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Estimating Rapidity of Change in Complex Urban Systems: A Multidimensional, Local-Scale Approach

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This study illustrates an exploratory approach based on a Multiway Factor Analysis (MFA) to estimate rapidity of change in complex urban systems, based on "fast" and "slow" variables. The proposed methodology was applied to 18 socioeconomic indicators of long-term (1960–2010) transformations in 115 municipalities of Athens' metropolitan area (Greece), including demography, land-use/planning, and urban form and functions. Athens was regarded as a dynamic urban area with diversified structures and functions at the local scale, expanding through a self-organized pattern rather than a centralized planning strategy. Athens' urban system was described using nine supplementary (topographic and territorial) variables and 30 independent indicators assessing the local context in recent times. Exploratory data analysis found an increasing connectedness and redundancy among socioeconomic indicators during the phase of largest urban expansion (1960–1990). Only the rate of population growth was classified as a "fast" variable for all five decades investigated. The overall rapidity of change was higher in 1960–1970, 1980–1990, and 2000–2010, decades that coincided with specific phases of urban expansion driven by migration inflow, second-home suburbanization, and Olympic games, respectively. Rapidity of change was high for functional indicators during all five decades studied, while demography indicators changed more rapidly in the first three decades and land-use/planning indicators in the last two decades. Rapidity of change was highest in peri-urban municipalities with a highly diversified economic structure dominated by industry. Our methodology provides a comprehensive overview of the transformations of a complex urban system, quantifying low-level indicators that are rarely assessed in the mainstream literature on urban studies. These results may contribute to design policies addressing complexity and promoting resilience in expanding metropolitan areas.

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Introduction

Urbanization processes driven by population growth, socioeconomic dynamics, and technological change are traditionally reflected in specific morphologies and functional relationships with the local context (Fielding 1982; van den Berg et al. 1982; Cross 1990). While different dimensions coexist, producing a dynamic interplay between form and functions, metropolitan regions are regarded as progressively complex systems shaped by (sometimes contrasting) socioeconomic factors (Champion and Hugo 2004). The evolution (more or less rapidly) of urban systems toward complexity, relocating activities on the fringe, redesigning central and peripheral functions and, more generally, remodeling settlement structures on a wider spatial scale has been demonstrated for several cities (Hall and Pain 2006; Turok and Mychnenko 2007; Kourtit, Nijkamp, Reid 2014). Among others, suburbanization, sprawl and polycentric development are well-known recent phenomena altering the long-established spatial organization of metropolitan regions (Cross 1990; Champion and Hugo 2004; Neuman and Hull 2009). Based on the dimensions cited above, more articulated visions of evolving metropolitan regions can better address the intimate, dynamic relationship between urban patterns and processes at the base of urban complexity (Mundia and Aniya 2006; Couch, Petschel-held, Leontidou 2007; Polyzos, Minetos, Niavis 2013; Serra et al. 2014). Systemic approaches are required for a better understanding of recent urban transformations that produce new economic spaces and thus alter the traditional urban-to-rural gradient typical of the mono-centric city (Hall 1997a; Pacione 2005; Parr 2014).

Cognitive systems in socioeconomic networks have greatly influenced the representation of complex system 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 (Portugali 2000). Within a context of urban fragmentation, economic uncertainty, and changing social attitudes and political rules, urban systems have increasingly been seen as open systems shaped by nonlinear dynamics involving agents capable of anticipation and emerging types of spatial units (Portugali 2011). The relatively low-level interactions between agents produce these new spaces at two main levels of observation: the morphological and social structures of a city that emerge from citizens' decisions and feedback interactions and the spatial organization of economic activities that reflects adaptive strategies and competitive relations between districts, municipalities and individual towns in a metropolitan region (Pumain 2005). The relational issues complicate the assessment of any metropolitan system; in fact, isolating the interactions between different levels of organization for purposes of measurement appears to be a daunting task (Forrester 1970). However, the evolutionary trajectory of urban systems reveals, in many cases, some common patterns including selection, cooperation, imitation, and adaptation to change (Hall 1997b; Turok and Mychnenko 2007; Schneider and Woodcock 2008). These patterns usually reflect self-organized development instead of collective behavior controlled by a central institution (Bura et al. 1996). Despite marked differences in size and specialization profile, among others, cities have adapted quickly to technical and social innovations producing similar development paths (Berry 2005).

A self-organized system is characterized by a macro-level structure produced by nonlinear interactions between micro-level elements. These interactions imply that the system is not attracted towards a pre-determined equilibrium, being influenced sharply by shocks linked with the amplification of internal fluctuations, external perturbations or changes in the relationships between the composing elements (Portugali 2011). Such alterations may impact the dynamic trajectory of the system, determining the persistence or volatility of specific socioeconomic attributes at local scale (Page et al. 2001). The design of frameworks and empirical models to interpret and understand the long-term evolution of complex urban systems is a challenging task. Every approach must ensure both theoretical parsimony and consistency with the state of knowledge. Previous studies have introduced simplified approaches linking individual-level surveys with statistical observation of aggregated spatial units of interest for both research and policy (Cabral et al. 2013; Zhang et al. 2013; Jacobs-Crisioni, Rietveld, Koomen 2014; Aguilera-Bonavente, Botequilha-Leitão, Díaz-Varela 2014; Raska, Klimes, Dubisar 2015; among others). Despite criticism rooted in the lack of empirical verification and theoretical support (Durlauf 2003), the analysis of complex urban systems is producing increasingly well articulated frameworks to explore system dynamics by focusing on the emergence of macro-level properties such as the result of the latent interactions between micro-level agents (e.g., Favaro and Pumain 2011). This development may fill a traditional gap in the theory of evolving urban systems, considering bottom-up constructions and giving value to the mass of statistical information and data generally available at aggregate levels. Municipalities are considered an interesting scale of analysis because they are seen as local institutions influenced by the collective action of micro-agents and by a rather stable territorial partition of policy relevance, possibly linked to long-term development of the area that can be revealed by analyzing freely available statistical data (Salvati and Carlucci 2014).

The selection of the properties describing the evolution of metropolitan regions is another crucial point in the “complex system” approach. For example, the spatio-temporal relationship expressed by the transformation of the hierarchical structure within a system is sometimes proposed as an ensemble of properties influencing the system’s evolution. Generally speaking, properties are often identified with (more or less) simple socioeconomic attributes of the local spatial units of analysis. These attributes are sometimes intended as proxies of processes regulating the size of the urban elements, according to the speed and intensity of spatial interactions at different geographical scales. These factors operate through the expansion of the built-up area at the urban scale, and through the modification of the pristine hierarchy of towns, the emergence of new sub-centers and the loss of urban gradients in favor of a structure based on a “metropolitan continuum” (Neuman and Hull 2009).

The Complex Adaptive System (CAS) framework, defined as a self-similar collective of interacting adaptive agents, is considered an effective approach to unraveling complexity in evolving urban systems (Forrester 1970). A CAS adjusts to the socioeconomic and territorial context formed by multifaceted components determining nonlinear development trajectories that evolve from one equilibrium (or disequilibrium) state to another (Holland 2006). A regime in the state space has a characteristic identity, profile and functions, in which the CAS tends to remain over a period of time, moving about (changing states) due to disturbances, changes in its components and other factors. The regime’s profile is mainly determined by limiting/controlling factors (slow variables) while the CAS moves around the regime (i.e., changes state) depending on the changing values of fast variables. Fast/slow variables, threshold (to change regime), critical functions, low-level properties and multi-scalar feedbacks are relevant elements of a CAS. External drivers cause change in slow variables and, as slow variables approach threshold levels, the fast-moving variables in the system fluctuate more in response to shocks (Walker et al., 2012). Classified as a low-level property of a CAS, system’s rapidity of change is the result of interplay between fast and slow variables, defined as “the capacity to meet priorities and to achieve goals in a timely manner to contain losses and thwart future disruption” (Bruneau et al. 2003).

Rapidity of change can be assessed using quantitative or qualitative measures. However, despite the relevance of CAS theory in ascertaining urban dynamics, ways of identifying fast and slow variables and measuring rapidity of change are poorly addressed in urban studies. Based on these premises, the present study proposes an approach to identify fast and slow variables of a CAS while simultaneously providing a multidimensional measure of a system's rapidity of change. Our methodology integrates multivariate and inferential statistics, working with a large set of socioeconomic indicators to assess the increased complexity of a metropolitan region (Athens, Greece) at the municipal scale over the last 50 years. The estimated rapidity of change at different points in time was correlated with a set of independent indicators with the aim to verify how intrinsic characteristics of the urban system influence its capacity to evolve towards a different territorial configuration, in turn shaping relations between the composing elements.

The metropolitan area of Athens was considered a coherent case to apply CAS theory to urban studies. Based on a long urban tradition, this area experienced population growth after World War II that has produced a chaotic and self-organized urban fabric suspended between planning and informality (Polyzos, Minetos, Niavis 2013; Souliotis 2013; Chorianopoulos et al. 2014). Competitiveness and crisis, social segregation and mixed land-uses, economic repolarization, and urban sprawl exemplify the increasing complexity of this metropolitan area—with important local differentiations—and demonstrate the urgent need of comprehensive approaches providing a focused picture of the overall urbanization process at the metropolitan scale. The approach proposed here may reconnect traditional paradigms such as the factorial ecology and the spatial life cycle theory with a more recent literature dealing with system complexity and urban resilience. The identification of fast and slow variables and the assessment of the local socioeconomic context influencing these variables in the case of Athens metropolitan area is a contribution to the debate addressing complexity, fractality, and isolation as main traits of the contemporary city.

Complex systems theory and the evolution of metropolitan regions

Nature, configuration and socioeconomic attributes of cities have been associated to major economic principles of spatial organization (agglomeration, accessibility, spatial interaction, hierarchy, and competitiveness), reflecting uneven relationships between urban form and functions, in turn influenced by place-specific territorial contexts (Lloyd and Dickens 1977; Hall 1997a, b; Pacione 2005). Urban studies have long described the "location factors" (related to the benefits deriving from urban functions such as the spatial concentration of infrastructures, facilities and services) at the base of "agglomeration economies" that affect higher accessibility and differential prices for urban land (Klaassen, Molle, Paelinck 1981).

Starting from the seminal studies by Christaller (1933), Losch (1940), and Alonso (1964) considering the distance from the inner city as the most relevant factor shaping urban structures, more recent models investigate aspects of the market for urban land and the location of residences and production activities based on a set of influencing variables—not only those representative of the urban-rural gradient, such as population density, employment, or the distance from the central city (Chen and Partridge 2013; Zhang et al. 2013; Aguilera-Benavente, Botequilha-Leitão, Díaz-Varela 2014; among others). At the same time, cities have developed a complex network of multidirectional relationships with the surrounding region at different spatial scales. These include trade relations, commuting, and exchange of information and collaboration between enterprises, social groups, individuals and local institutions. These networks organize on the basis of gravitational fields, sensitive to the size of the spatial assets and their relative distance, but also according to other drivers only indirectly linked with accessibility, density and proximity to an urban area (Jacobs-Crisioni et al. 2014; Parr 2014; Salvati 2014, among others).

Although recognized as an important ordering principle for metropolitan regions even in recent times (Couch, Petschel-held, Leontidou 2007), the declining influence of Christaller's (1933) central place theory in the analysis of urban systems coincided with the emergence of complex interactions between population density, spatial distribution of activities, the size of their market areas and the type of activities involved at the metropolitan scale (Haynes and Enders 1975). While the interpretation of the development of urban systems based on physical hierarchy and linear distances loses importance (Serra et al. 2014), competitive advantages based on a mix of both measurable and intangible inputs remain at the base of the competitiveness of metropolitan regions (Scott et al. 2013).

Empirical research during the late 1960s and early 1970s advocated the "factorial ecology" approach linking early traditions in urban ecology and social area analysis (Berry and Kasarda 1977). Social area analysis attempted to differentiate dimensions of both structure and process within an urban area in terms of social, economic and demographic variables assuming that individual characteristics of residents within a given territory can be delineated by the characteristics of that social area (Janson 1980). Factorial ecology provided a basis for analyzing the social geography of cities and a logical framework in the development of summary measures of urban structure and change (Murdie 1969). Comparative literature based on this approach suggests widely different ecologies of pre-industrial, industrial, and post-industrial cities (e.g., Berry and Rees 1969). By working on regional and national settlement systems, evidence for general trends in urban growth and change were collected, outlining the role of place-specific patterns at the same time (see, for instance, the comparative work on Canadian urban dimensions in 1951 and 1961 provided by King 1966).

Although factorial ecology represented a useful means to examine complex, multivariate changes over time in the contemporary city, a reaction to this largely inductive work at the end of the 1970s raised ideological and analytical concerns (e.g., Murdie 1980). Urban structure was increasingly characterized by decentralization, dispersion, and multiple employment centers shaped by the long-term interplay between agglomerative and dispersive forces operating at different spatial scales (Pacione 2005). However, despite subjected to critical appraisal—both in terms of its explanatory value and its inherent methodology (Hunter 1972)—, urbanization, thanks to factorial ecology, was increasingly interpreted as a multidirectional and non-linear process.

Complex dynamics in metropolitan systems are influenced by path-dependent direct factors and underlying causes linking morphology with urban functions (see Salvati and Carlucci 2014 and references therein). Within this articulated vision of the recent development of metropolitan regions, static interpretations of the growth of cities such as Spatial Cycle Theory (Klaassen, Molle, Paelinck 1981; Fielding 1982; van den Berg et al. 1982) have been progressively replaced by fuzzy logic (Grekousis, Manetos, Photis 2013) and a few processes independent of the urban-rural gradient that are better reflected by key words such as fragmentation, isolation, scattering and, ultimately, complexity (Batty and Longley 1994; Portugali 2011; Encarnação et al. 2013). Nevertheless the concepts of "cycles" and "transitions" introduced by the Spatial Cycle Theory can be meaningfully considered in analyzing complex urban systems characterized by different "stable states" and socioeconomic contexts underlying changes in a previously established state (Cross 1990; Champion and Hugo 2004; Cabral et al. 2013). An example is provided in the seminal work by Anas, Arnott, Small (1998) which identified urban spatial structures prone to multiple equilibria and dynamic path-dependence with implications for cycle-based metropolitan development. At the same time, the analysis of urban structures shifting to more complex morphology, such as polycentrism (see, for instance, the classical study by Gordon, Richardson, Wong (1986) on the distribution of population and employment in metropolitan Los Angeles), has fueled a broad debate on structural changes in urban form and on the role of sprawl in promoting regional economic growth (e.g., Parr 2014)—albeit with negative environmental impacts (Xu, Wang, Xiao 2000; Zhang et al. 2013; Beniston, Lal, Mercer 2015).

Complex system theory stimulates a thorough explanation of urban growth processes based on the dynamic fine-tuning of common economic rules (e.g., proximity, accessibility, mass) with place-specific paths based on the interplay of a number of factors that shape sociodemographic relationships, competitiveness, and specialization within a given spatial structure. The CAS paradigm appears as a meaningful framework to unravel complexity in evolving urban systems, reacting to the changing environment and its multifaceted components (Holland 2006): the systems are (i) complex, in that they are (more or less rapidly) evolving networks of interactions, and their relationships are not aggregations of the individual static entities and (ii) adaptive, in that the agents' behaviors mutate and self-organize in response to the change-initiating micro-event or collection of events.

Characterized by a number of distinct properties, a CAS has a high degree of adaptive capacity, giving it resilience in the face of perturbation and interactions between the involved agents. Any element in the system is affected by and affects several other elements; interactions are primarily but not exclusively with immediate neighbors and the nature of the influence is modulated by space (Portugali 2011). What distinguishes a CAS from a pure multiagent system is the focus on both top-level properties (self-similarity, complexity, emergence, and self-organization) and low-level properties (robustness, diversity, redundancy, connectedness and rapidity of change). Moreover, CAS interactions are nonlinear. Small changes in inputs, physical interactions or stimuli can cause large effects in outputs; any interaction can feed back onto itself directly or after a number of intervening stages. In other words, a CAS evolves and past behavior is coresponsible for present behavior. Finally, these systems operate under far from equilibrium conditions (Walker et al. 2004). Based on these characteristics, a CAS may simulate—supposedly better than other models—the interplay between several different factors involved in a complex system undergoing continuous changes and feedback relationships (Holland 2006).

Methodology

Study area

The study area covers a large part of the administrative region of Attica (Greece) that includes the Athens Metropolitan Area (AMA), a total surface area of 3,000 km^2 (European Environment Agency 2011). Until 2011, the AMA was administered by 114 municipalities (including those of the island of Salamina) responding to four government prefectures: central Athens (inner city and suburbs), Piraeus, western Attica and eastern Attica (Fig. 1). Apart from the plateau occupied by central Athens, the AMA landscape is characterized by rugged topography.

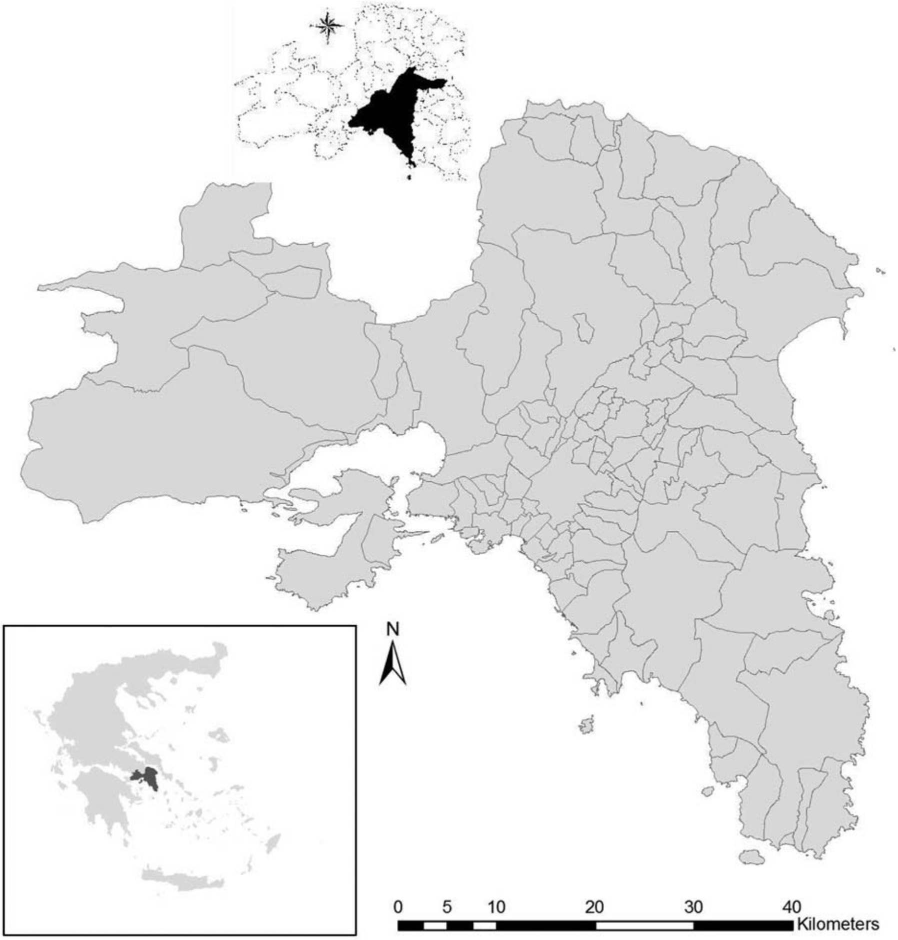

Figure 1. The boundaries of Attica municipalities and the position in Greece; the insert illustrates (in black) the municipalities belonging to the urban area of Athens.

Based on the availability of a homogeneous set of variables, the analysis covers five decades from 1960 to 2010. Municipal districts were selected as the basic unit of analysis. Although they represent arbitrary units of measurement (Jacobs-Crisioni, Rietveld, Koomen 2014), local administrative domains are commonly used as the denominator for demographic, social and economic analysis (see Salvati and Carlucci 2014 and references therein). Greek municipalities make decisions on land use, building volume, settlement size and local infrastructures, thus representing an interesting spatial domain for urban studies (Chorianopoulos et al. 2010).

Data and variables

An ensemble of 18 socioeconomic indicators were considered to describe the complex urban system of Athens, to identify fast and slow variables and to estimate the rapidity of change of each municipality in the AMA by decade and along the whole study period (Supporting Information Appendix 1). The 18 indicators were classified into four themes: population (4), land-use/urban planning (4), urban form (5), and urban functions (5). Data were derived from official statistical sources, mainly population, building, and agricultural censuses by the Hellenic

National Statistical Authority (ELSTAT) for each of the five decades. The selected indicators provide a multidimensional assessment of urban changes over a sufficiently long period to serve as proxies of a system's complexity and transitions along its development path. Previous studies have demonstrated that complex systems are formed by interplaying (and partly redundant) elements; connectedness between the distinct parts of a system is seen as one of the most relevant low-level properties characterizing a CAS. Therefore, partial or moderate correlations were also considered, using appropriate statistical procedures, to support the final objective of assessing the complexity of an urban system.

Nine supplementary topographic and territorial variables provided a detailed account of factors shaping the structure of residential and productive settlements at both regional and local scales (average elevation, proximity to the coast, municipal area and distances to four urban centers: Athens, Piraeus, and Maroussi and Markopoulo Messoghias). These centers were selected to test different spatial organization models (Salvati and Di Feliciantonio 2013): (i) a strictly mono-centric structure centered on the inner city of Athens; (ii) a model based on the gravitation around the poles of Athens (services) and Piraeus (industry, transport and logistics); (iii) a model based on the gravitation around the Olympic municipalities north-east of Athens representing a new urban core; and (iv) a suburbanization model based on the gravitation around both Messoghia municipalities, which represent the most evident sprawling area identified by Couch, Petschel-held, Leontidou (2007), Chorianopoulos et al. (2010), and Salvati and Carlucci (2014). Distance variables were measured using spatial functions such as the "centroid" command in ArcGIS (ESRI Inc., Redwoods, USA), which computes the center of gravity of each municipality and measures the distance to a fixed reference place.

An ancillary set of 30 independent indicators (reflecting urban land-use, economic specialization, labor market, demography and social characteristics) available only since 2000 at the local scale were also considered to test their influence on the estimated rapidity of change of each AMA municipality. This ensemble includes (i) 17 indicators assessing the urban use of land in 2010 (derived from European Environment Agency (2011) data by computation on the Athens Urban Area (UA) vector file describing the spatial distribution of classes labeled from "1110" to "1420") and a Shannon H' index of diversity in the urban use of land for each AMA municipality based on the UA data; (ii) three variables assessing the productive structure at the local scale, including the share of industrial and service activities in each municipality and a Shannon H' index of diversity in the economic activities at the municipal scale (data source: ELSTAT); (iii) two average per-capita disposable income variables, 2001 and 2011 (computationally derived from Hellenic Ministry of Finance statistics); (iv) four labor market indicators, consisting of participation rate, two ratios of qualified workers to total workers (ESEC 1 and 2 classes of the European nomenclature; see Salvati and Di Feliciantonio 2014 for technical details) and the percentage of active population working in the same municipality where they reside (derived from the 2001 census of population and households); and (v) four demographic indicators derived from the 2001 census of population and households, migration rate, birth rate, elderly index, and percentage of foreign residents who are citizens of the 15 European Union countries (2004 boundaries).

Empirical analysis

This study introduces a comprehensive framework to identify fast and slow variables determining changes in a complex urban system and to assess over time the rapidity of change in its elementary spatial domains. The proposed framework has three steps: (i) exploratory analysis of the 18 socioeconomic indicators available over time and space in the study area, providing an indirect assessment of low-level CAS properties such as connectedness and redundancy; (ii) Multiway Factor Analysis (MFA) identifying the most relevant dimensions of analysis, urban transitions at the regional scale and changes at the local scale, as linked with the socioeconomic indicators described above; fast and slow variables and rapidity of change of each AMA municipality were derived from computation on the MFA outputs; and (iii) inferential analysis correlating 30 independent indicators (described in section Data and variables) with the rapidity of change measured in both the medium-term (10 years, 2000–2010) and the long-term (50 years, 1960–2010) in each AMA municipality; based on pair-wise Spearman correlations and a Principal Component Analysis (PCA), this analysis identifies the main factors that determine (more or less rapid) changes in the studied urban system.

Exploratory data analysis

To identify (and rank the importance of) relevant relationships between a system's components, an exploratory analysis was developed incorporating Friedman analysis of variance and pair-wise Spearman nonparametric rank correlations. These statistical techniques were carried out using the STATISTICA 8 package (Tulsa, Oklahoma) on the data matrix containing 18 indicators made available for each municipal district in the AMA at the six years studied (1960, 1970, 1980, 1990, 2000, and 2010). Multivariate and non-parametric inferential approaches were chosen here because they do not require specific functional form and distributional assumptions, allowing identification of the latent relationship between socioeconomic indicators possibly underlying long-term growth factors (Salvati 2014).

A nonparametric Friedman ANOVA (testing at $P < 0.05$ after Bonferroni correction for multiple comparisons) was applied to assess significant differences in the statistical distribution of each indicator in the six years studied. The null hypothesis for the procedure is that the different columns of data (i.e., each indicator at the six points in time) contain samples drawn from the same population, or specifically, populations with identical medians. Using Kendall coefficients (ranging from -1 to 1), this procedure allows investigating the overall concordance (positive coefficients) or discordance (negative coefficients) of variables over the studied time period.

Spearman rank coefficients were used to investigate both linear and non-linear pair-wise correlations (i) within the ensemble of 18 socioeconomic indicators and (ii) between the 18 socioeconomic indicators and the 9 supplementary variables, testing for significance at $P < 0.05$ after Bonferroni's correction for multiple comparisons. The analysis was developed for each investigated time point between 1960 and 2010 with the aim to provide an informative basis for the subsequent multivariate analysis of fast/slow variables, rapidity of change and the relationship between rapidity of change and independent contextual indicators. The percentage of significant Spearman correlations on the total number of correlations run separately for analysis (i) and (ii) was calculated as a proxy for (internal and external, respectively) connectedness between the different components.

Identifying fast and slow variables and estimating rapidity of change through a multiway factor analysis

The MFA method was applied to the 18 socioeconomic indicators measured at each timepoint for every AMA municipality. This analysis captures complex structures in higher-order datasets (Coppi and Bolasco, 1988), where data have more than two dimensions (e.g., data recorded at three or more times). By associating different variables with similar spatio-temporal patterns on a few relevant axes, this analysis provides an indirect measure of redundancy, or the extent to which a system's elements (i.e., indicators) have substitutes to ensure functioning in the event of a transition or a shock (Escofier and Page 1994).

MFA is a generalization of PCA, which analyzes sets of variables collected on the same set of observations (Kroonenberg 2008). The general objectives of MFA are (i) to compare and analyze the relationship between the different data sets over time, (ii) to combine them into a common structure called "compromise" which is then analyzed via PCA to reveal the common structure between the observations, and (iii) to project each of the original data sets into the compromise to analyze communalities and discrepancies (Coppi and Bolasco 1988). The weights used to compute the compromise are chosen to make it as representative of all the data sets as possible. The choice of factors for subsequent analysis is based on the absolute eigenvalue >1. This criterion allows considering relevant factors that extract a satisfactory proportion of variance from the input data matrix.

Based on a joint analysis of changes in all the elements composing the urban system, the MFA allows evaluating if the position of each unit (indicator) or case (municipality) is stable or variable over time by projecting them into the same multivariate factor plane. This allows assessment of the rapidity of change in both units and cases along the study period. A multivariate measure of rapidity of change (R') for both MFA units and cases were calculated as the Euclidean, n-dimensional distance between loadings (or scores) observed at times t_1 and t_0 (e.g., 1970 versus 1960) separately for each indicator or municipality according to the following equation:

$$R' = \sqrt{\left(\left(x_{1,1} - x_{1,0}\right)^2 + \left(x_{2,1} - x_{2,0}\right)^2 + \left(x_{\ldots,1} - x_{\ldots,0}\right)^2 + \left(x_{n,1} - x_{n,0}\right)^2\right)}$$

where $x_{a,b}$ is the loading on factor a at time b and n is the number of factors with eigenvalues >1. Fast and slow variables and rapidity of change in each AMA municipality were thus investigated for two time horizons: (i) medium-term (considering each decade studied, 1960–1970, 1970–1980, 1980–1990, 1990–2000, and 2000–2010) and (ii) long-term (considering the whole study period). Socioeconomic indicators were classified as fast or slow based on the median value of the rapidity of change computed by time period; fast indicators are those with an above-median rapidity of change. A median rapidity of change was also calculated for each theme (population, land-use/planning, urban form, urban functions, described in section Data and variables) with the aim to rank the contribution of different themes to the overall system's evolution. Rapidity of change estimated for each AMA municipality was mapped by time period and analyzed for spatial structure at different distances (5, 10, 15, 20, 30, 40 km) using a global Moran's index of spatial auto-correlation using z-scores and testing at $P < 0.05$ for significant auto-correlation at the regional scale.

Relating rapidity of change of AMA municipalities to the local-scale socioeconomic context

Rapidity of change of each AMA municipality estimated by decade and over the whole study period was correlated pair-wise to (i) the 18 socioeconomic indicators and (ii) the 9 supplementary variables using Spearman non-parametric rank coefficients testing for significant correlations at $P < 0.05$ after Bonferroni's correction for multiple comparisons). The variables tested in this analysis are taken as candidate factors influencing the evolutionary path of the urban system in both the medium-term (2000–2010) and the long-term (1960–2010). Pair-wise correlations between the estimated rapidity of change at the municipal scale in the AMA and 30 independent, contextual indicators were also run using nonparametric Spearman rank coefficients testing for significance at $P < 0.05$ after Bonferroni correction for multiple comparisons. The analysis tests if the territorial context influences the rapidity of change of individual units forming the urban system. The final step includes a PCA developed on the same data matrix considering 32 variables (the 30 contextual indicators and the medium- and long-term rapidity of change) at each AMA municipality with the objective of investigating the latent, multidimensional relationship between the socioeconomic context and the potential for change in local-scale units forming Athens' urban system. Variable loadings $>|0.5|$ were considered in the subsequent analysis.

Results

Exploratory data analysis

Supporting Information Appendix 2 reports central tendency (median) and variability (coefficient of variation) metrics calculated for each socioeconomic indicator at the six years of study by computation on municipal data. Supplementary variables were also considered in this analysis. All variables showed (more or less important) changes over time determining (more or less intense) variations in the statistical distribution between 1960 and 2010. Taken together, the AMA experienced uneven expansion along the entire study period, with population density increasing from nearly 2,300 inhabitants/km^2 in 1961 to more than 4,400 inhabitants/km^2 in 2011, while showing decreasing variability. These results are in agreement with the two main phases in Athens' recent expansion identified by Salvati and Di Feliciantonio (2014), compact growth with population densification between 1960 and 1990 and a more scattered and discontinuous expansion afterward. Population growth rate on a yearly base declined from 2.8% to 0.7%, with a slightly increasing variability at the local level, possibly indicating the formation of growing poles outside the central city. A more detailed outlook at the post-war changes in the AMA socioeconomic context can be found in Salvati (2014) and Salvati and Carlucci (2015).

The Friedman rank statistic distinguished eight indicators with stable statistical distribution over time (from *r* to *g* in Fig. 2) from 10 indicators that varied significantly in the five decades (from *p* to *a*). Kendall coefficient of concordance along the five decades was relatively low for all variables apart from three indicators with a more evident spatial homogeneity: protected areas, density of hotels and sparse settlements (Kendall concordance statistic >0.3). Seven indicators showed a significant change over time in their statistical distribution, with a relatively low concordance (Kendall statistic <0.15). Results of Spearman rank correlation analysis carried out within the socioeconomic indicators' ensemble and between socioeconomic indicators and supplementary variables is shown in Supporting Information Appendix 3. Overall, the percentage of significant correlations within the ensemble of socioeconomic indicators describing the AMA urban system increased rapidly during 1960–1990, from nearly 30% in the early 1960s to almost 60% in the early 1990s, stabilizing afterwards to values around 50% (Fig. 3). The percentage of significant correlations between socioeconomic indicators and supplementary variables increased as well, from 30% observed in the early 1960s to the highest value in the early 1990s and 2010s, reaching 37% in both cases. These findings indicate that Athens' compact and dense expansion coincided with a transition to tighter

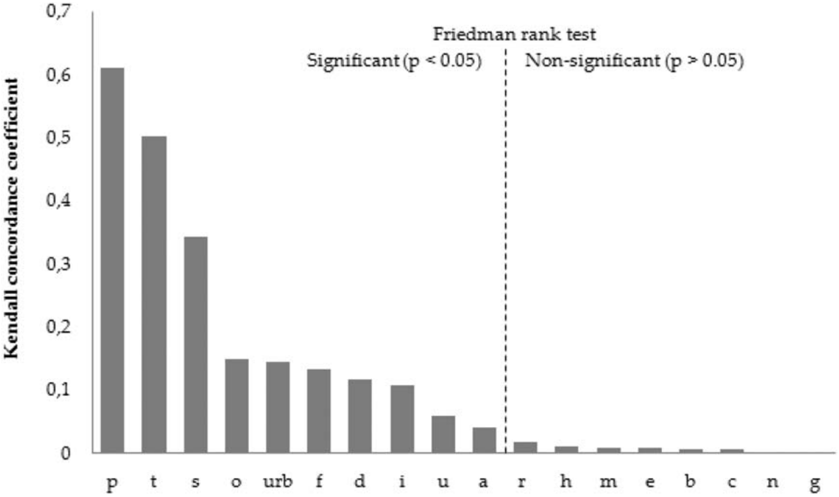

Figure 2. Kendall concordance coefficient and Friedman rank test by indicator.

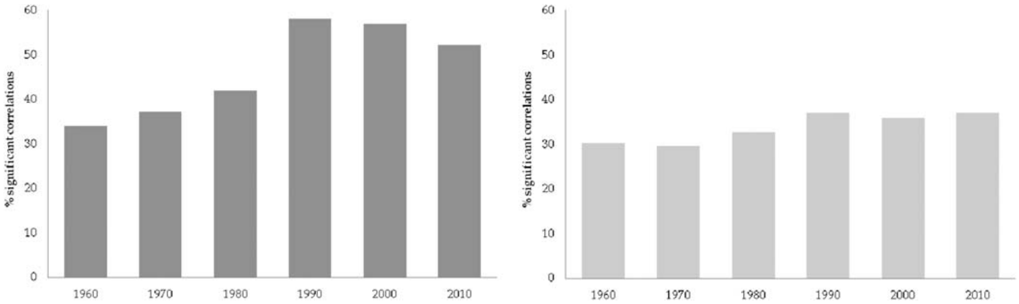

Figure 3. Percentage of significant Spearman pair-wise correlations ($P < 0.05$ after Bonferroni's correction for multiple comparisons) between socioeconomic indicators (left) and between socioeconomic indicators and supplementary variables (right) by year.

relationships between variables, underlying the increased connectedness and redundancy of the system.

Multiway factor analysis

The MFA applied to the 18 socioeconomic indicators for each point in time extracted three axes with eigenvalue >1, explaining 49.4% of the total variance. Table 1 shows variable loadings to the extracted axes. Except for one variable (hotel density), all indicators were significantly associated with at least one axis during the study period. The number of significant loadings (>|0.5|) increased markedly along axis 1 (7, 8, 9, 11, 12, and 10 variables for each year from 1960 to 2010) being relatively stable and lower along both axes 2 and 3. This result confirms the findings gathered from the non-parametric Spearman correlation analysis, which highlighted the increased connectedness and redundancy of system components between 1960 and 1990 and the substantial stability observed afterward.

Axis 1 extracted 33.1% of the total variance and identifies an urban-rural gradient in 1960 associated negatively with population density, vertical profile of buildings, multiple-use

Table 1. Multiway Factor Analysis Results: Significant Variable Loadings on the Three Main Factors by Year

	1960			1970			1980			1990			2000			2010		
Variable	Ax.1	Ax.2	Ax.3	Ax.1	Ax.2	Ax.3	Ax.1	Ax.2	Ax.3	Ax.1	Ax.2	Ax.3	Ax.1	Ax.2	Ax.3	Ax.1	Ax.2	Ax.3
d	−0.81			−0.86			−0.89			−0.90			−0.90			−0.90		
g										0.64			0.54					
s	0.59			0.62			0.62			0.65			0.64			0.55		
Urb							0.56			0.51			0.54			0.75		
a	0.64			0.68			0.68			0.83			0.84			0.79		
f			0.65			0.65			0.67			0.60			0.66			0.56
p			0.51			0.56			0.57			0.58			0.60			0.61
o													−0.50					
b				−0.65			−0.84			−0.85			−0.83			−0.84		
h	−0.79			−0.87			−0.87			−0.89			−0.87			−0.83		
c		−0.50					−0.45			−0.29								
n	0.82			0.91			0.92			0.93			0.90			0.71		
u	−0.67			−0.71			−0.67			−0.64			−**0**.64			−0.69		
r					0.74			0.76		0.51	0.67		0.63	0.62		0.66	0.59	
i		−0.61			−0.68			−0.71			−0.64			−0.57			−0.58	
t																		
e		−0.55			−0.54			−0.67		−0.56	−0.56		–	−0.56				
m	−0.66			−0.79			−0.87			−0.88			−0.88			−0.66		

Table 2. Rapidity of Change in each Socioeconomic Indicator Estimated by Multiway Factor Analysis by Decade ("fast" Variables are Marked in Bold; see section Identifying Fast and Slow Variables and Estimating Rapidity of Change Through a Multiway Factor Analysis)

Variable	1960–1970	1970–1980	1980–1990	1990–2000	2000–2010	1960–2010
d	0.06	0.09	0.09	0.04	0.04	0.27
g	**0.14**	**0.56**	**0.42**	**0.30**	**0.20**	**0.82**
s	0.04	0.03	0.06	0.04	0.10	0.10
Urb	**0.13**	**0.33**	**0.24**	0.09	**0.22**	**0.83**
a	**0.15**	0.06	**0.31**	**0.10**	**0.17**	**0.68**
f	0.08	0.04	0.10	**0.12**	**0.15**	0.22
p	0.08	0.08	0.11	0.06	0.12	**0.34**
o	0.06	**0.18**	**0.26**	**0.14**	0.11	0.33
b	**0.31**	**0.21**	0.09	**0.10**	0.02	0.54
h	**0.12**	0.08	0.07	0.03	0.08	0.08
c	**0.64**	**0.26**	**0.40**	0.04	**0.23**	**0.91**
n	0.10	0.12	0.06	0.05	**0.24**	0.22
u	0.07	0.10	0.04	0.02	0.08	0.14
r	**0.44**	**0.29**	**0.28**	**0.13**	0.04	**0.70**
i	**0.15**	0.08	0.08	**0.15**	**0.13**	0.19
t	0.09	**0.19**	**0.17**	**0.22**	0.07	0.17
e	0.06	**0.21**	**0.27**	**0.14**	**0.25**	**0.36**
m	**0.19**	**0.16**	**0.14**	0.04	**0.29**	**0.39**

buildings, and diversity in the use of urban land and positively with one-dwelling buildings, agricultural areas and sparse settlements. The changing structure of MFA axis 1 over time reflects the increasing polarization between urban and rural uses of land in the last fifty years, as pointed out by the loadings of population density (increasing from −0.81 in 1960 to −0.90 in 1990, 2000, and 2010) and the percentage of agricultural areas (0.64 in 1960, 0.83 in 1990 and 0.79 in 2010). Five variables were found increasingly associated to this gradient (population growth rate, inhabitants per building, proportion of residential buildings, service/commerce buildings and per-capita built-up area). Axis 2 extracted 9.2% of the total variance and represents a urban land-use gradient from residential (positive loadings) to industrial settlements (negative loadings). Industrial and commercial settlements were associated with self-contained urban expansion in 1960 only. Finally, axis 3 extracted 7.1% of the total variance and illustrates a natural/semi-natural land-use gradient with the percentage of forest land at the municipal scale increasing with the extent of protected areas.

Identifying fast and slow variables

Table 2 reports the Euclidean distance calculated for each variable and decade over the factorial plane as a measure of change in the composing elements of the urban system. The median distance was relatively stable over the study period, with the highest values observed in 1970–1980 and the lowest in 1990–2000, and a generalized decrease in distance variability was observed in the studied indicators. Based on the selected threshold, nine variables were classified as "fast" in all the studied decades. However, some indicators were classified as "fast" in one decade and "slow" in the subsequent decade, producing a quite articulated pattern. Population growth rate was the only indicator classified as "fast" throughout the whole period of observation. This finding is particularly interesting because it confirms the outstanding role of population-driven urban expansion compared with other important indicators of urban growth and change. Six indicators were classified as "fast" in four out of the five decades, and generally coincide with those showing the highest multivariate rate of change over the whole study period (self-contained urban expansion, per-capita built-up area, population growth rate, inhabitants per building, the percentages of residential buildings and agricultural land). These indicators are most likely related to the urban transformations observed in the AMA after World War II, influenced by compact urbanization with dense settlements (1960–1990) and later expansion that was less dense, with sprawl and land consumption (1990–2010). Vertical building profile, sparse rural settlements, diversity in the use of urban land, density of hotels and proportion of industrial buildings had the slowest index of change over the whole period, although some of them were classified as fast in single decades.

Trends over time in the rapidity of change of fast and slow variables corroborate these findings. For example, population growth rate showed the highest rapidity of change between 1970 and 1990, a period coinciding with the tumultuous growth of the city. A similar pattern was observed for the density of hotels and related activities. The proportion of residential buildings decreased continuously after the highest rapidity of change observed in the 1960s, coinciding with the "building boom" in the AMA. The highest rapidity of change for the percentage of agricultural areas was observed in the decade 1980–1990, when cropland around Athens was being massively developed. By contrast, rapidity of change increased in the last two decades for forest land, possibly influenced by the recent decrease of woodland due to severe fires since the early 1990s. A similar pattern was observed for the percentage of one-dwelling buildings. Rapidity of change of the proportion of self-contained settlement expansion declined rapidly from the early 1960s to the early 1990s, confirming the transition toward a more dispersed urban form.

By research theme, the median rapidity of change was highest for demography indicators (0.55), followed by urban function indicators (0.36) and land-use/planning indicators (0.34). Morphological indicators varied less rapidly. Demographic indicators changed especially in the first decades of the study interval (1960–1990), and land-use/planning indicators (Fig. 4a). The diverging pattern observed between these two groups corroborates the distinction in two urban phases respectively fuelled by population-driven compact growth and by low-density, discontinuous expansion that caused major transformations in fringe landscapes. Urban function indicators maintained a comparable rapidity of change over time, while morphology indicators showed moderate and negligible changes in the first and last decades, respectively.

Exploring rapidity of change in AMA municipalities (1960–2010)

The median rapidity of change in the AMA municipalities was computed by decade (Fig. 4b), illustrating the temporal evolution of Athens' urban system. The highest rapidity of change was observed in 1960–1970, 1980–1990, and 2000–2010; these three decades coincided with distinct phases of Athens' growth: demographic boom and compact expansion in 1960–1970; urban consolidation in greater Athens and suburbanization of neighboring (rural) districts in 1980–1990; and urban sprawl and infrastructure development in 2000–2010, driven by the 2004 Olympic Games.

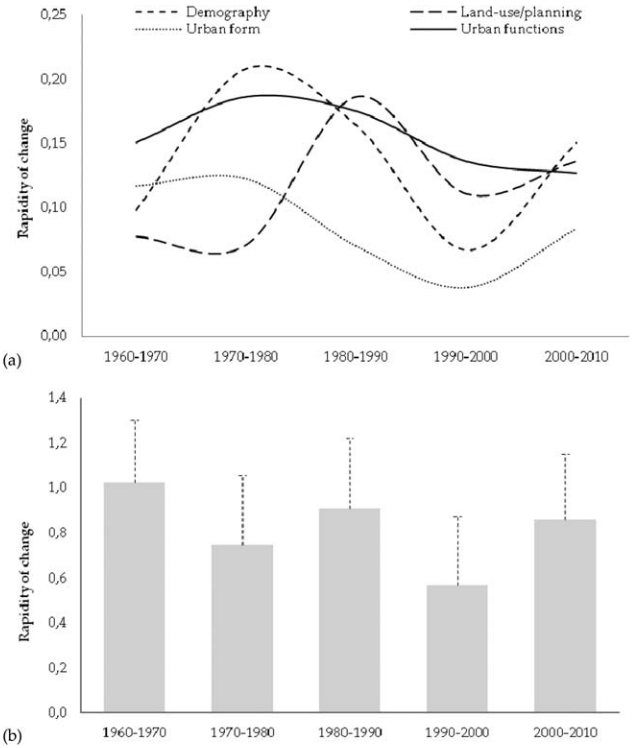

Figure 4. (a) Median rapidity of change by indicators' theme and time interval; (b) the overall rapidity of change of Athens' urban system by decade (the median value of each elementary spatial domain forming the system; bars indicate standard deviation).

Figure 5 illustrates the rapidity of change estimated by decade and along the whole study period for each AMA municipality. Urban municipalities around Athens and northern Attica municipalities changed most rapidly during 1960–1970. In the following decade a few municipalities in central Athens and northern and eastern Attica districts showed the highest rapidity of change. The municipalities with largest changes during 1980–1990 were located in central Athens and western suburbs, and more sparsely in northern and eastern Attica districts. In the following decade, municipalities with the highest rapidity of change were concentrated in northern districts and, more sparsely, on Athens' fringe. Finally, the highest rapidity of change in 2000–2010 was observed in peri-urban municipalities of western, northern and eastern Attica. Over the whole period, central Athens municipalities showed the highest rapidity of change. Taken together, our results underline the role of urbanization and suburbanization processes in greater Athens and the remaining rural districts of Attica, respectively. Finally, a Moran's global index of spatial auto-correlation was applied to the rapidity of change at the municipal scale in the AMA, producing nonsignificant results ($P > 0.05$) for all study periods. In summary, rapidity of change had a random spatial structure over time.

Relating rapidity of change to the local socioeconomic context

Rapidity of change for each municipality and decade was correlated with the socioeconomic indicators used to describe Athens' urban system, the supplementary topography and territorial

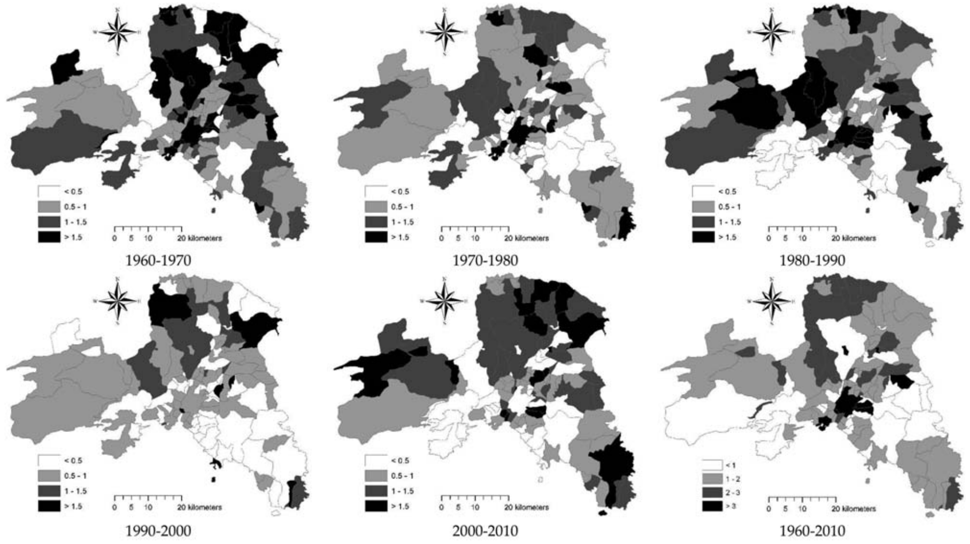

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Figure 5. Rapidity of change of each AMA municipality estimated according to the MFA results by decade and the whole time period.

variables and the 30 independent indicators assessing the local context in the more recent times. Spearman rank tests highlight a time-specific correlation pattern between rapidity of change and both the socioeconomic indicators and supplementary variables (Table 3). Rapidity of change decreased with population density in 1960–1970. The same pattern was observed in the subsequent decade, with negative correlations for population growth rate, inhabitants per building and the proportion of multiple-use buildings. This finding indicates that fringe municipalities experienced the highest rapidity of change in the decades immediately after World War II, indicating a classical radio-centric expansion process. In 1980–1990, rapidity of change was associated negatively with the population growth rate observed at the beginning of the study and positively with the share of forest land compared to the total municipal surface area and with the regime of land protection. A negative correlation was also found with the climate quality index. Results indicate that the highest rapidity of change in the AMA was concentrated, in that period, in municipalities surrounding the urban area of Athens that were strictly rural in the 1960s and have received progressive investment from urbanization processes in more recent decades. Although less intense, a similar spatial pattern was observed in 1990–2000. In the last decade studied, rapidity of change correlated positively with the distance from Piraeus and the share of forest land and negatively with population density, growth rate of population in the 1960s and the enforcement of a municipal master plan. These results evidence that in 2000–2010 the highest values of rapidity of change moved, on average, to areas more distant from Athens, following suburbanization processes (Couch et al. 2007). The average distance from Athens of the municipalities with above-median rapidity of change, calculated by decade, indicates a moderate increase over time (1960–1970: 5.2 km, 1970–1980: 5.1 km, 1980–1990: 7.8 km, 1990–2000: 10.3 km, 2000–2010: 13.6 km), confirming previous findings. Rapidity of change estimated for the whole period (1960–2010) was correlated negatively with population growth rate and positively with the distance from Markopoulo

Table 3. Spearman's Correlation Between Rapidity of Change of Each Spatial Unit ($n = 115$) and Socioeconomic Indicators (or Supplementary Variables) by Year (Significant Correlations at $P < 0.05$ After Bonferroni's Correction for Multiple Comparisons Were Shown)

Variable	1960–1970	1970–1980	1980–1990	1990–2000	2000–2010	1960–2010
Socioeconomic indicators						
d61	−0.28	−0.30				
d01					−0.26	
g61		−0.26	−0.35		−0.27	−0.20
g11						−0.21
f60			0.25	0.25		
f70					0.31	
f80				0.26		
f90					0.25	
p60						0.25
p80			0.27			
b60		−0.29				
m60		−0.25				
o00					−0.30	
Supplementary variables						
dPir					0.34	
dMak						0.21
Cqi			−0.27			

Messoghias. Taken together, these results confirm a suburbanization model where fringe peri-urban municipalities change more rapidly than urban municipalities.

Correlations between rapidity of change and the independent indicators evaluating the territorial context in recent times corroborate previously reported findings. The share of both compact and semi-dense settlements compared to the total municipal surface area and infrastructure density (both higher in the central cities), respectively, were negatively correlated to rapidity of change in 2000–2010 (compact settlements: $r_s = -0.25$, $P < 0.05$; semi-dense settlements $r_s = -0.30$, $P < 0.01$) and 1960–2010 (infrastructures: $r_s = -0.26$, $P < 0.05$; all comparisons with $n = 115$). The same pattern was observed for Shannon diversity in the use of urban land, increasing in central areas ($r_s = -0.27$, $P < 0.05$). In the last decade studied, municipalities with an economic structure dominated by industry or services showed a contrasting pattern in rapidity of change, which increased with the density of industrial activities ($r_s = 0.26$, $P < 0.05$) and decreased with the density of services ($r_s = -0.34$, $P < 0.01$). Rapidity of change also increased with the diversification of the economic structure at the local scale (in terms of both Shannon H' diversity and Pielou J evenness: both correlations $r_s = 0.34$, $P < 0.01$). Finally, rapidity of change decreased with the proportion of highly qualified workers (higher in central cities) in 2000–2010 ($r_s = -0.25$, $P < 0.05$) and with birth rate in both 2000–2010 ($r_s = -0.31$, $P < 0.01$) and 1960–2010 ($r_s = -0.32$, $P < 0.01$).

The PCA extracted four components with eigenvalue >2, accounting for 50% of the total variance (Table 4). The analysis provides evidence that long-term rapidity of change (1960–

Table 4. Principal Component Analysis Applied to a Set of Contextual Indicators Including Short-Term (2000–2010) and Long-Term (1960–2010) Rapidity of Change in Athens Metropolitan Area Municipalities (Indicators with Loading > |0.5| to the Principal Components with Eigenvalue >2 were Reported)

Variable	PC1	PC2	PC3	PC4
Rapidity of change (1960–2010)				0.52
Per-capita disposable income (2001)	0.87			
Per-capita disposable income (2011)	0.75			
Participation rate to job market	0.51			
High-skilled workers (Esec1)	0.87			
High-skilled workers (Esec2)	0.86			
Compact settlements (%)		−0.66		
Medium-density settlements (%)	0.59			
Low density settlements (%)		0.50		
Scattered settlements and isolated buildings (%)		0.51		
Industrial areas (%)				0.50
Fast transit roads and associated land			−0.53	
Other roads and associated land		−0.75		
Railways and associated land				0.50
Urban parks and gardens (%)	0.54			
Agricultural areas (%)	−0.58	0.69		
Industrial activities (%)	−0.68			
Service activities (%)	0.81			
Diversification of economic activities (Shannon H’)	−0.83			
Diversity in urban land use (Shannon H’)	0.57			
Self-contained travel-to-work jobs (%)	−0.67			
Migration rate (%)	0.50			
Birth rate (%)		−0.50		
Elderly index (% of population > 65 years old)			0.61	
Residents with European citizenship excluding Greeks (%)	0.67			
Variance explained (%)	23.4	14.0	7.0	5.9

2010) increases only with the share of industrial and infrastructural built-up areas in the total municipal surface area, component 4 (5.9% of the total variance). Components 1–3 illustrate three urban gradients that are not correlated to variations in rapidity of change. Component 1 (23.4% of the total variance) is a typical urban-rural gradient distinguishing central city municipalities (high per-capita disposable income, concentration of high-skilled workers, and European citizens, high workforce participation rate, service activities, diversity in the use of urban land and high migration rate) from outskirt areas (high share of cropland in the total municipal surface area, a highly diversified economic structure dominated by industrial activities and higher rate of self-contained travel-to-work jobs). Component 2 (14% of the total variance) identifies an urban gradient distinguishing discontinuous, dispersed and low-density settlements (intermixed with agricultural areas) from compact and dense settlements associated with a higher birth rate. Finally, component 3 (7.0% of the total variance) illustrates a population aging gradient correlated negatively with the density of road infrastructures.

Discussion

Traditional approaches based on "linear thinking" and econometric procedures based on consolidated economic assumptions have sometimes provided a partial interpretation of the recent transformations involving metropolitan regions around the world. The complexity of the relationship between form and functions in urban regions requires careful analysis (Portugali 2011); multidisciplinary approaches that consider both the spatial connections on a regional scale and the finer grain that characterizes the urban landscape are especially needed (Beniston, Lal, Mercer 2015). Relations between the central city and the surrounding areas experiencing rapid changes, the formation of an "urban continuum" that is gradually replacing the urban-rural gradient, the shift towards a polycentric and spatially balanced structure, being in turn less compact and more dispersed, represent different—but strongly interrelated—aspects of recent urban dynamics (Neuman and Hull 2009; Kourtit, Nijkamp, Reid 2014; Parr 2014).

Approaches that consider metropolitan areas as complex systems consisting of a multitude of interacting units, have taken a particular interest in the regional sciences (Cabral et al. 2013). The basic units can be represented by individual economic agents or aggregations of actors. These conditions reflect fragmented, and possibly self-organized, urban systems characterized by economic polarization, social disparities, isolation, fractality and entropy (Batty and Longley 1994; Portugali 2000; Page et al. 2001). The main CAS characteristics simulate this situation correctly and appear suitable to analyze the evolution of cities, metropolitan regions and entire urban systems. The novelty of this study lies in the use of simplified approaches, indicators of immediate accessibility, and exploratory statistical techniques for the analysis of the growth of a Mediterranean urban region along the last fifty years. The proposed indicators have allowed a multivariate description of Athens' metropolitan area at regular time intervals according to four analytical dimensions.

The data used in the present study are based on a long-established collection of statistical information from national censuses and other official statistical sources. The time period covered by this extensive data collection is rather long (1960–2010) and the spatial scale of analysis is enough detailed (municipalities). Such a collection allowed the construction of indicators fully comparable over time and space, covering several research domains of interest for understanding changes in the urban geography of Athens. Analysis of this dataset provides an informative overview of urban patterns and processes in a city sometimes considered as the archetype of the "Mediterranean city" (Salvati and Di Feliciantonio 2014). Missing data—especially for the 1960s and 1970s—prevented us to collect a larger number of informative variables at the geographical level required for this kind of analysis or recorded over time using comparable techniques and definitions. Nevertheless, we believe that the collected indicators may provide a comprehensive representation of long-term, local-scale territorial, and socioeconomic changes in the area. This is confirmed by the fact that the most relevant geographic gradients characterizing the metropolitan area of Athens were basically described by a relatively small number of variables included in our dataset. However, additional socioeconomic indicators were considered in a separate analysis correlating the results of the MFA with an enriched set of indicators available at the same spatial scale for the most recent decade. This analysis answers problems of data availability assuring the comprehensiveness of a diachronic approach based on a wide set of indicators (Salvati and Carlucci 2014). Results of the analysis indicate that some of these indicators are correlated with the basic gradients identified by the MFA.

The procedure shown in this study is sufficiently flexible and can adapt to different socioeconomic contexts, considering a set of information enriched with new variables and/or dimensions of analysis, thus allowing a comprehensive interpretation of the relevant aspects of urban transition. The approach proposed here focuses on several aspects of the evolution of a complex system, such as fast and slow variables that determine its evolution, the rapidity of change of the whole system and of its elementary units, and low-level properties such as connectedness and redundancy of a system's elements (Walker et al. 2004). Fast and slow variables were identified according to a multivariate exploratory data framework. Evidence from the analysis of fast and slow variables should be interpreted in connection with the results of descriptive statistics, nonparametric correlation analysis and MFA. In addition, MFA provided evidence documenting the latent interactions between "fast" and "slow" variables. The identification of fast or slow variables using the MFA is intended as a first step to reconnect traditional urban geography paradigms including factorial ecology and the spatial cycle theory with more recent approaches to the study of urban systems based on the concepts of sustainability and resilience. Moreover, the possible drivers of "fast" and "slow" variables characterizing Athens' urban system were studied by a supplementary analysis which correlates "fast" and "slow" local socioeconomic contexts with independent drivers of urban change (i.e. selected socioeconomic indicators collected at the same spatial scale in the most recent decades).

Objective evaluation of the basic parameters that characterize the evolution of a complex urban system, for example in terms of critical functions and low-level properties, is a topic of considerable interest for regional science, but at the same time it has been relatively little considered from the operational point of view (Bruneau et al. 2003; Walker et al. 2012). In our case, fast and slow variables, as well as the rapidity of change typical of the system studied over five decades of urban development, were quantified by MFA using comparable indicators over time. The proposed analysis was also able to identify the principal urban phases from the compact extension of the 1960s and the first wave of suburbanization observed in the 1980s, up to the infrastructure development that characterized the Olympic decade (Chorianopoulos et al. 2010). Therefore, our results correctly reflect the main stages of Athens' growth, as demonstrated by previous research, confirming the good correspondence between our proposed model and urban reality.

The relative stability of the two main axes extracted by the MFA is not surprising when referring to the "Mediterranean city" literature. For example, a recent study (Salvati 2014) demonstrated how changes in the socioeconomic context at the local scale were relatively moderate during the last four decades in the northern Mediterranean region. By discussing three different cases in southern Europe (Barcelona, Rome, Athens), the paper indicates that small changes in the economic functions of these cities followed a restructuring towards dispersed urban form in Barcelona and chaotic settlements in Rome, with Athens persisting in a sort of "latent stability" characterized by mono-centric structure and traditional functions (commerce, constructions, public service) dominating the economic base at the local scale (Salvati and Di Feliciantonio 2014).

The variables that best characterize the overall evolution of Athens' metropolitan system are manifold, but the most important is the growth rate of resident population, preceding indicators of settlement patterns and land-use regimes (Salvati and Carlucci 2014, but see also Grekousis et al. 2013). Nevertheless, these three factors play a variable role in the decades studied.

Functional indicators are those with the highest rapidity of change during the whole period investigated, while demographic indicators changed more rapidly in the first decades and the reverse pattern was observed for land-use/planning indicators. Morphological/settlement indicators were generally classified as "slow" variables determining only moderate changes in the system. As the statistical analysis refers to a concept of "multidimensional" changes in the urban system instead of considering the rate of variation of each indicator, the analysis of "fast" and "slow" variables is particularly interesting because it takes into account connectedness and redundancy and provides a comprehensive assessment of the system's transitions (Scott et al. 2013). Our results confirm an urban evolution based on the coexistence of different factors determining economic growth and socio-demographic transformations, reflected in a gradual consolidation of residential settlements and a moderate spatial reorganization of industrial activities and, more recently, services. This expansion mode is common to other Mediterranean cities (Salvati 2014).

The rapidity of change in the whole system highlights a heterogeneous time trend, stressing the sharper transitions identified during the decades 1960–1970, 1980–1990, and 2000–2010. These decades coincided with specific phases of urban expansion driven by migration inflow, second-home suburbanization and infrastructure development driven by the 2004 Olympic games, respectively (Chorianopoulos et al. 2010; Grekousis et al. 2013; Polyzos, Minetos, Niavis 2013). At the same time, rapidity of change in the elementary spatial units studied showed a random pattern with important variations over time. Taken together, peri-urban municipalities with a highly diversified economic structure dominated by industry showed the highest rapidity of change (Chorianopoulos et al. 2014). Apart from a few exceptions, central city municipalities with compact and dense settlements experienced much slower change. Between 1960 and 2010, municipalities with the highest rapidity of change were localized at progressively higher distances from the inner city of Athens, concurring with narrative studies of the recent AMA expansion that confirm a moderate trend towards suburbanization. Interestingly, rapidity of change was not correlated with context indicators such as disposable income, workforce participation or elderly index, suggesting that urban expansion in a poorly planned and self-organized system such as Athens is mainly driven by land availability, economic diversification and population relocation in the outer ring, following a typical suburbanization pattern (Salvati and Carlucci 2014).

In other words, these findings underline the persistence of a mono-centric spatial organization in the AMA (Salvati and Di Feliciantonio 2014), only moderately altered by recent transformations driven by a restricted set of "fast" variables (Gkartios 2013). Although the original model based on gravitation around Athens has been transformed into a more scattered structure, no direct evidence for the formation of subcenters and attraction poles distinct from the central city can be inferred from our results. By maintaining a marked urban-rural gradient, urban expansion in Athens was never polycentric, consolidating instead a continuous urban area organized in three poles (Athens, Piraeus and the north-eastern suburbs). As our variables indicate, persistent spatial organization is a distinctive trait of southern European cities.

Conclusions

Our methodology provides a comprehensive overview of the transformations of a complex urban system, quantifying low-level properties that are rarely assessed in the mainstream literature on urban studies. A "complex system" vision provides a thorough knowledge of the relationship between urban form and functions. Results can contribute to design policies that address complexity and promote resilience and sustainability in metropolitan areas, such as modulating path-dependence that is based on past development. Moreover, understanding the main factors driving medium- and long-term urban transitions contributes to strategies also designed to competitive rebalancing of the functional gap between cities and the surrounding areas. A sustainable planning of fringe land is needed in the light of urban sustainability, as these areas are the most rapidly changing, simultaneously generating economic opportunities, demographic challenges and socio-environmental concerns. By linking complexity in urban form and economic functions, the permanent assessment of metropolitan transformations is challenging for both research and policy. Mediterranean cities, characterized by unbalanced socioeconomic models, governance failures and planning ineffectiveness, provide outstanding examples for the analysis of complex adaptive urban systems.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Appendix 1. List of the indicators considered in the present study by research domain.

Appendix 2. Descriptive statistics of socioeconomic indicators and supplementary variables by year in the Athens metropolitan area.

Appendix 3. Spearman analysis between supplementary (topography and territorial) variables and the socioeconomic indicators in the municipalities of Athens metropolitan area by year (only significant correlations at $P < 0.05$ after Bonferroni corrections for multiple comparisons are shown).