of contribution (C) values with an absolute value >0.1 are displayed.

4. Discussion

Our analysis allowed us to conceptually link the main driving forces into a coherent schema of interdependencies, chains of drivers and feedback loops (Fig. 9). The following section links the findings of the study to Fig. 9, followed by sections discussing political drivers in detail and the limitations.

4.1. Driving forces for land change processes

Political driving forces are often among the most important drivers of landscape changes, although they usually act indirectly (Geist et al., 2006; Hersperger and Bürgi, 2009; Plieninger et al., 2016). Policies can affect land availability (e.g. limiting the supply) and land prices, as well as the transport network, and therefore determine the potential for land use and landscape change (Hersperger and Bürgi, 2009; Jepsen et al., 2015). LULC in NCSP was predominantly explained by political driving forces, especially after 2000. This is shown in the diagram top left and on III and V stages

The economic policies specifically allowed investment in access improvement (i.e. roads, ports and the airport), and in industrial infrastructure for the oil and gas sector at the end of the 20th century (Fig. 9, I) and thus supported accessibility. Our findings indicate that accessibility, and technological drivers in general, were very important to foster the observed land changes. Accessibility, fostering terrestrial and marine transportation of people and goods, has been confirmed as an important driving force (Bürgi et al., 2017; Antrop, 2005). For NCSP, its relevance has been suggested for changes from rural to urban land uses, and from forests to human dominated land uses (Pierri Daunt and Silva, 2019). Distances to the four main highways crossing the study area were the strongest technological drivers in all models, and mainly for fostering urban growth and undermining forest persistence. Seaports have also been discussed as driving forces of urban growth in coastal regions all over the world (Elmqvist et al., 2013; Felsenstein et al., 2014). In NCSP, the Ubatuba and São Sebastião seaports have been important factors for the economic development of coastal villages since the 16th century (Cunha, 2003). According to our analysis, seaports were important for fostering urban growth and deforestation and for undermining forest persistence from 1985 to 2000. The contribution of technological driving forces declined after 2000, probably because the industrial infrastructure, i.e. seaports and the airport are located near historical downtowns, where little additional change could take place.

Tourism has been discussed as important driver for urban growth in coastal tourist locations such as Ilhabela municipality in NCSP (Furlan, 2000), as well as coastal areas in Japan (Elmqvist et al., 2013) and Mexico (Corona et al., 2016). The literature suggests that income from the tourism sector, coupled with investments in access improvements, were responsible for labour migration to NCSP (Fig. 9, I, II, III), resulting in high rates of population growth (do Carmo et al., 2012; Comitê de Bacias Hidrográficas do Litoral Norte (CBHLN), 2016. Despite the strong population growth observed in the region, from 87,800 inhabitants in 1980 to 281,800 in 2010 (Instituto Brasileiro de Geografia e Estatística,

Table 4
Coefficient of contribution (C) between drivers (independent variables) and processes: model for the entire study area for the period 2000 to 2015. *The variables "States Parks", "HDI" and "population density" were multiplied by -1 to align the dimension of all variables.

Driving forces (explanatory variables)	Forest persistence	Deforestation	Urban growth	Peri-urban growth
Political				
States Parks	0.61	−0.38	−0.44	−0.25
EEZ 1	−0.28	0.12	0.08	0.13
EEZ 2	−0.30	0.23	0.18	0.14
EEZ 3	−0.30	0.18	0.15	0.15
EEZ 4	−0.29	0.21	0.43	0.08
EEZ 4OD	−0.19	0.19	0.25	0.06
EEZ 5	−0.13	0.01	0.07	−0.01
Waste collection service	−0.03	0.03	0.06	0.00
Sanitation services	0.02	0.05	0.07	0.00
Water service	−0.06	0.02	0.13	−0.03
Socio-economic				
Basic education	−0.13	0.11	0.11	0.09
HDI	0.06	−0.03	−0.06	−0.00
Mean income	−0.03	0.02	0.06	0.01
Population Density	−0.02	−0.09	−0.04	−0.04
Natural				
Distance to high-risk areas	0.41	−0.22	−0.26	−0.12
Slope	0.40	−0.27	−0.33	−0.17
TPI 300	0.06	−0.06	−0.06	−0.07
Technological				
Distance to highways	0.43	−0.22	−0.26	−0.13
Distance to industrial infrastructure	0.05	−0.03	−0.11	0.05
Cultural				
Distance to traditional communities	0.39	−0.21	−0.26	−0.11

2010; Instituto Brasileiro de Geografia e Estatística, 1980) and an increase in urban areas by 167 % and peri-urban areas by 26.6 % from 1985 to 2015 (Pierri Daunt and Silva, 2019), we found neither an effect of population growth nor an effect of housing-density increase on any LULC process.

The fact that neither population growth nor housing-density increase (and socio-economic driving forces in general either) were not very important in describing urban land-use change in our models stands in contrast with much of the literature, that has shown that socio-economic factors, and specifically population growth, have been very important to foster land changes (e.g. Hersperger and Bürgi, 2009; da Silva et al., 2016). For example, population growth and density have been suggested to be important drivers of land-use changes globally (Ellis and Ramankutty, 2008), but are rarely the only or major underlying causes (Lambin et al., 2001). For many cities in Latin America, Inostroza et al. (2010) have shown that population growth was a very important driver explaining urban expansion during the second half of the 20th century, losing importance later. For Brazil, population density, density of permanent housing, and mean income have been suggested as important driving forces to describe urban dynamics (World Bank, 2006).

The low importance of the socio-economic drivers in the study region might be due to the fact that here, urban areas mostly grew to accommodate non-residential uses, such as services, industry, hotels and second homes, (Comitê de Bacias Hidrográficas do Litoral Norte (CBHLN), 2016; IBGE, 2010; Rosemback et al., 2017). Second homes are the most widespread kind of tourism accommodation in NCSP and the region hosts more than 2000 touristic establishments (i.e. hotels and restaurants) (Comitê de Bacias Hidrográficas do Litoral Norte (CBHLN), 2016; Fundação SOS Mata Atlântica; Instituto Nacional de Pesquisas Espaciais, 2016). Furthermore in some Latin America cities, per capita land consumption has increased for the richer economic classes in urban areas (Inostroza et al., 2013, 2010), contributing to a decoupling between growth in urban land area and population. In NCSP, the existence of many high-end private condominiums for both residential and tourism purposes suggest that this phenomenon may also have a bearing on our results. The accommodation of the population and housing demand increase likely has resulted in urban densification and peri-urban sprawl (Fig. 9, IV) (but see also section 4.3 on limitations).

Especially from 1985 to 2000, natural driving forces were also important. Our results are in line with studies showing topography to be a very important driving force for both forest dynamics, including forest persistence and deforestation (Loran et al., 2017; Pazúr and Bolliger, 2017; Plieninger et al., 2016; da Silva et al., 2016), and for urban growth, which is observed mostly in flat areas (Schneeberger et al., 2007; da Silva et al., 2016). The Serra do Mar mountain range hosts many steep and unstable areas, and it is expected that human settlements will avoid these areas. In NCSP, urban and peri-urban growth were positively correlated with lower terrain slopes, which suggests that these processes occurred more frequently in flat areas, and forest persistence is in part ensured by steeper terrain slopes (Fig. 9, V). After 2000, deforestation was positively influenced by slope, since most flat areas had already been deforested and deforestation processes were displaced towards remote areas far from roads and on steeper slopes.

Distances from traditional communities negatively influenced forest persistence and positively affected peri-urban growth, suggesting that these communities can be considered an important driving force for forest persistence, controlling deforestation and urban growth (Fig. 9, V). The importance of Indigenous, Quilombola and Caiçara communities in fostering landscape multifunctionality and enhancing food security and provision of ecosystem services has been previously established for NCSP (Diegues, 2001; de Lima-Guimarães, 2011), but also for several other regions (Antrop, 2005; De Groot, 2006; McNeely and Scherr, 2009; Tuan, 1983). Our results confirm that the presence of traditional communities is therefore extremely important for maintaining landscape diversity and forest persistence.

In most of our models, urban and peri-urban growth were explained by the distances from high-risk areas, i.e. areas susceptible to landslides, especially when the entire NCSP territory was analysed. This finding suggests that urban and peri-urban uses are now approaching high-risk areas and surroundings. The opposite findings would be expected, however this is a common observation for developing countries, were urban sprawl increasingly occurs in areas with high vulnerability to natural hazards (Elmqvist et al., 2013; Maricato, 2003) driven by the increasing price of land in flatter areas combined with a lack of regulation enforcement.

Of the basic services, clean water provision contributed most to explaining the observed urban growth. The absence of sanitation service effects on urban and peri-urban growth suggests that the public sector has not kept up with providing the growing urban areas with healthy living conditions. Indeed, less than 40 % of NCSP houses receive public sanitation services (Comitê de Bacias Hidrográficas do Litoral Norte (CBHLN), 2018, and this is one of the major contributors to water pollution in NCSP (Comitê de Bacias Hidrográficas do Litoral Norte (CBHLN), 2014; de C. Panizza, 2004) (Fig. 9, VI).

Although not highlighted as main driver of change on our diagram, our findings shown that improvements in education might have influenced conservation efforts, especially during the period from 1985 to 2000. Additionally, from 2000 to 2015, HDI (outside State Parks) contributed positively to forest persistence. From 2000 to 2015, education and mean income negatively contributed to forest persistence, but were positively correlated with urban growth. The negative link to

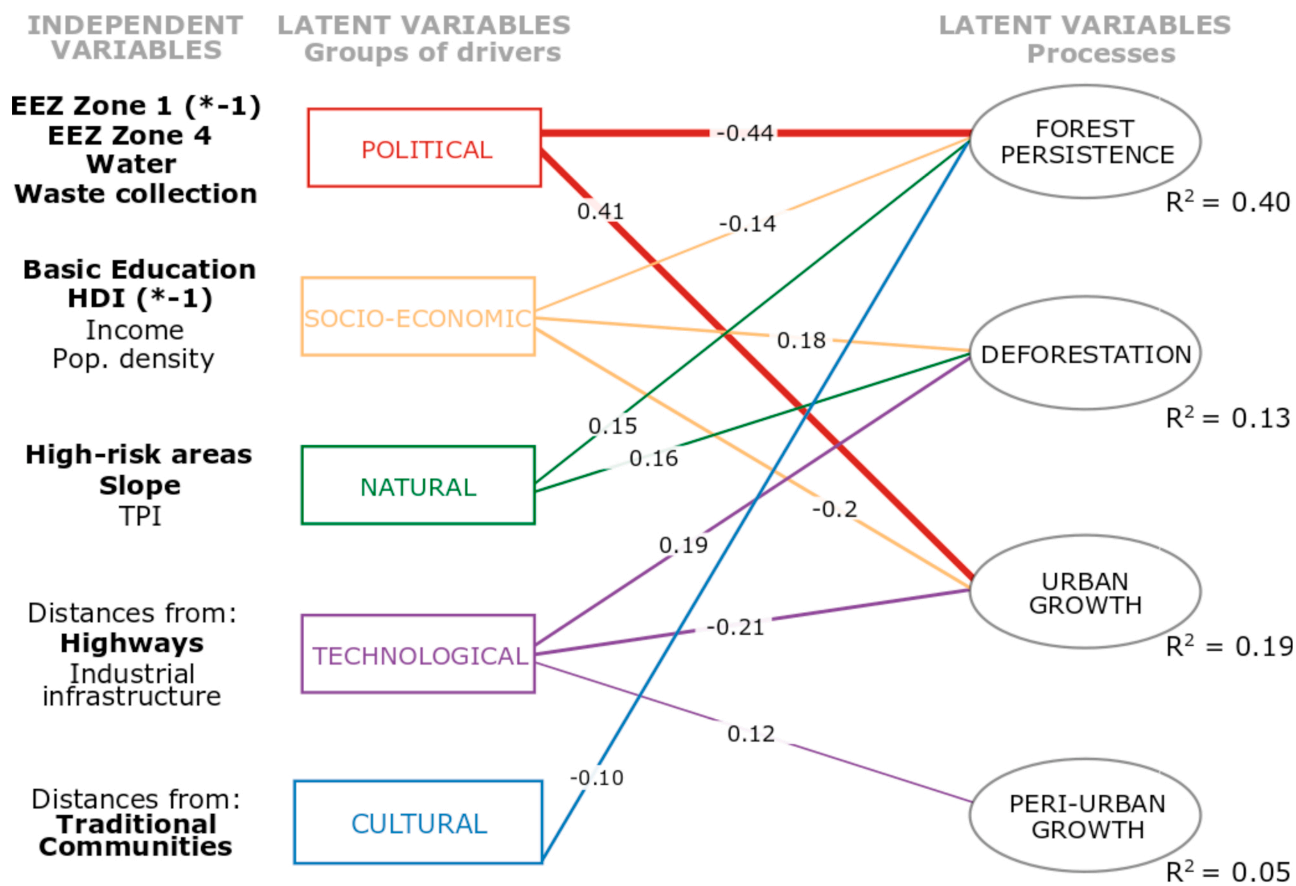

Fig. 8. Model for the study area outside State Park limits for 2000 to 2015. In **Bold**: Explanatory variables (driving forces) with effect >0.7 and weight >0.5. Coefficient of contribution (C) values with an absolute value >0.1 are displayed.

forest persistence might come as unexpected, but could be explained by the increase of poor people the inside protected areas, frequently deprived of access to education. Socio-economic aspects such as income, education and HDI can be interpreted as proxies for quality of life, which in turn is expected to contribute to forest persistence.

4.2. What impact did land-use policies and the designation of protected State Parks have on LULC dynamics?

The EEZ is a mixed policy that established a wide range of conservation and development strategies and the effect of the individual zones on the process of land change was evaluated and discussed separately. Persistent forest areas were strongly explained by the presence of the State Parks and the conservation EE Zones. Therefore, the policies establishing these can be suggested as the key driving forces for forest persistence (Fig. 9, V). Conservation policies and legislation have been extensively discussed as important driving forces for landscape stability in other contexts (Plieninger et al., 2016), and especially for forest persistence and afforestation (Loran et al., 2017).

Conversely, EEZ 4 and EEZ 4OD explained urban growth (Fig. 9, III), as expected. EEZ 5 did not explain any particular process, as it only delimits city centres and industrial areas that have been urbanized for many decades. Peri-urban growth was explained by EEZ 1, 2 and 3, which are designated for forest conservation (EEZ 1 and 2) and agricultural uses (EEZ 3). These zones were thus not effective in limiting peri-urban growth, suggesting a need for revision and/or better enforcement of the current zoning, coupled with policies to curb unregulated urban expansion.

Peri-urban growth can be understood as a suburbanization phenomenon, which is frequently observed in developing countries and other Latin American cities (Inostroza et al., 2013, 2010). Our models show that peri-urban growth in NCSP tends to be deprived of basic services. Moreover, peri-urban growth was linked to larger distances from main highways and industrial infrastructure and the distance to high-risk areas. Furthermore, zones designated for forest and landscape conservation and for rural development, i.e. EEZ 1, 2 and 3, were positively correlated with peri-urban growth. Our findings are thus in line with those of Fernandes (2007), who suggested that areas outside the urban core are often deprived of governance and strategical planning.

Even though it was not directly modelled, our results suggest that the urban areas grew mostly because the property market was catering primarily for second homes and services, rather than providing permanent housing for the local population, as a consequence, permanent housing spread into peri-urban areas (Fig. 9, II, III and IV). We therefore support the call raised by Rosemback et al. (2017) that planners and decision-makers in the Northern Coast of São Paulo state must urgently address the increasing necessity for housing areas. Furthermore, future research should focus on the integration of suburbanization and environmental conservation in land use plans and policies in peri-urban areas.

4.3. Limitations of the chosen method and data set

The PLS-PM delivered plausible results the about the complex relationships between driving forces and the dominant LULC processes in NCSP and allowed us to develop a conceptual understanding thereof as illustrated in Fig. 9. However, models on forest persistence and urban growth have performed better than models on less widespread processes, such as peri-urban growth and deforestation. Uncertainties are inherent in modelling driving forces of LULC. For example, the choice of raster or vector data has consequences for change detection and model

Table 5
Coefficient of contribution (C) between driving forces (explanatory variables) and processes: model for the area outside State Parks limits for the period 2000 to 2015. *The variables “EEZ 1”, “EEZ 2” “HDI” and “population density” were multiplied by -1 to align the dimension of all variables.

Driving forces (explanatory variables)	Forest persistence	Deforestation	Urban growth	Peri-urban growth
Political				
EEZ 1	0.54	0.10	−0.25	0.08
EEZ 2	0.20	0.05	−0.08	0.05
EEZ 3	−0.27	0.11	−0.05	−0.02
EEZ 4	−0.32	−0.16	0.34	−0.04
EEZ 4OD	−0.08	−0.18	0.15	−0.07
EEZ 5	−0.17	−0.05	−0.02	−0.08
Waste collection service	−0.44	−0.02	0.20	−0.08
Sanitation services	−0.34	0.00	0.19	−0.06
Water service	−0.24	−0.07	0.15	−0.05
Socio-economic				
Basic education	−0.45	0.09	0.07	0.01
HDI	0.40	−0.03	−0.12	0.10
Mean income	−0.22	0.03	0.08	0.02
Population density	0.06	−0.07	0.07	0.02
Natural				
Distance to high-risk areas	0.04	0.28	−0.21	0.13
Slope	0.41	0.13	−0.15	0.10
TPI 300	0.08	0.03	−0.05	−0.06
Technological				
Distance to highways	0.04	0.25	−0.18	0.09
Distance to industrial infrastructure	0.31	0.10	−0.23	0.15
Cultural				
Distance to traditional communities	0.05	0.29	−0.22	0.69

outcomes (Xu and Brown, 2017), while object based and polygonal unites are still very much recommended in terms of higher accuracy (Blaschke, 2010; Xu and Brown, 2017). Others highlight that the temporal dependence of classification errors has a significant effect on the accuracy of a land change map (Burnicki et al., 2007). Since our LULC data was good in terms of overall accuracy (0.94 and 0.88) and other validation metrics (See Supplementary Material A) we expect that this issue did not unduly influence our results.

Even though the selection of variables for modelling driving forces and processes should depended on the theoretical and behavioural assumptions (Verburg et al., 2004) we had to rely on available data. It is likely that the inclusion of additional explanatory variables, in particular, variables related to the tourism sector and the real estate market (i.e. land prices and land-use taxes) would have improved our results. Unfortunately, this information is only available from 2010 onwards and only at a municipality level.

The explanatory variables were acquired from different sources and differed in units and scales of measures. Errors propagated by the combination of these datasets during the generation of explanatory variables spread uncertainties to this variable, and consequently, on the model results. Especially the outlined aggregation procedure and the generation of the distance variables are expected to be sensitive. Nevertheless, spatial distances measurements such as cost distance measures and Euclidean Distances are frequently applied in land change modelling (Bolliger et al.;, 2017; Environmental Systems Research Institute (ESRI, 2016; Pazúr and Bolliger, 2017).

The fact that the Federal Census years (1991, 2000 and 2010) differs from the LULC years (1985, 2000, and 2015) might have introduced additional uncertainties. We adjusted for the mismatch partly by calculating the annual rates of change. However, the extrapolation beyond the common period from 1991 to 2010 remains a potential issue, especially because population growth rates were higher in the 1980’s than in the 1990’s. For this reason, the effect of socioeconomic drivers on process of changes might have been be underestimated in our models.

5. Conclusions

A complex set of forces has led to a clashing dichotomy between urban growth for tourism, secondary homes and services, and the persistence of forest areas within protected lands, leaving housing for the permanent population on the margins of decision-making and political and economic objectives for NCSP. Although the EEZ is a mixed policy coupling conservation and development dimensions with diverse strategies, we found that the most conservative zones have been effective to ensure forest persistence, and zones for urban development have been effective to support the development of the tourism sector. However, the policies have contributed little to improving basic sanitation or addressing the scarcity of affordable housing and support local agricultural development programmes. Technological investments, the property market and the tourism sector (Fig. 9, III) have guided peri-urban sprawl for residences to marginal areas without basic services (Fig. 9, IV). Conservation policy has still been an important driving force for the persistence of forests and landscapes (Fig. 9, V), but the rapid decrease in the availability of low-risk and non-protected areas for further development will place increasing pressures on the effectiveness of these policies for the next decades.

We suggest that the processes of land change narrated and modelled in this study are the result of an inequality in public policies, frequently influenced by economic interests, rather than lacking or inefficient planning, and we recommend that future research and actions address these causes. Future policies for land-use management in NCSP need to address the increasing demand for housing and basic services, support the development of local agroecological practices, and protect the traditional communities and their territories. Reconciling economic and urban growth with housing programmes and environmental conservation is the only path to ensure a continued and sustainable coexistence between conserved forests and multifunctional landscapes in the Northern Coast of São Paulo state.

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CRediT authorship contribution statement

Ana Beatriz Pierri Daunt: Conceptualization, Data curation, Methodology, Formal analysis, Writing - original draft, Writing - review & editing. **Thiago Sanna Freire Silva:** Conceptualization, Methodology, Supervision. **Matthias Bürgi:** Conceptualization, Writing - review & editing, Supervision. **Anna M. Hersperger:** Conceptualization, Writing - review & editing, Supervision.

Declaration of Competing Interest

The authors report no declarations of interest.

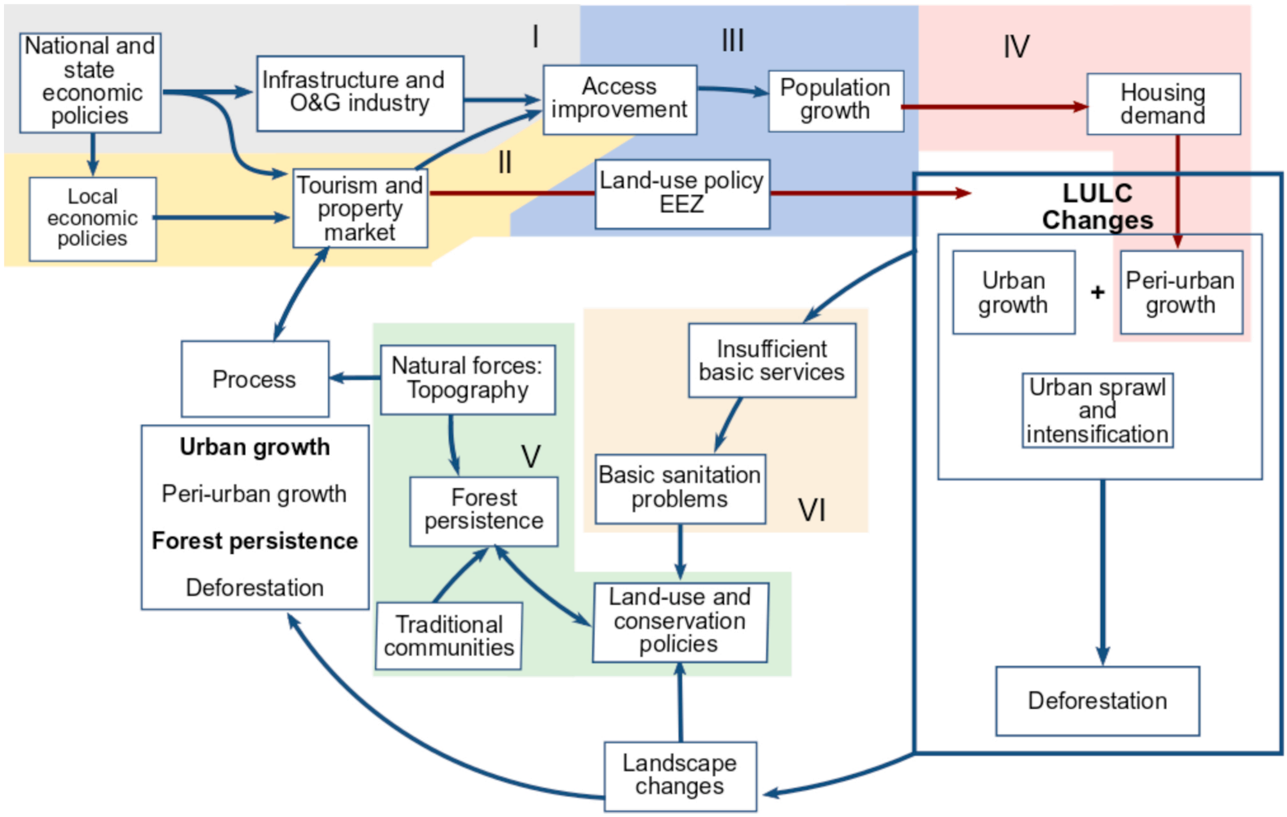

Fig. 9. Conceptual interlinkages between drivers of processes in NCSP from 1985 to 2015. (I) national and state economic policies, responsible for increasing investment in oil and gas (O&G) industries and for expanding access by roads and seaports (end of 20th century); (II) local and regional economic policies, governed mainly by tourism and the real estate and construction market (end of 20th and early 21st century); (III) items I and II were responsible for labour migration (end of 20th century) and have influenced the regional land-use policies (early 21st century); (IV) the resident population has been excluded from access to the housing market, and this has led to the occupation of peripheral peri-urban areas by new housing (end of 20th and early 21st century); (V) conservation policy and traditional communities have been extremely important for forest conservation and for the maintenance of forest cover (end of 20th and early 21st century); (VI) the percentage of public service provision did not follow the urban and peri-urban growth.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2020.105189.

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