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## 1 Beyond the park and city dichotomy: Land use and land cover change in the northern 2 coast of São Paulo (Brazil)

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11

12 **Abstract** The natural and cultural landscapes of the Northern Coast of São Paulo State (Brazil)  
13 are threatened by increasing urban growth, as a result of inefficient land use management and  
14 fast population growth. Our work analysed land use/cover changes (LULCC) between 1985 and  
15 2015 at 5 year intervals, to describe and understand the main processes and drivers of landscape  
16 change. LULCC were mapped using Landsat images and geographic object-based image analysis  
17 (GEOBIA), based on the Random Forests supervised algorithm. Over 30 years, we show a  
18 dichotomic trend for the two main land change trajectories: forest persistence and fast urban  
19 growth. We found only 8% of forest disturbance within the State Parks, while dense urban  
20 settlements grew 163% outside the park, mainly replacing rural uses. We estimate that all  
21 available land for human settlement may be occupied by 2030 as a result of this fast urban  
22 growth. Our study exemplifies a likely pattern of land use change for coastal regions, with fast  
23 urban growth driven by economic interests in transforming these regions into urban and touristic  
24 hubs, clashing with environmental policies for forest conservation and afforestation. The history  
25 of LULCC in the Northern Coast of São Paulo State has resulted in several land use conflicts in  
26 the present, especially when considering fast urban growth versus a very large proportion of  
27 areas where no human settlement is permitted. This complex combination of drivers has led to  
28 rural depopulation and decrease in small-scale agricultural uses, reducing the diversity and  
29 functionality of the studied landscape.

30

31

### 32 1. Introduction

33 Mankind has been shaping ecosystems and landscapes since the establishment of the first  
34 human settlements, but the speed, frequency and magnitude of landscape changes has increased  
35 mainly since the second half of the 20<sup>th</sup> century; presently, more than 75% of Earth's ice-free  
36 land shows evidence of alteration as a result of human land use (Antrop, 2000; Ellis &  
37 Ramankutty, 2008). Land use and land cover changes (LULCC) are difficult to predict and  
38 manage, and can result in severe consequences for climate, biodiversity, and ecosystem integrity  
39 and services, especially in the case of land build-up, which is usually irreversible (Elmqvist et

40al., 2013, Verburg et al., 2015). Also, modern landscape changes are characterized by the loss of  
41landscape diversity and changes in multifunctionality, mostly as a result of fast urbanization and  
42urban population growth (Antrop, 2005), as well as by increased *per capita* land consumption  
43(Inostroza, Baur & Csaplovics, 2010). Land conversion from rural to urban uses can lead to  
44several critical impacts on the quantity, quality and cost of food supply, and changes the complex  
45relationship between people and the landscape though cultural heritage, feelings and values  
46(Antrop, 2005; Bürgi, Verburg, Kuemmerle, & Plieninger, 2017; De Groot, 2006; McNeely &  
47Scherr, 2009; Nassauer, 1995; Tuan, 1983).

48        In South America, almost 84% of the total population lives in cities, and predictions  
49estimate that both urban population and urban areas will continue to increase rapidly in the next  
50years (Inostroza et al., 2010; UN 2009). Such fast and intense urbanization in developing  
51countries usually leads to vulnerability to extreme climate events, human settlement on socially  
52and environmentally risky areas, pollution, deforestation, habitat and biodiversity loss, violence,  
53and criminality (Elmqvist et al., 2013; Maricato, 2003).

54        In Brazilian coastal zones, fast urban growth is of large interest and concern in terms of  
55LULCC and landscape changes. The region known as the “Northern Coast of São Paulo State”  
56(NCSP) has a strong touristic vocation and has shown one of the highest annual rates of  
57population growth in the country (1.6% from 2015 to 2016), twice as large as the state average  
58(FSEADE, 2016) and caused mostly by migration from other regions and from local rural areas  
59to urban centers (Carmo, Marques, & Miranda, 2012; Roseback et al., 2017). Economical  
60interests in infrastructure development and expanding agricultural frontiers have been discussed  
61as the main drivers of urban sprawl and deforestation in tropical ecosystems (Geist & Lambin,  
622002), and the natural and cultural landscapes of the Northern Coast of São Paulo State are

63presently threatened by inefficient management of the increasing urban growth, leading to forest  
64fragmentation and losses of biodiversity (Ab’Sáber, 1986; Dean, 1996; Ribeiro, Metzger,  
65Camargo Martensen, Ponzoni, & Hirota, 2009)

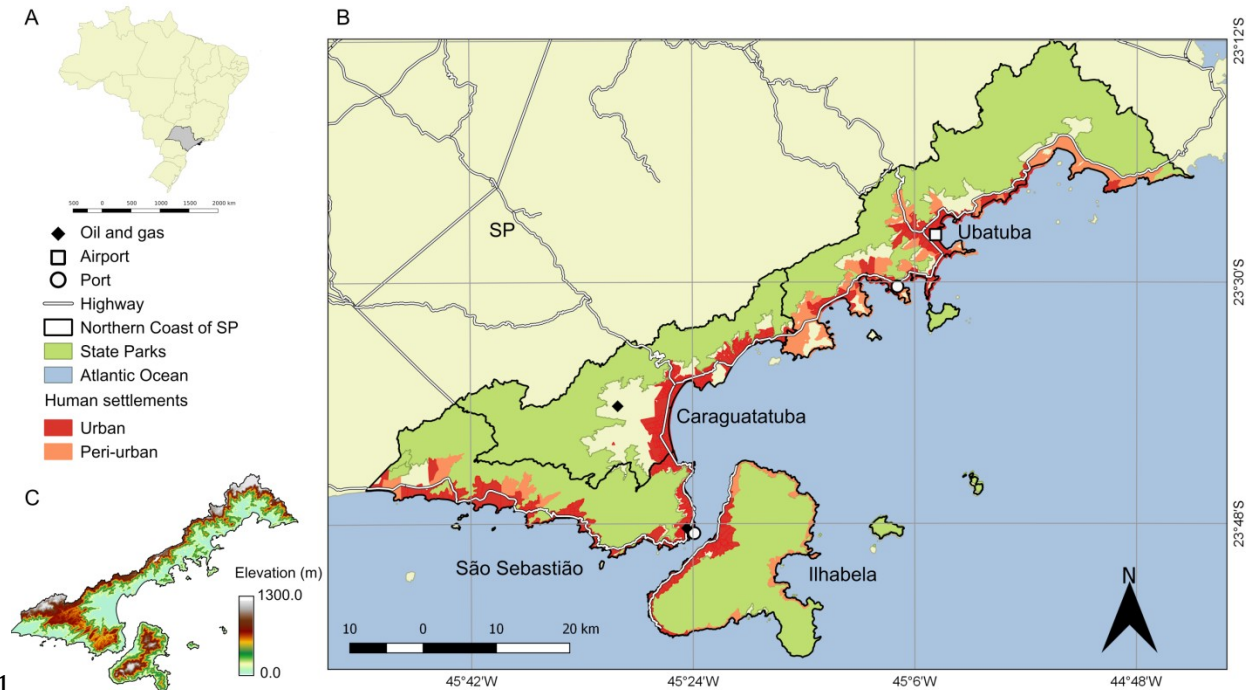
66 To control the impact of urban sprawl and to protect the Atlantic Forest, any form of  
67human settlement is strictly forbidden in more than 80% of the NCSP territory, according to  
68several environmental and land use policies and laws. Furthermore, long term LULCC data is not  
69widely available for Brazil and most developing countries, thus independent studies quantifying  
70LULCC are important to understand current occupation patterns and improve future urban  
71planning and governance. Our work thus mapped land use and land cover changes between 1985  
72to 2015, at five year intervals, to answer the following questions: 1) what are the main processes  
73and trajectories of land use/cover change in the NCSP during the last 30 years? 2) What could be  
74the main drivers of these changes? 3) What are the possible consequences of these changes on  
75natural and cultural landscapes? 4) Have environmental legislation and regulations been effective  
76in preserving forest cover?

## 772. **Methods**

### 78 2.1 Study area

79 The Northern Coast of São Paulo State is a recognized state administrative unit, mainly  
80located along the Serra do Mar mountain range, and including four municipalities:  
81Caraguatatuba, Ilhabela, São Sebastião and Ubatuba (Figure 1). The physical landscape of the  
82NCSP is composed by three main physiographic compartments: the upland plateau between 800  
83and 1300 m of elevation; the escarpments of the Serra do Mar mountain range, placed between  
84the coastal plains and the uplands and characterized by steep slopes; and the coastal plains, with  
85elevations below 20m and slopes of less than five degrees (Almeida & Carneiro, 1998; Rossi &

86Queiroz Neto, 2001). Most human settlements occur on the coastal plain, but recent urban  
 87growth has pushed new settlements towards the steeper inland transitions. Considering the high  
 88annual rainfall volume (between 800 and 1200 mm) and the very steep slopes, this region  
 89includes several high-risk areas for human settlement (Ab'Sáber, 2007; Rossi & Queiroz Neto,  
 902001).



91  
 92Figure 1. A) Map of Brazil showing the location of São Paulo State (SP). B) Northern Coast of  
 93São Paulo State showing the location of state parks, main highways, oil and gas infrastructure,  
 94major ports and airports, and urban and peri-urban census sectors (IBGE, 2010). C) Digital  
 95Elevation Model (ALOS World3D, <https://www.eorc.jaxa.jp/ALOS/en/aw3d30/index.htm>).

96

97 The NCSP is located within the Atlantic Forest biome, which has one of the most diverse

98tropical biotas in the world (Mittermeier et al., 2004) and is among the biomes most threatened

99by human land use changes and urbanization process globally (Dean, 1996; Ribeiro et al., 2009).

100The Atlantic Forest was recognized as a biosphere reserve by UNESCO in 1991, and the Serra

101do Mar mountain range holds some of the largest and best preserved Atlantic Forest remnants

102(Fundação SOS Mata Atlântica; Instituto Nacional de Pesquisas Espaciais, 2016; Ribeiro et al.,

1032009). To protect the Atlantic Forest, several environmental and land use policies and laws have  
104been passed during the late 20<sup>th</sup> and early 21<sup>st</sup> centuries, and three state parks were created in the  
105NCSP in 1977 to support biodiversity conservation, environmental education and scientific  
106research: “Serra do Mar”, “Ilhabela” and “Ilha Anchieta”. All state parks are classified as  
107“integral protection” conservation units under the Brazilian Protected Areas legislation (*Sistema*  
108*Nacional de Unidades de Conservação* - SNUC) (Brasil, 2000; São Paulo, 1977), thus any form  
109of human settlement or land use is strictly forbidden. As an exception, the management plan of  
110Serra do Mar State park has delimited a special restricted zone that allows sustainable use by  
111native populations under park management regulations (São Paulo, 2006). Federal Law n°  
11211428/2006 protects the Atlantic Forest biome and regulates the practices of deforestation,  
113classifying transgressions as environmental crimes (Silva, Batistella & Moran, 2006).

114 In addition to being an important biodiversity hotspot, the Northern Coast of São Paulo  
115State also has unique historical and cultural characteristics, currently preserved by indigenous  
116and traditional peoples (Ab’Sáber, 1986; São Paulo, 2006), such as the Tupi-Guarani nation and  
117the Caiçara and Quilombola ethnicities, which have historically contributed to landscape  
118sustainability and multifunctionality (Diegues, 2001; Antrop, 2005).

119 During the 20<sup>th</sup> century, coffee producers and the industrial aristocracy “rediscovered” the  
120coast of São Paulo for leisure and nature contemplation, occupying it with large secondary  
121residences, and turning the region into a tourism hotspot (Campos, 2000; São Paulo, 2006). Also  
122during the second half of the 20<sup>th</sup> century, the tourism and oil industries demanded increased  
123access to the NCSP, bringing the expansion of transportation networks and resulting in high rates  
124of migration and population growth, with a resulting decrease in rural areas and urban expansion  
125(Carmo et al., 2012; Cunha, 2003; Silva, 1975).

126        2.2 Land use and land cover data

127        We acquired seven Landsat Collection 1 Higher-Level Surface Reflectance images  
128(formerly known as Landsat Climatic Data Record images) distributed by the U.S. Geological  
129Survey (USGS), covering the entire study area (path 76 row 220, WRS-2 reference system,  
130<https://earthexplorer.usgs.gov/>). The series included six images acquired by the Landsat 5  
131Thematic Mapper (TM) sensor, on 1985-07-27, 1990-07-09, 1995-05-04, 2000-01-10, 2005-05-  
13215 and 2010-02-22, and one image from the Landsat 8 Operational Land Imager (OLI) sensor,  
133from 2015-08-15. To avoid variations caused by vegetation phenology and changes in solar  
134geometry, which could be detected as false cover changes (Kennedy, Yang, & Cohen, 2010), we  
135favoured images from the dry season of each year (May – August), with the exception of images  
136from 2000 and 2010, which had extensive cloud cover during this period.

137        We applied a geographic object-based image analysis (GEOBIA) approach, which has  
138become more popular for LULCC mapping during the last years (Blaschke, 2010). We chose this  
139method as it enables mixed use classification and requires less workload for manual post-  
140classification corrections. We segmented the images into objects with homogeneous spectral  
141responses using the Shepherd segmentation algorithm implemented in the open source library  
142“RSGISlib”, accessible through the Python programming language (Bunting & Clewley, 2013).  
143This algorithm requires three parameters: minimum object size in pixels (*minPixls*), maximum  
144number of clusters (*numClusters*), and distance threshold between object pixels (*disThres*). We  
145tested different parameter combinations, and chose the optimal combination based on visual  
146assessment of the spatial coherence and spectral homogeneity of the resulting objects (Blaschke  
147et al., 2014), corresponding to *minPixls* = 50, *numClusters* = 120 and *disThres* = 100 (Appendix  
148A). Mean spectral responses were then computed for each object across all multispectral Landsat

149bands (1, 2, 3, 4, 5 and 7 for TM; 1, 2, 3, 4, 5, 6 and 7 for OLI) to be used as inputs for the  
150classification algorithm (Blaschke, 2010).

151 We then classified land use and land cover at each imaged date using the Random Forests  
152supervised algorithm (Breiman, 2001) implemented in the “Sci-Kit learn” Python library  
153(Pedregosa et al., 2012). This algorithm is an ensemble learning method based on classification  
154and regression trees built through randomization of the training data (Breiman, 2001). In our  
155case, training data were the spectral responses of samples with known LULC categories (Table  
1561). Homogeneous regions were manually selected as training samples, and delineated separately  
157for each combination of LULC class and each imaged date, distributed as best as possible  
158throughout the study area. The total area sampled for training each class depended on the relative  
159proportion of the class within the scene, varying from 0.13 km<sup>2</sup> for bare soil to 14.10 km<sup>2</sup> for  
160mature forest (Appendix A). Selection was based on visual interpretation of the images aided by  
161visual comparison with high resolution datasets (see below).

162Table 1 - Land use and land cover classes used for mapping land cover changes in the Northern  
163Coast of São Paulo State, Brazil, between 1985 and 2015, using Landsat historical data.

Land use / land cover class	Description
Mature forest	Dense forest characterized by advanced successional stages and comprised mainly by primary forest, or occasional old-growth secondary forest.
Regenerating forest	Less dense forest at early to medium successional stages, mostly comprised by regenerating secondary forest.
Non-forest vegetation	Native or exotic vegetation including pastures, grasslands and agriculture.
Bare soil and rock	Exposed soil or rock surfaces lacking vegetation and buildings and including sandy beaches and rocky shores.
Peri-urban	Mixed areas with lower population density and sparse buildings, including a high diversity of rural uses, agroforestry, and small forest fragments.



Dense urban settlements	Dense built-up areas, mostly urban.
Water	Free water surfaces.

164

165 The Sci-Kit learn implementation of Random Forests takes the following main  
 166 parameters: “*n\_estimators*”, the number of trees used for decision, “*bootstrap*”, which is the  
 167 randomization method, “*out-of-bag*” (OOB), which estimates the classification error, and  
 168 “*class\_weight*”, which balances training samples. We optimized this parameter combination  
 169 based on minimization of the OOB error, leading to “*n\_estimators*” = 500 and “*class\_weight*” =  
 170 “balanced”. The remaining parameters were kept at the default values (Appendices A)  
 171 (Pedregosa et al., 2012). The automated classification was followed by careful visual inspection  
 172 and manual correction of the land cover maps at the 1:25.000 scale, to improve map accuracy for  
 173 all dates.

174

To aid image interpretation and support map validation and accuracy assessment, we  
 175 obtained digital georeferenced colour aerial photographs from 2001 and 2010 at the 1:10.000  
 176 scale, freely available at [www.datageo.sp.gov](http://www.datageo.sp.gov). We also used the GoogleEarth™ platform to  
 177 assess the accuracy of the most recent classification, based on Landsat 8 OLI. To generate the  
 178 ground truth dataset, we randomly distributed 40 random points per LULC class for each date,  
 179 which were then visually interpreted and classified based on the available high-resolution  
 180 imagery. We then used these sets to build confusion matrices and derive global accuracy, per-  
 181 class accuracy, the kappa index of agreement, and commission and omission errors (Congalton,  
 182 1991).

183

Land use and land cover changes were quantified using map algebra, by comparing  
 184 LULC maps in successive pairs. The area of each type of change was calculated using the  
 185 “*raster*” package (Hijmans et al., 2016) of the R programming language (R Core Team, 2012),

186which we then used to build the LULCC matrix. We then quantified the areal changes of each  
 187class in relation to the class area in the previous time step (PTS), both as absolute areas and as  
 188percentages. When relevant, we also determined changes in relation to the initial class area at the  
 189first time step (FTS), also in absolute and percentage values. We separately quantified absolute  
 190and PTS and FTS percent changes inside and outside State Parks, to better understand the  
 191different drivers on each type of land. For that, we used the official park limits provided by the  
 192Forestry Foundation of São Paulo. As the limits of Serra do Mar State Park were reviewed and  
 193expanded in 2010, changes prior to 2010 were quantified considering the original 1977 limits,  
 194and changes after 2010 considered the newly expanded limits.

### 1953. Results

196 Land use and land cover maps for 2015, 2010 and 2000 had overall accuracies of 0.94,  
 1970.88, and 0.88, respectively, after manual revision and correction. Corresponding Kappa  
 198agreement indices were 0.92, 0.86, and 0.86. Considering that map classes, imaging sensor and  
 199mapping methods were the same for all years between 1985 and 2010, and based on the close  
 200similarity between 2010 and 2000 accuracies, we assumed similar expected accuracies (0.88,  $\kappa =$   
 2010.86) for all remaining TM-based LULCC maps. The “dense urban settlement” class had the best  
 202Kappa index and the smallest errors, and the “peri-urban” and “regenerating forest” classes had  
 203the lowest Kappa indexes and the highest Omission and Commission errors (Table 2). Both  
 204“peri-urban” and “regenerating forest” classes comprised a more heterogeneous mixture of land  
 205cover elements than the remaining classes, which may explain the lower accuracies.

206Table 2. Kappa index of agreement and omission and commission errors for each LULC class  
 207from 2000, 2010 e 2015, after manual correction.

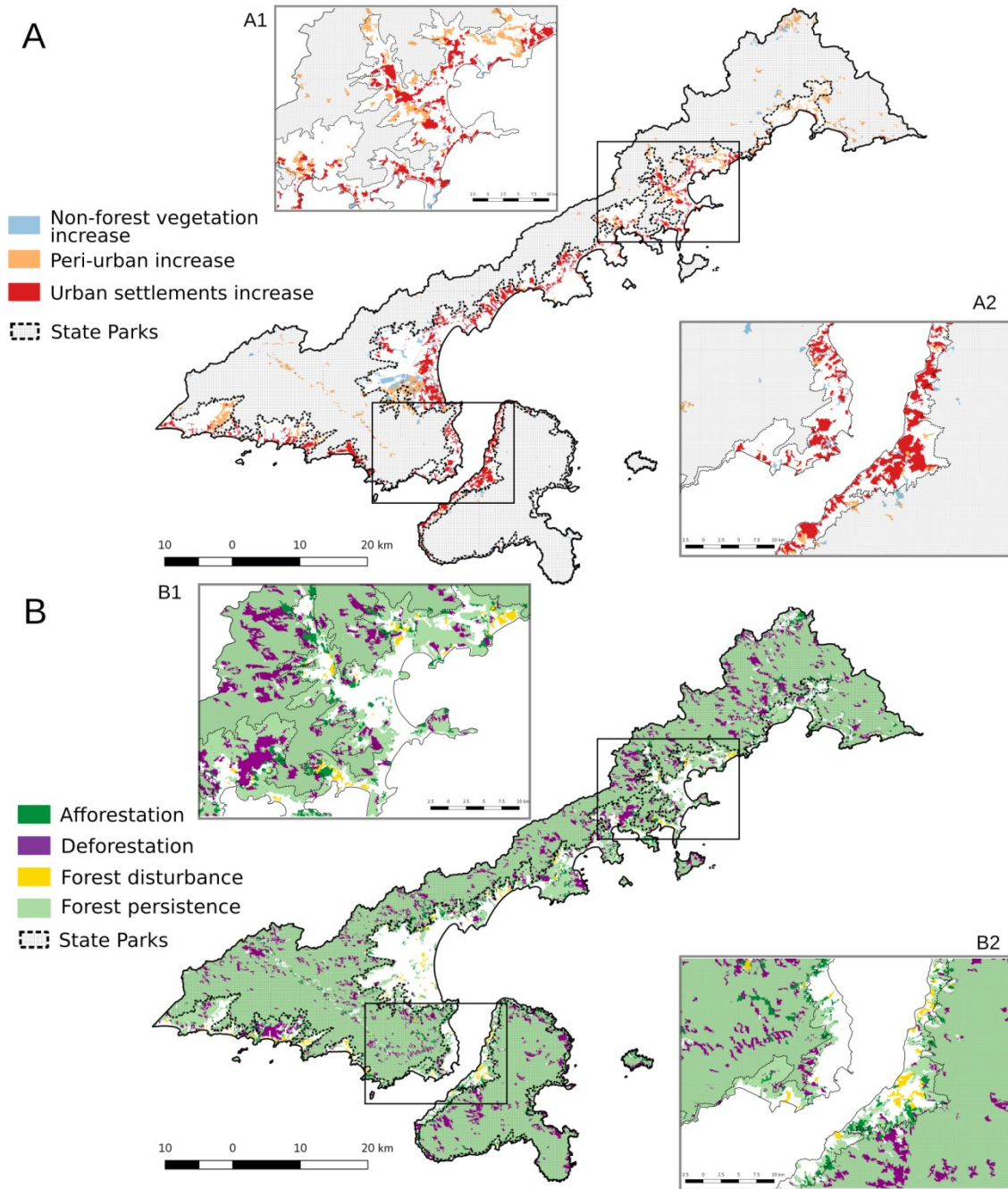
Classes	Kappa Index			Omission Error			Commission Error		
	2000	2010	2015	2000	2010	2015	2000	2010	2015

Non-forest vegetation	0.85	0.91	0.94	0.15	0.07	0.05	0.13	0.07	0.05
Peri-urban	0.79	0.68	0.85	0.13	0.17	0.07	0.18	0.28	0.13
Bare soil/rock	0.83	0.97	0.93	0.00	0.03	0.09	0.15	0.03	0.06
Dense urban settlements	1.00	1.00	0.88	0.05	0.00	0.03	0.00	0.00	0.10
Mature forest	0.85	0.88	1.00	0.10	0.10	0.06	0.13	0.10	0.00
Regenerating forest	0.81	0.72	0.93	0.26	0.31	0.08	0.15	0.23	0.06

208

209        3.1 Overall patterns of land use and land cover change

210        During the historical period investigated, we identified six main land cover change  
211 processes for the entire study area: increases in 1) dense urban settlements and 2) peri-urban  
212 cover, 3) afforestation, 4) deforestation (change to non-forest cover) and 5) forest disturbance  
213 (change from mature forest to regenerating forest); we also identified 6) a large amount of forest  
214 persistence. The expansion of dense urban settlements and peri-urban areas occurred mostly in  
215 the coastal plains. Forest persistence was the most dominant process along the 30 years studied,  
216 and was observed mostly at interior areas and over steep scarp terrain (Figure 2). The land cover  
217 and land use maps for each mapped date can be found in Appendix B.i.



218

219 Figure 2 Main land use and land cover change processes observed between 1985 and 2015. A) 220 Non-forest vegetation, peri-urban and dense urban settlement increase; B) Forest dynamics: 221 afforestation, deforestation, forest disturbance (primary to secondary forest), forest persistence. 222

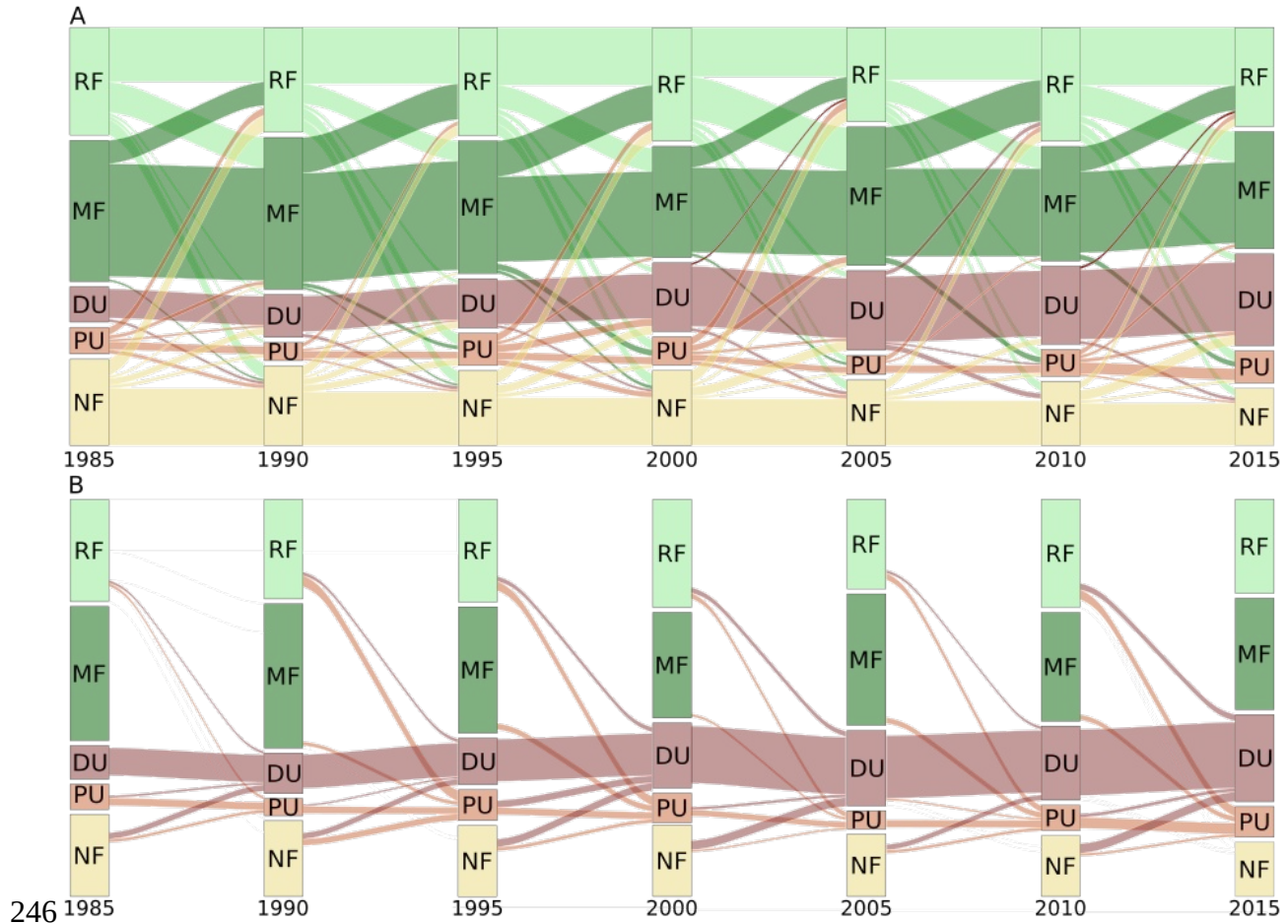
223 Dense urban settlements increased from 46.3 km<sup>2</sup> in 1985 to 123.8 km<sup>2</sup> in 2015, an 224 increase of 167% over 30 years, and the peri-urban cover increased 14 km<sup>2</sup> (26.6% of the class 225 area in FTS). From the initial 1985 map, by 2015 dense urban areas replaced 25% of non-forest

226cover (33.7 km<sup>2</sup> FTS), 28.6% of bare soil cover (5.6 km<sup>2</sup> FTS), 24.4% of peri-urban cover (12.4  
 227km<sup>2</sup> of urban intensification FTS) and 10.9% of mature forest (5.3 km<sup>2</sup> of deforestation FTS)  
 228(Appendices B). Regenerating forests in 1985 were replaced by other LULC classes by 2015:  
 2298.1% of non-forest vegetation (17.5 km<sup>2</sup>), 10.2% of peri-urban (22 km<sup>2</sup>), and 11% of dense urban  
 230settlement (23 km<sup>2</sup>).

### 231 3.2 Land use and land cover changes outside State Parks

232 From 1985 to 2015, dense urban settlements increased between almost all time steps,  
 233replacing mostly peri-urban uses and rural uses characterized by non-forest vegetation (Figure  
 2343), as well as a few natural cover areas, especially regenerating forests. Over the entire period,  
 235dense urban areas increased 74.5 km<sup>2</sup> (162.4% FTS) outside park limits, at an average annual  
 236rate of increase of 3.6%. The largest expansion of urban settlements occurred between 1995 and  
 2372000 (almost 28 km<sup>2</sup>, 43.6% of PTS), followed by 1985 and 1990 (23%, 11 km<sup>2</sup> PTS). Bare soil  
 238areas increased 12 km<sup>2</sup> (94.3% PTS) from 1990 to 1995 and then decreased almost 60% between  
 2391995 and 2000, reflecting the frequent practice in the NCSP of clearing large areas to build urban  
 240settlements and private condominiums (urban sprawl, Appendix B). We also observed urban  
 241intensification in this period, shown by substitution of 9.6 km<sup>2</sup> (23.6% PTS) of peri-urban areas  
 242in 1995 by dense urban areas in 2000. The rate of dense urban expansion then started to decrease  
 243by the beginning of the 21<sup>st</sup> century; 2005 to 2010 was the only interval without dense urban  
 244growth, and dense urban cover increased only 17.6 km<sup>2</sup> (17% PTS) from 2010 to 2015.

245



247 Figure 3. Land use and land cover change trajectories for the areas of the Northern Coast of São  
 248 Paulo outside park limits: A) All conversion types; B) land use / cover conversion to dense urban  
 249 settlements and peri-urban areas. RF = Regenerating forest; MF = Mature forest; DU = Dense  
 250 urban settlement; PU = Peri-urban; NF = Non-forest vegetation.

251

252 Peri-urban areas increased 6.7 km<sup>2</sup> (19.5% PTS) from 1985 to 2015, at an average annual

253 rate of increase of 1.9%. From 1985 to 1990 we quantified a peri-urban decrease of 33% PTS (10

254 km<sup>2</sup>) as a result of land abandonment and substitution by recovering forest and non-forest

255 vegetation (land abandonment, Figure 4). We then observed high peri-urban growth between

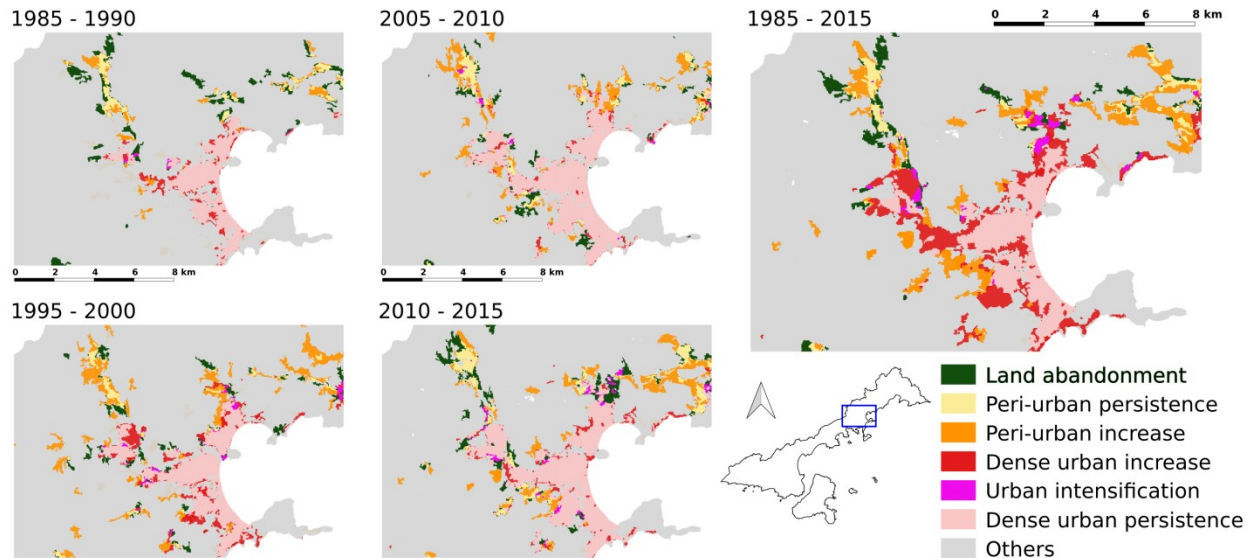
256 1990 and 1995 (73.8% PTS, 17 km<sup>2</sup>), 2005 to 2010 (40% PTS, 10 km<sup>2</sup>), and 2010-2015 (17%

257 PTS, 17.6 km<sup>2</sup>) (Figure 3B and Figure 4). This growth can be linked to new settlements (urban

258 sprawl and a few new rural villages). Between 1995 and 2000, a peri-urban decrease of 4 km<sup>2</sup>

259 (10% PTS) happened mostly due to urban intensification (Figure 4). Since dense urban

260settlement and urban intensification occurred mostly within the flat coastal areas, our data  
 261suggests that the peri-urban areas have been shifted towards interior and steeper areas (Figure 2  
 262and 4).



263Figure 4. Peri-urban and dense urban settlement dynamics: example from the central region of  
 264Ubatuba municipality. Land abandonment = peri-urban conversion to non-forest vegetation and  
 265regenerating forest; Peri-urban persistence = peri-urban maintenance during the time step; Peri-  
 266urban increase = conversion from any cover class to peri-urban; Dense urban increase =  
 267conversion from any cover class to dense urban; Urban intensification = conversion from peri-  
 268urban to dense urban, Urban persistence = dense urban maintenance during the time step.

269

270 During the entire studied period, mature forest cover outside park limits decreased 16%

271and regenerating forest decreased 8% FTS due to deforestation. Mature forests present in 1985

272were converted into peri-urban areas (5.1% FTS), dense urban settlements (3% FTS) and

273regenerating forests (24% FTS, i.e. forest disturbance) (Figure 3A). The 1995 to 2000 period had

274the largest loss of mature forest, 24 km<sup>2</sup> (15% PTS), while regenerating forests increased 11 km<sup>2</sup>

275(7.9% PTS) (Figure 3A). Forest cover outside park limits represented c.a. 50% of the NCSP

276territory in 2015, considering both mature and regenerating forests (Figure 2 and Figure 3A).

277Even outside park limits, we could quantify high percentages of forest cover persistence, with

27864% of the forested area in 1985 remaining forested in 2015. We also observed afforestation,

279resulting mostly from land abandonment, with a substitution of 20% of peri-urban and 15% of  
280non-forest vegetation by regenerating forests from 1985 to 2015 (Appendices B).

281 At the municipal scale, all municipalities had LULCC patterns similar to the entire study  
282area. During the 30 studied years, dense urban settlement increases were higher in percentage at  
283Ilhabela (758.9% FTS, followed by São Sebastião (174.4% FTS), Ubatuba (146.5% FTS) and  
284Caraguatatuba (126.2% FTS). Caraguatatuba lost 14.9%, São Sebastião lost 24%, and Ubatuba  
285lost 15% of mature forest, while Ilhabela gained 2.5% from FTS. LULCC data by municipality  
286can be found in the supplementary online material (Appendix B).

287

### 288 3.3 Land use and land cover changes within State Parks limits

289 The three state parks combined lost 100 km<sup>2</sup> of mature forest (8% FTS) from 1985 to  
2902015, replaced mostly by regenerating forest and peri-urban cover. About 85% of total park area  
291has persisted as mature forest (Figure 2). At the municipality scale, from 1985 to 2015,  
292Caraguatatuba lost 7% FTS, of mature forest, Ilhabela lost 8.5% FTS, São Sebastião lost 3%  
293FTS, and Ubatuba lost 10.4% FTS. The dense urban settlement areas increased from 1 km<sup>2</sup> to 2.7  
294km<sup>2</sup> from 1985 to 2015. Between 1985 and 1990, mature forest cover remained the same, and  
295regenerating forest area increased almost 8 km<sup>2</sup>, replacing non-forest vegetation (afforestation).  
296The peri-urban area increased 3 km<sup>2</sup> and bare soil increased 2.6 km<sup>2</sup>, substituting both forest  
297stages within park limits during 1990 and 1995. From 1995 to 2000, mature forest cover had a  
298decrease of 40 km<sup>2</sup> (5% PTS), mostly substituted by regenerating forest, which increased 45 km<sup>2</sup>  
299(44.9% PTS). Ilhabela State Park was the only park that did not lose mature forest cover between  
3001995 and 2000. We quantified an increase of 2 km<sup>2</sup> (12.6% PTS) in new peri-urban settlements  
301inside the parks between 2000 and 2005, and observed afforestation caused by changes from



302regenerating to mature forest; mature forest increased 15 km<sup>2</sup> while regenerating forest decreased  
30360 km<sup>2</sup>. Regenerating forests replaced 107.6 km<sup>2</sup> of mature forests between 2005 and 2010.

304There were no notable changes within park areas between 2010 and 2015 (Appendix B).

305

#### 3064. Discussion

307 4.1. Peri-urban and urban increases, land abandonment and rural decreases: why have  
308 people moved to cities?

309 The fast observed urban expansion in NCSP (167% of dense urban and 26.6% of peri-  
310urban from 1985 to 2015) can be linked to urban population growth, which went from 87,777  
311inhabitants in 1980 to 223,914 in 2000 and 281,800 in 2010, as a result of migration to urban  
312centers (Instituto Brasileiro de Geografia e Estatística, 1980, 2000, 2010). In 1970, 81% of the  
313censused population was classified as urban, increasing to 95% in 1980 and more than 98% in  
3141991, 2000 and 2010 (Carmo et al., 2012; IBGE, 1970, 1980, 2000, 2010; Rosembach et al.,  
3152017). Inostroza et al (2010) have investigated different cities in South America and shown that  
316population growth was a very important driver for urban expansion during the second half of the  
31720<sup>th</sup> century, led mostly by emigration from rural areas to the cities. Over time, population  
318increase has been losing its importance as a driving force for urbanization in Latin America, but  
319cities have continued to grow fast, mostly as a result of changes in demographic structure and  
320increases in the amount of per capita land consumption, influenced by economic changes (Geist  
321& Lambin, 2002; Inostroza et al., 2010).

322 Both urban growth and population increase by the end of the 20<sup>th</sup> century may have been  
323strongly influenced by the construction of new highways, especially the BR-101 highway, which  
324provided better and faster access to NCSP (Carmo et al., 2012; Cunha, 2003; Comitê de Bacias

325Hidrográficas do Litoral Norte, 2016). In coastal zones, the presence of seaports has been a  
326historically important driver of city development, influencing land use change both directly and  
327indirectly, especially by increasing urban and industrial uses (Cunha, 2003; Felsenstein, Lichter,  
328& Ashbel, 2014). On the NCSP, the São Sebastião and Ubatuba Ports were likely a key driver for  
329development, since their emergence as villages during the first half of 17<sup>th</sup> century. The presence  
330of the São Sebastião Port has in turn brought oil and gas companies to the same municipality  
331(Cunha, 2003; Teixeira, 2013), and during the early 21<sup>st</sup> century, the discovery of a new offshore  
332oil and gas deposit in 2003 (*pre-salt*) and the construction of the Natural Gas Treatment Station  
333of Caraguatatuba in 2007 increased investments in infrastructure and transportation projects  
334linked with the energy industrial sector. Based on this timing, we can suggest accessibility  
335improvements and the development of the oil and gas sector as two of the main drivers of the fast  
336urban expansion and intensification observed from 1985 and 2015, especially in São Sebastião  
337and Caraguatatuba municipalities. Landscape accessibility, considering terrestrial and marine  
338transportation of people and goods, is known to be an important driver of landscape change  
339influencing migration, rural depopulation, and the labor market, frequently resulting in rural  
340abandonment and urban expansion (Antrop, 2005; Bürgi et al., 2017). Technological drivers of  
341land use change in coastal zones have been confirmed for other countries; port construction and  
342expansion in Israel (Felsenstein et al., 2014), accessibility improvements in coastal cities in  
343Japan, Turkey, China and Brazil (Elmqvist et al., 2013), and the development of the energy  
344sector and the presence of industries in Italy (Montanari, Londei, & Staniscia, 2014), all leading  
345to rural abandonment and urban expansion.

346       Tourism linked to coastal and marine activities is the most important component of the  
347economy in the region, also demanding investments in infrastructure development, accessibility,

348and the construction sector (CBHLN, 2016; IBGE, 2010). NCSP hosts more than 2,000 touristic  
349establishments (i.e. hotels and restaurants), and the population frequently triples in number  
350during the high season (CBHLN, 2016; FSEAD, 2016). Secondary residences within private  
351condominiums are a frequent tourist accommodation in the NCSP, and the annual rate of  
352increase in built-up areas was higher than the annual rate of population growth (1.6%, FSEAD,  
3532016), for both dense urban (3.6%) and peri-urban (1.9%) increases, which may be explained by  
354the expansion of tourism infrastructure and vacation homes. It is thus reasonable to assume that  
355the tourism sector and the housing market are also strong drivers of the urban expansion  
356quantified by us in the NCSP, especially in the Ilhabela municipality, which has had the highest  
357percent growth in dense urban settlements, and that these activities are likely to continue  
358influencing land use changes and land governance. The role of tourism on land cover change has  
359also been shown for other coastal and touristic regions (Corona, Galicia, Palacio-Prieto, Bürgi, &  
360Hersperger, 2016; Elmqvist et al., 2013),

361       The complex interaction between economic and political drivers has been discussed  
362before as the main reason behind land use change in coastal and touristic zones, especially  
363regarding changes from agricultural use and forest cover to urban and industrial areas. The  
364presence of ports and industries, as well as other urban and touristic services, provides several  
365job opportunities and make coastal cities an attractive place for living, resulting in fast urban  
366expansion and intensification from migration (Elmqvist et al., 2013; Montanari et al., 2014). In  
367the NCSP, these processes are particularly well illustrated by the land abandonment quantified  
368by us from 1985 to 1990, followed by urban sprawl and urban intensification due to peri-urban-  
369expansion between 1990-1995 and 2005-2015, with dense urban increase during the entire  
370period. Regarding land abandonment in the NCSP, studies suggest that the conversion from rural

371to urban happened mostly prior to our studied period, between 1960 and 1980 (Campos, 2000;  
372Carmo et al., 2012; Silva, 1975). However, our results shown a continuing trend of conversion  
373from rural to urban uses between 1985 and 2015, which is also reported by the Brazilian Rural  
374Census data (LUPA 1995, 2007), where agricultural areas decreased in almost all NC  
375municipalities, from 20.5% (1995) to 13.9% (2007) of the NCSP territory.

376         Conversely, part of the observed peri-urban growth between 1985 and 2015 (26.6% of  
377FTS) can be also related to both transitions to mixed land uses and an increase in rural villages.  
378We could not discriminate between these two sources of peri-urban increases due to the spatial  
379resolution of our source images, and their relative contribution to LULCC in the region should be  
380better studied in the future. An increase in rural villages can be a consequence of land use  
381planning policies aiming to improve landscape sustainability provided by traditional populations  
382and small farmers. Protected areas such as Indigenous Territories and Natural Heritage Areas  
383were created during the late 1980's and early 1990's aiming to protect these population's  
384territories. The Serra do Mar State Park management plan has delimited the Historical-Cultural  
385and Archaeological Zone (São Paulo, 2006), allowing native people settlements to persist inside  
386park areas, and Federal Decree n° 6040 (National Policy for Sustainable Development of the  
387Traditional Communities and Populations) has defined and protected traditional populations as a  
388Brazilian Heritage, such as the *Caiçara*, Indigenous and *Quilombola* populations (Brasil 2007).  
389The presence of local stakeholders, non-profit organizations and non-governmental organizations  
390has been shown to be essential for developing sustainable cities, especially in regions with land  
391use conflicts such as coastal and touristic regions (Elmqvist et al., 2013; Morgado, Gomes &  
392Costa, 2014).

393

394 4.2. The effect of policies on forest persistence, afforestation, deforestation and  
395 disturbance

396 Mature forest loss and disturbance within park limits (100 km<sup>2</sup>) were a consequence of  
397 settlement intensification and sprawl outside and at the edge of the parks, likely because the  
398 footprint of urban expansion usually overcomes political borders (Antrop, 2005; Elmqvist et al.,  
399 2013). On the other hand, more than 95% of the state parks are still covered by mature forest  
400 (84.3%). As strictly protected areas, we suggest that the legislation instituting the three state  
401 parks has been an effective instrument for ensuring forest persistence and afforestation, even if a  
402 few deforested areas have been observed. The current policies for parks and other Brazilian  
403 protected areas are defined by the 2000 Brazilian Protected Areas federal legislation. This  
404 legislation forbids any human settlement inside Brazilian parks, and establishes that parks are  
405 created mainly for nature conservation, research and tourism. The federal legislation is usually  
406 complemented by the management plan of each protected area; the management plan of Serra do  
407 Mar State park (2006) establishes the strategic spatial plan for park management, defining  
408 different zones (including protective buffer zones around park limits), and its allowed uses.  
409 Considering this, we suggest that both instruments have been equally important for the observed  
410 forest persistence and afforestation process, and we recommend more effort by park managers in  
411 elaborating and implementing the required management plans. Several protected areas are  
412 created without having a management plan in place, or with plans that not integrated with other  
413 local land use plans, making it difficult to promote nature conservation strategies that are aligned  
414 with the economic and social life of neighbouring communities (Brasil, 2000; Freitas Lima;  
415 Ranieri, 2018).

416 Although urban expansion has mainly removed natural forest areas in the NCSP,  
417regenerating forest have remained as a dominant land cover class outside parks limits, covering  
418more than 40% of these areas and concentrating mostly in the foothills behind the coastal plains.  
419In agreement with our data, a joint report by the S.O.S Mata Atlântica Foundation and the  
420National Institute for Space Research (F.S.O.S & I.N.P.E, 2016) has also quantified a decline in  
421deforestation rates and increase in regenerating areas for the entirety of the Atlantic Forest in São  
422Paulo, between 2000 and 2016. For the NCSP, we suggest that the legal instruments for land use  
423planning and forest conservation published during the late 1990's and early 2000's are likely to  
424be the main drivers of forest persistence and afforestation outside park boundaries quantified  
425between 2000 and 2010. Internationally, the recognition of the Atlantic Forest as a Biosphere  
426Reserve (UNESCO, 1991) strongly influenced Brazilian authorities to improve protection efforts  
427for the Atlantic Forest; the Federal Law of Environmental Crimes (Law n° 9605 of 1998) and the  
4282006 Federal Law for Protection of the Atlantic Forest Biome criminalizes deforestation and  
429other environmental transgressions in this biome, even outside parks. This law was also the first  
430to protect secondary stage (regenerating) forests against any harvesting or exploring activities,  
431and we suggest that it may have influenced the afforestation process and the persistence of  
432regenerating forest we observed in the NCSP. Also, in terms of strategic spatial planning, the  
433Ecological-Economic Zoning (State Decree 49.215/2004), led by the São Paulo State  
434Government, has probably been an import driver of forest persistence and afforestation  
435quantified after 2005, as this legislation determined standards and policies for land use in the  
436NCSP, and delimited zones where forest cover maintenance is enforced, especially at foothills  
437and riparian forests, in agreement with the Brazilian Forestry Code (1965, 2012).

438 The topography itself also certainly plays a role in forest conservation on the NCSP. Most  
439 forested areas mapped by us were located in steep slope areas, and the parks mostly protect  
440 scarps and high elevation areas, while dense urban settlements mostly cover the flat lowlands  
441 near the coastline. Topography has been broadly discussed as a driver of forest persistence and  
442 afforestation in different landscapes and countries, as a result of human preferences of settling in  
443 flat areas (Ab'Sáber, 2007; Pazúr & Bolliger, 2017; Schneeberger, Bürgi, Hersperger, & Ewald,  
444 2007; Silva et al., 2016).

445

#### 446 4.3. Consequences of the dichotomy between fast urban growth and forest persistence

447 Presently, the NCSP shows high rates of human settlement expansion and a continuous  
448 decrease in rural areas, while still maintaining more than 80% of its territory protected by the  
449 three state parks and by general environmental laws. This trajectory of land use and land cover  
450 change between 1985 and 2015 has resulted in loss of landscape heterogeneity and  
451 multifunctionality, resulting on a strong dichotomy between urban use and forest cover.  
452 Population growth rates have declined since 2000, but are still among the highest in the state  
453 (FSEADE, 2016; Instituto Brasileiro de Geografia e Estatística, 2010). Rosembach et al. (2017)  
454 predicts that the number of primary residences (i.e. main homes of local residents, excluding  
455 tourism-oriented secondary residences) in the in NCSP will increase by 48% by 2030, due to  
456 changes in demographic structure. The authors also conjecture that this growth will be mostly  
457 located in peri-urban areas, since the dense urban areas are already mainly occupied by tourism  
458 infrastructure, and the urban land available for new development is very expensive.

459 Outside park limits, dense urban and peri-urban areas occupy 160 km<sup>2</sup> (30%), forests  
460 occupy c.a. 50% and all other land cover types occupy less than 15% (80 km<sup>2</sup>). If our observed

461average annual rate of urban and peri-urban expansion remains unchanged (business-as usual  
462scenario), we can expect that urban areas will increase by 65.7 km<sup>2</sup> and peri-urban areas will  
463increase by 11.9 km<sup>2</sup>, for a total of 77.6 km<sup>2</sup> of built-up areas by 2030. Therefore, for this growth  
464to be accommodated almost all remaining non-protected lands will need to be converted to urban  
465and peri-urban uses by 2030. This assumption is not unreasonable, as several authors have  
466predicted that rates of urban growth will continue to increase rapidly in many parts of the world,  
467considering both sprawl and intensification, especially the peri-urban areas of developing  
468countries and coastal zones surrounded by biodiversity hotspots (Ellis & Ramankutty, 2008;  
469Elmqvist et al., 2013; Verburg et al., 2015). The UN (2009) has also predicted that urban  
470population in South American cities will increase by 34% until 2050, and Inostroza et al. (2010)  
471have predicted that the urban core area of major cities in South America will double by 2035,  
472assuming that rates of change continue at their current levels.

473        These expected land cover changes are likely to result in negative effects that go beyond  
474a land use planning crisis. The increase in peri-urban use quantified by us between 1990-1995  
475and 2005-2015 is likely associated to informal settlement leading to disadvantaged  
476neighbourhoods (e. g. “slums”), which suffer from a combination of economic, health, and  
477environmental issues resulting from unplanned urban sprawl and expansion of urban limits. This  
478suburbanization phenomena has been described as a frequent consequence of the fast urban  
479sprawl in several Latin America cities and developing countries in general, usually led by  
480economic drivers (Elmqvist 2013, Inostroza et al., 2010). In Latin America, per capita land  
481consumption has increased for the richer economic classes in urban areas, increasing land prices  
482and driving the poorest segments of the population away from urban centres and facilities  
483(Inostroza et al., 2010).



484 Furthermore, the loss of traditional rural landscapes will negatively impact quality of life  
485in the region. Traditional uses promote sustainable landscapes (Antrop 2005), and the  
486replacement of rural areas can result in loss of landscape functionality and diversity and critically  
487impact food security, also changing the complex relationship between people and the landscape  
488(Antrop, 2005; Bürgi, Verburg, et al., 2017; De Groot, 2006; McNeely & Scherr, 2009;  
489Nassauer, 1995; Tuan, 1983). Traditional peoples and small farmers still present in the NCSP are  
490currently the main drivers of landscape multifunctionality maintenance. However, most of the  
491territories occupied by these communities are not properly delimited by legal instruments, and if  
492the observed rates of urbanization persist, traditional peoples and landscape multifunctionality  
493will be both under severe threat.

#### 4945. **Conclusions**

495 Our work provides a detailed characterization of urban expansion and sprawl, and  
496advances our understanding of the main drivers of land use and cover change in the Northern  
497Coast of São Paulo state. These results are an important subsidy for future land use planning and  
498landscape management, as we show that available land for human settlement has been decreasing  
499steadily in the studied region, especially since c.a. 80% of the entire region is still comprised by  
500park areas under very strict land use regulation.

501 Our observed results and the supporting literature show that economic policies, including  
502the expansion and improvement of road accessibility and the presence of large industrial  
503enterprises were important drivers of population growth until now, resulting in dense urban and  
504peril-urban expansion. Another important driver is the continued expansion of the tourism and  
505housing markets, which also influence migration and increases the demand for both primary and  
506secondary residences, further driving the expansion of built-up areas paired with rural use

507decline. Current economic and demographic observations suggest that the same rates and  
508trajectories of past land changes can be expected to continue in the future, as there has been no  
509significant changes in land use planning policies and/or efforts to create a more diverse and  
510multifunctional landscape for the NCSP region. If this expectation is proven true, urban and  
511peri-urban expansion will replace all other land uses and cover types outside park areas by 2030,  
512including unprotected forest areas, native and traditional people's territories and the remaining  
513rural uses. Considering that the Northern Coast of São Paulo state still shows high rates of  
514population growth that demand the construction of new primary residences, and that there are  
515large scale logistic enterprises such as road and port expansion and increases in oil exploration  
516planned for the near future, the region may be fast approaching a land use planning and  
517management crisis.

518       To authorities and planners, we thus suggest more effort in establishing long-term and  
519sustainable housing and development programs, instead of focusing solely on business and  
520industry growth. For instance, we suggest the development of a tiered municipal urban service  
521tax regime that taxes more highly properties corresponding to industrial uses, high value  
522accommodations, hotels and other enterprises that more heavily consume landscape space and  
523ecosystem services, while providing tax incentives for primary residence uses and for the  
524implementation of sustainable uses and landscape diversification practices in private land.

525       The role of local actors and institutions has been essential for maintaining landscape  
526multifunctionality and protecting traditional rural landscapes, promoting sustainable interactions  
527between forest cover conservation and diverse agricultural uses, but more concrete actions are  
528needed to protect traditional rural landscapes and promote landscape multifunctionality. We urge  
529government agencies and decision-makers involved in the planning and administration of the

530NCSP to review current policies and regulations for land use both within and outside parks to  
531make them more inclusive, with strong participation from all stakeholders, otherwise these  
532alternative uses will be lost within a few decades and the progressive urban encroachment will  
533start to strongly threaten the effectiveness of existing protected areas. The developing of more  
534participatory management instruments and regulations that effectively engage public  
535administrators, traditional communities, small farmers, representatives of the tourism sector and  
536other important stakeholders in the land use planning process may improve the success of  
537strategic spatial planning and governance, developing more sustainable and multifunctional  
538landscapes in the region. We also hope our results may help guide landscape management and  
539conservation policies in similar coastal regions throughout the world.

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708Table 1 - Land use and land cover classes used for mapping land cover changes in the Northern  
709Coast of São Paulo State, Brazil, between 1985 and 2015, using Landsat historical data.

710Table 2. Kappa index of agreement and omission and commission errors for each LULC class  
711from 2000, 2010 e 2015, after manual correction.



712Table 1 - Land use and land cover classes used for mapping land cover changes in the Northern  
713Coast of São Paulo State, Brazil, between 1985 and 2015, using Landsat historical data.

Land use / land cover class	Description
Mature forest	Dense forest characterized by an advanced successional stage comprised mainly by primary forest, or occasional old-growth secondary forest.
Regenerating forest	Less dense forest, early to medium successional stages, mostly comprised by regenerating secondary forest.
Non-forest vegetation	Native or exotic vegetation including pastures, grasslands and agriculture.
Bare soil and rock	Exposed soil or rock surfaces lacking vegetation and buildings and including sandy beaches and rocky shores.
Peri-urban	Mixed areas with lower population density and sparse buildings, including a high diversity of rural uses, agroforestry, and small forest fragments.
Dense urban settlements	Dense built-up areas, mostly urban.
Water	Free water surfaces.

714

715Table 2. Kappa index of agreement and omission and commission errors for each LULC class  
716from 2000, 2010 e 2015, after manual correction.

Classes	Kappa Index			Omission Error			Commission Error		
	2000	2010	2015	2000	2010	2015	2000	2010	2015
Non-forest vegetation	0.85	0.91	0.94	0.15	0.07	0.05	0.13	0.07	0.05
Peri-urban	0.79	0.68	0.85	0.13	0.17	0.07	0.18	0.28	0.13
Bare soil/rock	0.83	0.97	0.93	0.00	0.03	0.09	0.15	0.03	0.06
Dense urban settlements	1.00	1.00	0.88	0.05	0.00	0.03	0.00	0.00	0.10
Mature forest	0.85	0.88	1.00	0.10	0.10	0.06	0.13	0.10	0.00
Regenerating forest	0.81	0.72	0.93	0.26	0.31	0.08	0.15	0.23	0.06

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721Figure 1. A) Map of Brazil showing the location of São Paulo State (SP). B) Northern Coast of  
722São Paulo State showing the location of state parks, main highways, oil and gas infrastructure,  
723major ports and airports, and urban and peri-urban census sectors.

724

725Figure 2. Main land use and land cover change processes observed between 1985 and 2015. A)  
726non-forest vegetation, peri-urban and dense urban settlement increase; B) Forest dynamics:  
727afforestation, deforestation, forest disturbance (primary to secondary forest), forest persistence.  
728C) Digital Elevation Model (ALOS World3D).

729

730Figure 3. Land use and land cover change trajectories for the areas of the Northern Coast of São  
731Paulo outside park limits: A) All conversion types; B) land use / cover conversion to dense urban  
732settlements and peri-urban areas. RF = Regenerating forest; MF = Mature forest; DU = Dense  
733urban settlement; PU = Peri-urban; NF = Non-forest vegetation

734Figure 4. Peri-urban and dense urban settlement dynamics: example from the central region of  
735Ubatuba municipality. Land abandonment = peri-urban conversion to non-forest vegetation and  
736regenerating forest; Peri-urban persistence = peri-urban maintenance during the time step; Peri-  
737urban increase = conversion from any cover class to peri-urban; Dense urban increase =  
738conversion from any cover class to dense urban; Urban intensification = conversion from peri-  
739urban to dense urban, Urban persistence = dense urban maintenance during the time step.

740List of appendices

741A) Methods: Scripts for processing on “RSGISlib” free algorithms library, in Python language:

742

743 A.i) Segmentation

744 A.ii) Random Forest Classification

745 Aiii) Training samples area (km<sup>2</sup>) for the implementation of Random Forests algorithm

746

747B) Results

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749 B.i) Land use and land cover maps

750 B.ii) Land use and cover characterization inside and outside state parks

751 B.iii) Transitional matrix of land use and land cover change Northern Coast of São Paulo

752State

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