Land Use Policy 129 (2023) 106659

Contents lists available at ScienceDirect

Land Use Policy

journal homepage: www.elsevier.com/locate/landusepol

Functions follow structures? The long-term evolution of economic dynamics, social transformations, and landscape morphology in a Mediterranean metropolis

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ARTICLE INFO

Keywords:
Settlement form
Mathematical morphology
Urban Cycle
Socioeconomic functions
Southern Europe

ABSTRACT

Identification of the intrinsic properties regulating complex systems' development contributes to a refined comprehension of their inherent transformations over time. Seen as a local context undergoing non-linear changes as a response to socioeconomic dynamics, landscape evolution over time provides a paradigmatic issue when examining the key property of 'rapidity-of-change' characteristic of any complex system. The present study introduces an exploratory approach grounded on mathematical morphology to investigate 'rapidity-of-change' of a landscape system evolving in response to external stimuli over 70 years (1948–2018). This framework was applied to a real case (metropolitan Athens, Greece) assessing structural changes in built-up settlements reflected in seven landscape types derived from mathematical morphology. A Multi-way Factor Analysis (MFA) quantified the evolution of landscape types from diachronic land-use maps. A standardized metric of 'rapidity-of-change' was calculated from MFA outcomes over six sub-periods and confronted with the background socioeconomic context. Taken as an intrinsic attribute of complex systems, 'rapidity-of-change' in Athens' landscape was largely heterogeneous over time, being more intense during the last economic expansion (2000–2006) under the impulse of the Olympic Games. Intermediate values of 'rapidity-of-change' were associated with population growth and intense social transformations. The lowest level of 'rapidity-of-change' was finally recorded in correspondence with 2007 recession. Reflecting the intrinsic pressure of socioeconomic growth in contemporary cities, 'rapidity-of-change' in landscape systems demonstrated to be a honest proxy of metropolitan cycles, economic downtowns, and socio-demographic dynamics. Delineating long-term transformations in the 'form-function' relationship allows evaluation of (direct or indirect) planning impacts on metropolitan development.

1. Introduction

Cognitive systems in regional science have influenced the representation of complex dynamics by emphasizing the emergence of new structures centered on adapting agents, local interactions, the development of attracting poles, and the increased capacity of innovation (Walker et al., 2004; Pumain, 2005; Portugali, 2011). With resilience implying a (more or less rapid) recovery from external system's shocks, equilibrium in regional systems' dynamics depends on the related socioeconomic structure and intrinsic properties – being stable or allowing for a rapid transition between different configurations (Favaro and Pumain, 2011; Fischer, 2018; Preiser et al., 2018). The vast spectrum of possible system's responses to external shocks is based on (both linear and non-linear) interactions among composing elements characteristic of self-organized, open systems (Chen et al., 2020). With this perspective in mind, analysis of complex metropolitan systems focused on (macro-level) properties reflecting (latent) interactions between micro-level actors of change (e.g. Daya Sagar and Murthy, 2000).

Complex system thinking was demonstrated to appropriately address the intimate relationship between landscape patterns and processes at

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https://doi.org/10.1016/j.landusepol.2023.106659
Received 6 September 2022; Received in revised form 6 February 2023; Accepted 22 March 2023
Available online 29 March 2023

the base of metropolitan complexity (Holland, 2006; Walker et al., 2012; Serra et al., 2014). Systemic approaches are specifically required for a refined understanding of recent landscape transformations that produce new economic spaces - shaping metropolitan gradients characteristic of mono-centric cities and more articulated polycentric regions (Berry, 2005; Parr, 2014; Salvati and Serra, 2016). A self-organized system is, in turn, characterized by a macro-level structure (namely, a landscape matrix) produced by non-linear interactions between micro-level elements such as land-use and morphological types (Petrosillo et al., 2021). Such modifications impact the dynamic trajectory of the system, determining the persistence of specific landscape patterns at local scale (Tress et al., 2001; Shaker, 2018; Zhao et al., 2020).

Despite criticism rooted in the lack of empirical verification and theoretical support (Terzi and Bolen, 2009; Chen and Partridge, 2013; Salvati et al., 2017), the analysis of landscape systems oriented toward systemic thinking is promising when envisaging interpretative frameworks of landscape dynamics grounded on the evolution of macro-level properties and the latent interactions between micro-level agents (e.g. Batty and Longley, 1994; Bura et al., 1996; Cabral et al., 2013). Individual land-use – and especially urban settlements – can be regarded as an appropriate analysis' scale, being influenced by the collective action of micro-agents, and represents a territorial partition of policy/planning relevance, possibly associated with long-term development of a broader area (Alberti, 2005, 2010).

The relational issue complicates the assessment of any metropolitan landscape (Antrop, 2005). More specifically, isolating the interactions between different organizational levels for purposes of measurement, appears to be a daunting task (Redman and Jones, 2005; Sun et al., 2018; Seifollahi-Aghmiuni et al., 2022). The selection of properties delineating long-term evolution of metropolitan landscapes is a crucial aspect of 'complex thinking' (Grekousis et al., 2013; Grafius et al., 2018; Egidi and Salvati, 2020). System's properties represent an individual (or composite) attribute of local communities (Ferrara et al., 2016), and often reflect the outcome of processes that regulate size and functions of metropolitan systems (Egidi et al., 2021). Such processes depend on the speed and intensity of spatial interactions at different organizational levels and geographical scales (Darvishi et al., 2020). While evolving towards complexity (Neuman and Hull, 2009), 'rapidity-of-change' is a relevant property that can be intuitively connected with external dynamics – with the final aim at delineating the intrinsic (long-term) relationship between form and functions in metropolitan regions (Phillips and Ritala, 2019).

Based on these premises, our study provides a comprehensive overview of the transformations of a complex urban system, quantifying 'rapidity-of-change' as a property that was unfrequently assessed in the mainstream literature on regional studies (Salvati and Serra, 2016). More specifically, the methodology illustrated here proceeds with a diachronic analysis (1948–2018) of settlement structure and land-use change in a metropolitan region of Mediterranean Europe (Attica, Greece) using a complex system thinking that mixes multi-domain landscape indicators based on mathematical morphology and advanced exploratory statistical techniques. Using a simplified model elaborating on the results of such techniques, we estimated both short-term and long-term 'rapidity-of-change' of a given landscape system as a contribution to a refined understanding of metropolitan development (Marull et al., 2009; Ortega et al., 2020; Bianchini et al., 2021).

As a system property ultimately delineating the paradigmatic evolution of the form-function relationship characteristic of a given area, 'rapidity-of-change' was evaluated considering together changes in landscape structure and functions (Parcerisas et al., 2012). The study further correlates the estimated 'rapidity-of-change' in urban landscapes with the sequential waves of the metropolitan cycle, the economic downturns observed at the regional scale, and the (evolving) socio-demographic context at the local scale (e.g. Wang and Zhang, 2001; Perrin et al., 2018; Luo et al., 2018). Next to this introduction, a methodological section and the description of the main results achieved in this study are developed. A discussion commenting the empirical results of this study in light of complex adaptive systems, and outlining some basic conclusions about the intrinsic nexus between settlement morphology and land-use functions in metropolitan regions is finally provided.

2. Methodology

2.1. Study area

The present study investigates a major area (3025 km^2) encompassing the Athens' Metropolitan Region (AMR) that corresponds, for a large part, to the administrative region of Attica in Central Greece (Pili et al., 2017), including the Salamina island close to Piraeus – the main Athens' harbour – and excluding the other islands in the Argosaronic gulf, Aegean Sea (Fig. 1). The area mostly consists of mountain reliefs that border the flat areas hosting Greater Athens (the so called 'Lekanopedio Attikis'), Messoghi, and Thriasio agricultural districts (Morelli et al., 2014). Climate is semi-arid with rainfall averaging 400–500 mm in lowlands and mean annual temperature amounting to 19 °C (Salvati et al., 2018). Based on the scrutiny of recent literature (e.g. Economidou, 1993; Couch et al., 2007; Ioannidis et al., 2009), the recent history of Attica was summarized in Fig. 2 considering four development dimensions (namely, metropolitan cycle, economic downturns, demographic dynamics, and social transformations).

Being associated with uneven population growth in the 1950s and the 1960s, the traditional socioeconomic divide in central and peripheral areas maintained rather stable over time in Attica (Zambon et al., 2018). Since the late 1960s, life quality degradation downtown led high-income households to move to Athens' suburbs (Salvati and Serra, 2016). The demographic rise of Greater Athens slowed down during the 1970s and the 1980s (Chorianopoulos et al., 2010), and resident population progressively re-localized in the surrounding areas in the 1990s – producing atypical suburbs with scattered (residential) settlements and mixed land-use (Morelli et al., 2014), but also stimulating economic diversification and, in some case, pushing competitive activities to relocate out of the city boundaries (Egidi et al., 2021). With economic expansion in the early 2000s, Athens was aiming to attract foreign investment to sustain substantial peri-urban growth (Grekousis et al., 2013). The 2004 Olympic Games have been a major impact on the infrastructural development of the city (Pili et al., 2017). Recession beginning in 2007 created conditions for austerity urbanism, diffused conditions of poverty, and a latent out-migration toward rural areas searching for better living standards, cheaper housing and job opportunities, even in the primary sector (Gkartzios, 2013).

2.2. Data and indicators

The spatial distribution of built-up settlements in the Athens' metropolitan region at seven points in time (1948, 1975, 1990, 2000, 2006, 2012, 2018) was derived from a geo-database of diachronic, homogeneous land-use maps covering the entire area at 1:100,000 scale (Table 1). The following data sources were used to compile the geo-database: (i) the soil map of Attica realized by the Institute of Pedology and Chemistry (Piraeus, Greece) in 1948 and including a land-use class that represents urban areas (polygon representing built-up settlements were digitalized from a geo-referenced high-resolution TIFF image provided by Joint Research Centre, Ispra); (ii) the LaCoaste (LC) digital cartography available for 1975, and five, diachronic releases (iii–vii) of the Corine Land Cover (CLC) pan-European digital cartography available for 1990, 2000, 2006, 2012, and 2018. A unique land-use type representing built-up settlements was derived from topological overlap and physical merge of the separate 1.xx classes of the first hierarchical level of the CLC nomenclature system. These maps were presented (and technical details provided) in earlier studies (Salvati

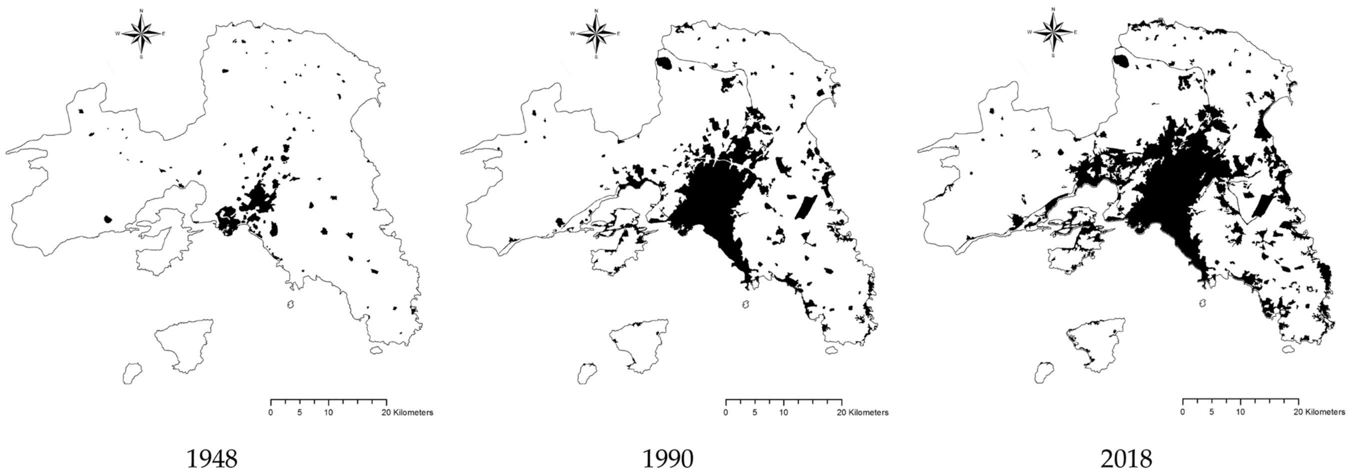

Fig. 1. The spatio-temporal evolution of built-up settlements (black) in Athens' region, selected years.

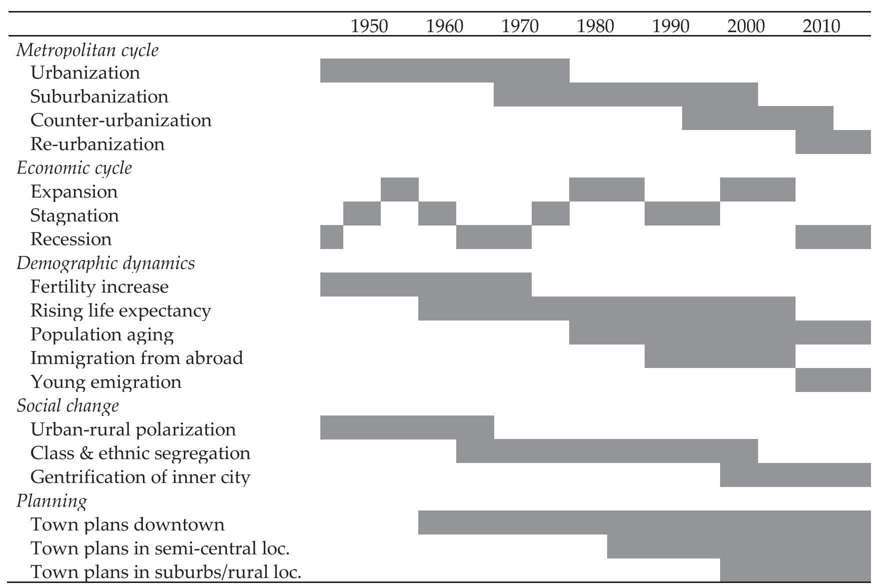

Fig. 2. Timing of relevant socioeconomic dynamics in the study area (grey indicates the time period with the occurrence of a given urban phenomenon distinguishing relevant characteristics of metropolitan cycles, the related economic cycle, demographic dynamics, social change and planning aspects.

Table 1
Indicators illustrating Athens' urban expansion between 1948 and 2018, selected years.

Variable	1948	1975	1990	2000	2006	2012	2018
Built-up area in total landscape (%)	3.3	15.6	16.3	18.7	24.1	24.4	24.7
Median area of built-up parcels (ha)	25.0	33.1	53.1	56.2	50.0	47.1	45.9
Median distance of built-up parcels from downtown Athens (km)	21.3	26.8	25.7	27.5	30.4	30.6	30.7
Non-'core' parcels in total built-up area (%)	4.6	2.3	2.8	3.0	3.2	3.3	3.4

et al., 2018).

2.3. Estimating developmental trajectories in landscape systems

This study introduces innovative landscape analyses based on morphological metrics (Park et al., 2014; Luo et al., 2018; Ortega et al., 2020) with the aim at delineating long-term urban growth, the consequent trajectories of change in the surrounding rural areas, and the related socioeconomic context. Selection of elementary metrics and identification of landscape dimensions have been set up adopting criteria of comprehensiveness, reliability, and calculation easiness (Li and Wu, 2004; Parcerisas et al., 2012; Masini et al., 2019). Two dimensions have been explored in this study – namely functions and structure of a given landscape system (Luck and Wu, 2002). Four landscape dimensions representative of different functions associated with metropolitan development were adopted (Salvati, 2014). Seven structural types have been also selected with the aim at providing a comprehensive description of landscape morphology (Salvati et al., 2012). Considering together structure and functions, these metrics quantify multiple landscape dimensions such as fragmentation, patch shape, fractal dimension, and land-use complexity (Longhi and Musolesi, 2007; Schneider and Woodcock, 2008; Tombolini et al., 2016).

2.3.1. *Mathematical morphology*

Urban landscape was partitioned in seven structural types ('cores', 'perforations', 'islets', 'bridges', 'loops', 'branches', 'edges') using mathematical morphology, an operational framework that quantifies shape and form of a given landscape element, namely a patch (Soille, 2003). We specifically adopted a Morphological Spatial Pattern Analysis (MSPA) implementing image processing routines that identify hubs, links (i.e. corridors), and other features relevant to a structural assessment of landscapes (Vogt et al., 2007). 'Cores' are defined as the inner part beyond a certain distance to the boundary. 'Islets' are those parcels that are too small (and isolated) to form a core area (Soille and Vogt, 2009). 'Edges' and 'perforations' surround core areas (Scott et al., 2013); more specifically, 'perforations' are identified as the transition zone between 'cores' and a different land-use class (Riitters et al., 2009); 'edges' represent a transition between 'core' and 'non-core' parcels within the same land-use class (Riitters et al., 2007). 'Loops', 'bridges', and 'branches' are small and mostly convoluted parcels connecting core areas (Petrosillo et al., 2021). More specifically, 'loops' are corridors connecting the same 'core', 'bridges' connect at least two distinct 'cores', and 'branches' connect a 'core' area with a non-core area within the same land-use class (Daya Sagar and Murthy, 2000).

Landscape classification based on MSPA was realized through Guidos software running on the shapefiles representing the spatial distribution of built-up settlements at seven time points (1948, 1975, 1990, 2000, 2006, 2012, 2018) appropriately rasterized using the 'spatial analyst' tool available in the ArcGIS package (Batty and Longley, 1994). The surface area of the seven MSPA categories (see above) was calculated separately for each observation year (Zhao et al., 2020). MSPA processes start with the identification of core areas based on connectivity rules defining neighbours and the value used to define edge width (Soille and Vogt, 2009). Consequently, connectivity was set for a given pixel node to its adjacent neighbouring pixels by considering 8 neighbours (i.e. a pixel border and a pixel corner in common) allowing identification of the remaining landscape categories (Soille, 2003).

2.3.2. Landscape dimensions

Four landscape dimensions (*sensu* Tian et al., 2014; Shaker, 2018; Siles et al., 2019) were considered in this study as a representative overview of territorial functions in Athens: (i) class area (%) in urban landscape (namely reflecting built-up settlements and hereafter marked with the 'urban' label), (ii) class area (%) in total landscape ('total'), (iii) per cent frequency of built-up parcels by class ('parcel'), and (iv) the distance of each parcel from downtown Athens by class ('distance'). Dimension (iv) was calculated as a standardized indicator dividing the average distance of each parcel (km) by the maximum (linear) distance between downtown Athens and the farthest border in Attica (km). For each dimension, indicators were calculated separately for each structural type and year with the aim at quantifying composition (dimension [i]), dominance (dimension [ii]), fragmentation (dimension [iii]), and spatial distribution (dimension [iv]) of landscape elements – in turn reflecting significant landscape functions in the area (Salvati et al., 2018).

2.4. Statistical analysis

Covering a wide range of spatial patterns, the joint analysis of landscape (functional) indicators and structural types derived from MSPA provides a comprehensive investigation of (latent) form-function relationships at the base of metropolitan transformations (e.g. Parr, 2014). The proposed framework was articulated in three steps: (i) an exploratory, dynamic analysis of two landscape components (structure and functions) and their latent (multivariate) relationship, providing an indirect assessment of the latent evolution of a given system (Grafius et al., 2018); (ii) identification of 'fast' and 'slow' (structural and functional) attributes of the landscape system (Ferrara et al., 2016); (iii) estimation of 'rapidity-of-change' of the whole system derived from computation on specific analysis' outputs (Salvati and Serra, 2016). More specifically, the analysis allows evaluating if the joint position of units (functional class) and cases (structural types) is stable (or variable) over time by projecting them into the same factorial plane (Coppi and Bolasco, 1989). This approach identifies 'fast' and 'slow' attributes of the studied system and provides a global estimation of 'rapidity-of-change' (Holland, 2006).

2.4.1. Multi-way Factor Analysis

A Multi-way Factor Analysis (MFA) was run on a time series of seven matrices (1948, 1975, 1990, 2000, 2006, 2012, 2018), each including seven structural types (by column) and four landscape (functional) dimensions (by row) after data standardization (Duvernoy et al., 2018). MFA delineates complex structures in higher-order datasets – where data have more than two dimensions (Escofier and Pages, 1994). In this case, MFA decomposes changes by three sources of variability (structure, functions, time). By associating different variables with similar spatio-temporal patterns on a few significant axes, MFA also provides an indirect measure of redundancy (Escofier and Pages, 1994).

Belonging to the broad family of exploratory multivariate techniques, MFA is a generalization of factorial ordination methodologies (Kroonenberg, 2008) such as Principal Component Analysis (PCA). MFA allows a comparative investigation of the relationship between different data sets over time, identifying a common data structure called 'compromise' – which is then analysed via spectral decomposition of common structures between the observations (Coppi and Bolasco, 1989). Each data set was projected into the 'compromise' space with the final aim at analysing communalities and discrepancies (Salvati and Serra, 2016). The 'compromise' weights were chosen maximizing the representativeness of all the seven data sets. Significant axes were selected if the respective eigenvalue overpassed 1 (Lavit et al., 1994). This criterion allows considering factors that extract a satisfactory proportion of variance from the input data matrices (Salvati, 2014). Starting from a simple 'units • variables • times' three-way array (e.g. Bove and Di Ciaccio, 1994).

$$X_{(I,J,T)} = \{x_{ijt}\}, \ i = 1,\ldots,I; \ j = 1,\ldots,J; \ t = 1,\ldots,T \tag{1}$$

Where indexes i, j, and t correspond with variables, units, and times, respectively, MFA combines (i) a cross-section PCA through spectral decomposition of a correlation matrix computed on the input dataset with (ii) an explicit investigation of the time series dimension balancing data matrices' contribution to the overall variability (Coppi et al., 2010). MFA assumes constant weights for the variables of the same group (Escofier and Pages, 1994), and varying weights assigned to variables belonging to different groups (Pagès, 1996).

Weights are constructed in a way that the maximum axial inertia of a variable's group is equal to unity (Coppi, 1994), i.e. assigning a weight equal to the inverse of the first eigenvalue of the group's factor analysis to each within-group variable (Lavit et al., 1994). Having normalized each cloud of variables-observations making its highest axial inertia equal to 1 (Escofier and Pagès, 2008), this weighting system does not balance total inertia of the different sets, thus implying that a set having a high dimensionality will have a high global influence in the sense that this set will contribute to several (extracted) axes (Escofier and Pages, 1994).

As an exploratory analysis not grounded on hypothesis testing, the selection of significant factors in MFA was based on *a-priori* eigenvalue threshold (Escofier and Pagès, 2008). At the same time, MFA provides, for each axis, classical outputs of a general factor analysis, including (i) coordinates, contributions and squared cosines of individuals, as well as (ii) correlation coefficients between axes and input variables (Kroonenberg, 2008). We specifically considered loadings and scores respectively from dimension (i) and (ii) when defining independent directions of landscape transformation in the study area (Morelli et al., 2014). MFA results thus allow an explicit evaluation of changes over time in the position of each unit and case since they are projected into the same factorial plane (Kroonenberg, 2008).

2.4.2. Identifying 'fast' and 'slow' landscape attributes

The procedure shown in this study is sufficiently flexible and can adapt to different socioeconomic contexts, thus allowing a comprehensive interpretation of the relevant aspects of landscape transitions (Walker et al., 2012). The approach proposed here focuses on distinctive aspects of the trajectory over time of a complex system, such as 'fast' and 'slow' variables that determine its evolution and the overall 'rapidity-of-change' (Walker et al., 2004). MFA provided evidence documenting the latent interaction between 'fast' and 'slow' variables (Ferrara et al., 2016). Evidence from the analysis of 'fast' and 'slow' variables should be interpreted in connection with the results of preliminary, descriptive statistics (Salvati et al., 2018). In other words, identification of 'fast' or 'slow' variables from MFA outcomes was considered a knowledge step reconnecting traditional paradigms in regional science and urban economics, with more recent approaches to the study of metropolitan systems based on the notions of sustainability and resilience (De Rosa and Salvati, 2016).

Following Salvati and Serra (2016), a standardized metric depending on time (t) was introduced separately for each i-th landscape (functional) indicator (X' metric) and for each j-th structural type (Y' metric) derived as the Euclidean, n-dimensional distance between factor loadings (or scores) at the beginning and the end of each time interval (e.g. 1948–1975, 1975–1990, 1990–2000, 2000–2006, 2006–2012, 2012–2018), and standardized by the number of observation years (s) as follows:

$$X'(t) = \sqrt{((x_{1,1} - x_{1,0})^2 + (x_{2,1} - x_{2,0})^2 + (x_{...,1} - x_{...,0})^2 + (x_{n,1} - x_{n,0})^2)}/s \quad (2)$$

$$Y'(t) = \sqrt{((y_{1,1} - y_{1,0})^2 + (y_{2,1} - y_{2,0})^2 + (y_{...,1} - y_{...,0})^2 + (y_{n,1} - y_{n,0})^2)}/s \quad (3)$$

where $x_{a,b}$ is the loading on factor a at time b, $y_{a,b}$ is the score on factor a at time b, and n is the number of factors with eigenvalues > 1 (Salvati et al., 2017). 'Fast' and 'slow' variables were investigated separately for (i) a short-term horizon, i.e. considering each time interval separately (Salvati and Serra, 2016), and for (ii) a long-term horizon, i.e. considering the whole study period between 1948 and 2018 (De Rosa and Salvati, 2016). 'Fast' and 'slow' attributes were defined as having, respectively, an above-median or below-median rapidity of change calculated for each dimension (structure and functions) separately (Egidi and Salvati, 2020). These metrics ultimately aimed at estimating the contribution of settlement structure and land-use functions to the overall landscape system's evolution (Wang and Zhang, 2001; Walker et al., 2004; Chen et al., 2020).

2.4.3. Estimating rapidity-of-change in the development path of a landscape system

At the same time, considering all the indicators together, a diachronic estimation of whole-system 'rapidity-of-change' (namely, year by year), was carried out with the same logic, i.e. estimating the differential intensity (i.e. speed) of landscape dynamics considering time sub-periods separately (Morelli et al., 2014). Estimation of whole-system 'rapidity-of-change' was carried out introducing a standardized metric (M') depending on time (t) and calculated as the Euclidean, n-dimensional distance between axes' coordinates separately for each observation (i.e. year) and normalized by the number of observation years (s) as follows:

$$M'(t) = \sqrt{((u_{1,1} - u_{1,0})^2 + (u_{2,1} - u_{2,0})^2 + (u_{...,1} - u_{...,0})^2 + (u_{n,1} - u_{n,0})^2)}/s \quad (4)$$

where $u_{a,b}$ is the observation coordinate on factor a at year b and n is the number of extracted factors overpassing the eigenvalue threshold mentioned above (Pili et al., 2017). 'Rapidity-of-change' estimated for each time interval was illustrated graphically (Salvati and Carlucci, 2016).

3. Results

3.1. Descriptive statistics

The present exercise proposes a preliminary investigation of the most characteristic trends over time in metropolitan Athens, considering dynamics in the main landscape indicators disaggregated by structural type, as an output of the mathematical morphology technique adopted in this study. The empirical findings reported in Table 2 were commented in light of the socioeconomic timing depicted in Fig. 2. The intrinsic dynamics characteristic of landscape indicators – whether linear or non-linear – showed an explicit association with metropolitan cycles, economic development, and socio-demographic transformations in metropolitan Athens, as summarized in Fig. 2.

Considering the 'class area' indicator that reflects the composition of both 'urban' and 'total' (i.e. including both urban and non-urban) landscapes, major dynamics took place until 2006, and then abruptly slowed down with the 2007 economic crisis. 'Core' parcels represented the vast majority of built-up areas, showing a moderate increase between 1948 (95.5 %) and 1975 (97.7 %), and a slighter decline in the following years (from 97.2 % in 1990 to 96.8 % in 2018). For all the years analysed, parcels classified as 'urban edge' constituted another dominant structural type as far as class area is concerned – moving from 4.4 % in 1948 to 2.2 % in 1975, and keeping stable afterwards (from 2.7 % in 1990 to 2.8 % in 2018).

The other structural classes (islets, perforations, loops, bridges, branches) accounted for a small proportion of urban landscapes, increasing slightly from 0.1 % (1948) to 0.6 % (2018). Such dynamics reflected a substantial expansion of spatially dispersed and structurally fragmented settlements. The greatest degree of compaction in built-up settlements was observed in 1975, at the end of the 'urbanization' wave. In line with these findings, the contraction of areas classified as

Table 2
Summary statistics of four landscape indicators (class area in urban landscape, class area in total landscape, number of parcels in total parcels, distance from downtown) in the study area by structural land type and year.

Structural land type	1948	1975	1990	2000	2006	2012	2018
Class area in urban landscape (%)							
Core	95.5	97.7	97.2	97.0	96.8	96.8	96.8
Islet	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Perforation	0.1	0.1	0.1	0.2	0.3	0.4	0.4
Edge	4.4	2.2	2.7	2.8	2.8	2.8	2.8
Loop	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bridge	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Branch	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Class area in total landscape (%)							
Core	3.1	15.2	15.9	18.2	23.4	23.6	23.9
Islet	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Perforation	0.0	0.0	0.0	0.1	0.1	0.1	0.1
Edge	0.1	0.3	0.5	0.5	0.7	0.7	0.7
Loop	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bridge	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Branch	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Number of parcels in total parcels (%)							
Core	21.0	18.5	18.3	15.5	7.7	7.7	7.8
Islet	0.0	2.6	0.24	0.1	0.2	0.2	0.2
Perforation	0.4	0.9	0.6	1.8	1.3	1.4	1.4
Edge	25.1	20.3	20.2	17.9	21.3	21.1	21.1
Loop	1.8	1.6	0.12	0.8	7.2	7.1	7.1
Bridge	0.0	1.7	0.85	0.8	1.1	1.0	1.0
Branch	51.7	54.3	59.7	63.0	61.3	61.5	61.4
Distance from downtown (0–1 standard measure, 0 corresponds with inner city)							
Core	0.21	0.21	0.20	0.19	0.19	0.19	0.19
Islet	0.40	0.41	0.41	0.41	0.41	0.41	0.41
Perforation	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Edge	0.48	0.49	0.49	0.49	0.49	0.49	0.49
Loop	0.35	0.35	0.35	0.35	0.35	0.35	0.35
Bridge	0.36	0.36	0.36	0.37	0.37	0.37	0.37
Branch	0.39	0.39	0.40	0.40	0.40	0.40	0.40

’urban edge’ was more intense in 1975. The subsequent time intervals (1975–1990 and 1990–2000), coincided with a moderate expansion of built-up settlements and a somehow greater stability of landscape structures, possibly in line with stagnant economic dynamics. The early 2000s economic expansion – a result of investments and infrastructures preparing for 2004 Olympic Games – fuelled a mostly discontinuous urban growth. The most intense settlement dispersion, however, was observed in 2018, at the end of a latent ‘counter-urbanization’ wave. Although with growth rates varying over time, built-up settlements have grown continuously over the last 70 observation years, extending 3.2 % of the whole landscape in 1948 and 24.7 % in 2018.

3.2. Multidimensional analysis

Assumed as a complex system adapting (more or less rapidly) to dominant socioeconomic transformations, the three-way analysis of Athens’ landscape was run on 4 functional indicators, 7 structural types, and 7 years. The empirical results of the analysis were summarized in a biplot (Fig. 3) – a graphical representation that delineates the latent relationship between functional indicators and structural types. Multi-way analysis extracted two axes that explain respectively 75.3 % and 18.0 % of the overall variance in the (evolving) landscape system. This specification provided a complete description of the variance (93.3 %) associated with matrices’ dynamics over time. Axes 1 and 2 distinguished ’core’ and ’branch’ types (associated with Axis 2, having received loadings around |0.7| but with opposite signs) from the remaining types loaded on Axis 1, with positive coefficients ranging between 0.97 and 0.98. This evidence indicates a substantial discrepancy in the temporal dynamics of ‘core’ parcels (typically associated with consolidated and semi-dense urban areas) and those types that reflect a more fragmented and chaotic landscape structure (basically islets, perforations, loops, and bridges) possibly associated with urban sprawl.

The position of the functional indicators in the biplot delineated differential behaviours along Axes 1 and 2, highlighting a fairly complex form-function relationship in the Athens’ landscape. More specifically, Axis 1 distinguished latent dynamics associated with the ‘distance’ of settlements from downtown (positive scores) from those characteristic of class (‘total’) area (negative scores) – delineating a metropolitan gradient from urban to rural areas. Axis 2 finally distinguished the compact morphological structure (’urban’) of built landscapes (positive scores) from more fragmented and isolated settlements (’parcel’) associated with negative scores on the axis.

3.3. ‘Fast’ and ‘slow’ variables

Based on the results of the multi-way analysis, functional indicators and structural types were classified according to the ’fast’ (or ’slow’) transformations they experienced along the six investigated time intervals, i.e. reflecting short-term dynamics (Fig. 4). Considering landscape structural types (left), the standardized transformation metrics discriminated the dynamics of ’core’ and ’branch’ parcels from those related to the remaining five structural types. ’Core’ and ’branch’ parcels resulted to be particularly dynamic between 1948 and 1975 and, in part, between 1975 and 1990. On the contrary, ’islets’ and ’loops’ parcels underwent more intense transformations during 1990–2000 and 2000–2006 – in correspondence with the economic expansion associated with 2004 Olympic Games. Finally, the standardized metrics associated with ’edge’, ’bridge’, and ’perforation’ parcels showed a mostly linear growth over time. Taken together, these results confirm the relevance and persistence of a metropolitan cycle dominated by compact urbanization (1948–1990) and dispersed suburbanization (1990–2006). Suburbanization prolonged with less intensity in more recent time as a result of complex territorial dynamics (e.g. recession, demographic decline, social/ethnic segregation). Considering the whole study period, i.e. assessing long-term landscape dynamics, ‘core’ (Y’ = 0.147), ‘islets’ (Y’ = 0.158), ‘loops’ (Y’ = 0.158), and ‘branches’ (Y’ = 0.129) were classified as ‘fast’ (structural) attributes of change

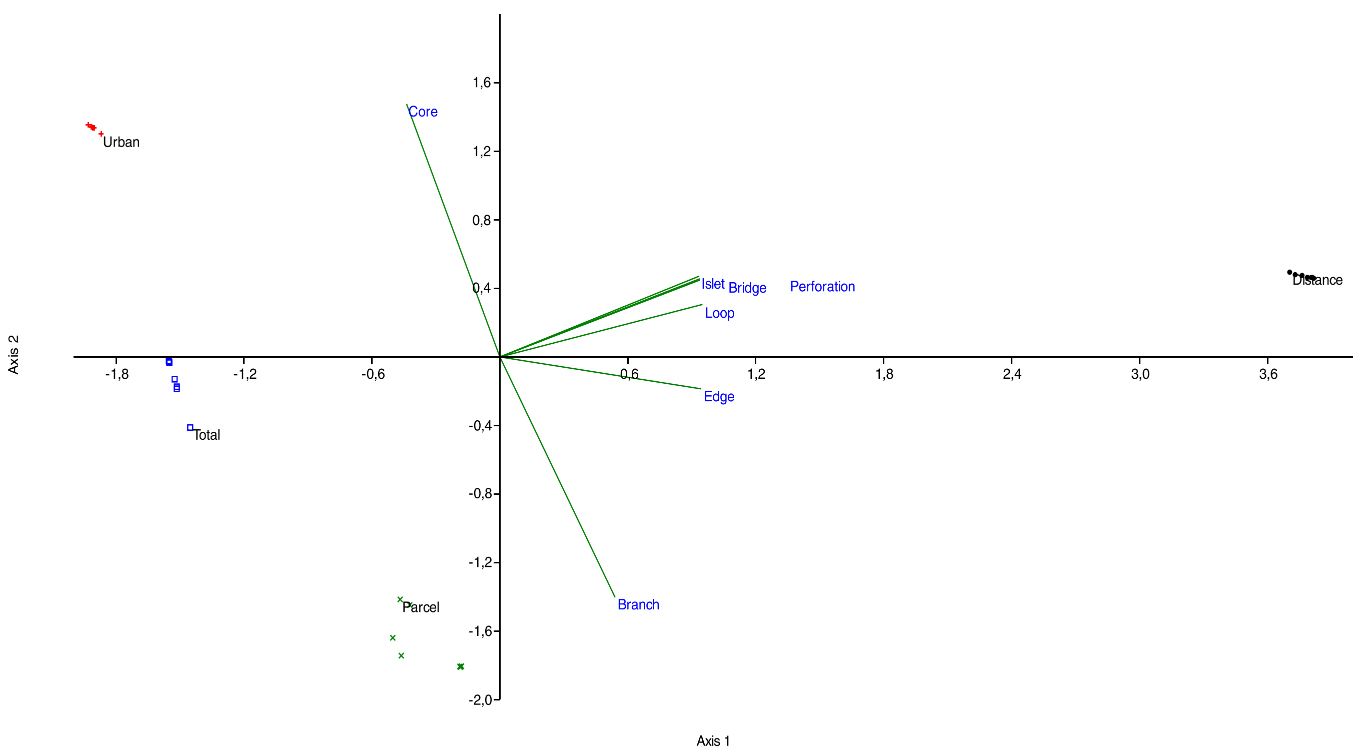

Fig. 3. Biplot of a multivariate statistical analysis extracting the two main axes that illustrate the latent relationship between seven structural types (‘core’, ‘islet’, ‘perforation’, ‘loop’, ‘edge’, ‘bridge’, ‘branch’) and four indicators (‘urban’, ‘total’, ‘parcel’ and ‘distance’) representing the main landscape functions in the study area.

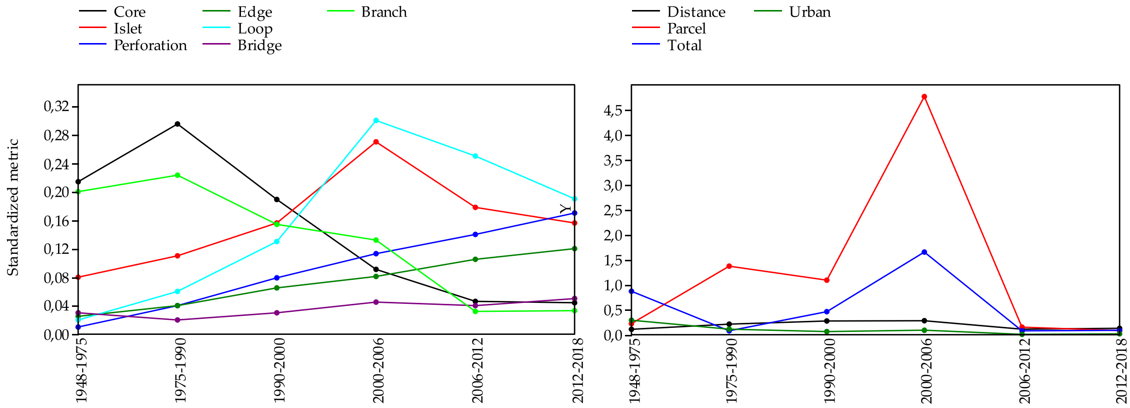

Fig. 4. Standardized metrics estimating 'fast' and 'slow' variables depicting structural types (left) and landscape functions (right) in the study area by time interval.

based on Y' metric, as opposed to 'perforation' (Y' = 0.092), 'edge' (Y' = 0.073), and 'bridge' (Y' = 0.036) types considered as 'slow' components of change.

Among the functional indicators (Fig. 4, right), the fastest transformations were observed for 'parcel' and 'total' dimensions (both reached the maximum intensity of change between 2000 and 2006). The 'distance' dimension totalled much less intense values of the relevant metric, growing slightly until 2000–2006 and declining considerably in the following phases. The 'urban' dimension in turn revealed the greatest dynamism in the first two development stages (1948–1975 and 1975–1990). In general, the last phases of the cycle had almost negligible transformation metrics, likely reflecting the negative impact of the economic crisis on urban growth. Considering the whole study period, 'parcel' (X' = 1.28) and 'total' (X' = 0.54) landscape dimensions were classified as 'fast' components of change, as opposed to 'distance' (X' = 0.19) and 'urban' (X' = 0.10) dimensions, classified as 'slow' components of landscape change.

3.4. *Landscape system's 'rapidity-of-change'*

Considering together the multi-temporal dynamics of matrix columns (functional indicators) and rows (structural types), the 'rapidity-of-change' characteristic of the whole landscape system was recognized as highly heterogeneous in the study period (Fig. 5). In particular, the standardized metric estimating 'rapidity-of-change' was greater in the early development stages, decreasing in the last recession's time. According with the standardized metric, the most intense dynamics were observed between 2000 and 2006 – paralleling a short, while intense, wave of economic expansion. Less intense, but nevertheless considerable, transformations were detected between 1975 and 1990, in line with (i) a dynamic demographic context, (ii) moderate economic growth following the restoration of a completely democratic regime in the mid-1970s, and (iii) the dominance of medium-density suburbanization. Finally, the period 1948–1975 – although heavily influenced by population inflow from rural areas – showed a lower value of the standardized metric, in spite of economic dynamics featuring sequential acceleration and deceleration waves.

These results highlight how the rapidity-of-change of the landscape system under investigation reflects the sequential stages of the metropolitan cycle, and incorporate the effect of regional economic downturns and the main socio-demographic transformations at the local scale. Based on these findings, the standardized metric was intended as a proxy of the intensity of change characteristic of a landscape system resulting from settlement expansion, the most basic (and easily observable) manifestation of metropolitan growth.

4. Discussion

Representing the complex interplay of settlement morphology and socioeconomic functions in advanced economies, long-term metropolitan growth revealed novel landscape structures in spatially polarized regions (Alberti, 2010), whose cities have been recognized for a long time as characteristic examples of compactness, economic diversification, and social cohesion (Bruegmann, 2005; Couch et al., 2007; Catalàn et al., 2008). In more recent times, landscape transformations have been associated with a low-density expansion of large cities and medium-size towns consequent to latent processes of urban de-concentration and economic decentralization (Kourtit et al., 2014; Jacobs-Crisioni et al., 2014; He et al., 2020). In these contexts, complexity in both landscape trajectories and the related socioeconomic change claims for better conceptualization and a broader empirical knowledge based on appropriate indicators and assessment methodologies (Kasanko et al., 2006; Longhi and Musolesi, 2007; Schneider and Woodcock, 2008).

Based on these premises, our study investigates spatio-temporal dynamics of urban growth and the consequent landscape change in a metropolitan region of Mediterranean Europe using high-resolution land-use maps as a primary information source (e.g. Duvernoy et al., 2018; Perrin et al., 2018; Zambon et al., 2018). Processes leading to landscape change were identified and assessed over time making use of adequate indicators, with a specific, joint focus on settlement morphology and landscape functions (Salvati and Serra, 2016). The operational approach benefited from the application of a mathematical morphology technique to a wide collection of statistical data mainly derived from official land-use and land cover maps (Vogt et al., 2017). In this perspective, use of a multi-way analysis exploring the joint dynamics of morphological and functional indicators over time proved appropriate to advance scientific knowledge in vast disciplinary fields – from land-use science to regional studies, from applied economics to environmental ecology (e.g. Salvati et al., 2019).

Although being far from providing a univocal assessment of metropolitan growth, the empirical results of our study explicitly delineate a relationship between urban morphology and socioeconomic functions, suggesting the relevance of latent interactions among different organizational levels of landscape systems (Hasse and Lathrop, 2003; Tian et al., 2011; Lamy et al., 2016). In this regard, Greece provides a key example of Mediterranean urbanism with sequential and distinctive waves of the metropolitan cycle having a direct linkage with landscape structure and land-use functions (Carlucci et al., 2017). More specifically, the study links long-term landscape change with territorial dynamics at large (namely, the sequential waves of the metropolitan cycle), identifying the relationship of 'rapidity-of-change' – an intrinsic property of transitioning landscape systems – with economic downturns and socio-demographic transformations (Tan et al., 2005; Wu et al., 2011; Salvati and Carlucci, 2016).

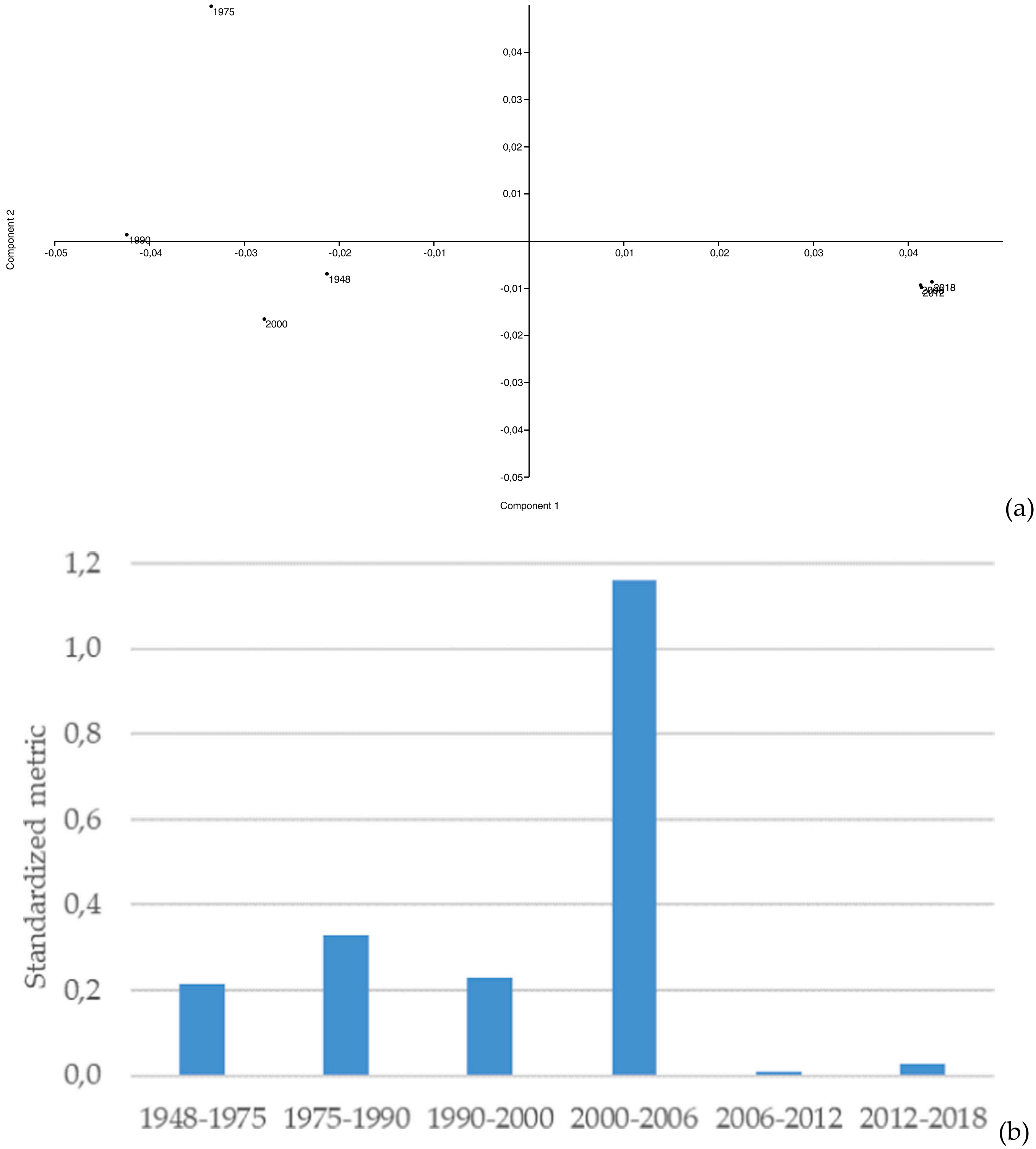

Fig. 5. The average position of the variable 'urban settlements' (a) projected, for each observation year (1948–2018), along the main two axes illustrated in Fig. 3 (and thus delineating long-term Athens' expansion); a standardized metric of rapidity-of change characteristic of the investigated landscape system (b) by time interval.

By distinguishing six time intervals with different territorial dynamics, the multidimensional analysis run in this work profiles development stages as characterized by specific structural traits in terms of compactness, fragmentation, and spatial complexity – in turn related with peculiar landscape functions (Zhang et al., 2013). Results also indicate that the highest 'rapidity-of-change' in landscape transformations was associated with a particularly intense wave of economic growth (2000–2006). Intermediate values of 'rapidity-of-change' were observed during periods of intense population growth and social transformations (Salvati and Serra, 2016). The lowest level of 'rapidity-of-change' was finally recorded in correspondence with the last recessionary phase – likely the most intense in Greece since one century (Gkartzios, 2013).

Shedding further light in the analysis of form-function relationships in (evolving) metropolitan regions, the intrinsic association between landscape change and territorial dynamics may provide an indirect information tool when investigating (latent or less evident) territorial transformations through indicators (Paul and Tonts, 2005). As a matter of fact, urban expansion is likely the most studied outcome of regional development – being the direct manifestation of economic growth, population increase, and social change (Ferrara et al., 2014). Seen from another point of view, the largely heterogeneous level of 'rapidity-of-change' may reflect a sort of growth path featuring sequential 'urban pulses', in line with the empirical results of earlier studies (Egidi et al., 2021). Pulses corresponded with sequential accelerations or decelerations of socioeconomic dynamics at the base of landscape change (Nickayin et al., 2022).

By linking complexity in urban form and economic functions, the permanent assessment of metropolitan transformations is thus challenging for both research and policy (Salvati et al., 2019). From a research perspective, further studies are requested to clarify the intrinsic, spatio-temporal interconnection between landscape functions and the evolution of mono-centric (or polycentric) settlement structures (Zambon et al., 2018). Original indicators matching information from official statistics, high-resolution land-use maps and remote surveys seem to be particularly appropriate to this aim (Alberti, 2005). Official statistical systems should in turn develop a more effective operational framework based on relevant indicators (Salvati et al., 2016), that may assess landscape transformations over different time windows distinguishing short-term from long term dynamics (Alberti, 2010).

From a normative perspective, understanding the main factors driving medium- and long-term socioeconomic transitions contributes to planning strategies designed to a competitive rebalancing of the functional gap between cities and the surrounding areas (European Environment Agency, 2006). For instance, a sustainable planning of fringe land is recommended in light of metropolitan sustainability (Perrin et al., 2018), as these districts are the most rapidly changing (Duvernoy et al., 2018), simultaneously generating economic opportunities, demographic challenges, and socio-environmental concerns (Champion and Hugo, 2004). Delineating long-term transformations in the 'form--function' relationship finally allows evaluation of (direct or indirect) planning impacts on metropolitan development (Giannakourou, 2005).

5. Conclusions

The empirical results of this work may support regional policies and a more efficient spatial planning of metropolitan regions in Southern Europe, addressing multiple objectives of environmental sustainability, social cohesion, and economic competitiveness. Regulating urban expansion, containing land consumption, and preserving natural landscapes are practical actions benefiting from a broader (indicator-based) operational framework that interprets long-term socioeconomic dynamics in light of (structural and functional) landscape changes. The empirical findings of our study underline the appropriateness of an in-depth, timely assessment of landscape change vis à vis socioeconomic transformations that may inform development policies in homogeneous territorial systems.

CRediT authorship contribution statement

Gianluca Egidi: Data curation and editing. **Enrico Maria Mosconi**: Writing – original draft. **Rosario Turcoc**: Data analysis and writing - revisions. **Luca Salvati**: Writing – original draft.

Data Availability

Data will be made available on request.

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