



Managing urban coastal areas through landscape metrics: An assessment of Mumbai's mangrove system



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ABSTRACT

The loss of coastal landscapes resulting from urban sprawl has become a growing concern that is difficult to manage. The consequences of sprawl are often lasting, leading to the irreversible loss of vulnerable and valuable natural landscapes in favour of urban land. In this paper I analyse the spatiotemporal differences of the urban footprint in Mumbai, India, and compare these changes to the existent mangrove systems in the coastal stretches of metropolitan Mumbai. Based on the extracted urban footprint of the coastal mangrove regions, landscape metrics are performed to understand the impacts of urbanisation on the relative increase and decrease of mangrove systems. Of the entire mangrove system in the Mumbai Metropolitan Area, 36% has been lost to urban land since 1973. Over the four time periods studied, an area of urban sprawl comprises the southeastern border of Mumbai, where, since 2000, pressure on the wetlands has been largely aggravated. The high correlation of coastal stretches and urbanisation is one of the main reasons for the current fragile state of Mumbai's mangroves. A combination of a decrease and an increase in mangrove sites suggests that certain urban typologies, such as denser urban areas and older urban regions, are more prone to mangrove recovery, whereas unplanned urban settlements and highly fragmented urban areas lead to a less favourable mangrove landscape. A spatial accounting of the distribution of landscape metrics is proposed in this paper to understand land use transitions where (1) a significant increase of dense urban areas along Mumbai's fragile coastal stretches is reported; (2) this loss of mangroves is underpinned by urban typology over time; and (3) a combination of metrics vis-à-vis zones where mangroves increase and decrease are spatially and temporally addressed. With the increase in economic development that Mumbai has exhibited in recent decades, it is important to monitor the impacts on natural regions. This is a challenging task where spatial metrics combined with urban footprints may lead to a better understanding of the environmental impacts on coastal stretches. The current planning policies suggest that attention has been given to the mangrove systems of the MMR, equating to beneficial results if economic prosperity and preservation measures in Mumbai continue to take place.

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1. Introduction

The so-called “urban century” in which more than half of the world population is found in urban areas has led to dramatic changes in the configurations of land use (Foley et al., 2005). The increasing growth of cities is leading to more megacities that command the landscape (Griffiths et al., 2010). Polycentric urban agglomerations shape a new trend in urban patterns, especially in developing countries. These new urban agglomerations bring

unprecedented challenges for urban planning and land use management. These challenges are chiefly a product of the nature of the agglomeration of urban areas, and the combination of anthropogenic activity in fragile ecological areas (Zhang and Seto, 2011). Advances in land use and spatial analysis have led to a better understanding of the underlying patterns, helping to create more sustainable urban regions (Lambin et al., 2001). In particular, when facing urban change in suburban and rural areas and accentuated population dynamics, spatial modelling has brought significant advances. The detailed information of the spatial distribution of environmental and natural land use has supported the optimal planning of urban regions (Verburg et al., 2002; Pettit et al., 2013). Spatial analysis has the possibility of being transferred to legislators and planners, as well as to state and local governmental entities,

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allowing these individuals and entities to (i) determine better land use policies and improve transportation and utility demand (Waddell, 2002), (ii) identify future development pressure points (Barredo and Demicheli, 2003), and (iii) implement effective plans for regional development through integrated support systems (Vaz et al., 2012; Geertman et al., 2013). The long-term effect of these actions can support sustainable development at the regional level, providing a systemic control that optimises the use of available resources as drivers of sustainable decision-making practices (Nijkamp et al., 1992; McGee et al., 2012). Significant contributions in the field of Geographic Information Systems (GIS) that relate land use/land cover change (LULC) (Koomen et al., 2007) have allowed for a bridge thorough empirical analysis of the consequences of urban change on different scales (Mahiny and Clarke, 2012). This has been a result of the growing number of remote sensing techniques, which aid in more accurate satellite imagery (Wentz et al., 2008) that, when allied to spatial analysis, provide more accurate methods for understanding the spatial morphology of cities and the environment and can subsequently lead to more sustainable urban regions. In developing countries, urban regions currently face a bottleneck: on one hand, cities act as engines of socio-economic growth and development (Richardson, 1989), but on the other hand, cities escort environmental degradation, including the surrounding natural land, heritage, and biodiversity. The consequence is an irreversible loss of the natural environment and an increase in urban pressure (Fazal, 2000; Gowda et al., 2000). This is particularly realized in vulnerable coastal areas, where ecological diversity is higher and integrated systemic assessments are very beneficial for optimal land use distribution (Pouerebrahim et al., 2011), supporting local and regional planning (Turner et al., 1998). Systemic assessment becomes even more important in the context of megacities, where urban changes often have irreversible results on the environment. The available data sources compiled from remote sensing imagery and land use databases support planners in the process of adopting suitable regional policies (Dühr and Müller, 2012). Such combined techniques lead to a better understanding of the intrinsic complexity between urban growth and the negative externalities of excessive urban pressure on fragile environments (Newman, 2006). These applications are particularly welcomed in developing countries, where an unprecedented expansion of the urban footprint has occurred in recent decades (Cohen, 2004). This increase in the urban footprint has a direct impact on land use and results partially from increased population growth (Brockhoff, 1999), socioeconomic dynamics, and economic disparity. It is expected that 60 per cent of the world's population will be living in urban areas by 2030, and most of the urban growth will occur in developing countries (Hall, 2003; Girard et al., 2007). Monitoring the pressure on environmental resources is thus of utmost importance in such regions facing urban sprawl (Bhatta et al., 2010), making India and, in particular, Mumbai a very important region to assess such phenomenon. Measuring sprawl is important to plan whether the city is becoming compact or dispersed, as well as to identify areas of pressure that affect different attributes of urban and rural interactions including growth, density, occupation typology, accessibility, fragmentation and decentralisation (Torrens, 2008). This makes the phenomenon of urban sprawl rather difficult to define (Wilson et al., 2003). For the purpose of this paper, a spatial and ecological perspective is adopted, where the impact of density and fragmentation as well as decentralisation are of utmost importance for the environmental stability of fragile ecological areas (Nagendra et al., 2004); a particular focus is on Mumbai's mangrove system and its surrounding landscape. The physical characteristics and patterns of sprawl on urban landscapes can be detected, mapped, and analysed using remote sensing and geographical information system (GIS)

technologies in conjunction with secondary and ground truth data. This allows for a better understanding of urban sprawl in combination with spatial techniques (Sun et al., 2007). The integration of spatial accounting methods, such as deriving landscape metrics, allows for the quantification of urban sprawl and the ability to register a better understanding of the urban form (Yeh and Li, 2001), as well as to generate a better understanding of the landscape fragmentation induced by anthropogenic activities that often create conflicting trade-offs (Setälä et al., 2013). Comparison of this information on wetland systems and mangroves, therefore, permits an accurate observation of the loss of mangrove systems and a better understanding of the long-term impacts along vulnerable mangrove stretches (Vaz et al., 2013).

2. Study area

The megacity of Mumbai extends from 18° 53' to 19° 16' N and 72°–72° 59' E. It is one of the most emblematic cities in India as well as the main city of the western state of Maharashtra. Currently ranked as the fifth largest city in the world, it had a total population of 12.5 million inhabitants in 2011. Consisting of a peninsula originally composed of seven islets, drainage and reclamation have caused the islets to join and form the Bombay (Mumbai) Island, which is bordered by the Arabian Sea to the west and Bombay harbour and the Thane Creek inlet to the east. In addition to being India's leading economic and financial district, Mumbai (Fig. 1) is also strongly linked to the new, modern and industrialised India, having been one of the main regions responsible for India's booming economy, holding over 40 000 industries in the region alone. The total urban area of Mumbai is 466.35 km², with a maximum width of 17 km east to west and 42 km north to south.

The availability of good infrastructure supported by the government and local authorities has facilitated Mumbai's economic prosperity. The abundance of different modes of transportation (railway networks, airways, sea transportation, ports, and the recent national four lane golden quadrilateral road), as well as an ample supply of electricity and water, has further supported the current economic growth of the Mumbai Metropolitan Region (MMR). Mumbai has a tropical savannah climate with a heavy southwest monsoon rainfall, measuring 2166 mm annually. The temperature ranges from 16.5 °C to 34.7 °C with only marginal changes between summer and winter months. The relative humidity is quite high, ranging between 54.5 per cent and 85.5 per cent. The city has an abundant natural landscape consisting of natural resources such as lakes, coastal waters, forest areas, wetland systems and mangroves. The wetlands and mangroves serve as an important part of the coastal ecosystem and offer natural protection as an erosion barrier, preserving the shoreline against tidal currents. Currently, however, much of the marine wildlife species and their natural habitats have been decimated and become greatly endangered because of the massive urban expansion, which has resulted in excessive waste and debris from dumping as well as several industries that threaten Mumbai's ecological carrying capacity. An assessment conducted by the United Nations (2012) predicts continuous growth of Mumbai's urban area, leading to an increase in the total population to 27 million people by 2025, becoming one of the largest urban regions worldwide and creating a dysfunctional enclave in the region (Wissink, 2013).

3. Data

3.1. Mumbai's urban footprint

An "urban footprint" represents the extent of artificial urban land use at the regional level (Landis and Reily, 2003). This

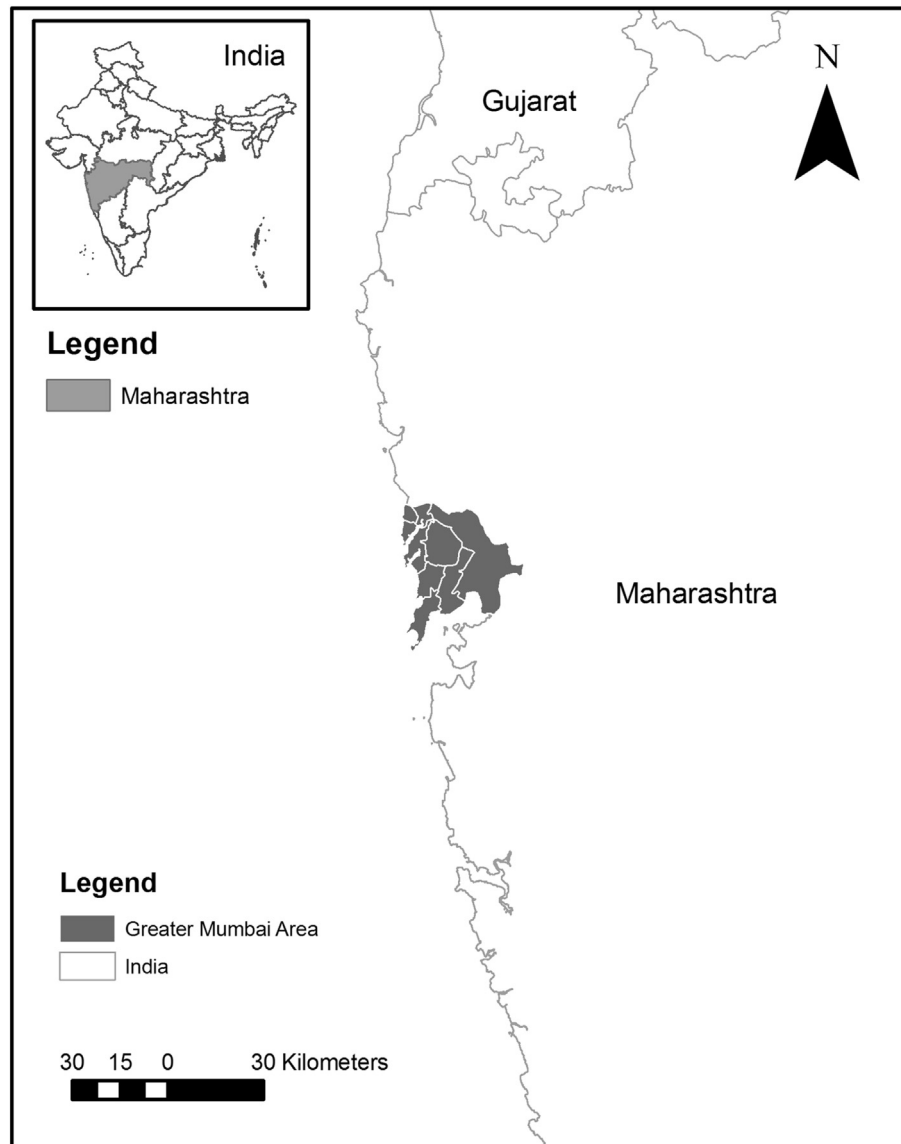


Fig. 1. Location of the greater Mumbai area.

definition of urban land use is particularly important for the assessment of megacities given the existence of large urban regions that often develop natural land. This is aggravated by the fact that coastal megacities throughout the world tend to be built on young sedimentary strata, leading to groundwater withdrawal, damaging coastal ecosystems and amplifying sea level rise and climate change (Nicholls, 1995). The effect is one of degraded marine environments, resulting from anthropogenic activities in coastal areas that must be managed for more sustainable urban development (Jiang et al., 2001). The use of satellite imagery at the regional scale has been useful in generating large land use datasets to measure change in urban regions, and in particular for third world cities, with important results for planning and policy implications (Lavalle et al., 2001). The integration of different anthropogenic land activities into the urban footprint allows for a regional level assessment over time. This brings a systemic approach to the consequences of both urbanisation and anthropogenic activities on the surrounding landscape. The urban footprint for Mumbai was assessed in 1973, 1990, 2001, and 2010, conducted using an object-oriented classification with an additional manual enhancement in a

step-wise process from the latest Landsat ETM + imagery to the earliest available datasets with several accuracy assessments. These datasets originated from urban footprints that were combined with a pixel-based classification approach using TerraSAR-X data and resampled at 30 m (Taubenböck et al., 2009). The authors adopted the available data from 1972 with a geometric resolution of 79 m (multispectral scanner), 28.5 m (thematic mapper) or 15 m (enhanced thematic mapper). The data were used to analyse the land use coverage on a multi-temporal basis. The Landsat imagery presents an adequate choice given the size of Mumbai's metropolitan region, and although the spatial resolution is somewhat coarse, it allows for an accurate depiction of urban land use. An object-oriented hierarchical approach was adopted to combine the spectral features with shape, neighbourhood and texture. An oriented fuzzy-based methodology was used to combine spectral features. The accuracy assessment, as discussed by Taubenböck et al. (2009), achieved an overall high range between 86% and 93% for all studied cities. The authors adopted a post-classification comparison based on a pixel-wise detection for the available years. This dataset was then embedded as evidence for further

classification based on the Landsat imagery from 2001 (enhanced thematic mapper), thus allowing a categorical classification of land use classes for the Greater Mumbai Area (Fig. 2). A projection of the UTM Zone 43 North study area was used, and a classification of satellite imagery was followed using geometric corrections and an integration of a maximum likelihood algorithm (Blaschke, 2010). An overall accuracy of 85% was confirmed using a kappa coefficient calculation.

Mumbai's urban footprint has changed dramatically over the previous decades (Fig. 3), whereas urban sprawl has been evident in the last 30 years; this sprawl is aggravated by the population dynamics that characterize Mumbai's Metropolitan Region (MMR).

Developmental pressures have aggravated the agricultural and forestry components of the region, currently making agricultural land less available than industrial land with an increased incidence over time of developing business hubs transforming Mumbai's economic landscape (Vaz, 2013). This development brings economic growth to a region that is slow to improve the equitable distribution of wealth and boosts population growth for a city that had little more than 6 million inhabitants in the 1970s and by 2011 had doubled the size of its population to 12 478 447 inhabitants. However, according to the latest census, Mumbai's population decreased between 2001 and 2011, suggesting that Mumbai's economic growth is following a population distribution pattern that

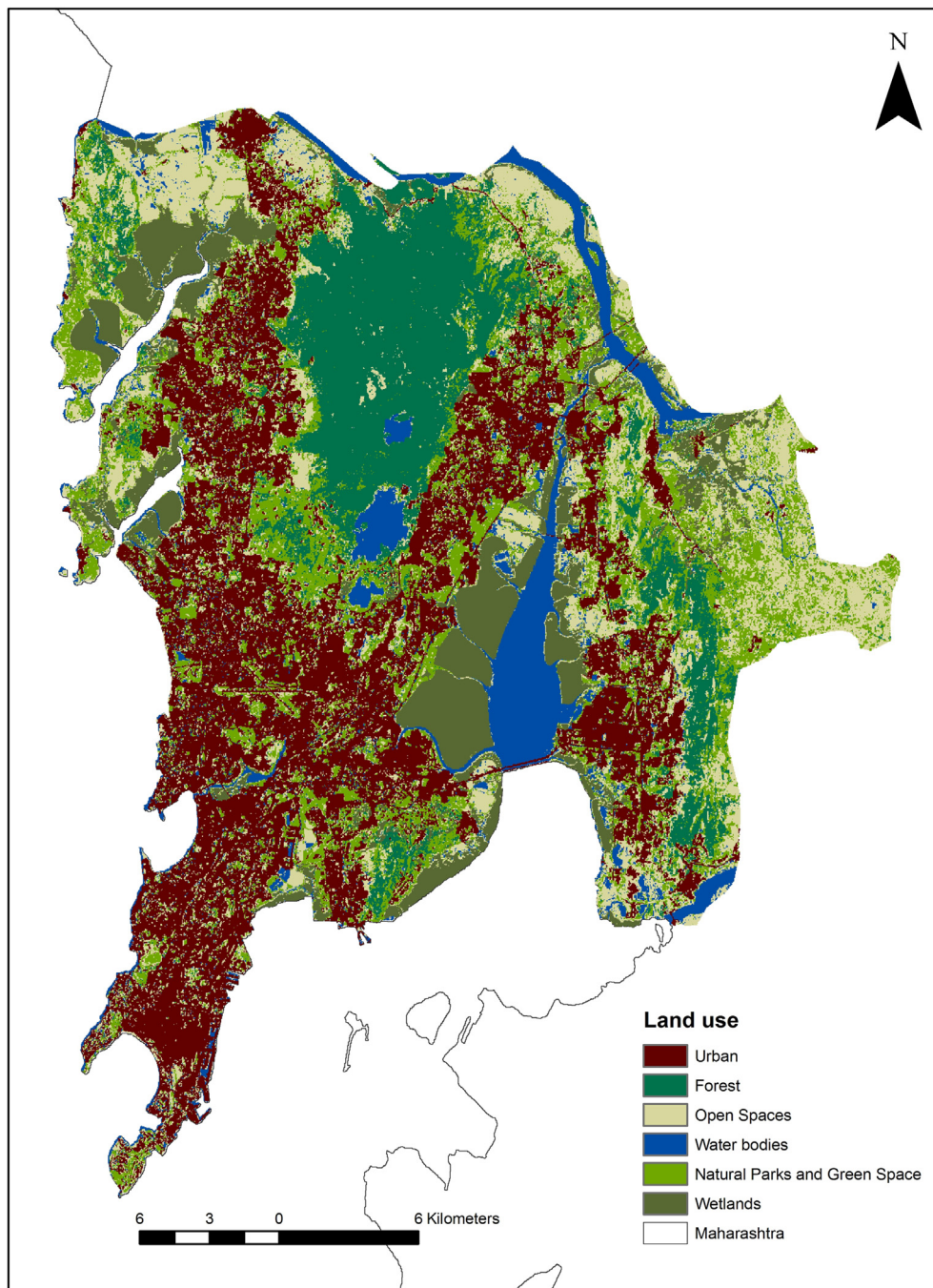


Fig. 2. Mumbai land use classification.

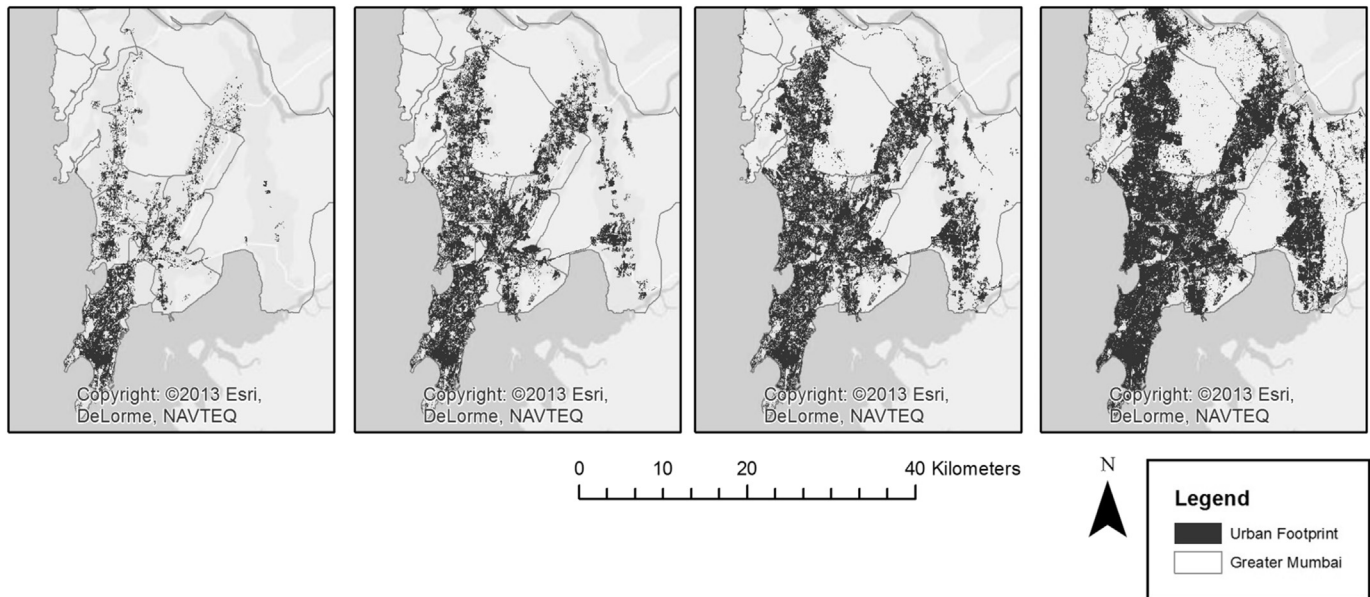


Fig. 3. Mumbai's urban footprint in 1973, 1990, 2001 and 2010.

may be less environmentally damaging in the future provided such issues as poverty and slum areas are controlled.

3.2. Mangroves

Mangroves are one of the trademarks of Mumbai's coastlines. They are long-lasting, natural phenomena that stretch from the northern part of Thane Creek south to Kaibadevi, close to the historical core of Mumbai. The mangroves formed a 37-km² enclave in the surrounding city in the early 1990s. In recent decades, more than half of this natural wetland protecting system has been lost as a result of urbanisation, population growth and sewage treatment. The rapid urbanisation processes that Mumbai has experienced over the last decades, and the successful economic growth that has led to rapid population growth and vitality in Mumbai's business district, make it of utmost importance to consider the sustainable relationship between biodiversity and habitats in a compromise of economic growth and ecological sustainability. Mangroves, part of saline coastal sediment habitats, are found in tropical and sub-tropical regions. They offer a unique coastal environment, preventing erosion by absorbing wave energy, and can be used to develop natural systems that protect extensively eroded stretches of coastline in the south-eastern hemisphere (Othman, 1994). Not only do mangroves offer a unique habitat for biodiversity with inimitable functions for the environment and ecosystems (Field et al., 1998), but their conciliatory characteristic of standing at the interface between land and sea equates to a hidden potential for useful advances in bioremediation and offers unique biotechnological potential given their plethora of microbial activity (Thatoi et al., 2013). The importance of coastal management in Mumbai and the role of mangrove systems have been widely recognised as the most important component for the sustainability of Mumbai's coastal ecosystem and soil erosion prevention (Murthy et al., 2001). The mangrove dataset for Mumbai was adapted from the study carried out by Vijay et al. (2005).

4. Methodology

At the first stage, a combination of urbanisation over time is tested using a common method that integrates landscape metrics,

which allows for the assessment of changes in the urban dynamics (Luck and Wu, 2002; Puertas et al., 2014). The available urban footprints were extracted and then overlaid over the mangrove system, assessing the change in urban form over time in relation to the mangrove systems. Landscape metrics explained the changes in urbanisation on the geomorphological and temporal characteristics. This is primarily possible given the quantitative explanatory characteristics of profiling heterogeneous characteristics of the landscape (Vaz et al., 2014), providing a better understanding of the fragmentation of fragile areas and land use changes. The created mosaic of urban land use that resulted from the contribution of a raster model establishes a functional and geovisual inference of quantifiable spatiotemporal patterns (Farina, 2006), which help to assess the fragility of the mangrove system and its subsequent loss. The existence of a plethora of different metrics resulted in the choice of compactness and fragmentation as key metrics for understanding the differences over time on the fragile mangrove regions. The usage of Patch Analyst (Rempel et al., 1999) permitted the calculation of these landscape metrics. The urban typology was considered to be predominant in the configuration and quantification of patterns along the landscape leading to a land use mosaic (Farina, 2006). This led to a discrete space where the fragmentation of existing landscapes can be calculated (Hargis et al., 1997, 1998; Vaz and Bowman, 2013) by defining areas that (i) maintained their mangroves, (ii) lost mangroves, or (iii) gained mangroves. These three categories of mangrove trends across the Mumbai coastal region from 1990 to 2001 (Fig. 4) were the extension sites used to understand the differences within the urban form, determining which types of urban forms represent predominant characteristics for the morphology of mangrove systems.

The landscape was calculated using the Patch Analyst program developed by Elkie et al. (1999), which allows for a structural assessment of the landscape's composition. A total of 17 metrics were conducted following the implementation of the Patch Analysts' function of shape metrics developed in the FRAGSTATS environment (McGarigal et al., 2002) of algorithms (Table 1).

Of particular interest are the consequences on the shape as well as on the quantity and distribution of the existent urban patches over time on the mangrove system. The assembly of the metrics used was composed by means of a cumulative interpretation of

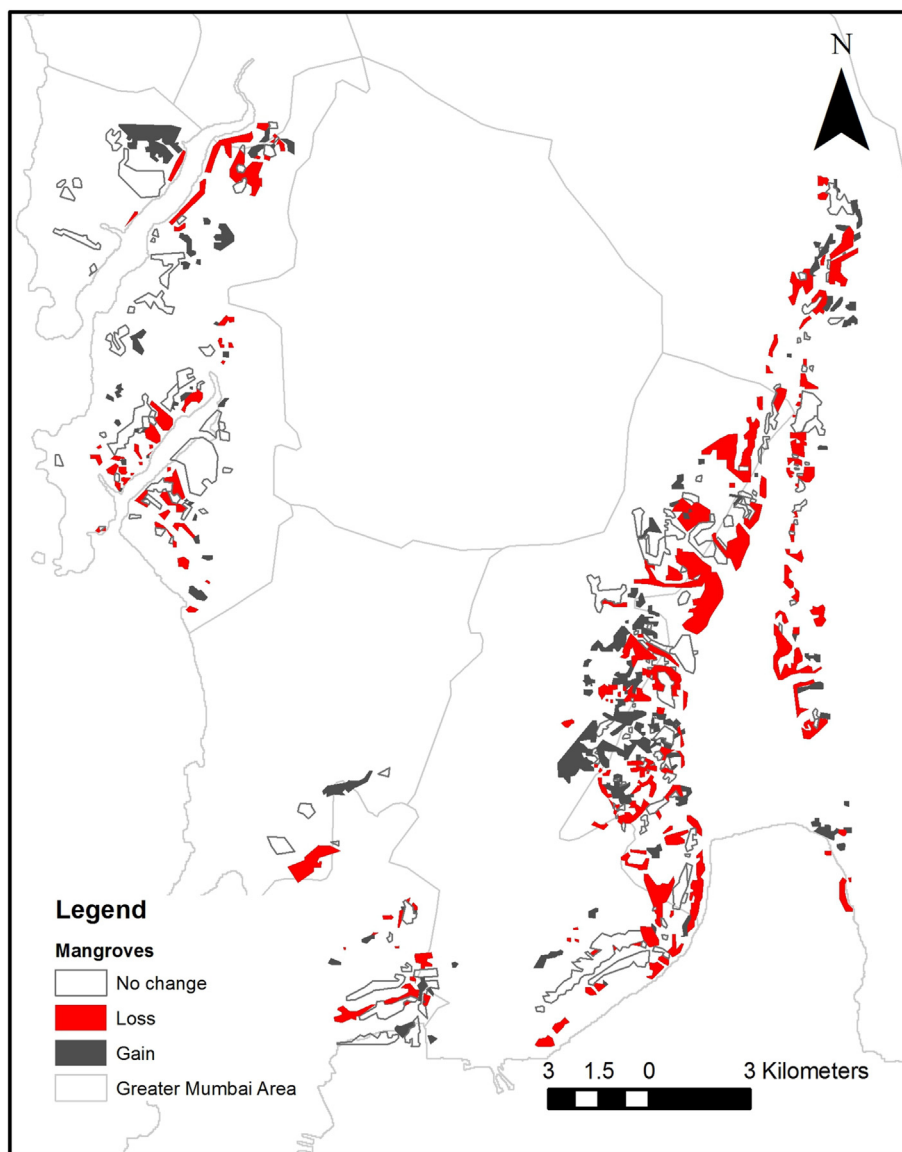


Fig. 4. Gain and loss of Mumbai's mangrove system.

urban areas on top of the multi-temporal land use patterns, which allowed for the calculation of these metrics for 1972, 1991 and 2001. Although additional and even more expressive growth was observed in 2010, the mangrove survey was conducted between 1990 and 2000, suggesting the difference within this period and, therefore, only a similar temporal period was considered. The multi-temporal layers of urban and mangrove interactions were then calculated, resulting in the spatiotemporal interpretation of effects on the mangrove system.

5. Discussion

The metrics for the type, diversity and rapid change of India's mangrove systems is rather appalling, especially given reported losses through 2001 of a total of 39.32 per cent. The classified mangrove systems were assessed on high-resolution satellite imagery for ancillary correction using additional integration from Google Earth. This led to a spatial inventory of the mangrove systems, which was then reclassified into three classes—gain, loss or

Table 1
Landscape metrics included in the analysis.

	Acronym	Metric name
1	AWMPFD	Area Weighted Mean Patch Fractal
2	AWMSI	Area Weighted Mean Shape Index
3	CA	Class Area
4	CACOV	Core Area Coefficient of Variance
5	CAD	Core Area Density
6	CASD	Core Area Standard Deviation
7	ED	Edge Density
8	MCA	Mean Core Area
9	MPFD	Mean Patch Fractal Dimension
10	MPS	Mean Patch Size
11	MSI	Mean Shape Index
12	NUMP	Number of Patches
13	PSCOV	Patch Size Coefficient of Variance
14	PSSD	Patch Size Standard Deviation
15	TCAI	Total Core Area Index
16	TE	Total Edge
17	TLA	Landscape Area

maintain—leading to several spatial conclusions on the distributions of the mangroves and their loss and gain (Fig. 5). Although mangrove systems declined significantly within the years studied, the gain in other areas also decreased proportionately, further suggesting that the difference between mangrove loss and gain is becoming more accentuated in recent decades.

Whereas unchanged mangrove systems registered the highest values (i.e., little difference over the twenty-year time period was observed), additional losses have been found in particular mangrove locations, leading to the conclusion that the urbanisation process is in fact the largest spatial culprit of mangrove loss, which is contrary to the gain of sparse mangrove systems that appeared to increase in areas where more natural environments and less anthropogenic activity was found. Overall, the decrease in mangroves is highly correlated with urban expansion, shown by the high number of patches (NUMP = 198). Net changes of urban land use in comparison to net changes of mangroves were assessed (Fig. 6). Urban and mangrove patches were standardised to the maximum value and compared for the years 1973, 1990, 2001 and 2010. Urban areas increased significantly in recent decades, whereas mangroves lost approximately 5% of their area per time-frame. A closer look at the yearly percentage loss between the intervals 1973 to 1990, 1990 to 2001, and 2001 to 2010, shows that the temporal interval from 1973 to 1990 had a 0.33% yearly loss of mangrove systems, whereas the interval between 1990 and 2001 registered a yearly loss of 0.49% and the last interval from 2001 to 2010 had the greatest loss of mangrove per annum at a rate of 0.57%. The rate of loss suggests a decreasing temporal pattern, a result of the combination of the absence of urbanisation along the mangrove systems and the implementation of more efficient policies in mitigating mangrove loss. However, it is important to note that the standardised values suggest that in circa 2005, the amount of urbanisation surpassed the initial availability of mangroves in their relative proportion. The current trend in urbanisation depicts an interesting summary in the combined relationship of urban sprawl and mangrove system loss.

From a planning perspective, this suggests that awareness of Mumbai's mangrove systems is focused on abandoning urbanisation processes in areas that are fomenting new policies and strategies concerning the importance of mangroves. Therefore, in areas where mangroves have increased, less urban patches are present, whereas in regions where urban patches have increased, there exists a link to additional ruptures and a strain on the mangrove systems. The sustainability of coastal and urban interactions with Mumbai's mangroves has a direct consequence on the current trends in the urbanisation process and how urbanisation expands. Edge density was also considered a fine estimator as it refers to the

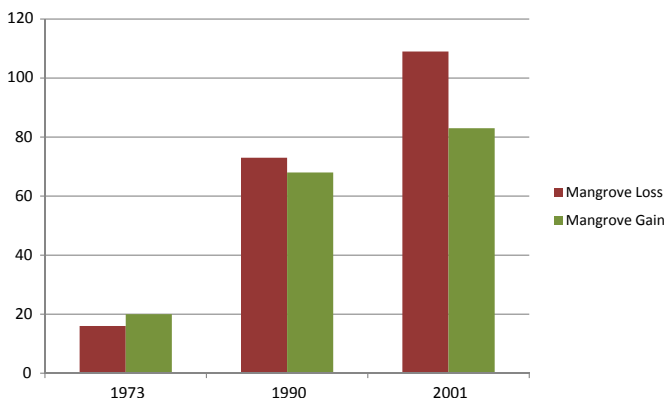


Fig. 5. Spatial changes in Mumbai's mangrove systems for 1973, 1990 and 2001.

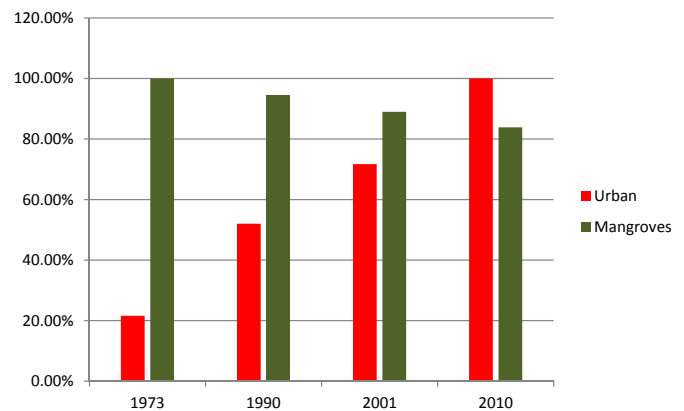


Fig. 6. Temporal distribution of urban growth and loss of mangrove systems between 1973 and 2010.

borders between different classes. In this case, the classes considered were urban and non-urban hectares in the areas where the mangroves maintained, gained or lost structure during the processing period. Edges were contrary to the number of patches and varied little ($ED_{1973} = 1\ 213.70$, $ED_{1990} = 1\ 239.84$, $ED_{2001} = 1\ 267.84$). The calculus that was performed for the Edge Density assessment was as follows:

$$ED = \frac{E}{A} \quad (1)$$

where ED is Edge Density, E is the total edge in metres and A is the total area in ha. It is important to note that an edge corresponds to the border between non-urban and urban (in m), juxtaposing the total length of all borders in ha. The small difference between ED_{1973} and ED_{1990} further suggests that between these time periods the urban morphology was similar. Since 2001, the morphology of the urban areas has changed little, leading to an increase in ED as a result of urban concentration rather than sprawl in the areas; this is further noted through a geovisual interpretation. A more analytical interpretation of each individual metric permits a quantitative analysis of the consequences of urbanisation in areas where mangrove gain, loss and no change were found. Urbanisation processes and anthropogenic activity appear to play an important role in the sustainability of the mangrove system, and landscape metrics may help to better quantify these changes (Tables 2–4). A graph explaining these metrics (Fig. 7 and Fig. 8) summarises a normalised interpretation of the landscape metrics performed.

The metrics presented in the figures below were normalised to vary between 0 and 1, thus allowing a comparison over the different calculated analytical values. It is pertinent to note that Class Area (CA) and Landscape Area (TLA) both showed the highest increase in 2001 for mangrove loss, whereas Core Area Density (CAD) steadily dropped in areas that registered mangrove gain. The spatial conclusions from this are rather important, indicating the possibility of measuring the type of urbanisation processes and their consequences on the management of wetland systems. Whereas an increase of urbanisation observed through the CA and TLA metrics show that an increase affects urbanisation patterns, the areas where mangroves have grown also have shown an increase in urbanisation. The CAD metric, however, shows that there is a significant difference between the morphology of urban areas in areas where mangroves were lost and where mangroves were gained. Areas where mangroves were gained show denser and older (1973) urban areas, whereas areas where mangroves were lost show urbanisation patterns which are more recent (1990 and 2001) and are less densely

Table 2
Construction of landscape metrics for mangrove loss.

Timeframe	CACOV	MCA	CASD	TCAI	CAD	AWMSI	MSI	MPFD	AWMPFD
1973	108.02	1.84	1.99	46.46	25.25	2.03	1.25	1.04	1.12
1990	205.93	0.92	1.90	42.85	46.38	2.00	1.32	1.05	1.12
2001	216.86	1.32	2.87	51.31	38.82	1.86	1.34	1.06	1.10
Timeframe	TE	ED	MPS	NUMP	PSCOV	PSSD	TLA	CA	
1973	8 080.00	408.08	1.24	16.00	207.72	2.57	19.80	19.80	
1990	38 920.00	440.27	1.21	73.00	212.51	2.57	88.40	88.40	
2001	65 880.00	365.35	1.65	109.00	209.85	3.47	180.32	180.32	

Table 3
Construction of landscape metrics for mangrove gain.

Timeframe	CACOV	MCA	CASD	TCAI	CAD	AWMSI	MSI	MPFD	AWMPFD
1973	117.33	0.67	0.79	37.84	56.31	1.60	1.29	1.05	1.09
1990	204.55	1.18	2.40	49.12	41.79	1.94	1.37	1.06	1.11
2001	225.87	1.44	3.25	53.95	37.48	1.96	1.35	1.06	1.11
Timeframe	TE	ED	MPS	NUMP	PSCOV	PSSD	TLA	CA	
1973	8 760.00	493.24	0.89	20.00	141.25	1.25	17.76	17.76	
1990	39 120.00	398.70	1.44	68.00	210.46	3.04	98.12	98.12	
2001	54 760.00	347.90	1.90	83.00	217.15	4.12	157.40	157.40	

Table 4
Construction of landscape metrics for mangrove unchanged.

Timeframe	CACOV	MCA	CASD	TCAI	CAD	AWMSI	MSI	MPFD	AWMPFD
1973	238.06	0.75	1.80	42.38	56.18	2.11	1.37	1.05	1.12
1990	212.32	1.06	2.25	49.84	43.81	2.06	1.42	1.07	1.13
2001	206.91	1.23	2.54	48.51	39.54	2.07	1.44	1.07	1.12
Timeframe	TE	ED	MPS	NUMP	PSCOV	PSSD	TLA	CA	
1973	11 240.00	451.04	1.31	19.00	207.18	2.72	24.92	24.92	
1990	45 080.00	420.21	1.47	73.00	203.73	2.99	107.28	107.28	
2001	77 240.00	396.59	1.68	116.00	202.35	3.40	194.76	194.76	

distributed. This leads to the conclusion that Mumbai's coastal approach to the sustainable management of wetland systems and mangroves must consider (i) the shape of urbanisation brought by metrics such as the edge density discussed above, (ii) the density of urbanisation to prevent future damage to mangrove systems, and (iii) the recovery rate needed for mangrove systems. The integrated assessment of land use dynamics and urbanisation processes is of utmost importance (Pontius et al., 2004). In line with landscape metrics, analytical metric approaches may greatly benefit coastal management issues and conservation (Musacchio and Coulson,

2001), allowing for the delineation of sounder strategies that cope with environmental and anthropogenic interactions at the spatial level through an integrative prism, which is greatly needed in Mumbai's Metropolitan Region (Murthy et al., 2001).

The growing economic disparity in a megacity such as Mumbai aggravates the consequences on the environment and the mangrove system. An evaluative spatial approach concludes that the population plays an integrative role in urban processes for megacities and urban regions of highly occupied and developing cities throughout the world. Mumbai's wetland systems are a

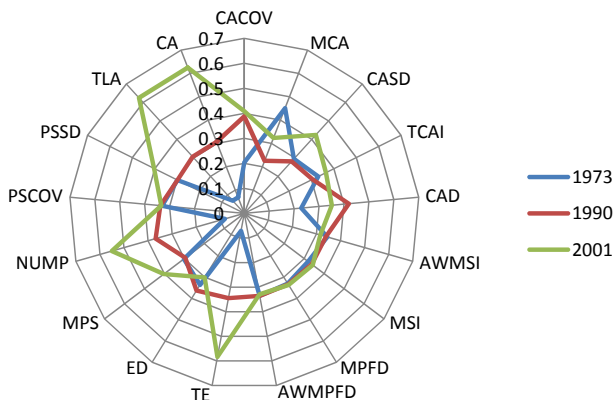


Fig. 7. Landscape metrics for the gain of mangroves.

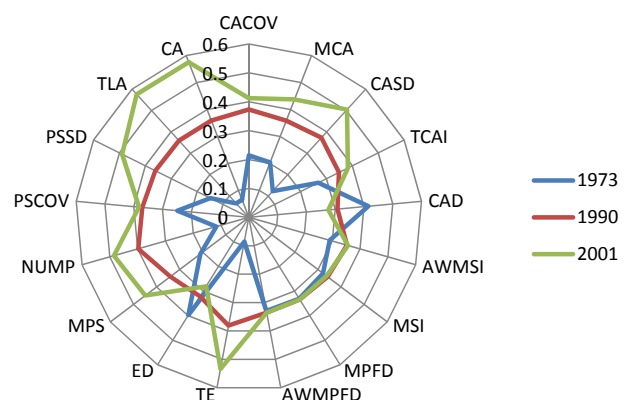


Fig. 8. Landscape metrics for the gain of mangroves.

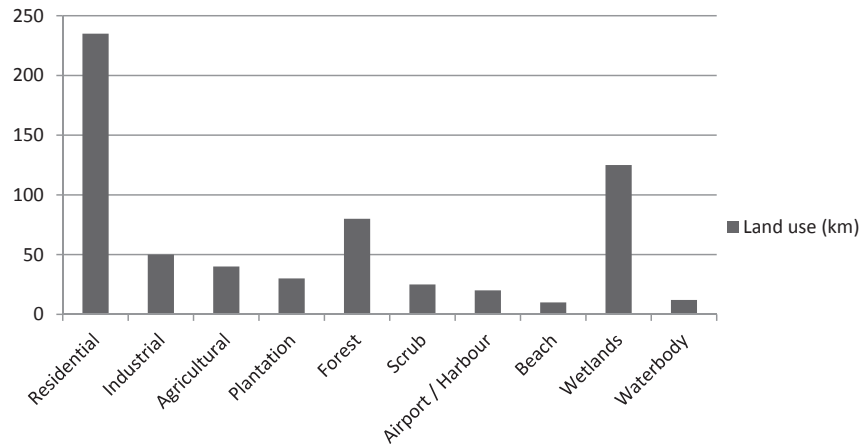


Fig. 9. Land use distribution (km²) in the Mumbai Metropolitan Region (adapted from Murthy et al., 2001).

prominent feature of its land use (Fig. 9). There is strong evidence, however, that urban sprawl will continue to shape negative consequences on the region's coastal perimeter where the mangrove systems and its wetlands are located.

A closer inspection on the land use types was performed to understand the correlation of mangroves lost and gained within different land use classes: urban, forest, open spaces, water bodies, natural parks, green spaces, and wetlands (Figs. 9 and 10).

As expected, areas that gained the most mangroves were located in the wetland systems (64.39%); these account for the only significant determinant of mangroves gained in Mumbai. The other land use types exert pressure on mangrove systems predominantly leading to mangrove loss. A gain of mangroves also occurs, however, in other land use types, such as urban areas, particularly those resulting from urban agglomeration. In terms of land use, the most significant contributor to mangrove loss, besides urban sprawl, is the design of open spaces – often housing and infrastructure creation for new land use typologies of anthropogenic exploration (22.94%).

6. Conclusions

Megacities are both a blessing and a concern for urban futures. Mumbai has witnessed unprecedented urban change as a result of

social, economic and regional development (Seto and Fragkias, 2005). The Mumbai Metropolitan Region is one of the fastest growing urban regions in the world, with unprecedented impacts regarding urban sprawl and its consequences on the wetland fringes (Murthy et al., 2001). Where population dynamics are strongly linked to population shifts in the urban fringes, fragmentation of the MMR is leading to increased socio-spatial implications (Zerah, 2008). This increase in urbanisation is proportional to the creation of new infrastructure to support the population dynamics, causing additional concern in the spatial fragmentation of urbanisation (Young and Jarvis, 2008). An integrative approach must be adopted that accounts for the complex spatial patterns of recreation and tourism and the interaction with responsive coastal management that fosters the sustainable management of mangroves and wetland systems (Murthy et al., 2001). Multipurpose planning must be considered for more sustainable decision processes by taking into account the spatial information (Turner et al., 2004). Commuting and population dynamics play a major role in urban sprawl and should be planned for in advance. The integration of spatial analysis tools and urban growth modelling applied to landscape metrics offer a better understanding of the probable outcomes and directions megacities are facing. The intricate loss of landscape and the underlying concern for biodiversity in the future shows that megacities must consider spatial analysis now to hinder

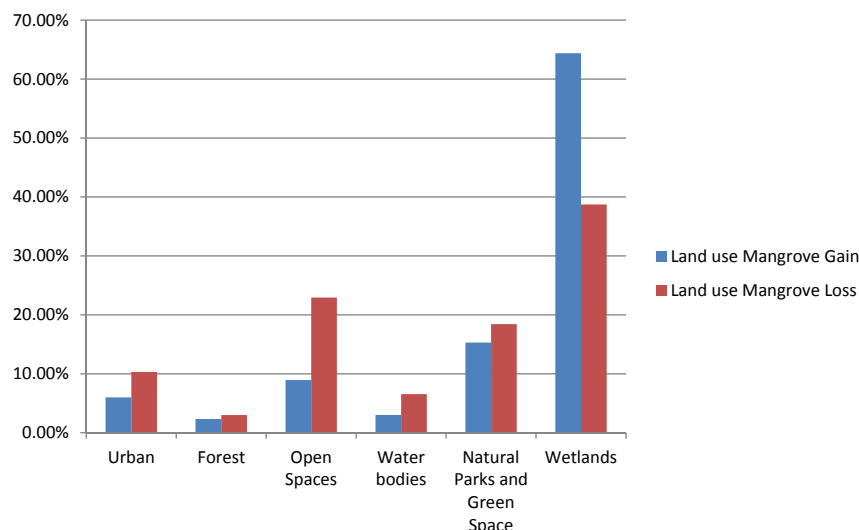


Fig. 10. Distribution of land use types per mangrove gained or lost.

the ecological impacts and create sustainable regions. Although this paper has proven that there are determinants to urban growth in Mumbai, it presents a generic framework for urban processes and stresses the importance of maintaining larger cities and growing cities in context with ecological dynamics and biodiversity.

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