Social Indicators Research

Shaping Dimensions of Urban Complexity: The Role of Economic Structure and Socio-demographic Local Contexts

--Manuscript Draft--

Manuscript Number:	SOCI-D-19-00184R2
Full Title:	Shaping Dimensions of Urban Complexity: The Role of Economic Structure and Socio-demographic Local Contexts
Article Type:	Original Research
Keywords:	Social mix, Economic structure, Spatial inequalities, Evenness, Mediterranean city.
Corresponding Author:	Luca Salvati Italian Council for Agricultural Research and Economics Rome, ITALY
Corresponding Author's Institution:	Italian Council for Agricultural Research and Economics
Order of Authors:	Luca Salvati
	Margherita Carlucci
Funding Information:	
Abstract:	Diversification in urban functions – a key component of urban complexity – was analysed using Pielou's evenness indexes for 12 socioeconomic dimensions (economic structure, working classes, education, demographic structure by age, composition of non-native population by citizenship, distribution of personal incomes, land-use, land imperviousness, building use, vertical profile of buildings, building age, construction materials) at the local scale in the Athens' metropolitan region, Greece. Urban and rural districts were found respectively the most and less diversified contexts, outlining a diversification gradient negatively associated with the distance from Athens. A canonical correlation analysis characterized local contexts with high and low diversification in socioeconomic functions. A spatially-explicit regression model finally demonstrates that local-scale complexity increases with urban concentration, population growth and average per-capita income. A multivariate analysis of individual dimensions of urban complexity is a promising tool to assess socioeconomic transformations in contemporary cities.

Shaping Dimensions of Urban Complexity: The Role of Economic Structure and Socio-demographic Local Contexts

Luca Salvati[1,2], Margherita Carlucci[3]

[1] *Council for Agricultural Research and Economics (CREA), Viale Santa Margherita 80, I-52100 Arezzo, Italy*

[2] *Global Change Research Institute of the Czech Academy of Sciences, Lipová 9, CZ-37005 České Budějovice, Czech Republic*

[3] *Sapienza University of Rome, Department of Social and Economic Sciences, Piazzale A. Moro 5, I-00185 Rome, Italy*

Running Title: Unraveling latent patterns and determinants of urban complexity.

Acknowledgements: This work was supported by the Ministry of Education, Youth and Sports of CR within the National Sustainability Program I (NPU I), grant number LO1415.

Correspondence to:

Luca Salvati, Ph.D.

CREA

Viale Santa Margherita 80

I-52100 Arezzo, Italy

Fax: +39 6 61.57.10

E-mail: luca.salvati@uniroma1.it

Shaping Dimensions of Urban Complexity: The Role of Economic Structure and Socio-demographic Local Contexts

Abstract

Diversification in urban functions – a key component of urban complexity – was analysed using Pielou's evenness indexes for 12 socioeconomic dimensions (economic structure, working classes, education, demographic structure by age, composition of non-native population by citizenship, distribution of personal incomes, land-use, land imperviousness, building use, vertical profile of buildings, building age, construction materials) at a local spatial scale in the Athens' metropolitan region, Greece. Urban and rural districts were found respectively the most and less diversified contexts, outlining a diversification gradient negatively associated with the distance from Athens. A canonical correlation analysis characterized local contexts with high and low diversification in socioeconomic functions. A spatially-explicit regression model finally demonstrates that local-scale complexity increases with urban concentration, population growth and average per-capita income. A multivariate analysis of individual dimensions of urban complexity is a promising tool to assess socioeconomic transformations in contemporary cities.

Key words: Socioeconomic functions, Territorial disparities, Entropy, Indicators, Southern Europe.

1. Introduction

Cities could be seen as a paradigmatic example of complex systems. Everyday cities exchange people, material and energy flows, information, among themselves and with the natural environment. Processes driving urban development, grounded on the mutual interplay among socioeconomic factors and settlement structure at the city scale (Frenken et al., 2007; Haase et al., 2010; De Rosa and Salvati, 2016), linked by multiple 'feedforward and feedback loops', give rise 'to an urban system which in time becomes more and more complex' (Portugali, 2006). Each city assumes a specific internal hierarchy, defined by the spatial distribution of key functions, including population size and economic dimension of each composing district (Malheiros, 2002; Kabisch and Haase, 2011; Cabral et al., 2013; Carlucci et al., 2017, Cottineau et al., 2017). Cities are

the core of economic and social development and their role as growth engine is as much relevant as much they are the nest of a wide range of human activities (Duranton and Puga, 2001; Ellerman, 2005; Stanley, 2012; Thisse, 2018). Urban regions play the major role in generating processes of innovation and entrepreneurship (Ejermo, 2005; O'Donoghue and Townshend, 2005; Markusen and Schrock, 2006; Florida et al., 2017). Empirical evidence demonstrates how businesses prefer to locate in a diversified context that gives more opportunities for economic expansion and social interactions, a competitive environment open to globalization and a fertile ground for innovation (Desrochers, 2001; Andersson et al., 2005; Desrochers and Hospers, 2007; Smets and Salman, 2008).
Assuming that land-use variety and social mix are factors positively affecting urban vitality and local competitiveness (Jacobs, 1969; Fincher and Jacobs, 1998; O'Donoghue, 1999; Hirt, 2012; Sun and Zhao, 2018), cities act bringing together the diversity of economic assets and actors required for innovative and entrepreneurial activity (Hill, 1998; Duranton and Puga, 2000; Rosenthal and Strange, 2001; Frenken et al., 2007). Diversification is thus considered a typical feature of socioeconomic functions in urban systems (e.g. Viladecans-Marsal, 2004; Ottaviano and Peri, 2006; Grant and Perrott, 2009; Kroll and Kabisch, 2012), reflecting heterogeneous economic structures, a varied job-related mix and diversified socio-spatial structures (Davies and Donoghue, 1993; O'Donoghue and Townshend, 2005; Burger and Meijers, 2012; Youn et al., 2016).
While experiencing increased specialization of sub-central locations, urban regions are often consolidating new growth poles (Munafò et al., 2013; Van Oort et al., 2015; Hirt, 2016). Consequently, metropolitan regions change and reshape their socioeconomic structures in response to both endogenous and exogenous stimuli (Desrochers and Hospers, 2007; Venerandi et al., 2017; Zambon et al., 2018), resulting in a land-use mix and a related variety which can be seen as critical constituents of urban complexity (Jacobs, 1969). Since spatial proximity among different land uses increases the potential for social interactions and economic benefits (Thomas et al., 2012), identifying and characterizing the latent interplay among socio-spatial and economic structures, territorial patterns, cultural and political processes of urban transformation is thus essential to determine the most relevant factors shaping metropolitan complexity (Salvati et al., 2016).
Based on this interpretative framework, morphological and functional diversification is hypothesized to be the highest in core cities with high-rank economic functions and a stratified social structure, reflecting diversification in planning practices at the same time (Hirt, 2012; Psycharis et al., 2014; Zambon et al., 2017). Diversity in land-use, physical attributes of buildings, spaces (mainly public spaces and amenities) and street patterns, economic activities, define the

character of urban quality (Montgomery, 1998). Assuming that spatial distribution, demographic size and economic power of central and sub-central locations - and the related socioeconomic linkages - are characteristic attributes of urban regions (Iceland, 2004; Hospers, 2006; Dahly and Adair, 2007; Hoyler et al., 2008; Comer and Greene, 2015), the same theory applies to larger spatial scales, with diversification being a typical concept applicable to regions constituted of one or multiple growth poles (Kleinhans, 2004; Maloutas, 2007; Inostroza, 2014; Jiao et al., 2018).

Earlier studies have demonstrated that a comprehensive analysis of diversified metropolitan structures contributes to outline (i) the essential challenges in recent urbanization processes and (ii) the spatial linkages underlying urban complexity. In this regard, Jacobs externalities were effectively measured by related variety within economic sectors using methodologies based on entropy measures (Schmidt, 1977; Tochterman, 2012; Wood and Dovey, 2015). It was also demonstrated that Jacobs externalities enhance employment growth, while unrelated variety dampens unemployment growth (Frenken et al., 2007; Hou and Wu, 2009; Cabral et al., 2013), possibly boosting class segregation and social inequalities (Yang and Jargowski, 2006; Stanley, 2012; Van Oort et al., 2015). Class segregation, social diversification, deviance and crime in cities were also extensively investigated using diversity and entropy indexes, often based on the information theory paradigm (see, for instance, Massey and Denton, 1998; Maloutas, 1993; Malheiros, 2002; Iceland, 2004; Arapoglou and Sayas, 2009; Wo, 2019). At the same time, diversification in land-use, building age or the level of land imperviousness – regarded as attributes reflecting the inherent complexity in socioeconomic functions at the local scale –, have been increasingly considered as indicators of urban centrality (Wood, 2003; Meijers and Burger, 2010; Van Criekingen, 2010; Serra et al., 2014; Zambon et al., 2017). Salvati (2014) proposed an entropy-based function to evaluate heterogeneity in soil sealing levels for representative regions in Europe. Such function, based on the Pielou's evenness index, was demonstrated to identify core cities and peri-urban districts likely better than other empirical approaches (Zitti et al., 2015), allowing a detailed analysis of metropolitan growth and change (Salvati et al., 2016).

By considering the unique bond between form and functions in each city, the present study offers a reflection on urban diversity in line with Jacobs (1969) thinking, proposing an operational approach to assess metropolitan complexity, and performing a comprehensive analysis of the linkage between urban diversification and local context. In this regard, metropolitan complexity was seen as a multi-domain notion, integrating diversification in social, economic and territorial dimensions in a unique concept that may reflect the peculiar interplay between form and functions characterizing each city. Complexity theory can embrace a myriad of processes and elements that combine into organic wholes, evidencing how bottom-up processes combine with new forms of geometry and spatial relationships, and providing advanced knowledge of highly complex systems such as cities (Manson and O'Sullivan, 2006). Considering structural similarities between complexity theories and theories oriented toward social philosophy (Portugali, 2006), complexity theories have the potential to bridge the geographies of space and place, offering a more comprehensive overview of urban dynamics (Batty, 2007). In this line of thinking, complex systems have become a popular lens for analysing cities, and complexity theory has many (positive) implications for urban performance and resilience (Boeing, 2018). Being scattered throughout diverse bodies of literature, metrics at multiple scales contribute to formalize what "urban complexity" is and are demonstrated to have useful applications in analysing the linkage between adaptive complexity and diversification that results from urban dynamics (Salvati and Serra, 2016). Measuring urban complexity is a challenging issue. Following Boeing (2018), indicators of urban complexity could be grouped according to which dimension of complexity they are aimed to capture. Thus, measures assess (1) temporal, (2) visual, (3) spatial, (4) scaling and (5) connectivity dimensions. In these regards, analysis of urban diversification seems particularly relevant as a tool providing an informed base to policies that promote resilient metropolitan systems and sustainable paths of regional development (Di Feliciantonio and Salvati, 2015; Cuadrado-Ciuraneta et al., 2017; Duvernoy et al., 2018). With empirical evidence deriving from an integrated analysis of multi-domain indicators, this study introduces a composite index of spatial urban complexity that integrates 12 diversity indicators assessing different social, economic and territorial dimensions. To delineate divergent development paths based on (apparent and latent) linkages between morphology and functions, the proposed index is related to specific characteristics of local contexts (Ellerman, 2005; Ejermo, 2005; Frenken et al., 2007).

Hypothesizing that diversified forms and socioeconomic functions are more likely associated with advanced productive contexts, offering jobs, attracting population and sustaining entrepreneurial milieu (e.g. O'Loughlin, 1983; Cicerchia, 1996, 1999; Comer and Greene, 2015), the approach proposed in this study was tested on an emblematic case in southern Europe, the Athens' metropolitan region in Greece. Urban form, socioeconomic functions and the resulting spatial structure in Mediterranean cities - and especially Athens - resulted from different factors that derive from a complex interplay of demographic, territorial and cultural processes (Grekousis et al., 2013; Marchetti et al., 2014; Rontos et al., 2016; Gounaridis et al., 2018). At the same time, traditionally compact forms reflect a diversity of smaller-scale assets attracting multifaceted socioeconomic contexts at local scale (Maloutas and Karadimitriou, 2011; Di Feliciantonio and Salvati, 2015; De Rosa and Salvati, 2016), making Athens a good example to illustrate new patterns and processes of urban change grounded on intrinsically-complex and spatially-varying ties between morphology and functions.

2. Methodology

2.1. Study area

The study area (Athens' Metropolitan Region, AMR) coincided for the large part with the boundaries of the administrative region of Attica, Greece. Attica is characterized by a steep topography. Mountain chains surrounding the Greater Athens area (Parnitha, Pendeli, Imitos, Egaleo) have contained urban expansion in rural areas, reducing accessibility of some rural municipalities and making land availability to building one of the most relevant constraint to urban growth (Morelli et al., 2014; Colantoni et al., 2016; Pili et al., 2017). Urban settlements in the Greater Athens' area (430 km^2) are still expanding, although at a very low pace (Maloutas, 2007). Central districts have a particularly high share of built-up areas in total municipal area that declines linearly with the distance from Athens (Zitti et al., 2015). This suggests that the AMR is still organized as a mono-centric region, despite intense suburbanization of the 1980s and the 1990s (Grekousis et al., 2013; Rontos et al., 2016; Gounaridis et al., 2018). Population density ranged between 15,000 inhabitants/km^2 in central municipalities and 100 inhabitants/km^2 in rural districts (Salvati and Serra, 2016).

2.2. Dimensions of metropolitan complexity

Following an earlier study by Carlucci et al. (2019), 12 dimensions of metropolitan complexity (Table 1) assessing morphology (land-use, land imperviousness, building use, vertical profile of buildings, building age, construction materials) and socioeconomic functions (economic structure, working classes, education, demographic structure by age, composition of non-native population by citizenship, distribution of personal incomes) were considered in this work at the spatial scale of municipalities. Morphological variables include: 1) land-use composition (hereafter 'land'); 2) land imperviousness profile ('soil'); 3) building use ('use'); 4) vertical profile of buildings ('vert'); 5) building age ('buil'); 6) variety in construction materials ('mat'). Land-use composition (percent class area in total municipal area) was derived from a high-resolution land-use map (1: 10,000 scale) referring to 2012 and disseminated through the European Urban Atlas (UA) initiative on behalf of the Global Monitoring for Environment and Security (GMES) framework adopting a nomenclature system composed of 20 classes organized in three basic categories (built-up areas: code 1, cropland: code 2, and forests: code 3).

Land imperviousness profile for each municipality of the study area was assessed using a 100 m-grid map (2012) disseminated by Land Copernicus initiative in collaboration with the European Environment Agency (2011). A land imperviousness profile was determined by computing percent area in total municipal area of 22 classes with different sealing intensity (0%, 1-5%, 6-10%, ..., 91-95%, 96-99%, 100%). The other 4 variables assessing settlement characteristics were derived from the national census of buildings carried out by Greek Statistical Authority (ELSTAT) aggregating elementary data (2011) at municipal scale (Zitti et al., 2015). Building types were classified using 18 categories that distinguish residential from industrial, commercial and service use. <The percent share of each building class in total municipal building stock was calculated accordingly. Building age was determined considering 10 classes that assess construction time period and computing the percent share of buildings by age class in total building stock. Vertical profile of buildings was evaluated considering 6 classes according to the number of floors and calculating the percent share of buildings by height class in total building stock. Finally, buildings were classified according to the dominant construction material using 6 types and calculating the percent share of buildings by construction material in total building stock.

Socioeconomic variables investigate the following aspects: 1) economic structure (hereafter 'Econ'); 2) working class composition ('Work'); 3) educational level of active population ('Educ'); 4) demographic structure by age ('Pop'); 5) composition of non-native resident population by citizenship ('Fore'); 6) distribution of personal income ('Dist'). The economic structure was assessed at municipal scale calculating the percent share of enterprises by sector in total enterprises registered in the national business archive (2010). Economic activities were classified in 15 sectors compatible with the NACE-Rev2 nomenclature. Working class composition was evaluated according to 24 categories that distinguish different professional positions recorded in the national census of population and households (2011). Based on these data, the percent share of workers by job position in total workers was computed for each municipality (Di Feliciantonio and Salvati, 2015). Education of active population was studied with reference to a nomenclature system with 13 levels and, consequently, the percent share of active population by education level in total active population was calculated for each spatial domain. Population structure by age was investigated adopting 7 classes and computing the percent share of population by age class in total resident population. Composition of non-native population by citizenship was analysed aggregating resident population in 7 classes (the most frequent citizenships in Greece and a residual class) based on census data (2011) and computing the percent share of each class in total resident population. Finally, the distribution of personal incomes across resident population was analysed considering data from individual tax declarations (provided by the Hellenic Ministry of Finance and referring to 2014), and aggregating personal incomes into 10 progressive classes.

2.2.1. Indicators of urban diversification

According to the widespread use of entropy-based indexes to measure complexity issues (Batty et al, 2014), Pielou's evenness indexes (J) were calculated for the dimensions described above with the aim to assess urban diversification within each municipality. Based on a Shannon diversity function (see references in Zambon et al., 2017), Pielou's J index is an entropy index standardized to the level of diversification in a given spatial domain (Salvati and Serra, 2016). Ranging from 0 (complete homogeneity) to 1 (the highest heterogeneity according to the level of local-scale diversification), Pielou's J index was calculated as follows:

$$J = H'/H_{max}$$

where H' is the Shannon diversity index calculated as:

$$H' = -\sum_{i=1}^{n} p_i \ln p_i$$

and p_i is the proportion of observations falling in the i-th class in the total number of observations for each dimension. H_{max} is the logarithm of the number of classes with at least one observation.

2.2.2. Indicators of metropolitan complexity

Based on the assumption that metropolitan complexity is a multi-domain attribute integrating diversification in social, economic and territorial dimensions (Viladecans-Marsal, 2004; Wood and Dovey, 2015; Wo, 2019), two indexes were calculated for each municipality with the aim to provide local-scale measures of metropolitan complexity: (i) a median measure of the 12 Pielou J indexes of evenness for each dimension of urban diversification (hereafter 'Med') and (ii) a standardized coefficient of variation (per cent standard deviation / average) of the same 12 values (hereafter 'Cov'). These measures contribute to a generalized, spatially-explicit evaluation of metropolitan complexity. Values of 'Med' and 'Cov' ranged from 0 to 1; higher values of 'Med' indicate a local context with higher urban complexity. Higher values of 'Cov' indicate a particularly heterogeneous context, with highly diversified and less diversified functions coexisting at local scale. A median metric was regarded as a more flexible measure of central tendency in respect with more classical average measures, considering the possible deviations from normality of the statistical distribution of the 12 Pielou's J indexes at the municipal scale. However, the correlation between median and average values of the Pielou's J indexes for the whole study area was linear and highly significant ($r = 0.74$, $p < 0.001$, $n = 114$ municipalities), suggesting a remarkable stability of the 'metropolitan complexity' measure irrespective of the adopted metric of central tendency.

2.2.3. Contextual indicators

To identify the spatial relationship between diversification in urban functions and local contexts, 36 background indicators (Table 1) were calculated for each municipality in the Athens' Metropolitan Region (AMR). Their choice derived from extensive literature review (Maloutas, 1993, 2004, 2007; Chorianopoulos et al., 2010, 2014; Kaika, 2012; Grekousis et al., 2013; Souliotis, 2013; Di Feliciantonio and Salvati, 2015; Zitti et al., 2015; Rontos et al., 2016; Salvati and Serra, 2016; Gounaridis et al., 2018). All indicators are available from public sources.

2.3. Data analysis

A multi-step statistical analysis of urban diversification was run with the following objectives: (i) to characterize the spatial structure of each dimension of urban diversification, (ii) to assess the strength of the multiple relationship between dimensions of urban diversification and contextual variables, and (iii) to identify spatial factors of metropolitan complexity in the AMR. These objectives were addressed using an exploratory approach that integrates spatial statistics (local Moran's I spatial autocorrelation indexes) with descriptive analysis and mapping (objective 1), canonical correlation analysis (objective 2), global ordinary least square regressions and geographically weighted regressions (objective 3).

2.4.1. *Spatial autocorrelation analysis*

Local Moran's coefficients of spatial autocorrelation were calculated and tested for significance for each dimension of urban diversification using municipalities as the elementary analysis' domain (Thomas et al., 2012; Kazemzadew-Zow et al., 2017; Zambon et al., 2017). Since contiguity matrix is not the best choice when the boundaries between units are defined by administrative criteria (Patacchini, 2008) the conceptualization of spatial relationships between analysis' domains was based on inverse distance weighting. The Moran's scatterplot was used to identify 'hot spots' of positive and negative spatial autocorrelation, classifying municipalities in the HH (High-High), LL (Low-Low), HL (High-Low) or LH (Low-High) type of spatial clusters. HH and LL regimes indicate spatial clustering of similar units, while HL and LH regimes indicate local heterogeneity associated to a spatial divide reflecting a (more or less steep) gradient in the studied variable.

2.4.2. *Canonical correlation analysis*

To identify (apparent and latent) relationships between metropolitan complexity and the underlying socioeconomic context, a Canonical Correlation Analysis (CCA) was run on the municipal-scale dataset illustrated above and constituted of 12 indicators of urban diversification (section 2.2.1, hereafter 'left' dataset) and 36 contextual indicators (section 2.3, 'right' dataset). The general objective of a CCA is to investigate multiple correlations between two sets of variables ('left' *vs* 'right' datasets), combining them into a structure formed by few independent and representative axes (hereafter 'canonical roots', or simply 'roots'). The roots' structure was investigated by analysing root loadings assigned to each indicator and root scores attributed to each case (i.e. municipality). CCA results allow a preliminary identification of factors underlying metropolitan complexity in Athens.

2.4.3. *Regression analysis*

To ensure that predictor variables were statistically valid and significant (Wang et al., 2019), the relationship between urban complexity and contextual variables at local scale was preliminary investigated adopting a global model. . An Ordinary Least-Square (OLS) multiple regression was therefore estimated through a linear form where the dependent variable is a measure of complexity ('Med' or 'Cov') and **X** (X_1, X_2, …, X_n) is a set of predictors based on the results of the CCA (section 2.4.2). More specifically, the *n* roots extracted from the CCA were considered as uncorrelated predictors of urban complexity, providing a summary evaluation of the most relevant variables characterizing each local context. Giving specific scores to each municipality, canonical roots were also preferred to individual variables (i.e. the 36 contextual indicators) since they are non-redundant and represent intrinsically-independent, multivariate socioeconomic and territorial attributes influencing metropolitan complexity. Correlation between individual variables and canonical roots was determined using root loadings, as explained above (section 2.4.2). A forward step-wise procedure (F-to-enter: 5; F-to-remove: 2.5) was run with the aim to measure and rank the impact of each predictor on the dependent variable. Regressions were estimated separately for 'Med' and 'Cov' variables, evaluating model's goodness of fit with adjusted R^2. Statistical significance (a *t*-statistic testing for significant regression coefficients at $p < 0.05$) was considered an additional criterion for model evaluation. Since in this first analysis spatial characteristics of data were not explicitly modelled, Durbin-Watson statistic was computed with the aim to control for (spurious) serial autocorrelation due to model misspecification (Billé et al., 2017). Values of this statistic close to 2 indicate a negligible serial autocorrelation in the available data.

Local-scale variability in the relationship between metropolitan complexity and background socioeconomic contexts was analysed adopting a spatially-explicit model. One way to tackle spatial heterogeneity consists in stratifying data, according to a known fixed quality, such as the region in which a city is located, or to some socioeconomic or territorial variable, then fit separate regressions obtaining different parameters' values in each spatial regime thus obtained. To avoid imposing *a-priori* hypotheses on data structure, semi-parametric or non-parametric approaches are preferable, such as the Geographically Weighted Regression (GWR) approach (Fotheringham et al., 2002). Thus, a GWR was run to identify the most relevant predictors of metropolitan complexity and heterogeneity in urban functions (Rontos et al., 2016). The specification of a basic GWR model for each location s = 1, …, n, is:

$$Y(s) = X(s)B(s) + e(s)$$

where Y(s) is the dependent variable at location s ('Med' or 'Cov'), X(s) is the vector of predictors at location s (the score of canonical roots for each municipality), B(s) is the column vector of regression coefficients at location s, and e(s) is the random error at location s. As a result, GWR gives rise to a spatial distribution of estimated parameters including adjusted R^2, intercept, slope coefficients, and standard residuals (Colantoni et al., 2016). GWR in this study is part of a more articulated statistical strategy aimed at reducing multidimensionality and redundancy of variables assessing local contexts (with intrinsic collinearity that was managed using Canonical Correlation Analysis and a step-wise regression approach for selection of important predictors). GWR incorporates the results from step-wise selection of predictors and provides a refined overview of spatial relationships among the dependent variable and the individual predictors, including maps illustrating the local-scale impact of each predictor (Salvati and Serra, 2016).

3. Results

3.1. A descriptive analysis of urban diversification

The spatial distribution of median Pielou's J evenness index ('Med') calculated on 12 dimensions of urban diversification and the related coefficient of variation for each municipality of the study area ('Cov') were presented in Figure 1. High diversification in urban functions was observed in central districts of the Greater Athens' area (> 0.75), with the highest values (> 0.8) being recorded in fringe municipalities north-east and south-east of Athens. Peri-urban areas were characterized by a lower diversification in urban functions, with intermediate values of Pielou's J index found in sub-central municipalities of Western Attica (Elefsis, Aspropyrgos) and Eastern Attica (Lavrio, Rafina). Conversely, 'Cov' followed a substantially different spatial pattern, being particularly high in suburban districts, especially in Western and Northern Attica (> 0.4), and reaching medium-high values (> 0.3) in fringe and peri-urban municipalities of Eastern Attica.

Municipalities in central areas and in peri-urban districts north-east of Athens shared a richer variety of forms in dimensions such as land imperviousness, building age, vertical profile of buildings, as well as in specific demographic aspects, such as population structure by age and citizenship of non-native population (for more details, see SM.Figure 1). Assuming variety as a sign of urban quality, a gradient (high-low clusters) highlighting a mono-centric pattern of urban expansion was observed in north-eastern peripheral areas, considering purely economic functions (productive base, working classes, distribution of personal income, and educational levels). Municipalities situated along the eastern borders of the metropolitan region shared a reduced variety in land-use. Reflecting latent modifications in urban structures caused by the intense building activity related to the Olympic Games, building use gave rise to a high-high hotspot around the Maroussi sub-center. Conversely, variety in construction materials characterized non-central locations affected by informal urbanization, with Greater Athens' municipalities sharing low levels of variety (SM.Figure 2). The relationship between median Pielou J index ('Med') indicating urban complexity and the related coefficient of variation ('Cov') indicating heterogeneity in urban functions (Figure 2) was negative ($r = -0.54$, $p < 0.001$, $n = 114$) and allows discrimination of urban municipalities (belonging to the 'Greater Athens' area') from rural municipalities. A particularly low median value (0.51) associated to a relatively high value of the related coefficient of variation (0.49) was found for a municipality in Western Attica (Inoi), a rural community poorly connected with Athens and displaying low population density, aging, and agriculture as a dominant sector of economic activity.

Local Moran's coefficients of spatial autocorrelation for each municipality of the study area (SM.Figure 3) evidence similar spatial clusters for the following dimensions of urban diversification: land-use, building use, economic base, educational levels, composition of non-native population by citizenship and distribution of personal income. Municipalities in north-eastern Athens' fringe belong to a high-low cluster indicating a significant gradient dividing urban and rural districts. Municipalities classified as high-high clusters were concentrated in both central areas and peri-urban districts for 5 dimensions (population age structure, building age, vertical profile of buildings, soil sealing profile and land-use composition), indicating a spatial structure more oriented toward a metropolitan continuum.

3.2. Canonical analysis

A Canonical Correlation Analysis (CCA) was run on a dataset composed of 12 indicators of urban diversification ('left' set) and 36 contextual variables ('right' set) acting as candidate predictors of urban complexity. The CCA represents (Table 2) the entire variance of the 'left' variables' set and a relevant proportion of the 'right' variables' set (56%). Three canonical factors (roots) were extracted, linking indicators of urban diversification to variables depicting the related local context. Root 1 (explaining 33% and 30% respectively of the 'left' and 'right' sets) was associated positively with diversification in building materials and negatively with diversification in land-use and land imperviousness, vertical profile of buildings, income distribution and non-native population (Table 3). This root clearly illustrates the urban-rural gradient in Athens, with negative and positive scores associated respectively with urban and rural municipalities (Figure 3). A total of 12 (33%) contextual variables were associated to this gradient: hotel and restaurant density, per-capita built-up area, percentage of workers living and working in the same municipality in total workforce, distance from Athens, Piraeus, Maroussi and Markopoulo Messoghias, municipal size (positive loadings), density of registered businesses, concentration of research and development activities, job participation rate, population growth rate during 1951-1961 (negative loadings). Variables with positive and negative loadings increased respectively in rural and urban areas.

Root 2 (explaining 13% and 12% respectively of the 'left' and 'right' sets) was associated positively with diversification in educational levels and negatively with diversification in population age structure. Population growth rate in 2001-2011 and crude birth rate received positive loadings to Root 2 and, conversely, elderly index received a negative loading to the same axis. Root 2 illustrates a latent gradient separating demographically-dynamic peri-urban municipalities north-west and east of Athens from both strictly rural and peripheral municipalities – with ageing and more static population dynamics – and strictly urban municipalities classified in-between.

Root 3 (explaining 16% and 11% respectively of the 'left' and 'right' sets) was associated positively with diversification in building use and negatively with diversification in economic structure and building age. Four variables were negatively associated to this axis: per-capita declared income, concentration of financial enterprises, percentage of non-Greek, European-native residents in total population, and percentage of residential buildings in total buildings. Root 3 identifies an industrial-service gradient in Athens, separating industrial municipalities (Piraeus' district, Athens, and Thriasio district, all receiving positive scores) from municipalities in north-eastern Athens fringe with a productive structure dominated by service activities and more affluent local communities.

3.3. Regression models

To identify spatial factors of metropolitan complexity in Athens, a global Ordinary Least Square regression was run considering separately median and coefficient of variation in urban diversification as dependent variables and canonical roots (section 3.2) as independent predictors.

Model's performances are relatively high for both dependent variables (Table 4), with adjusted R^2 reaching 0.67 for median diversification (model 1) and 0.53 for coefficient of variation (model 2). Model 1 outlines the negative impact of Roots 1 and 3 on median diversification and a positive impact of Root 2. These findings indicate that urban complexity increases in service-oriented districts with a young and more dynamic demographic structure. Urban municipalities display high diversification ('Med') and low variability in the composing functions ('Cov'). Model 2 evidences the positive impact of Root 1 and the negative influence of both Root 2 and 3 on 'Cov' variable. This means that the highest variability in the individual components of metropolitan complexity was found in less accessible, rural districts, suggesting that non-urban municipalities have heterogeneous and less diversified socioeconomic functions.

Results of a refined model using a Geographically Weighted Regression approach were presented in Table 5. Goodness-of-fit of both models improved substantially (global R^2 = 0.71 and 0.64 respectively for 'Med' and 'Cov'). The highest goodness-of-fit of a local model for median diversification was observed in Western Attica (local $R^2 > 0.8$). The highest negative impacts of Root 1 (urban-rural) and 3 (income) on median diversification were found in municipalities south-east of Athens (Messoghia and Lavrio districts). Root 2 (demographic dynamics) showed the highest positive impact on urban complexity in fringe municipalities south-east of Athens (Figure 4). These results outline a pattern of socioeconomic diversification quite differentiated over space, with factors identified in previous models (urban concentration, demographic dynamics, income) impacting negatively (and more strongly) on peripheral, rural municipalities in south-eastern Attica. By contrast, the highest positive impact of these factors was observed in fringe municipalities east and south-east of Athens, being actually the most dynamic districts in the study area.

The highest goodness-of-fit of a local model for 'Cov' was observed in both Western and South-eastern Attica (local $R^2 > 0.7$). The highest positive impact of Root 1 (urban concentration) was observed in Western and Northern Attica districts (more socially-disadvantaged and economically-marginal than Eastern Attica districts). Root 2 (demographic dynamics) impacted negatively on peripheral districts in both Western, North-eastern and South-eastern Attica (Figure 5). Finally Root 3 (income) impacted 'Cov' negatively in municipalities south-east of Athens (Lavrio district).

4. Discussion

Mechanisms of urban growth are intimately related with the maintenance of metropolitan stability and metabolism (O'Donoghue, 1999; Florida et al., 2017; Zambon et al., 2017; Jiao et al., 2018), where hierarchical differentiation is linked to the development of more resilient cities (Duranton and Puga, 2000; Inostroza, 2014; Salvati et al., 2016). Although form-function relationships have been investigated in earlier studies considering specific indicators at both local and regional scale (Hirt, 2016), defining the way in which changes in form and functions can influence local-scale urban structures and diversification contributes to understand and characterize a complex system of feedbacks at the base of metropolitan complexity (Rosenthal and Strange, 2001; Stanley, 2018; Thisse, 2018). A multivariate, spatially-explicit notion of 'metropolitan complexity' is therefore a promising tool to assess urban functions evolving along specific geographical gradients (Viladecans-Marsal, 2004; Talen, 2005, 2006; Hadjimichalis, 2014).

With empirical evidence deriving from a spatially-explicit analysis of evenness indexes that quantify local-scale heterogeneity and diversification in the level of key urban functions, our work identifies socioeconomic and territorial factors promoting urban diversification in Athens. More specifically, this study identified (i) urban and rural municipalities respectively as the most and less diversified – with peri-urban areas ranking in-between, (ii) a spatial distribution of hotspots of positive (or negative) spatial autocorrelation along the urban gradient, and (iii) few sub-centres fostered by increased building activity due to external factors, such as the 2004 Olympic Games (Gospodini, 2009; Chorianopoulos et al., 2010; Gounaridis et al., 2018). The key role of density gradients shaping spatial patterns of urban diversification was confirmed by a canonical correlation analysis (section 3.2), investigating linkages between settlement form, socioeconomic functions and the resulting regional structure. A latent interplay of demographic, territorial and cultural processes was also outlined, in line with the results of earlier studies (Maloutas, 2004; Grekousis et al., 2013; Rontos et al., 2016). Our findings finally provide substantial evidence of how socioeconomic diversification, emerging with processes of metropolitan expansion, has defined new patterns of urban change grounded on intrinsically-complex and spatially-varying bonds between form and functions (section 3.3).

The traditionally-compact Athens' form reflected a diversity of smaller-scale assets, attracting multifaceted socioeconomic contexts at local scale (Iceland, 2004; Wood and Dovey, 2015; Venerandi et al., 2017; Carlucci et al., 2019). Despite recent transformations in architectonical outlines and infrastructural networks (Zitti et al., 2015; Colantoni et al., 2016; Pili et al., 2017), the

Athens' structure resulted in persistent disparities of economic nature (Maloutas, 1993; Arapoglou and Sayas, 2009; Souliotis, 2013), class segregation (Rontos et al., 2016; Zambon et al., 2017; Panori et al., 2018), and territorial heterogeneity (Maloutas and Karadimitriou, 2001; Grekousis et al., 2013; Hadjimichalis, 2014; Di Feliciantonio and Salvati, 2015;).

The inverse relationship between metropolitan complexity and variability in the composing dimensions of urban diversification, as well as the multifaceted linkages between urban complexity and background indicators, clearly show how the highest complexity was observed in local districts that attract (i) economies of scale and agglomeration, (ii) a dynamic demographic context, and (iii) advanced services. In Athens, these contexts are mainly localized in semi-central areas, which have grown considerably during the last two decades thanks to intense processes of suburbanization (Arapoglou and Sayas, 2009; Di Feliciantonio and Salvati, 2015; Rontos et al., 2016). On the contrary, the most marginal and peripheral rural areas have low complexity and diversification (Salvati and Serra, 2016; Pili et al., 2017; Zambon et al., 2017), being characterized by static demographic contexts exposed to progressive aging and an economic base dominated by primary activities or traditional tertiary businesses (trade, construction and small-scale tourism). Hyper-compact urban areas, with a high population density and an economic structure oriented towards manufacturing, are distinctively characterized by medium-high complexity and high heterogeneity in the individual factors of diversification (Salvati et al., 2016). Peri-urban municipalities occupy an intermediate position, with medium levels of complexity and greater heterogeneity in the individual components of socioeconomic diversification (Maloutas, 2007; Chorianopoulos et al., 2014; Duvernoy et al., 2018).

Based on these results, the interpretative model proposed in this study identifies a gradient of metropolitan complexity, attributing the highest degree of complexity to semi-central areas with economic expansion led by advanced tertiary sectors (Souliotis, 2013). These areas also display a particularly dynamic and socially-mixed demographic context (Kandylis et al., 2012; Maloutas, 2014; Gounaridis et al., 2018). Conversely, compact urban areas, originally hosting industrial activities, have a lower degree of complexity, and are associated with a less dynamic local context (Maloutas, 2004; Grekousis et al., 2013; Panori et al., 2017). Urban recovery and regeneration measures in such areas should take account of this peculiar background context, introducing (and promoting the expansion of) new economic functions supporting local entrepreneurship (Tochterman, 2012).

Our model also identifies peri-urban areas as highly dynamic contexts, transforming from a less complex rural structure to more articulated configurations that may attract diversified functions typical of urban areas (Grant, 2002; Malheiros and Vala, 2004; Vaughan and Arbaci, 2011). Finally, economically-marginal rural areas are characterized by the lowest level of metropolitan complexity, associated with a particularly static local context, where a progressive aging of the population emerges, together with social inequalities and latent forms of poverty (Arbaci, 2008; Arapoglou and Sayas, 2009; Kaika, 2012; Serra et al., 2014). Based on the empirical evidence of this study, development policies for these districts should be oriented towards spatially-balanced and socially cohesive growth, capable of promoting diversity in the prevailing economic functions as an engine of socioeconomic diversification (Malheiros, 2002; Arbaci, 2007; Balaoura, 2017).

5. Conclusions

Under the assumption that diversified forms and socioeconomic functions are more likely associated with advanced productive contexts, offering jobs, attracting population and sustaining entrepreneurial milieux, our study presented a unifying definition of (and an operational approach to assess) metropolitan complexity, performing a comprehensive analysis of the linkage between urban diversification and local contexts. Considering together evenness indexes related to different dimensions of diversification in key socioeconomic functions and related territorial attributes, definitely provides a comprehensive evaluation of metropolitan structures, quantifying local-scale heterogeneity in the level of key urban functions.

6. Reference

Andersson, R., Quigley, J.M., Wilhelmsson, M. (2005). Agglomeration and the spatial distribution of creativity. Papers in Regional Science 84(3), 445-464.

Arapoglou, V.P., Sayas, J. (2009). New facets of urban segregation in southern Europe. European Urban and Regional Studies 16(4), 345-362.

Arbaci, S. (2007). Ethnic segregation, housing systems and welfare regimes in Europe. European Journal of Housing Policy 7(4), 401-433.

Arbaci, S. (2008). (Re) viewing ethnic residential segregation in Southern European cities: Housing and urban regimes as mechanisms of marginalisation. Housing Studies 23(4), 589-613.

Balaoura, O. (2017). The Geography of Manufacturing in Athens During the Debt Crisis. Territorio 81, 86-91.

Batty, M. (2007). Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals. The MIT press, Boston.

Batty, M., Morphet, R., Masucci, P., Stanilov K. (2014). Entropy, complexity, and spatial information. Journal of Geographic Systems 16, 363-385.

Billé, A.G., Benedetti, R., Postiglione, P. (2017). A two-step approach to account for unobserved spatial heterogeneity. Spatial Economic Analysis 12(4), 452-471.

Boeing, G. (2018). Measuring the complexity of urban form and design. Urban Design International 23(4), 281-292.

Burger, M., Meijers, E. (2012). Form follows function? Linking morphological and functional polycentricity. Urban Studies 49(5), 1127-1149.

Cabral, P., Augusto, G., Tewolde, M., Araya, Y. (2013). Entropy in Urban Systems. Entropy 15(12), 5223-5236.

Carlucci, M., Grigoriadis, E., Rontos, K., Salvati, L. (2017). Revisiting a Hegemonic Concept: Long-term 'Mediterranean Urbanization' in Between City Re-polarization and Metropolitan Decline. Applied Spatial Analysis and Policy 10(3), 347-362.

Carlucci, M., Zambon, I., Salvati, L. (2019). Diversification in Urban Functions as a Measure of Metropolitan Complexity. Environment and Planning B, 2399808319828374.

Chorianopoulos, I., Pagonis, T., Koukoulas, S., Drymoniti, S. (2010). Planning, competitiveness and sprawl in the Mediterranean city: The case of Athens. Cities 27(4), 249-259.

Chorianopoulos, I., Tsilimigkas, G., Koukoulas, S., Balatsos, T. (2014). The shift to competitiveness and a new phase of sprawl in the Mediterranean city: Enterprises guiding growth in Messoghia–Athens. Cities 39, 133-143.

Cicerchia, A. (1996). Indicators for the measurement of the quality of urban life. Social Indicators Research 39(3), 321–358.

Cicerchia, A. (1999). Measures of Optimal Centrality: Indicators of City Effect and Urban Overloading. Social Indicators Research 46(3), 273–299.

Colantoni, A., Grigoriadis, E., Sateriano, A., Venanzoni, G., Salvati, L. (2016). Cities as selective land predators? A lesson on urban growth, deregulated planning and sprawl containment. Science of the Total Environment 545-546, 329 339.

Cottineau, C., Hatna, E., Arcaute, E., Batty, M. (2017). Diverse cities or the systematic paradox of urban scaling laws. Computers, environment and urban systems, 63, 80–94.

Comer, D., Greene, J. (2015). The development and application of a land-use diversity index for Oklahoma City, OK. Applied Geography 60, 46-57.

Cuadrado-Ciuraneta, S., Durà-Guimerà, A., Salvati, L. (2017). Not only tourism: unravelling suburbanization, second-home expansion and "rural" sprawl in Catalonia, Spain 2017. Urban Geography 38(1), 66-89.

Dahly, D.L., Adair, L.S. (2007). Quantifying the urban environment: A scale measure of urbanicity outperforms the urban–rural dichotomy. Social Science & Medicine 64(7), 1407–1419.

Davies, W.K., Donoghue, D.P. (1993). Economic diversification and group stability in an urban system: the case of Canada, 1951-86. Urban Studies, 30(7), 1165-1186.

De Rosa, S., Salvati, L. (2016). Beyond a 'side street story'? Naples from spontaneous centrality to entropic polycentricism, towards a 'crisis city'. Cities 51, 74-83.

Desrochers, P. (2001). Local Diversity, Human Creativity and Technological Innovation. Growth and Change 32, 369-394.

Desrochers, P., Hospers, G.J. (2007). Cities and the Economic Development of Nations: An Essay on Jane Jacobs' Contribution to Economic Theory. Canadian Journal of Regional Science 30(1), 119-134.

Di Feliciantonio, C., Salvati, L. (2015). 'Southern' Alternatives of Urban Diffusion: Investigating Settlement Characteristics and Socio-Economic Patterns in Three Mediterranean Regions. Tijdschrift voor Economische en Sociale Geografie 106(4), 453 470

Duranton, G., Puga, D. (2000). Diversity and Specialisation in Cities: Why, Where and When Does it Matter? Urban Studies 37, 533-555.

Duranton, G., Puga, D. (2001). Nursery cities: Urban diversity, process innovation, and the life cycle of products. American Economic Review 91(5), 1454-1477.

Duvernoy, I., Zambon, I., Sateriano, A., Salvati, L. (2018). Pictures from the other side of the fringe: Urban growth and peri-urban agriculture in a post-industrial city (Toulouse, France). Journal of Rural Studies 57, 25 35.

Ejermo, O. (2005). Technological diversity and Jacobs' externality hypothesis revisited. Growth and Change 36(2), 167-195.

Ellerman, D. (2005). How Do We Grow? Jane Jacobs on Diversification and Specialization. Challenge 48(3), 50-83.

European Environment Agency (2011). Mapping guide for a European urban atlas. EEA: Copenhagen (Version 1.1).
Fincher, R., Jacobs, J.M. (1998). Cities of difference. Guilford Press, New York.
Florida, R., Adler, P., Mellander, C. (2017). The city as innovation machine. Regional Studies 51(1), 86-96.
Fotheringham, A.S., Brunsdon, C., Charlton, M. (2002). Geographically weighted regression. The analysis of spatially varying relationships. Chichester: Wiley.
Frenken, K., Van Oort, F., Verburg, T. (2007). Related variety, unrelated variety and regional economic growth. Regional Studies 41, 685–697.
Gospodini, A. (2009). Post-industrial trajectories of Mediterranean European cities: the case of post-Olympics Athens. Urban Studies 46(5-6), 1157-1186.
Gounaridis, D., Chorianopoulos, I., Koukoulas, S. (2018). Exploring prospective urban growth trends under different economic outlooks and land-use planning scenarios: The case of Athens. Applied Geography 90, 134-144.
Grant, J. (2002). Mixed Use in Theory and Practice: Canadian Experience with Implementing a Planning Principle. Journal of the American Planning Association 68(1), 71–84.;
Grant, J., Perrott, K. (2009). Producing diversity in a new urbanism community: Policy and practice. Town Planning Review 80(3): 267-289.
Grekousis, G., Manetos, P., Photis, Y.N. (2013). Modeling urban evolution using neural networks, fuzzy logic and GIS: The case of the Athens metropolitan area. Cities 30, 193–203.
Haase, A., Kabisch, S., Steinführer, A., Bouzarovski, S., Hall, R., Ogden, P. (2010). Spaces of reurbanisation: exploring the demographic dimension of inner-city residential change in a European setting. Population, Space and Place 16(5), 443–463.
Hadjimichalis, C. (2014). Crisis and land dispossession in Greece as part of the global 'land fever'. City 18(4-5), 502-508.
Hill, D.R. (1988). Jane Jacobs' ideas on big, diverse cities: A review and commentary. Journal of the American Planning Association 54(3), 302–314.
Hirt, S. (2012). Mixed use by default: how the Europeans (don't) zone. Journal of Planning Literature 27(4), 375-393.
Hirt, S.A. (2016). Rooting out mixed use: Revisiting the original rationales. Land Use Policy 50, 134-147.
Hospers, G.-J. (2006). Jane Jacobs: Her life and work. European Planning Studies 14(6), 723–732.

Hou, F., Wu, Z. (2009). Racial diversity, minority concentration, and trust in Canadian urban neighborhoods. Social Science Research 38(3), 693-716.
Iceland, J. (2004). Beyond Black and White Metropolitan residential segregation in multi-ethnic America. Social Science Research 33, 248–271.
Inostroza, L. (2014). Measuring urban ecosystem functions through 'Technomass' - A novel indicator to assess urban metabolism. Ecological Indicators 42, 10–19.
Jacobs, J. (1969). The economy of cities. New York: Vintage.
Jiao, L., Liu, J., Xu, G., Dong, T., Gu, Y., Zhang, B., Liu, Y., Liu, X. (2018). Proximity Expansion Index: an improved approach to characterize evolution process of urban expansion. Computer, Environment and Urban Systems 70, 102-112.
Kabisch, N., Haase, D. (2011). Diversifying European agglomerations: evidence of urban population trends for the 21st century. Population, Space and Place 17(3), 236–253.
Kaika, M. (2012). The economic crisis seen from the everyday: Europe's nouveau poor and the global affective implications of a 'local'debt crisis. City 16(4), 422-430.
Kandylis, G., Maloutas, T., Sayas, J. (2012). Immigration, inequality and diversity: socio-ethnic hierarchy and spatial organization in Athens, Greece. European Urban and Regional Studies 19(3), 267-286.
Kazemzadeh-Zow, A., Zanganeh Shahraki, S., Salvati, L., Samani, N.N. (2017). A spatial zoning approach to calibrate and validate urban growth models. International Journal of Geographical Information Science 31(4), 763 782.
Kleinhans, R. (2004). Social implications of housing diversification in urban renewal: A review of recent literature. Journal of Housing and the Built Environment 19(4), 367-390.
Kroll, F., Kabisch, N. (2012). The Relation of Diverging Urban Growth Processes and Demographic Change along an Urban–Rural Gradient. Population, Space and Place 18(3), 260–276.
Malheiros, J. (2002). Ethni-cities: residential patterns in the northern European and Mediterranean metropolises - implications for policy design. International Journal of Population Geography 8(2), 107-134.
Malheiros, J.M., Vala, F. (2004). Immigration and city change: the Lisbon metropolis at the turn of the twentieth century. Journal of Ethnic and Migration Studies 30(6), 1065-1086.
Maloutas, T. (1993). Social segregation in Athens. Antipode 25(3), 223-239.

Maloutas, T., Karadimitriou, N. (2001). Vertical social differentiation in Athens: alternative or complement to community segregation? International Journal of Urban and Regional Research 25(4), 699-716.

Maloutas, T. (2004). Segregation and residential mobility: spatially entrapped social mobility and its impact on segregation in Athens. European Urban and Regional Studies 11(3), 195-211.

Maloutas, T. (2007). Socioeconomic Classification Models and Contextual Difference: The European Socioeconomic Classes (ESeC) from a South European Angle. South European Society and Politics 12(4), 443-460.

Maloutas, T. (2014). Social and spatial impact of the crisis in athens-from clientelist regulation to sovereign debt crisis. Région et Développement 39, 149-166.

Manson, S., O'Sullivan, D. (2006). Complexity theory in the study of space and place. Environment and Planning A, 38(4), 677-692.

Marchetti, M., Vizzarri, M., Lasserre, B., Sallustio, L., Tavone, A. (2014). Natural capital and bioeconomy: challenges and opportunities for forestry. Annals of Silvicultural Research 38(2), 62-73.

Markusen, A., Schrock, G. (2006). The distinctive city: divergent patterns in growth, hierarchy and specialisation. Urban Studies 43(8), 1301-1323.

Massey, D.S., Denton, N.A. (1988). The Dimensions of Residential Segregation. Social Forces 67(2), 281-315.

Meijers, E., Burger, M. (2010). Spatial structure and productivity in US metropolitan areas, Environment and Planning A 42, 1383–1402.

Montgomery, J. (1998). Making a city: Urbanity, vitality and urban design. Journal of Urban Design 3(1), 93-116.

Morelli, V.G., Rontos, K., Salvati, L. (2014). Between suburbanisation and re-urbanisation: revisiting the urban life cycle in a Mediterranean compact city. Urban Research and Practice 7(1), 74-88.

Munafò, M., Salvati, L., Zitti, M. (2013). Estimating soil sealing rate at national level - Italy as a case study. Ecological Indicators 26, 137-140.

O'Donoghue, D. (1999). The relationship between diversification and growth: some evidence from the British urban system 1978 to 1991. International Journal of Urban and Regional Research 23(3), 549-566.

O'Donoghue, D., Townshend, I.J. (2005). Diversification, specialization, convergence and divergence of sectoral employment structures in the British urban system, 1991–2001. Regional Studies 39, 585–601.

O'Loughlin, J. (1983). Spatial inequalities in Western cities: A comparison of North American and German urban areas. Social Indicators Research 13(2), 185–212.

Ottaviano, G.I., Peri, G. (2006). The economic value of cultural diversity: evidence from US cities. Journal of Economic Geography 6(1), 9-44.

Panori, A., Ballas, D., Psycharis, Y. (2017). SimAthens: A spatial microsimulation approach to the estimation and analysis of small area income distributions and poverty rates in the city of Athens, Greece. Computers, Environment and Urban Systems 63, 15-25.

Panori, A., Psycharis, Y., Ballas, D. (2018). Spatial segregation and migration in the city of Athens: Investigating the evolution of urban socio-spatial immigrant structures. Population, Space and Place, e2209.

Patacchini, E. (2008). Local analysis of economic disparities in Italy: a spatial statistics approach. Statistical Methods & Applications 17(1), 85-112.

Pili, S., Grigoriadis, E., Carlucci, M., Clemente, M., Salvati, L. (2017). Towards sustainable growth? A multi-criteria assessment of (changing) urban forms. Ecological Indicators 76, 71-80.

Portugali J. (2006). Complexity Theory as a Link between Space and Place. Environment and Planning A: Economy and Space 38(4), 647-664.

Psycharis, Y., Kallioras, D., Pantazis, P. (2014). Economic crisis and regional resilience: detecting the 'geographical footprint' of economic crisis in Greece. Regional Science Policy & Practice 6(2), 121-141.

Rontos, K., Grigoriadis, E., Sateriano, A., Syrmali, M., Vavouras, I., Salvati, L. (2016). Lost in protest, found in segregation: Divided cities in the light of the 2015 "Οχι" referendum in Greece. City, Culture and Society 7(3), 139-148.

Rosenthal, S.S., Strange, W.C. (2001). The determinants of agglomeration. Journal of Urban Economics 50(2), 191-229.

Salvati, L. (2014). Agro-forest landscape and the 'fringe' city: A multivariate assessment of land-use changes in a sprawling region and implications for planning. Science of the Total Environment 490, 715-723.

Salvati, L., Sateriano, A., Saradakou, E., Grigoriadis, E. (2016). 'Land-use mixité': Evaluating urban hierarchy and the urban-to-rural gradient with an evenness-based approach. Ecological Indicators 70, 35-42.

Salvati, L., Serra, P. (2016). Estimating Rapidity of Change in Complex Urban Systems: A Multidimensional, Local-Scale Approach. Geographical Analysis 48(2), 132-156.

Schmidt, C.G. (1977). Influence of land-use diversity upon neighborhood success: An analysis of Jacobs' theory. The Annals of Regional Science 11(1), 53–65.

Serra, P., Vera, A., Tulla, F., Salvati, L. (2014). Beyond urban–rural dichotomy: exploring socioeconomic and land-use processes of change in Spain (1991–2011). Applied Geography 55, 71-81.

Smets, P., Salman, T. (2008). Countering urban segregation: Theoretical and policy innovations from around the globe. Urban Studies 45(7), 1307-1332.

Souliotis, N. (2013). Cultural economy, sovereign debt crisis and the importance of local contexts: The case of Athens. Cities 33, 61-68.

Stanley, B. (2012). An historical perspective on the viability of urban diversity: lessons from socio-spatial identity construction in nineteenth-century Algiers and Cape Town. Journal of Urbanism 5(1), 67-86.

Sun, Y., Zhao, S. (2018). Spatiotemporal dynamics of urban expansion in 13 cities across the Jing-Jin-Ji urban agglomeration from 1978 to 2015. Ecological Indicators 87, 302-313.

Talen, E. (2005). Land-use zoning and human diversity: Exploring the connection. Journal of Urban Planning and Development 131(4), 214-232.

Talen, E. (2006). Design that enables diver-sity: The complications of a planning ideal. Journal of Planning Literature 20(3), 233-249.

Thisse, J.-F. (2018). Human capital and agglomeration economies in urban development. The Developing Economies 56(2), 117-139.

Thomas, I., Frankhauser, P., Badariotti, D. (2012). Comparing the fractality of European urban neighbourhoods: do national contexts matter? Journal of Geographical Systems 14(2), 189-208.

Tochterman, B. (2012). Theorizing neoliberal urban development: A genealogy from Richard Florida to Jane Jacobs. Radical History Review (112), 65-87.

van Criekingen, M. (2010). Gentrifying the re-urbanisation debate, not vice versa: the uneven socio-spatial implications of changing transitions to adulthood in Brussels. Population, Space and Place 16(5), 381–394.

Van Oort, F., de Geus, S., Dogaru, T. (2015). Related variety and regional economic growth in a cross-section of European urban regions. European Planning Studies 23(6), 1110-1127.

Vaughan, L., Arbaci, S. (2011). The challenges of understanding urban segregation. Built Environment 37(2), 128-138.

Venerandi, A., Zanella, M., Romice, O., Dibble, J., Porta, S. (2017). Form and urban change – An urban morphometric study of five gentrified neighbourhoods in London. Environment and Planning B 44(6), 1056-1076.

Viladecans-Marsal, E. (2004). Agglomeration economies and industrial location: city-level evidence. Journal of Economic Geography 4(5), 565-582.

Wang, S., Liu, Y., Zhao, C., Pu, H. (2019). Residential energy consumption and its linkages with life expectancy in mainland China: A geographically weighted regression approach and energy-ladder-based perspective. Energy 177, 347-357.

Wo, J.C. (2019). Mixed land use and neighborhood crime. Social Science Research 78, 170-186.

Wood, M. (2003). A balancing act? Tenure diversification in Australia and the UK. Urban Policy and Research 21(1), 45-56.

Wood, S., Dovey, K. (2015). Creative Multiplicities: Urban Morphologies of Creative Clustering. Journal of Urban Design 20(1), 52-74.

Yang, R., Jargowsky, P.A. 2006. Suburban development and economic segregation in the 1990s Journal of Urban Affairs 28(3), 253-273.

Youn, H., Bettencourt, L.M., Lobo, J., Strumsky, D., Samaniego, H., West, G.B. (2016). Scaling and universality in urban economic diversification. Journal of the Royal Society Interface 13(114), 20150937.

Zambon, I., Benedetti, A., Ferrara, C., Salvati, L. (2018). Soil Matters? A Multivariate Analysis of Socioeconomic Constraints to Urban Expansion in Mediterranean Europe. Ecological Economics 146, 173-183.

Zambon, I., Serra, P., Grigoriadis, E., Carlucci, M., Salvati, L. (2017). Emerging urban centrality: An entropy-based indicator of polycentric development and economic growth. Land Use Policy 68, 365-371.

Zitti, M., Ferrara, C., Perini, L., Carlucci, M., Salvati, L. (2015). Long-term urban growth and land use efficiency in Southern Europe: Implications for sustainable land management. Sustainability 7(3), 3359 3385.

Table 1. List of variables considered in this study.

Acronym	Variable's name	Data source
Mixité variables	*Indicators of diversification (Pielou's evenness J index) in a specific field (see below)*	
Land	Land-use composition (Urban Atlas/Corine Land Cover classification)	Urban Atlas
Soil	Soil sealing intensity (EEA classification)	Eur. Env. Agency
Econ	Productive structure (economic business NACE-REV2 classification)	Business register
Work	Socioeconomic working classes	Population census
Educ	Education levels	"
Use	Building use	Building census
Vert	Vertical profile of buildings (floors)	"
Buil	Building age (construction year)	"
Mat	Building materials	"
Pop	Population age by class	Population census
Fore	Non-native population by citizenship	"
Dist	Income distribution (by basic income classes)	Greek Min. Finance
Contextual variables	*Socioeconomic background indicators*	
Ent	Density of registered businesses (per km^2, 2010, logarithm)	Business register
Hot	Share of hotels and restaurants in total businesses (2010, %)	"
Fin	Share of finance enterprises in total businesses (2010, %)	"
Hig	Share of high-tech enterprises (research & development) in total businesses (2010, %)	"
Tel	Share of telecommunication enterprises in total businesses (2010, %)	"
Ind_Ser	Industry to service businesses ratio (2010)	"
Pro	Protected land (0: absent; 1: at least one land patch protected under national regulation)	Territorial statistics
Sel	Self-contained settlements (constructed in already urbanized districts, % in total buildings)	Building census
g11	Population growth rate (2001-2011, % per year)	Population census
Pla	Town master plan (0: lacking approval or not available; 1: approved and active)	Org.Rith.Sch.Athinon
u10	Per-capita built-up area (2010, m^2)	Urban Atlas
Sqi	Soil quality index (score from 2: low quality to 1: high quality)	Eur.Env.Agency
Cqi	Climate quality index (score from 2: low quality to 1: high quality)	"
Inc	Per-capita declared income (2011, Euros, logarithms)	Greek Min. Finance
d_inc0108	Change over time in per-capita declared income (2001-2008, %)	"
d_inc0811	Change over time in per-capita declared income (2008-2011, %)	"
Part_rate	Participation rate to the job market (2011)	Population census
Self_cont_work	Share of population residing and working in the same municipality 5 years before the census date (2011, % in total population)	"
Res_Mob	Share of population residing in the same municipality 5 years before the census date (2011, % in total population)	"
Migr	Share of non-native resident inhabitants (2011, % in total population)	"
Birth	Crude birth rate (2010, per 100 resident inhabitants)	Population register
Aging	Share of population > 65 years old (2011, % in total population)	Population census
Native	Share of native Greek population (2011, % in total population)	"
Europe	Share of non-native residents born in a European country (2011, % in total population)	"
g61	Population growth rate (1951-1961, % per year)	"
u60	Per-capita built-up area (1960, m^2)	Urban Atlas
Res_bui	Share of residential buildings (2011, % in total building stock)	Building census
Com_dis	Compact settlements to dispersed settlements ratio (2012)	Urban Atlas
Agr_For	Farmland to forest land ratio (2012)	"
Ele	Average elevation (m)	Territorial statistics
Sea	Proximity to the sea coastline (0: inland municipality; 1: coastal municipality)	"
dAth	Distance from downtown Athens (km)	"
dPir	Distance from Piraeus (km)	"
dMar	Distance from the Olympic Stadium, Maroussi (km)	"
dMak	Distance from Markopoulo Messoghias (km)	"
Area	Municipal area (2011, km^2)	"

Table 2. Results of a canonical correlation analysis.

	Mixité variables	Contextual variables
No. variables	12	36
Variance (%)	100.0	55.7
Redundancy (%)	74.0	42.4
	Root's variance (%)	
Root 1	32.8	30.3
Root 2	12.5	11.9
Root 3	16.3	11.4

Table 3. Canonical root's loadings (bold indicates significant coefficients at $p < 0.01$).

Variable	Root 1	Root 2	Root 3
Mixité variables			
Land	**-0.76**	0.25	0.08
Soil	**-0.85**	0.27	0.11
Econ	0.05	-0.04	**-0.50**
Work	-0.20	-0.15	-0.30
Educ	-0.18	**0.42**	-0.13
Use	-0.17	0.11	**0.70**
Vert	**-0.89**	0.06	0.11
Buil	0.08	0.36	**-0.43**
Mat	**0.71**	-0.19	0.22
Pop	0.05	**-0.95**	-0.17
Fore	**-0.72**	0.10	-0.34
Dist	**-0.64**	0.14	-0.35
Contextual variables			
Ent	**-0.90**	0.16	0.27
Hot	**0.57**	-0.35	-0.13
Fin	-0.07	0.04	**-0.46**
Hig	**-0.62**	0.08	-0.40
Tel	-0.11	0.07	-0.24
Ind_Ser	0.40	0.23	0.18
Pro	0.10	-0.09	-0.14
Sel	-0.14	-0.14	-0.12
g11	0.18	**0.48**	-0.41
Pla	-0.39	0.34	0.21
u10	**0.81**	-0.22	-0.17
Sqi	-0.06	-0.28	-0.23
Cqi	-0.04	0.21	0.25
Inc	-0.40	0.11	**-0.66**
d_inc0108	-0.09	0.02	0.32
d_inc0811	0.10	0.05	-0.38
Part_rate	**-0.46**	0.23	-0.05
Self_cont_work	**0.68**	-0.07	0.38
Res_Mob	0.08	-0.21	0.34
Migr	-0.14	0.09	-0.36
Birth	-0.28	**0.58**	0.04
Aging	-0.06	**-0.96**	0.01
Native	-0.16	-0.04	0.08
Europe	-0.21	0.04	**-0.52**
g61	**-0.54**	0.37	-0.04
u60	0.10	0.01	-0.42
Res_bui	-0.16	-0.11	**-0.56**
Com_dis	-0.23	-0.07	0.35
Agr_For	-0.13	-0.08	0.07
Ele	0.41	0.11	-0.22
Sea	0.18	-0.13	0.04
dAth	**0.85**	-0.21	-0.21
dPir	**0.76**	-0.11	-0.39
dMar	**0.70**	-0.33	0.05
dMak	**0.52**	-0.11	0.33
Area	**0.55**	-0.03	0.05

Table 4. Results of a global regression analysis with median and coefficient of variation indicators of urban complexity as the dependent variable and canonical root scores (Table 2) as predictors.

Variable	Beta	St.Error	t(110)	p
Median				
Adj-R^2 = 0.67; $F_{(3,110)}$ = 60.0; p < 0.0001; D.W. = 1.99				
Root 1	-0.780	0.053	-14.6	*
Root 2	0.200	0.053	3.7	*
Root 3	-0.195	0.053	-3.6	*
Coefficient of variation				
Adj-R^2 = 0.53; $F_{(3,110)}$ = 33.2; p < 0.0001; D.W. = 2.05				
Root 1	0.510	0.060	7.9	*
Root 2	-0.260	0.061	-4.1	*
Root 3	-0.471	0.061	-7.3	*

Table 5. Global results of a Geographically Weighted Regression with indicators of urban complexity (median or coefficient of variation) as the dependent variable and predictors derived from the canonical correlation analysis.

Diagnostic statistic	Median	Coefficient of variation
Adjusted R^2	0.709	0.644
Akaike information criterion	-429.7	-382.9
Residual squares	0.120	0.179
Sigma	0.035	0.043

Figure 1. Spatial distribution of median (left) and coefficient of variation (right) indicators of urban complexity in the study area.

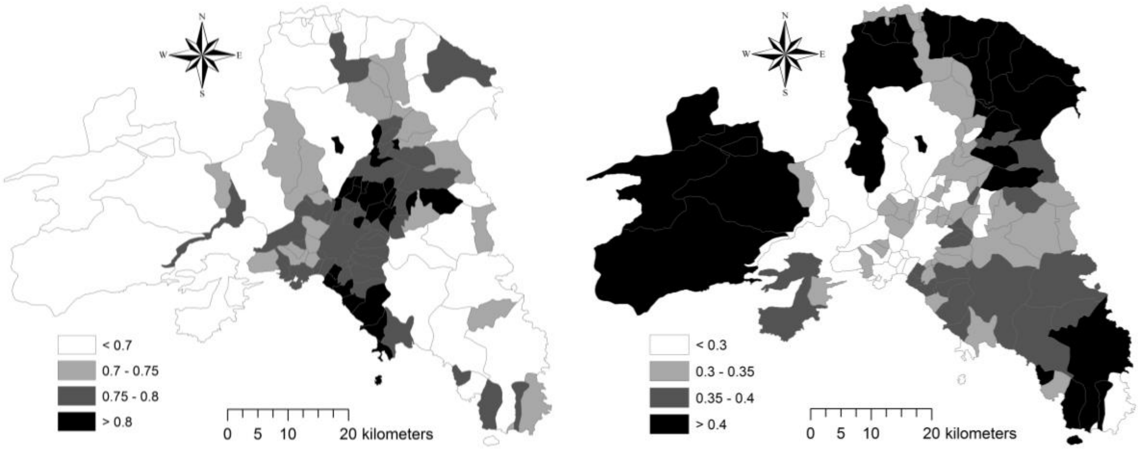


Figure 2. Relationship between median ('Med') and coefficient of variation ('Cov') of Pielou's evenness J indexes considering 12 dimensions of urban diversification by municipality, Athens' metropolitan area (urban municipalities belong to the Greater Athens' area, rural municipalities include the remaining part of the study area).

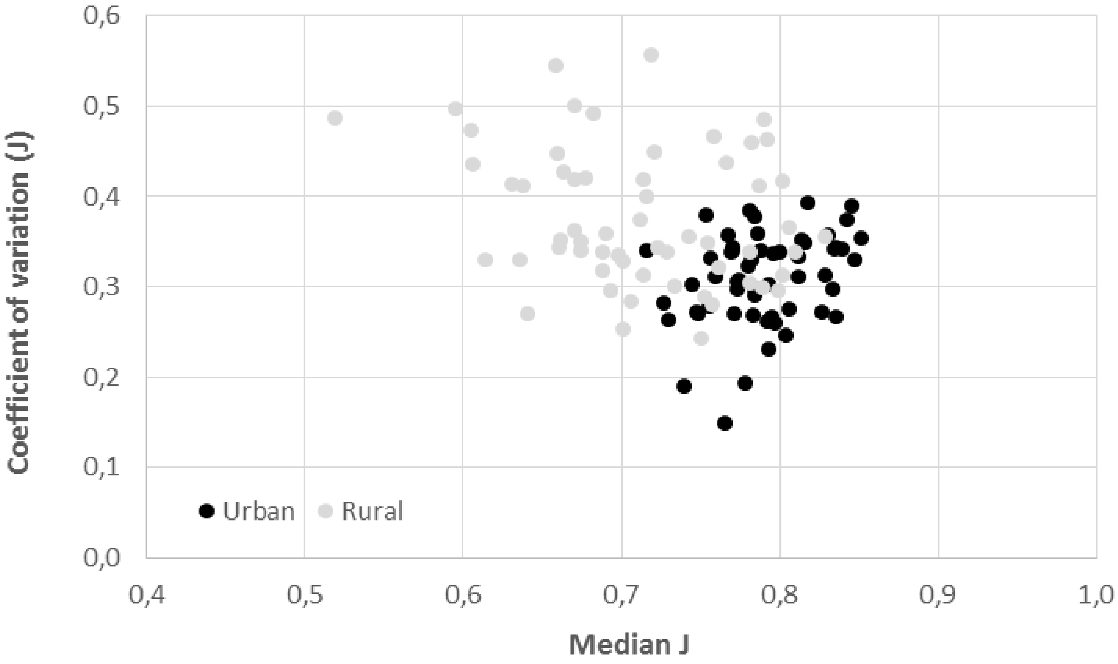
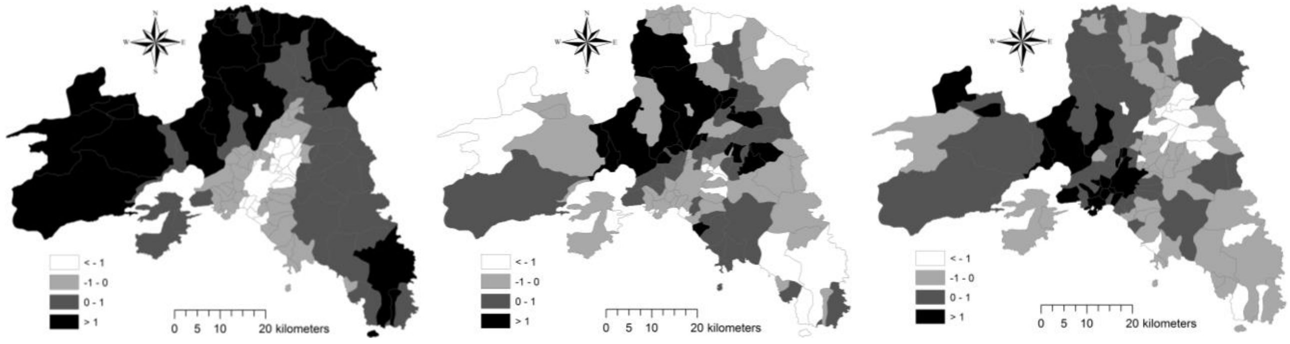
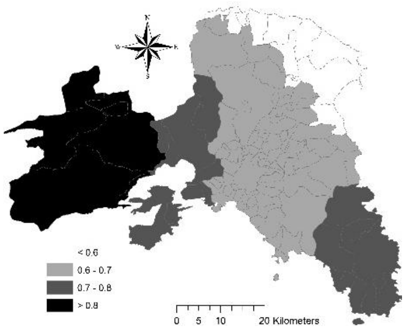


Figure 3. Spatial distribution of the scores of the selected canonical roots (Table 2) in the study area.

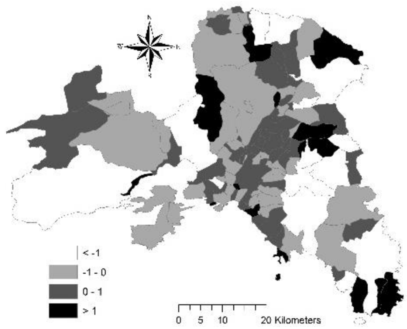


Canonical root 1 Canonical root 2 Canonical root 3

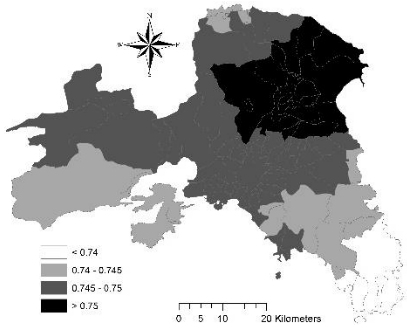
Figure 4. Local results of a Geographically Weighted Regression with the median indicator of urban complexity as the dependent variable and predictors derived from the canonical correlation analysis.



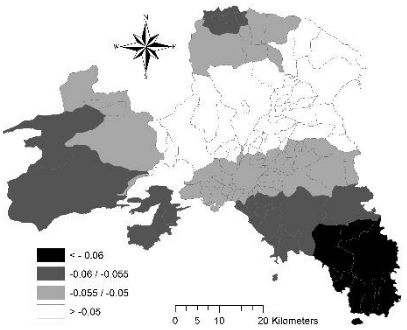
Local R^2



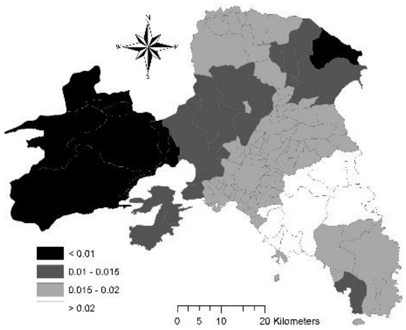
Standardized residuals



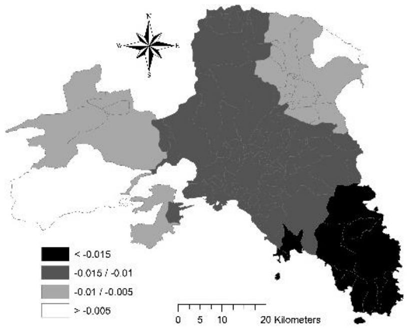
Intercept



Canonical root 1 coefficient

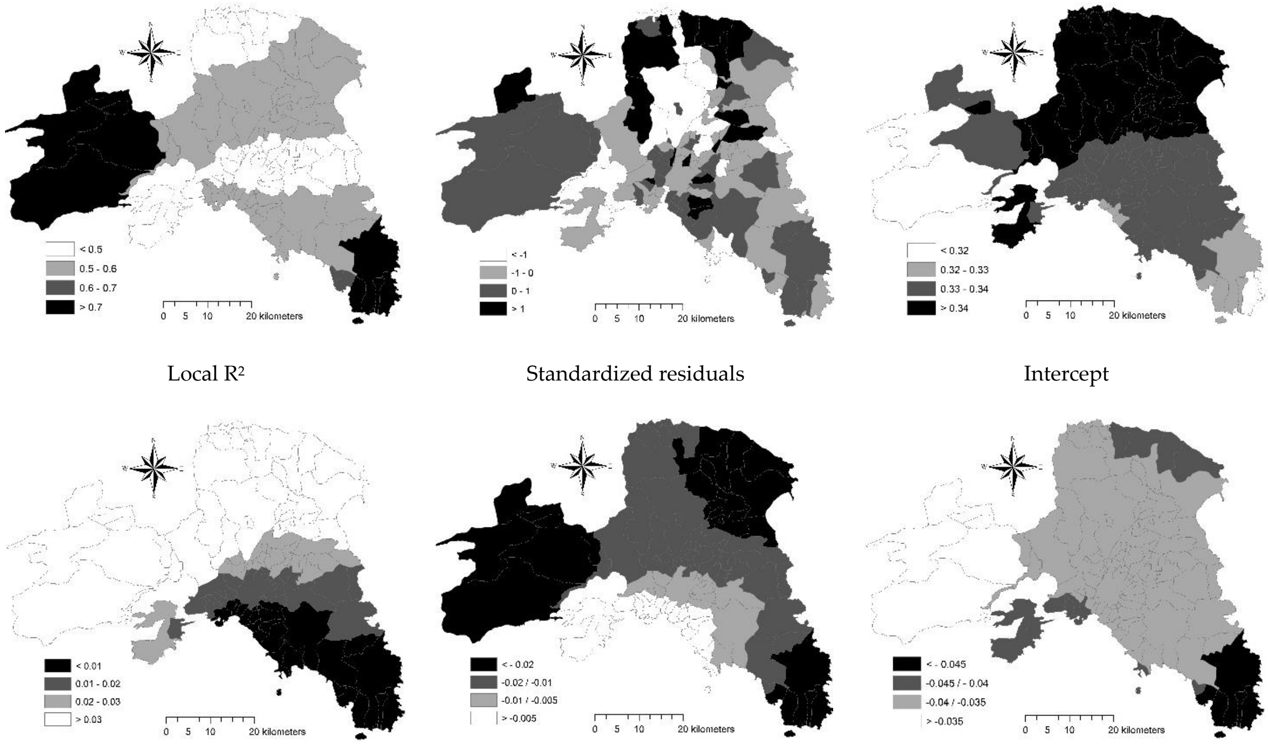


Canonical root 2 coefficient



Canonical root 3 coefficient

Figure 5. Local results of a Geographically Weighted Regression with the coefficient of variation indicator of urban complexity as the dependent variable and predictors derived from the canonical correlation analysis.



Local R^2 | Standardized residuals | Intercept

Canonical root 1 coefficient | Canonical root 2 coefficient | Canonical root 3 coefficient