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Research Paper

Towards sustainable growth? A multi-criteria assessment of (changing) urban forms

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ABSTRACT

A multi-criteria approach based on descriptive, correlation and multivariate statistics and mathematical morphology was proposed to investigate long-term morphological changes in a metropolitan region (Attica, Greece) representative of the 'Mediterranean compact city' archetype. A total of 33 metrics measured at 6 time points (1948, 1975, 1990, 2000, 2006, 2012) from diachronic land-use maps were used to identify urban phases characterized by variable intensity of growth and reflecting distinct socioeconomic contexts at the local scale. The Attica's urban spatial structure has rapidly changed following Athens' expansion. Fragmentation, dispersion and shape complexity of built-up patches have been continuously increasing over time. Metrics' patterns differed significantly between two time intervals (1948–1990 and 1990–2012), with the highest spatial variability of landscape metrics being observed in the last two decades. Fractal indexes have reached the highest values in 2006 and 2012. Based on critical thresholds of per-capita land consumption, settlement dispersion and patch fragmentation, a Principal Component Analysis has indicated that the Athens' spatial structure of late 1980s and early 1990s was more sustainable than earlier and more recent urban morphologies. Results of this study contribute to a better understanding of long-term form-function relationships in compact and dispersed cities, offering an empirical base to identify sustainable urban forms.

1. Introduction

Recent urban transformations in developed countries have been primarily associated to the expansion of large- and medium-size cities stimulated by population deconcentration and economic decentralization (Kasanko et al., 2006; Longhi and Musolesi, 2007; Schneider and Woodcock, 2008). New spatial structures have emerged based on the assumption that metropolitan regions are becoming increasingly dispersed, central business districts attracting less jobs and new sub-centers emerging at the edge of large cities (Turok and Mykhnenko, 2007).

Urban sprawl has been intended as a key factor causing modifications in the form of compact and dense cities (Schwarz, 2010). Earlier studies suggest that patterns and processes of sprawl well reflect unexplored relationships between urban morphology and socioeconomic functions in cities characterized by mono-centric and continuous settlements (Leontidou, 1990; Bruegmann, 2005; Couch et al., 2007; Salvati, 2014a). The resulting metropolitan structures are becoming progressively more complex and entropic, with increased patchiness and fractal urban landscapes (Paul and Tonts, 2005; Terzi and Bolen, 2009; Chorianopoulos et al., 2010; Serra et al., 2014).

Sprawled development has become a growing concern as regards urban sustainability. Stemming from the idea of 'compact, mixed-use and walkable' cities, the concept of sustainable urban form (Talen, 2011) encompasses the morphological dimensions of density, diversity and nodality, while low-density development is likely to bring about higher infrastructure costs, increased air pollution, uncontrolled growth of land consumption, weakened social connection (Ferrara et al., 2015).

Due to the implications of changes in urban spatial structures for sustainable development, optimal city forms have been investigated in different socioeconomic contexts (Anas et al., 1998). Garcia-López and Muñiz (2013) pointed out that urban structure

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is important for economic growth in an intra-metropolitan context, demonstrating the existence of neighborhood specialization economies and metropolitan localization economies fostering local development. Camagni et al. (2002) indicated polycentrism as a way towards balanced and sustainable territorial development, combining the agglomeration economies typical of compact cities with the reduced congestion of decentralized urban diffusion.

Based on a comprehensive analysis of urban sustainability in European cities, Shaker (2015) has shown that conventional urbanization will continue to disconnect socioeconomic welfare from life-supporting ecosystem services. Dispersed urban growth negatively influences ecosystems both directly (in and near the city) and remotely through land conversion, use of natural resources and generation of emissions and waste (Alberti et al., 2003; Alberti, 2005, 2010; Biasi et al., 2015). Despite soil is a crucial land resource for many ecological processes (Keesstra et al., 2016; Brevik et al., 2015), soil consumption and land degradation usually reflect dispersed urbanization (Beniston et al., 2016). Air pollution is also a relevant outcome of discontinuous urban expansion (Trujillo-González et al., 2016). Fragmentation of priority habitats is also a common process related to urban sprawl (Aguilera et al., 2011; Colantoni et al., 2015), affecting both landscape structure and functions and causing a potential loss of biodiversity (Botequilha-Leitão and Ahern, 2002; Tombolini and Salvati, 2014). Conversely, sustainable urban form and appropriate land-use planning may contain loss of natural habitats and biodiversity (European Environmental Agency, 2006).

Jabareen (2006) identified multiple design concepts related to urban morphology (compactness, sustainable transport, density, mixed land-use, diversity, passive solar design and greening), proposing four types of sustainable urban forms: the neo-traditional development, the urban containment, the compact city, and the eco-city. Compact cities, characterized by high population density, mixed land-use and spatially-concentrated economic functions (e.g. in a Central Business District) have been proposed as one solution for sustainable urban planning (Westerink et al., 2013; Qureshi and Haase, 2014; Salvati, 2014b). However, the applicability of a more compact setting to expanding already dense cities remains questionable (Redman and Jones, 2005). Critical debate on the compact city includes crucial questions of the environmental benefits accruing to compaction, and its acceptability to local communities (Breheny, 1997; Burgess and Jenks, 2002; Frey, 2003; Colantoni et al., 2016). Major doubts are raised about the economic, political and technical dimensions of compaction and particularly the unacceptability of higher densities to many urban residents (Williams et al., 2000; Dovey and King, 2011; Jenks et al., 2013). Essential to the decision-making is a deeper understanding about the relationship between urban compactness and the sustainable performance of growing cities (Holden, 2004).

Urban sustainability indicators play an important role helping policy-makers to ensure the continued success of their metropolitan regions (Tan et al., 2005; Chen et al., 2008; Ioannidis et al., 2009). Land saving is critical to long-term sustainability of urban expansion and is considered a target criterion informing policies that reduce the environmental impact of sprawl (Zitti et al., 2015). Efficiency in the use of land is a widely accepted concept in the analysis of urban sustainability (Munafò et al., 2013), providing relevant information on land consumed by specific forms of urban expansion (Grădinaru et al., 2015). Although polycentric development has been hypothesized to contribute to more sustainable (spatially-balanced, economically depolarized and socially mixed) spatial structures than mono-centric urban expansion, it has been demonstrated that a polycentric metropolitan growth may consume a higher rate of non-urban land than cities dominated by a central core and with suburbs expanding radio-centrically (Munafò et al., 2010).

Urban morphology is spatially measurable through metrics, supporting studies on sustainability of urban forms (Burton et al., 2003). Tsai (2005) proposed four dimensions to evaluate urban structures at the metropolitan level: city size, activity intensity, the degree that activities are evenly distributed, and the extent that high-density sub-areas are clustered. Formulation of new indicator systems and quantitative approaches to the identification of sustainable urban forms in both compact and dispersed metropolitan areas is a relevant issue in regional planning and urban studies. Multivariate approaches analyzing diachronic land-use maps may help identify a set of working indicators of sustainability in a given urban structure, possibly replacing traditional, univariate metrics (Westerink et al., 2013). Comparing different spatial configurations of a given metropolitan region with multi-criteria approaches (e.g. based on a wide set of morphological indicators) may provide a relevant contribution in the identification of more (or less) sustainable urban forms (e.g. Carlucci et al., 2016). Sustainable urban forms can be evaluated comparatively on the same (expanding) city over time or among different cities at the same time.

The present study illustrates an original, multi-criteria framework assessing conditions for sustainability of different urban forms. To fill the gap between theory and practice and to overcome vague definitions of urban sustainability, we identified relevant conditions appropriate to evaluate urban forms based on few target indicators (Keirstead and Leach, 2008). Subsequently, we have expanded the analysis considering a wide set of indicators representative of 4 themes (urban concentration, spatial expansion pattern, patch fragmentation/fractal dimension, landscape complexity). The approach was used to evaluate the sustainability of different settlement morphologies in the light of land-saving processes of urbanization by investigating changes in the form of a compact and mono-centric metropolitan region (Athens, Greece) throughout six years (1948, 1975, 1990, 2000, 2006, 2012). By displaying one of the lowest amounts of per-head sealed land in the European capitals (Salvati, 2016), Athens is a paradigmatic example for the identification of sustainable urban forms alongside its long-term expansion.

2. Methodology

2.1. Study area

The investigated area encompasses the Athens Metropolitan Region (AMR) which extends nearly 3000 km^2 in the Nuts-2 administrative region of Attica, central Greece (Fig. 1). All mainland areas and the island of Salamina were considered in this study being administered by 115 municipalities on the base of the 'Kapodistrian' administrative asset in force during the study period. The AMR mostly consists of mountains bordering a flat area known as 'Lekanopedio Attikis' [water basin of Athens] and hosting Greater Athens, a compact urban area extending nearly 400 km^2 and being administered by 58 municipalities. Three coastal plains (Messoghia, Marathona, Thriasio) are situated in the Attica region outside the Greater Athens' area. The climate is semi-arid since land received nearly 400 mm rainfalls (30-years average) with a mean annual temperature above 19 °C. Since the early 1990s, the city was aiming to attract investments to sustain peri-urban growth (Delladetsima, 2006). The 2004 Olympic Games have positively impacted the city's economic background attracting investments and promoting the construction of new infrastructure (Chorianopoulos et al., 2010). Later on, the economic crisis has reduced building activity by more than 50% over few years (Salvati, 2014a).

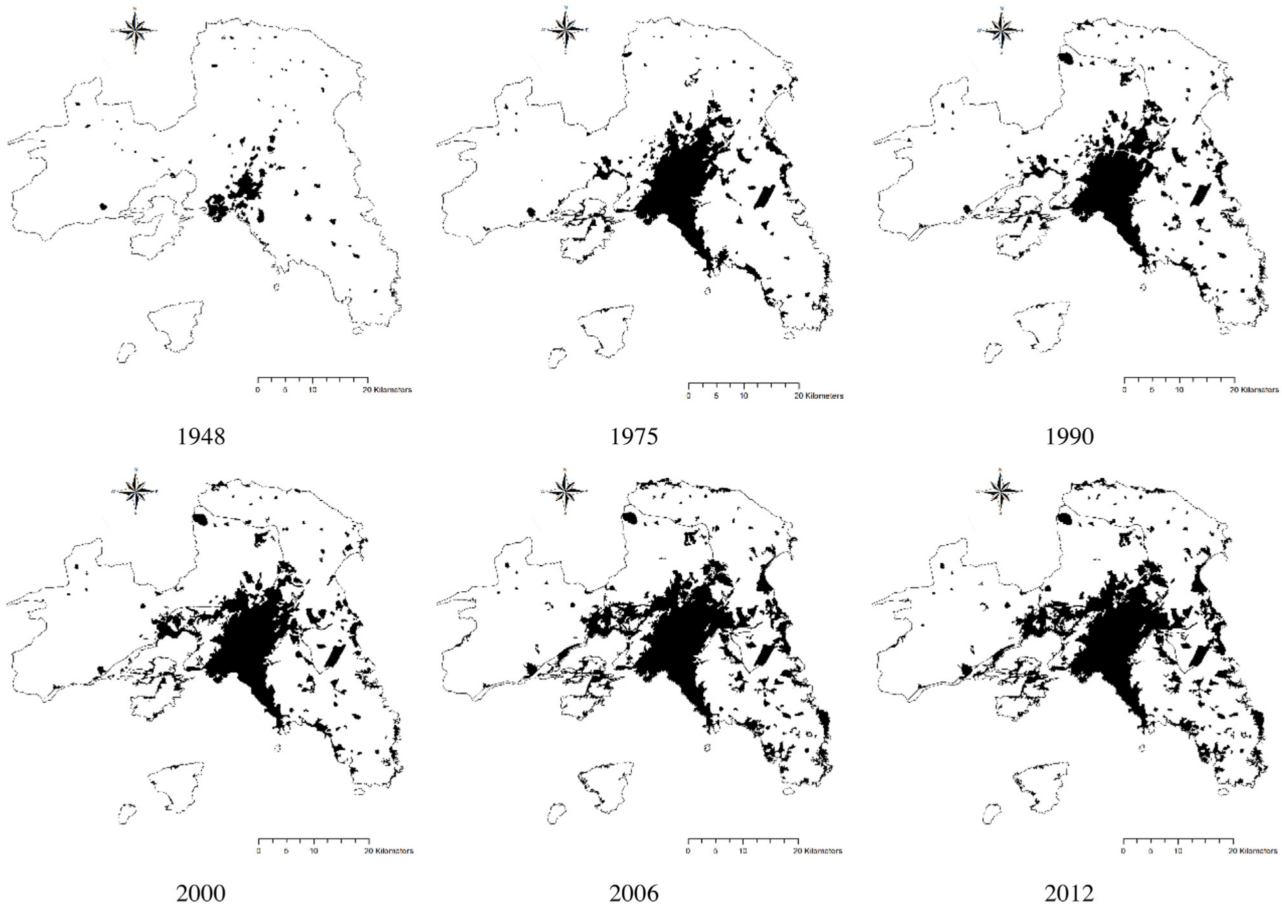

Fig. 1. The spatial distribution of built-up areas in the Athens' metropolitan region by year (1948–2012).

2.2. Land-use maps

The spatial distribution of built-up areas in the AMR was assessed at 6 years (1948, 1975, 1990, 2000, 2006 and 2012) using homogeneous and comparable maps: (i) the soil map of Attica produced by the National Institute of Pedology and Chemistry (Piraeus, Greece) in 1948 at 1:100,000 scale including a land-use class that represents built-up areas (urban polygons were digitalized from a geo-referenced high-resolution TIFF image provided by Joint Research Centre, Ispra); (ii) the LaCoast (LC) digital cartography available for 1975 at 1:100,000 scale (Perdigao and Christensen, 2000), and (iii-vi) the Corine Land Cover (CLC) pan-European digital cartography disseminated at the same spatial scale for 1990, 2000, 2006 and 2012. A unique 'urban' land-use category that incorporates the '1.xx' classes belonging to the first hierarchical level of the CLC nomenclature system was considered to map built-up areas.

2.3. Morphological indicators

The latent transformation of Athens' metropolitan structure (1948–2012) was investigated using maps of built-up areas at each studied year and basic variables assessing urban growth (share of built-up area in total landscape, mean size of built-up patches, patch perimeter-to-area ratio). Conditions for a sustainable urban form were preliminarily evaluated using 3 target variables: (i) per-head built-up area (m^2) assessing efficiency in the use of urban land (Zitti et al., 2015), (ii) average distance of built-up patches from Athens' centre (km) indicating urban expansion more or less sprawled around the central city (Colantoni et al., 2016) and (iii) an index of land fragmentation calculated as the ratio of the average size of built-up patches (ha) to the total extent of urban fabric (km^2), indicating the amount of continuous or discontinuous settlements (Salvati and Carlucci, 2014). Each of the four themes introduced above (urban concentration, spatial expansion patterns, patch fragmentation/fractal dimension, landscape complexity) was investigated using a specific operational approach (respectively land-use statistics, spatial autocorrelation indexes, landscape metrics and Morphological Spatial Pattern Analysis). These approaches were finally integrated using multivariate statistical techniques with the aim of deriving comprehensive profiles of the AMR spatial structure through time. Profiles allow identifying the most coherent spatial configuration(s) with conditions for sustainable urban forms identified using the 3 target variables illustrated above. Table 1 summarizes data and methods relevant to each analysis' dimension.

2.3.1. Land-use statistics

Descriptive statistics were used to assess the spatial distribution of percent built-up area in total landscape at the scale of local municipalities in the AMR: (i) the average percentage of built-up area in total landscape, (ii) the median-to-average percentage of built-up area in total landscape, (iii) the coefficient of variation of percent built-up area in total landscape, (iv) the range (max-min)-to-median percent built-up area in total landscape, (v) the 75th-to-25th percentile ratio of percent built-up area in total landscape, (vi) kurtosis and (vii) asymmetry in the statistical distribution of percent built-up area in total landscape. These indicators evaluate the (changing) spatial structure of the AMR highlighting the predominance of a mono-centric model or a more balanced (and possibly polycentric) asset (Salvati and Carlucci, 2014). A balanced

Table 1
List of indicators and thematic dimensions considered in this study.

Acronym	Variable	Thematic dimension	Analytical approach	Spatial scale	Measurement unit
Mean	Average share of built-up area in total landscape	Spatial expansion pattern	Land-use statistics	Municipal boundaries	%
Med	Median-to-average percent built-up area in total landscape				
CV	Coefficient of variation of percent built-up area in total landscape				
Range	Range(max-min)-to-median percent built-up area in total landscape				
Perc	75th-to-25th percentile of percent built-up area in total landscape				
Kurt	Index of kurtosis in the statistical distribution of percent built-up area in total landscape				Abs. value
Asym	Index of asymmetry in the statistical distribution of percent built-up area in total landscape				
M5	Global Moran's index of spatial autocorrelation of built-up areas (distance band = 5 km)	Urban concentration	Spatial autocorrelation	Municipality	
M10	Global Moran's index (d = 10 km)				
M15	Global Moran's index (d = 15 km)				
M20	Global Moran's index (d = 20 km)				
M25	Global Moran's index (d = 25 km)				
M30	Global Moran's index (d = 30 km)				
M35	Global Moran's index (d = 35 km)				
M40	Global Moran's index (d = 40 km)				
MPS	Median Patch Size	Patch fragmentation/fractal dimension	Landscape metrics	Urban parcel	Ha
PSCV	Coefficient of Variation of Patch Size				%
ED	Egde Density				m/m^2
MPE	Mean Patch Edge				m
MSI	Mean Shape Index				Abs. value
AWMSI	Average Weighted Mean Shape Index				|
MPAR	Mean Perimeter to Area Ratio				m/m^2
MPFD	Mean Patch Fractal Dimension				Abs. value
AWMPFD	Avg. Weigh. Mean Patch Fractal Dim.				
Core	Percent core area in the landscape*	Landscape complexity	Morph. Spatial Pattern Analysis	Urban parcel	%
Islet	Percent islet area in the landscape*				
Perforation	Perc. perforated area in the landscape*				
Edge	Percent edge area in the landscape*				
Loop	Percent loop area in the landscape*				
Bridge	Percent bridge area in the landscape*				
Branch	Percent branch area in the landscape*				

*the '%' symbol after a given class acronym indicates the percent area in total urban fabric; the '#' symbol after class name indicates the percent number of patches in total built-up patches.

Table 2
Metrics illustrating expansion of the Athens' metropolitan region, 1948–2012, and the related morphological indicators.

Year	Urban metrics			Morphological indicators		
	Built-up area in total landscape (%)	Mean size of built-up patches (ha)	Perimeter-to-area ratio	Per-head built-up area (m^2)	Avg. distance from Athens (km)	Land fragmentation index (ha patch/km^2 urban fabric)
1948	3.0	97	3.71	59.3	3.4	1.07
1975	16.0	96	5.10	175.0	10.2	0.20
1990	16.7	112	4.90	144.7	11.0	0.22
2000	19.2	116	4.75	155.7	12.9	0.20
2006	24.9	253	4.04	200.8	16.1	0.34
2012	25.2	253	4.04	201.8	18.3	0.33

spatial structure of urban settlements is observed when the distribution of percent built-up area in total landscape at the municipal scale displays (i) a low coefficient of variation, (ii) a median-to-average ratio close to 1, (iii) a range-to-median ratio approaching 1, (iii) low kurtosis and (iv) asymmetry index close to 0 (Salvati et al., 2016).

2.3.2. Spatial autocorrelation indexes

To identify the spatial autocorrelation regime characterizing Athens' urban structure, global and local Moran's indexes of spatial autocorrelation were run on the per cent built-up area in total landscape calculated for each municipality and study year at 8 fixed distance bands (d = 5, 10, 15, 20, 25, 30, 35 and 40 km). By varying d, the analysis of spatial dependence evaluates whether urban fabric is clustered or dispersed (Colantoni et al., 2016). The global

Moran's statistic was used to summarize in a single value the overall pattern in the data (Altieri et al., 2014) and to indicate different spatial relationships for a given subset of data. Maps of Moran's local autocorrelation indexes complement the study providing an assessment of long-term spatial trends for each municipality of the study area. A positive and significant ($p < 0.05$) value of the local Moran's statistic (z-score) indicates spatial clustering of similar (high: HH or low: LL) values; negative and significant ($p < 0.001$) values of Moran's statistic indicate spatial clustering (HL) of dissimilar values (LH) between an area and its neighbors (Salvati and Carlucci, 2014).

2.3.3. Landscape metrics

Landscape metrics have been extensively used to detect spatial patterns driven by urbanization (Alphan, 2003; Weber et al., 2005; Catalàn et al., 2008; Terzi and Bolen, 2009). In this study, the identification of the thematic dimensions adequate to describe changes over time in urban morphology, the selection of relevant variables and the procedures for indicators' construction, were set up according to general criteria of comprehensiveness and reliability (Li and Wu, 2004). Nine class metrics of patch fragmentation, shape and fractality were chosen with the aim of providing a comprehensive assessment of the Athens' spatial configuration over time (Salvati and Carlucci, 2014). These metrics were derived from the above-mentioned land-use maps using simple computational tools from ArcGIS (ESRI Inc., Redwoods, USA) and 'Patch Analyst' packages and are well suited to a vast audience of planners and stakeholders.

2.3.4. Morphological Spatial Pattern Analysis

The Morphological Spatial Pattern Analysis (MSPA) analyzes the shape and form of selected objects through quantitative indicators implementing a series of image processing routines to identify hubs, links (such as corridors) and other features that are relevant to the land-use structure assessment (Vogt et al., 2007). The basic landscape elements identified by the MSPA include (i) core areas, (ii) islets, (iii) bridges, (iv) loops, (v) branches, (vi) edges and (vii) perforation areas (Soille, 2003). These categories cover a wide range of spatial patterns which are of interest in the study of urban morphology (Soille and Vogt, 2008). Guidos software was used to carry out urban landscape classification based on the MSPA. For each morphological category, Guidos statistics provided percent class area (i) in total built-up area and (ii) in total landscape, as well as (iii) the number of patches, separately for each of the 6 study years.

2.4. Exploratory data analysis

To identify spatio-temporal patterns of urban expansion, a Principal Component Analysis (PCA) was run on a data matrix formed by 33 morphological indicators selected on the base of empirical results of each approach described in Sections 2.3.1–2.3.4 and made available for each of the 6 study years with no missing data. The final objective of the PCA was to summarize changes towards sustainability in the Athens' spatial configuration over time, based on target variables illustrated in Section 2.3 (per-head built-up area, average distance of built-up patches from Athens' centre, land fragmentation index). The PCA is an exploratory analysis suited to describe multiple relationships among indicators, eliminating (or reducing) the redundancy of the information due to high levels of serial autocorrelation within the data. Having used a PCA based on the correlation matrix, the number of relevant axes was chosen by retaining the components with eigenvalue higher than >2. The Kaiser-Meyer-Olkin (KMO) measure of sampling adequacy, which tests whether the partial correlations among variables are small, and Bartlett's test of sphericity, which tests whether the correlation matrix is an identity matrix, were considered to assess the quality of the analysis' outputs.

Table 3
Spatial distribution of built-up areas (percent share in total municipal area) in the Athens' metropolitan region by year (1948–2012): descriptive statistics.

Variable	1948	1975	1990	2000	2006	2012
# municipalities	115					
Arithmetic average	0.09	0.46	0.46	0.49	0.55	0.55
Median-to-average	0.13	0.86	0.95	0.89	0.97	0.97
Coefficient of variation	2.02	0.84	0.82	0.77	0.65	0.65
Range-to-median	10.61	2.15	2.17	2.02	1.79	1.78
Perc75th-Perc25th	0.07	0.85	0.72	0.78	0.74	0.74
Kurtosis	8.25	−1.61	−1.53	−1.59	−1.52	−1.51
Asymmetry	2.85	0.22	0.26	0.15	−0.10	−0.10

3. Results

3.1. A visual assessment of athens' expansion, 1948–2012

Built-up areas extended by 3% of the Athens' metropolitan region in 1948, expanding to more than 25% in 2012 (Table 2). Maps representing the long-term expansion of the AMR (Fig. 1) evidence settlement compaction and population densification during 1948–1975 and a more fragmented urban growth during 1975–2012. Long-term processes of urban expansion in Athens were classified in three waves characterized by different rates of growth and land fragmentation patterns. The first wave encompassed the time period 1948–1975 and was characterized by rapid growth of settlements (0.48% per year) leading to urban saturation and densification of peripheral areas. On average, the size of built-up patches maintained below 100 ha with an increasing perimeter-to-area ratio (from 3.7 to 5.1), per-head built-up area (from 59 m^2 to 175 m^2 per inhabitant) and average distance of built-up patches from central Athens (from 3.4 km to 10.2 km). An intermediate urban wave encompassing 1975–2000 totalized a modest settlement growth (0.13% per year) consolidating peripheral settlements that expanded radio-centrically around the central city. The moderate increase of the distance of built-up patches from central Athens (from 10.2 km to 12.9 km on average) clearly confirms this spatial pattern. Urban expansion and settlement consolidation has increased land-use efficiency, since per-head built-up area decreased from 175 m^2 to 156 m^2 as a consequence of population densification of the Athens' suburbs. The size and shape of built-up patches as well as land fragmentation index were relatively stable in this period: the average patch size increased from 96 ha to 116 ha, the perimeter-to-area ratio decreased moderately from 5.1 to 4.8 and the average patch size in total urban fabric remained stable at 0.2. The most recent wave of urban expansion (2000–2012) was particularly rapid (0.5% per year) with a more than double average patch size (from 116 ha to 253 ha) and a reduced perimeter-to-area ratio (from 4.8 to 4.0). Land fragmentation index and per-head built-up area increased respectively from 0.20 to 0.33 and from 156 m^2 to 202 m^2 as a consequence of settlement dispersion and population de-concentration. Small built-up patches expanded into rural areas at increasing distances from central Athens (from 12.9 km to 18.3 km).

3.2. Land-use statistics

The spatial distribution of built-up areas in the AMR was analyzed using descriptive statistics calculated at the spatial scale of municipalities (Table 3). The share of built-up area in total municipal area ranged between 0.09 (1948) and 0.55 (2012) with a median-to-average ratio increasing from 0.13 (1948) to 0.97 (2012). A median-to-average ratio close to 1 indicates a more

Table 4
Global Moran's index of spatial autocorrelation for percent built-up area in total municipal area in the Athens' metropolitan region, 1948–2012.

Band (km)	1948	1975	1990	2000	2006	2012
5	12.6*	16.3*	16.4*	16.5*	14.3*	14.2*
10	13.0*	25.3*	26.1*	26.5*	22.9*	22.9*
15	13.0*	28.4*	29.1*	30.3*	26.4*	26.3*
20	9.5*	25.1*	25.7*	28.4*	25.1*	25.1*
25	6.5*	19.9*	20.0*	22.3*	20.0*	20.0*
30	3.8*	11.8*	12.1*	13.0*	12.4*	12.3*
35	0.9	3.4	3.7	3.2	3.5	3.4
40	−2.1	−5.7*	−6.2*	−7.6*	−6.4*	−6.4*

* indicates significant Moran's coefficient at $p < 0.001$.

balanced settlement distribution in recent years compared to earlier times. Accordingly, the coefficient of variation in the share of built-up areas for each studied municipality decreased over time passing from 200% to 65% and the standardized range of percent built-up area between the most and the less urbanized municipality decreased from 11% in 1948–2% in 2012. The highest value of the absolute difference between the 75th and 25th percentile of built-up areas at the municipal scale was observed in 1975, indicating the highest settlement concentration and the largest urban-rural divide along the investigated time period. The asymmetry in the distribution of built-up areas across Attica's municipalities decreased coherently from 2.8 to −0.1, indicating a more balanced distribution in the last two years. Kurtosis moved from positive values in 1948 to slightly negative values between 1975 and 2012.

3.3. Spatial autocorrelation regime

The global Moran's index of spatial autocorrelation for the proportion of built-up areas in total municipal area assumed positive and highly significant values for distance bands between 5 km and 30 km, indicating a short-range autocorrelation regime in the study area that reflects a typical urban-rural gradient dominating the spatial structure of metropolitan Athens (Table 4). Moran's index for the above-mentioned distance bands increased rapidly between 1948 and 2000 and decreased consistently in the last 12 years. The highest spatial autocorrelation coefficients were associated to the metropolitan configuration observed in 2000. Moran's index at the highest distance bands (35 and 40 km) showed a relatively different pattern, with smaller (and non-significant) values increasing over time for the 35 km distance band, and negative values (increasingly slightly over time up to a peak observed for the year 2000) for the 40 km distance band. These findings reflect the increased fragmentation and complexity of the Athens' morphology. The spatial distribution of local Moran's indexes of spatial autocorrelation (Fig. 2) outlines the consolidation of a density gradient reaching the highest polarization in urban and rural areas during the 1990s.

3.4. Landscape metrics

The number of built-up patches increased between 1948 and 1975 stabilizing in the subsequent time period until 2000 and decreasing afterwards (Table 5). A higher number of built-up patches indicates discontinuous urban expansion in Athens. The median size of built-up patches (MPS) increased moderately reaching a peak in 2006 (60.2 ha) and decreased slightly in 2012 (59.7 ha). The coefficient of variation in the size of built-up patches (PSCV) declined from 992% to 177% between 1948 and 2000 increasing to 373% in the most recent decade (2000–2012). The average edge density of built-up patches (ED) grew continuously in Athens from 1.6 (1948) to 9.7 (2012). Starting from a very high value (9652), the mean patch edge (MPE) decreased in the period 1975–2000 to a low of 4602 (1975), doubling in 2012 (10,138). The mean shape index (MSI) reached its peak in 1990 (3.3), stabilizing to values ranging between 1.8 and 2.0 in more recent years. The average weighted mean shape index (AWMSI) showed the reverse pattern, with minimum values being observed for 1975 and 1990. The mean perimeter-to-area ratio (MPAR) increased progressively over time reaching a peak in 1990 (1086) and decreasing afterwards. Indexes of fractal dimension of built-up patches (MPFD, AWMPFD) increased moderately from 1.2 (1948) to 1.3 (2012) (Fig. 3).

3.5. Mathematical morphology indicators

Built-up patches were mostly classified as core with few edge, perforation and branch patches (Table 6). Core patches accounted for 95.5% of built-up area in 1948 reaching a peak in 1975 (97.7%) and decreasing slightly to 96.8% in 2012. This result indicates urban saturation and maximum densification of the AMR between 1975 and 1990. The surface area of patches classified as 'edge' decreased abruptly from 4.4% of total built-up area in 1948–2.2% in 1975, swinging around this value afterwards. Patches classified as 'perforation' accounted for 0.14% of total built-up area in 1948 decreasingly slightly to 0.06% in 1990 and subsequently growing to 0.34% in 2012. Such dynamics indicate changes towards a discontinuous metropolitan spatial structure in recent years. Patches classified as 'branch' were relatively stable to 0.2%-0.3% of total built-up area, reaching a low in 2000 (0.01%). The remaining MSPA classes (islet, loop, bridge) accounted for a limited amount of built-up areas for all examined time points.

3.6. Principal component analysis

PCA extracted two axes accounting respectively for 71.4% and 21.4% of total variance. The study years were clearly discriminated along both axes: years from 1948 to 2000 were oriented from negative to positive scores along axis 1; years from 2000 to 2012 were oriented from negative to positive scores along axis 2. These findings provided empirical evidence to the identification of multiple waves of urban growth in Athens illustrated in Section 3.1. Significant loadings to components 1 and 2 were attributed respectively to 28 and 11 indicators (out of 33 input indicators) Land-use statistics indicating urban expansion, settlement concentration and population densification (Avg, Med, Ran, Perc) received positive loadings to component 1 (increasing between 1948–2000); conversely, variables indicating a spatially-balanced distribution of settlements (CV, Kurt, Asy) received (more or less intense) negative loadings. All Moran's global indexes received a positive loading to component 1 except for the index calculated using a 40 km distance band that received a negative loading. Edge density, mean shape index and indicators of fractal dimension received highly positive loadings to component 1 with perimeter-to-area ratio and patch size coefficients of variation showing the reverse pattern. Component 1 was finally associated to an increasing proportion of urban core areas and high number of perforation and edge patches and to a decreasing proportion of urban 'edge' and 'branch' areas. Component 2 was negatively correlated with short-distance (5 km) spatial autocorrelation regime and positively correlated with median patch size and mean patch edge, areas of 'perforation' patches and number of 'branch' patches. The structure of extracted loadings to component 2 outlined that larger and more convoluted urban patches were the most relevant features characterizing recent changes in Athens' morphology. This configuration has progressively altered the urban-rural divide promoting low-density and medium-density settlements and consolidating a mixed and fragmented use of land in peri-urban districts (Table 7).

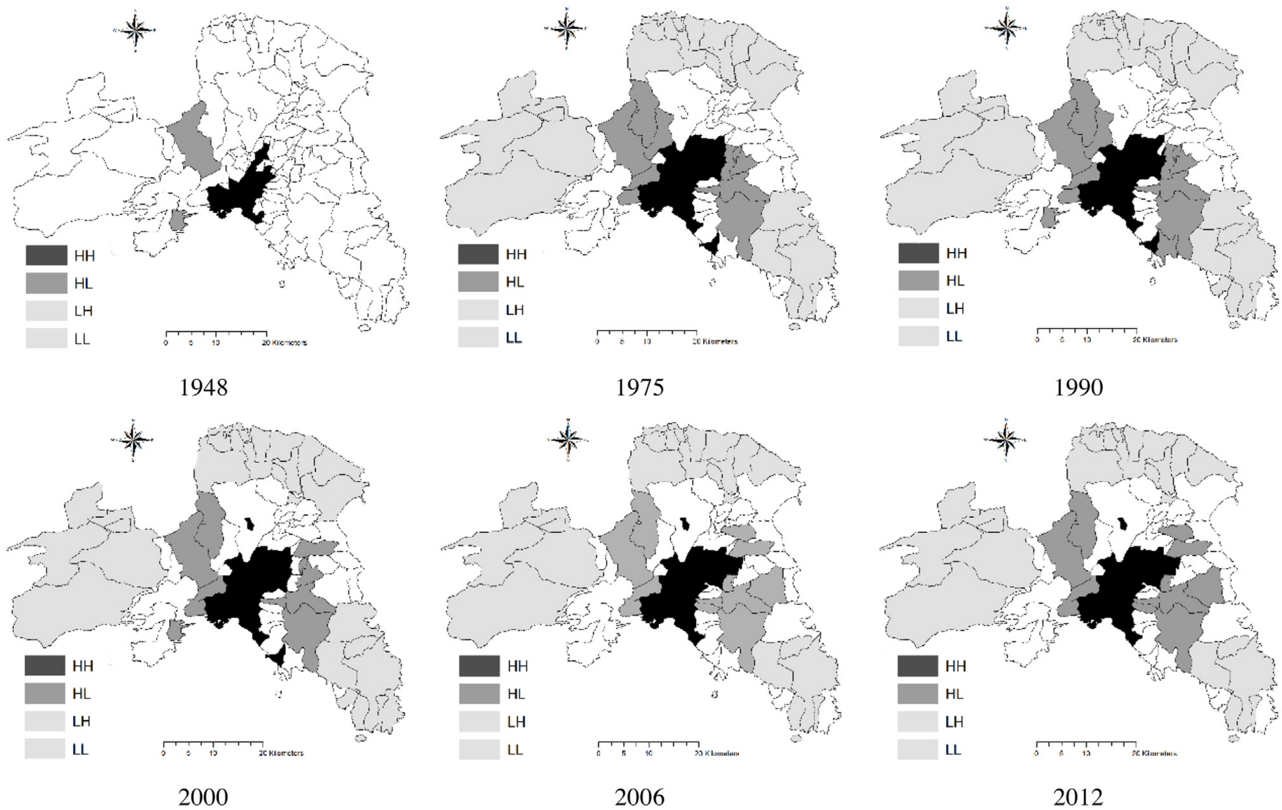

Fig. 2. Local Moran's index of spatial autocorrelation in the Athens' metropolitan region, 1948–2012 (white indicates municipalities with a non-significant local Moran's index; see Section 2.3.2 for acronyms).

Table 5
Landscape metrics assessing the spatial configuration of metropolitan Athens, 1948–2012.

Year	# patch	MPS	PSCV	ED	MPE	MSI	AWMSI	MPAR	MPFD	AWMPFD
1948	106	26.2	991.8	1.6	9652	1.3	3.2	92.0	1.2	1.2
1975	499	31.0	203.9	7.4	4602	1.8	1.9	490.7	1.3	1.3
1990	449	47.9	176.6	8.0	5494	3.3	1.9	1086.2	1.3	1.3
2000	495	48.5	176.8	9.2	5735	1.8	2.0	749.8	1.3	1.3
2006	296	60.2	373.9	9.7	10143	2.0	3.4	85.0	1.3	1.3
2012	298	59.7	373.1	9.7	10138	2.0	3.4	85.2	1.3	1.3

Table 6
Morphological Spatial Pattern Analysis (MSPA) of the Athens' metropolitan region, 1948–2012.

Class	1948			1975			1990			2000			2006			2012		
	% area		#	*% area*		#	*% area*		#	*% area*		#	*% area*		#	*% area*		#
Core	95.46	3.12	105	97.66	15.20	162	97.10	15.85	151	97.10	18.21	130	96.81	23.38	159	96.80	23.62	162
Islet	0.00	0.00	0	0.00	0.00	23	0.00	0.00	2	0.00	0.00	1	0.00	0.00	4	0.00	0.00	4
Perf	0.14	0.00	2	0.11	0.02	8	0.06	0.01	5	0.27	0.05	15	0.33	0.08	27	0.34	0.08	29
Edge	4.36	0.14	125	2.20	0.34	178	2.83	0.46	167	2.62	0.49	150	2.83	0.68	440	2.82	0.69	444
Loop	0.00	0.00	9	0.00	0.00	14	0.00	0.00	1	0.00	0.00	7	0.00	0.00	149	0.00	0.00	149
Bridge	0.00	0.00	0	0.00	0.00	15	0.00	0.00	7	0.00	0.00	7	0.00	0.00	23	0.00	0.00	21
Branch	0.04	0.00	258	0.02	0.00	476	0.02	0.00	494	0.01	0.00	527	0.03	0.01	1268	0.03	0.01	1294

% area indicates percent class area in total built-up area (left column) and percent class area in total landscape (right column), # indicates number of patches in each MSPA class.

4. Discussion

Our study proposes a comparative approach identifying more or less sustainable urban forms in a representative European metropolitan region using freely-available information at the spatial scale of municipalities and land-use parcels. Urban-rural polarizations have progressively altered the development of land-saving, dense and mono-centric settlements, with implications on urban sustainability especially in southern Europe, a region characterized by compact cities, land-saving urban forms and medium-high efficiency in the use of urban land (Antrop, 2005; Serra et al., 2014; Carlucci et al., 2016). Since the early 1950s, southern European countries underwent socioeconomic transformations reflecting a progressive shift towards regional economic structures dominated by traditional and advanced services (e.g. Chorianopoulos et al., 2014). Low-density, discontinuous settlements expanding into rural areas have more recently formed residential sub-centers, creating mixed and fragmented peri-urban

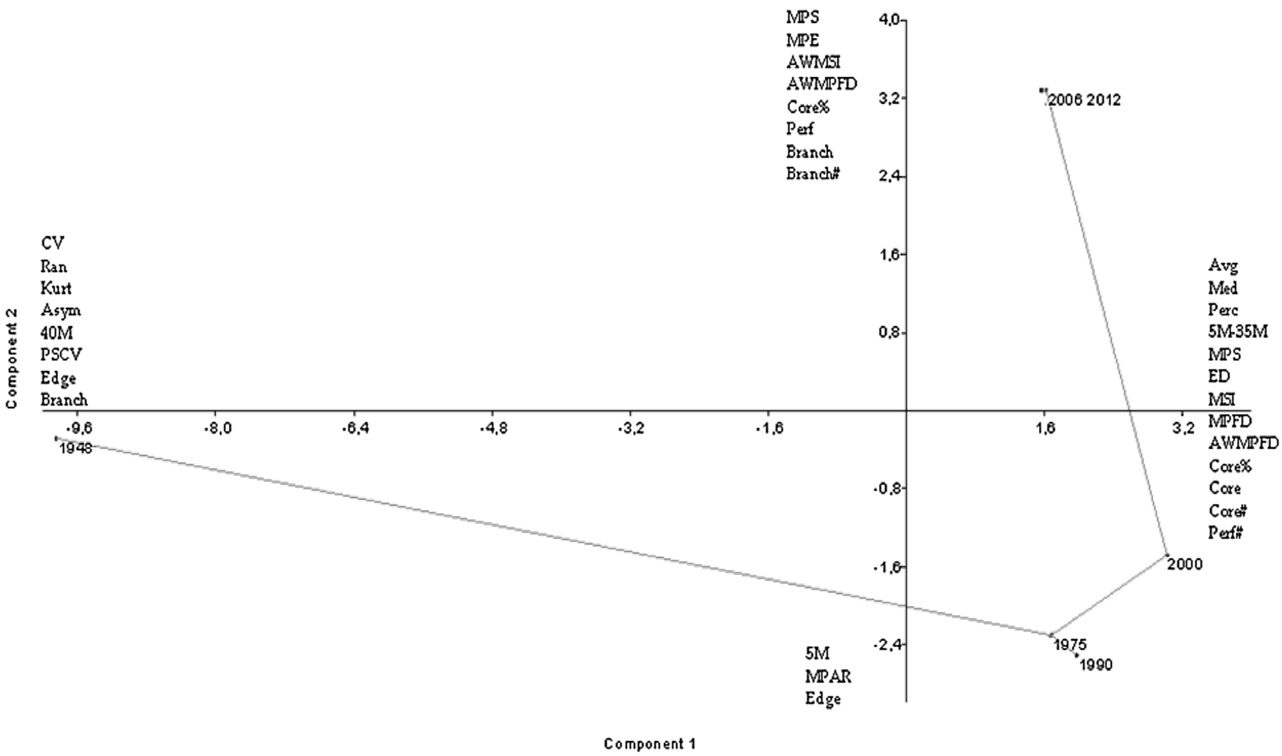

Fig. 3. Principal Component Analysis of morphological indicators in the Athens' metropolitan region, 1948–2012: component's score plot (PC 1 *vs* PC 2); continuous line links the position of the six investigated years.

Table 7
Principal Component Analysis results: variables with loading >|0.5| (acronyms in Table 1).

Variable	PC 1	PC 2
Avg	0.96	
Med	0.98	
CV	−0.98	
Range	−0.99	
Perc	0.98	
Kurt	−0.99	
Asym	−0.98	
5M	0.79	−0.61
10M	0.97	
15M	0.99	
20M	1.00	
25M	1.00	
30M	1.00	
35M	0.98	
40M	−0.97	
MPS	0.65	0.65
PSCV	−0.97	
ED	0.95	
MPE		0.89
MSI	0.53	
AWMSI		0.91
MPAR		−0.79
MPFD	0.83	
AWMPFD	0.65	0.75
Core%	0.85	0.52
Core	0.90	
Perf		0.85
Edge	−0.94	
Branch	−0.77	0.54
Core#	0.87	
Perf#	0.94	
Edge#	0.62	−0.58
Branch#		0.96
Expl.Var.%	*71.4*	*21.4*

landscapes (Leontidou, 1990; Gemmiti et al., 2012; Cuadrado-Ciuraneta et al., 2016). Since the early 1970s, middle-class workers and even popular strata moved from inner cities to settle in unplanned or self-financed property developments (Delladetsima, 2006). Dispersed urbanization became even more pervasive in the 1990s, invading rural areas progressively farther from core cities with leapfrog and ribbon morphologies. Urban sprawl has been indirectly stimulated by increased (private) mobility and the diffusion of suburban lifestyles (Tombolini et al., 2015).

The long-term development of Athens is indicative of changing urban forms with distinct values of per-head land consumption rates, patch fragmentation and settlement dispersion (Salvati, 2016). The identification of distinct phases of the Athens' expansion may benefit from empirical findings provided in this study and is crucial to evaluate their contribution to a (more or less) sustainable urban form. Based on PCA results, the most evident breakpoint in the Athens' development was identified at the end of the 1990s. Between 1990 and 2000 Athens' morphology was the most compact along the examined time period, reaching the highest land-use efficiency and displaying the lowest expansion rate, a decrease in population density (mitigating the uneven divide in urban and rural areas observed since the late 1980s) and a relatively low fractal index.

By reaching a dynamic balance between compaction, densification and land-use efficiency, such a spatial configuration represents a more sustainable urban form compared with the dense and hyper-compact 1975 Athens' structure and the discontinuous, land-consuming model emerging in the most recent decade. On the one side, since the early 1970s suburbanization of economic activities has involved distinct sub-centers (Thriasio: industry, logistics, commerce and retail; Messoghia: research and development, telecommunication, finance and real estate: Salvati, 2014a), resulting in complex and fragmented settlement forms with an increased rate of land take and reduced land-use efficiency (Zitti et al., 2015). On the other side, urban dispersion driven by real estate speculation, settlement informality and planning deregulation, altered the relatively compact form of Athens' suburbs in the years immediately following the 2004 Olympics (Salvati, 2014a). The Olympic Games have attracted foreign capitals, determining investments and the continuous development of public and private infrastructures (Delladetsima, 2006). New spatial links between urban and rural areas have emerged in the mid 2000s, influencing real estate dynamics and promoting a new wave of urban expansion (Tombolini et al., 2015).

In this sense, dispersed settlements expanded into rural countryside creating inhomogeneous and disarticulated urban networks characterized by mixed use of land (residential, commercial and industrial). The mitigation of the population density gradient is one of the most evident results of transitions from compact to dispersed cities (Antrop, 2005; Paul and Tonts, 2005; Marull et al., 2009; Schwarz, 2010). The economic crisis altered this pattern only in part, reducing the building activity and stimulating an increasing rate of land consumption (Tombolini et al., 2015). Evident urban transformations in Attica were especially observed in the municipalities north-east of Athens (Maroussi, Kifissia, Chalandri) whose productive base evolved rapidly towards advanced services, telecommunications and high-tech productions, supported by improved accessibility due to construction of the Attica highway and Athens' International Airport (Salvati, 2014a). Findings of this study clearly indicate that Athens' discontinuous and dispersed expansion (2000–2012) has coincided with a transition to tighter spatial relationships between morphological variables, possibly underlying, on the one hand, a latent shift toward a more balanced urban structure and, on the other hand, the increased fractal dimension of the Athens' urban configuration (Salvati and Carlucci, 2014).

In this sense, our study demonstrates that a semi-compact, mono-centric spatial organization is compatible with medium levels of population density and high levels of land-use efficiency in a metropolitan context. Although dense settlements are often associated with negative environmental externalities (e.g. pollution, traffic congestion, scarcity of green spaces), semi-compact cities expanding radio-centrically around a core remain a land-saving model for metropolitan growth. In this model, spatial relationships between urban and rural areas are regulated by the gravitation on a central city displaying the highest density of population and economic activities (Breheny, 1997). Urban and rural districts have distinct roles: the former act as places of consumption, production of industrial goods and traditional/advanced services; the latter are devoted to agricultural production and conservation of natural amenities, with a pivotal role in the provision of ecosystem services to metropolitan regions (Alberti, 2005, 2010).

Although a progressive shift from mono-centric cities to increasingly polycentric (and dispersed) urban regions has been widely recognized (Vasanen, 2012), Arribas-Bel and Sanz-Gracia (2014) have provided contrasting evidence from the cities of the United States, demonstrating that the mono-centric structure persists in a majority of metropolitan areas. Compact cities dominating mono-centric regions and expanding in a continuous and semi-dense fashion are still common in Europe, outlining the important role of compact urban forms in a context of rapid socioeconomic transformations.

5. Conclusions

This study illustrates a diachronic analysis of the spatial structure of a metropolitan region in Europe based on a comprehensive set of indicators contributing to long-term assessment of sustainable urban forms. Our study has documented how the recent expansion of Athens, a representative example of compact and semi-dense cities experiencing scattered expansion in recent decades, has been characterized by morphological changes that reflect fragmentation, fractality and entropy and may negatively impact urban sustainability. Based on these findings, dispersed urban expansion in formerly compact cities requires dedicated policy strategies going beyond standard town planning and possibly referring to holistic visions for a sustainable growth of metropolitan regions concealing socioeconomic development and land-saving urban forms. The methodological approach illustrated in this article contributes to design policies of urban containment promoting a higher land-use efficiency. The approach is based on indicators derived from diachronic land-use maps and is applicable to vastly different socioeconomic contexts. It produces a comprehensive information base contributing to the long-lasting debate on principles and practices for sustainable urban development.

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