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Article

Long-Term Urban Growth and Land Use Efficiency in Southern Europe: Implications for Sustainable Land Management

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Abstract: The present study illustrates a multidimensional analysis of an indicator of urban land use efficiency (per-capita built-up area, LUE) in mainland Attica, a Mediterranean urban region, along different expansion waves (1960–2010): compaction and densification in the 1960s, dispersed growth along the coasts and on Athens' fringe in the 1970s, fringe consolidation in the 1980s, moderate re-polarization and discontinuous expansion in the 1990s and sprawl in remote areas in the 2000s. The non-linear trend in LUE (a continuous increase up to the 1980s and a moderate decrease in 1990 and 2000 preceding the rise observed over the last decade) reflects Athens' expansion waves. A total of 23 indicators were collected by decade for each municipality of the study area with the aim of identifying the drivers of land use efficiency. In 1960, municipalities with low efficiency in the use of land were concentrated on both coastal areas and Athens' fringe, while in 2010, the lowest efficiency rate was observed in the most remote, rural areas. Typical urban functions (e.g., mixed land uses, multiple-use buildings, vertical profile) are the variables most associated with high efficiency in the use of land. Policies for sustainable land management should consider local and regional factors shaping land use efficiency promoting self-contained expansion and more tightly protecting rural and remote land from dispersed urbanization. LUE is a promising indicator reflecting the increased complexity of growth patterns and may anticipate future urban trends.

Keywords: urban gradient; urban containment; indicators; socioeconomic context; Southern Europe

1. Introduction

The multifaceted economy-environment interactions observed in dynamic socio-ecological systems contribute to triggering social problems and increase the vulnerability of places and people [1]. Urban growth is one of the most relevant factors determining irreversible landscape changes, affecting ecosystem health and human well-being for generations to come [2]. Urbanization stimulates land use changes, determining the contraction of agricultural land, the consolidation of forests and other natural land and the expansion of urban land [3]. While society benefits from economic development and conservation of natural areas, this trend has a number of adverse implications, related to expanding unsustainable use of land, rural-urban migration, abandonment of cropland, land marginalization, inadequate social security and health provision and decreasing food and environmental security at the regional scale [4]. Secure tenure is essential for both effective and sustainable land use, including adequate levels of investment in enhancing land productivity and allocating land to the most efficient user(s) [5]. As the key to meeting commitments for both national and international policy targets (e.g., Agenda 21), the sustainable management and use of land resources is essential for urban sustainability [6–8].

It was demonstrated that the conversion of productive farmland with fertile soil into urbanized areas, especially with sprawling, low-density settlements, may lead to inefficient land allocation [9]. A sprawling urban expansion can have on-site and off-site negative impacts [10], e.g., fragmenting the agro-forest landscape and reducing the environmental quality of entire regions [11]. These issues are clearly linked and inherently complex [12,13], since sprawl determinants are many and well differentiated (tourism growth, second-home expansion, decentralization of business activities, internal and foreign migration, change in lifestyles and consumption patterns, among others [10]).

Efficiency in the use of land is a representative concept adhering to the sustainable development paradigm. Following Jaeger *et al.* [14], we associate this concept with a pattern of land use assuring spatial, long-term sustainability from both the ecological and the socioeconomic points of view. With the understanding that sprawl has been loosely defined as dispersed and possibly inefficient urban growth, several indicators that examine the critical impact of urbanization on land resources have been developed [15]. Land use efficiency in urban areas (LUE) is operatively linked to the ratio of developed land to resident inhabitants. Despite new and more complex indexes having been recently introduced [11,12], the LUE indicator has been demonstrated to be particularly suited to regional- and local-scale diachronic studies grounded in official statistics.

In Europe, although reusing peri-urban brownfields or simply abandoned areas, together with a better use of infrastructures are considered ‘retro-fitting’ measures to control sprawl, promoting self-contained urban expansion within a sustainable land management framework is a challenging policy target [16,17]. The consideration of the impact of European Union policy and instruments on land development strategies is not straightforward. While approaching these issues from the point of view of interventions in the processes of land development, the EU has influenced (but has limited direct competence) in this area [10]. A thorough analysis of land use efficiency should thus focus on the regional (e.g., administrative regions, provinces, prefectures, economic districts) and local scales (e.g., municipalities, rural communities), since these collectives have the authority to allocate land to the most efficient uses, possibly screening alternative choices for long-term environmental sustainability and residents' well-being [18–20].

How urban growth paths shape, both in the medium term and in the long term, the allocation of land to more (or less) efficient uses at the local scale is poorly addressed in the recent literature. This issue represents indeed a challenge for urban studies with implications on regional planning and urban sustainability, and thus, it deserves further investigation. The present study hypothesized that the efficiency in the use of land varies along different phases of urban expansion following changes in a multifaceted set of socioeconomic and territorial drivers. The stratification of distinct growth waves and the uneven complexity in urban structures and socioeconomic local contexts make European Mediterranean cities intriguing cases for assessing the relation between urban growth and land use efficiency. As a matter of fact, southern European urban regions often developed through paths distinct from either those observed in Western Europe and those found in non-European Mediterranean countries [21–24]. Sprawl-driven settlement scattering and polycentric development constitute the most recent expansion phase, altering the typical mono-centric spatial organization with negative implications for land use efficiency [25,26].

Based on these premises, the present study proposes an exploratory data analysis of urban land use efficiency over different waves of urban expansion in a southern European region (Attica, Greece). In this ambit, Athens can be considered an exemplificative case of expanding Mediterranean urban areas with an intricate relationship between morphology and economic functions. By applying a multi-step statistical strategy incorporating descriptive statistics, correlation and regression analysis and multivariate techniques to a wide set of morphological and functional indicators between 1960 and 2010, our analysis aims at investigating the socioeconomic context most associated with low land use efficiency at the local scale, identifying also the main factors contributing to containing urban expansion at the regional scale. In detail, urban growth is related to changes in land use efficiency using a multi-step empirical analysis. A basic analysis of the spatio-temporal distribution of land use efficiency between 1960 and 2010 was initially developed. Spatial convergence (or divergence) in land use efficiency was subsequently investigated over time along the urban-rural gradient with the aim of identifying the efficiency of different land use regimes. The relation between land use efficiency and socioeconomic variables was also investigated diachronically, and a summary analysis of long-term urban growth paths and changes in land use efficiency was finally developed using multivariate strategies. The multidimensional approach proposed in this study is regarded as an original contribution to the analysis of complexity in urban patterns and processes over time and space.

2. Methodology

2.1. Study Area

The metropolitan region of Athens (AMA), Greece, covering approximately 3,000 km^2, is the area investigated in the present study. The time period between 1960 and 2010 was considered in this study on the basis of the largest set of (homogeneous) socioeconomic and territorial variables available for analysis. The prevailing climate regime in the area is Mediterranean dry, with annual rainfall totaling 400–500 m and annual temperatures averaging 18 °C. The landscape is mainly upland and mountain bordering the flat area occupied by central Athens (Figure 1). The area has a very long settlement history, which has resulted in extensive ecological impoverishment [27]. Restricted land availability due to the mountainous topography of the region and rapid population growth had determined a compact settlement expansion around the main centers of Athens and Piraeus in the decades immediately following World War II.

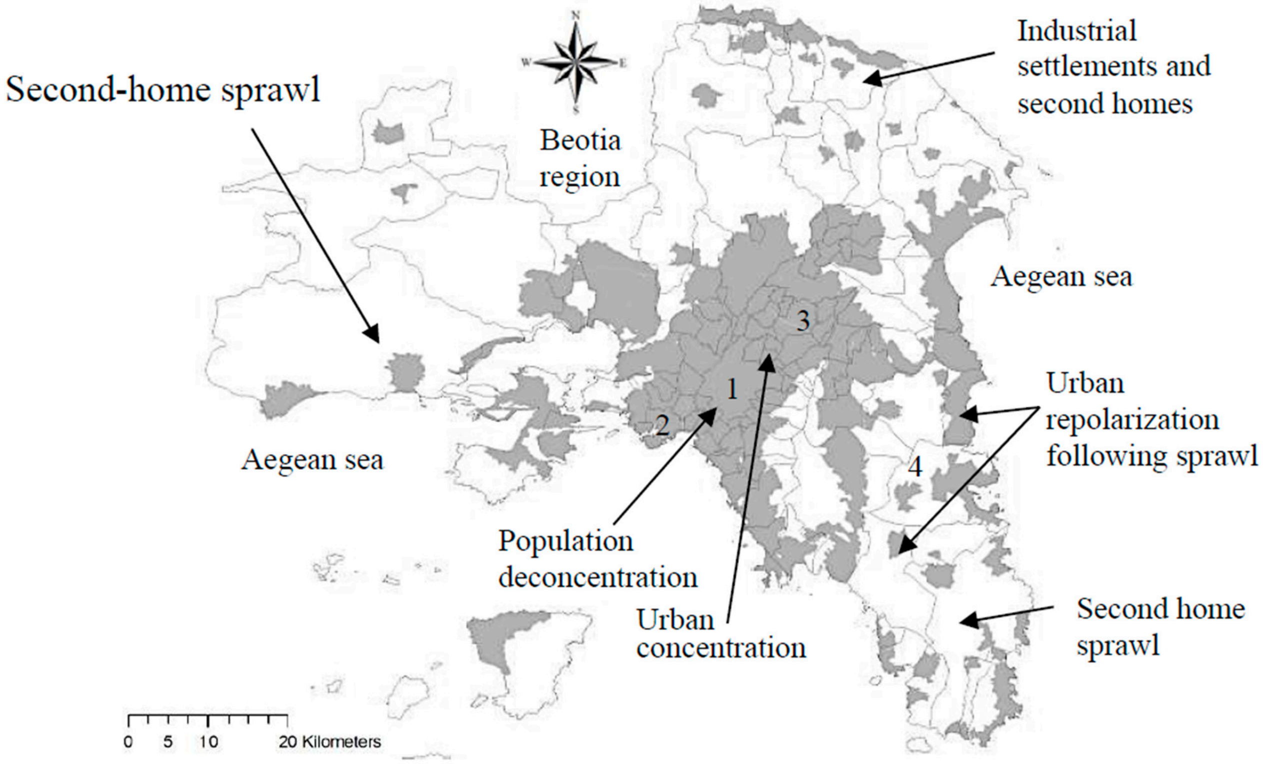

Figure 1. Maps of Athens' metropolitan region: municipal boundaries and urban footprint (in grey; 1: Athens; 2: Piraeus; 3: Maroussi; 4: Markopoulo Mesogaias).

In the early 1960s, Athens; structure was centered on the manufacturing industry and traditional services (construction, commerce, public sector), slowly shifting to capital-intensive and high-technology services in the last few decades [28]. Since the early 1990s, the de-concentration of the central city followed by the expansion of discontinuous settlements on the fringe was observed [29]. The 2004 Olympic Games had a major impact on fringe development, with massive investments and some transport infrastructure [23,24,30], determining soil sealing and land consumption.

Up to 2011, the AMA was administered by 114 municipal authorities with 58 urban municipalities belonging to the conurbation of Athens-Piraeus and 56 rural municipalities. All mainland municipalities, together with Salamina Island, have been considered in the present study [31]. The population density shows a clear trend increasing from nearly 1500 inhabitants/km^2 in 1951 to more than 4400 inhabitants/km^2 in 2011 with decreasing variability over time. This indicates a denser, but possibly more balanced settlement distribution in the AMA. At the same time, the annual population growth rate declined from 2.8% to 0.7% with a slightly increasing variability at the local scale. This may indicate the formation of growing poles outside the consolidated city.

Municipalities have been selected as the basic analysis unit. Although they represent arbitrary measurement units, local administrative domains were frequently used as the denominator for socioeconomic and, sometimes, environmental studies [31]. The use of the municipal boundaries as the elementary analysis domain assures homogeneous comparisons with external sources [32], such as statistical data, and is usually more familiar to stakeholders, planners and non-technical users than spatial domains based on environmentally-relevant boundaries, geo-statistical partitions or regular grids [33]. Moreover, municipalities are responsible for urban plans and release building permits (the surface area and volume for both new constructions and enlargement of existing buildings).

2.2. Assessing Per-Capita Built-Up Area

An index of per-capita consumption of land (the ratio of built-up areas to resident population, LUE) has been calculated for each municipality of the study area by decade (1960, 1970, 1980, 1990, 2000 and 2010). Resident population at the municipal scale was derived from the National Census of Population carried out by the National Statistical Service of Greece (NSSG) for each decade (1961, 1971, 1981, 1991, 2001 and 2011). Data on built-up areas were derived from the NSSG land use census for the years 1960, 1970, 1980, 1990 and 2000 and from the Urban Atlas (UA) map referring to 2010 [34]. Built-up area in each municipality of the region was derived for 2010 by overlying the respective land map (UA) with a shapefile illustrating the municipal boundaries using ArcGIS software (ESRI Inc., Redwoods, USA). The analysis domain chosen in the present study allows for a spatial analysis of urban land use during the whole time period, making comparisons possible with external data sources, including statistical datasets derived from official sources.

The data collected were checked for internal and external consistency following the approach proposed by Salvati *et al.* [31]. To assess the reliability of urban land cover measured for each of the reference years, additional data providing independent estimates of built-up area in Attica's municipalities were considered: (i) a soil map produced by the Institute of Geology and Soil Chemistry (Athens) delimitating the urban areas for 1948; (ii) the LaCoast (LC) project database mapping land use in coastal regions of Europe for 1975 [35]; (iii) CORINE Land Cover (CLC) maps referring to 1990 and 2000 [10]; (iv) the pan European GlobCorine map referring to 2009 [32]; (v) maps of settlement distribution in 1960, 1970, 1980, 1990 and 2000 derived from the Greek National Census of Buildings; and, finally, (vi) municipal data on cropland cover derived from the Greek National Census of Agriculture for 1961, 1970, 1980, 1990, 1999 and 2009. Although representing the base for previous analyses of land use change in the area ([31] among others), heterogeneous data sources underline the urgent need of improving country and supra-national surveys and tools for diachronic land use mapping in Greece and, possibly, in Europe.

2.3. Territorial and Socioeconomic Indicators

A total of 23 indicators have been considered in the present study (Table 1) covering four research domains: (i) population dynamics/environment/land availability; (ii) urban morphology; (iii) urban functions; and (iv) territorial variables. Indicators have been derived from statistics data (primarily collected on behalf of NSSG population and agricultural censuses and geo-cartographical databases) at the municipal scale for each decade between 1960 (or 1961) and 2010 (or 2011). Few variables (such as resident population) were made available for a longer period (1951–2011). Considering the long time interval covered in the present study, these variables may provide a homogeneous, multidimensional description of changes in urban forms and functions at the local scale [32].

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

Acronym	Variable	Measurement unit	Source	Time interval
		Dependent variable		
LUE	Per-capita built-up area	m^2	Census of land-uses	1960–2010
		Population dynamics, environment, land availability		
d	Population density	inhabitants/km^2	Census of population	1951–2011
g	Annual population growth rate	%	Census of population	1961–2011
s	Sparse population	% on total population	Census of population	1961–2011
Area	Municipal surface area	km^2	Territorial statistics	1960–2010
a	Agricultural area	% on total municipal area	Census of land-uses	1960–2010
f	Forest area (% per municipal area)	% on total municipal area	Census of land-uses	1960–2010
p	Protected land by municipality	Dummy (0: non-protected; 1: protected)	Territorial statistics	1960–2010
		Urban morphology		
b	Inhabitants per building	Number of inhabitants	Census of buildings	1960–2010
h	Average building height	Number of floors	Census of buildings	1960–2010
c	Self-contained settlements	% on total buildings	Census of buildings	1960–2010
n	One-dwelling buildings	% on total buildings	Census of buildings	1960–2010
u	Diversity in urban land use	No of building uses on the municipal area	Census of buildings	1960–2010
		Urban functions		
r	Residential buildings	% on total buildings	Census of buildings	1960–2010
i	Industrial buildings	% on total buildings	Census of buildings	1960–2010
t	Hotel-use buildings	% on total buildings	Census of buildings	1960–2010
e	Service/commerce buildings	% on total buildings	Census of buildings	1960–2010
m	Multiple usage buildings	% on total buildings	Census of buildings	1960–2010
		Territorial variables		
Ele	Mean elevation	m	Census of population	Once per time
Lit	Closeness to the sea	Dummy (0: internal; 1: coastal)	Territorial statistics	Once per time
dAth	Distance from Athens	km	Territorial statistics	Once per time
dPir	Distance from Piraeus	km	Territorial statistics	Once per time
dMar	Distance from Maroussi	km	Territorial statistics	Once per time
dMak	Distance from Markopoulo Mesogeia	km	Territorial statistics	Once per time

Territorial variables include specific descriptors of urban structure (average elevation, proximity to the coast, municipal area and distances to four distinct urban centers: Athens, Piraeus, Maroussi and Markopoulo Mesogaias; see the numbers in Figure 1). These centers were selected to test the importance of different spatial organization models in the AMA: (i) a strictly mono-centric pattern centered on Athens as the main urban pole [31]; (ii) a two-center model based on the gravitation around Athens and Piraeus, seen as urban poles with distinct socioeconomic functions (Athens: services; Piraeus: industry, transport and logistics; e.g., [4]); (iii) a model based on the gravitation of the Olympic municipalities northeast of Athens (centered on the municipality of Maroussi hosting the Olympic stadium and representing the new urban core of the AMA [31]); and (iv) a suburbanization model based on the gravitation around Mesogaias municipalities (*i.e.*, Markopoulo M.), which is considered the largest sprawling area in Attica [28,29]. Distances from urban centers were measured using spatial functions, such as the "centroid" command provided by ArcGIS that computes the center of gravity of each municipality and measures the distance to a fixed, reference place (Environmental System Research Institute Inc., Redlands, CA, USA).

2.4. Exploratory Data Analysis

The exploratory strategy proposed in this paper is constituted by different analysis steps: (i) a general analysis of the spatio-temporal distribution of land use efficiency using descriptive statistics and maps representing the urban LUE indicators; (ii) an analysis of spatial convergence in land use efficiency over time using linear regression models and non-parametric Spearman rank correlations; (iii) profiling municipalities for urban land use efficiency using clustering; (iv) exploring land use efficiency along the urban-rural gradient using principal component analysis; (v) investigating the relation between land use efficiency and selected socioeconomic and territorial variables using non-parametric Spearman rank correlations; (vi) exploring changes in the spatial determinants of urban land use efficiency over time using a step-wise multiple regression analysis; and, finally; (vii) a summary analysis of urban growth and change between 1960 and 2010 using a multiple factor analysis. The objective of the multi-step statistical strategy proposed in this study is to provide a comprehensive analysis of urban growth patterns and the implication of urban change processes on land use efficiency. The analysis strategy is considered an original contribution to understanding urban complexity and a practical tool informing policies for urban sustainability at the regional and local scales.

2.4.1. Descriptive Analysis of Land Use Efficiency in Attica

Descriptive statistics and diachronic maps were prepared for each collected variable. Statistics, including the LUE arithmetic and geometric mean, median, the ratio of median-to-mean and the coefficient of variation, have been calculated for each studied point in time.

2.4.2. Exploring Spatial Convergence in Land Use Efficiency over Time

A convergence analysis was developed by the pair-wise comparison of the spatial distribution of the LUE index at the municipal scale for t and t + 1 decades (e.g., 1960 *vs.* 1970, ..., 2000 *vs.* 2010) and for the first and last decade (*i.e.*, 1960 and 2010) using the non-parametric sign statistic testing at $p < 0.05$.

A linear regression has been also carried out between the spatial distribution of LUE at t and t + 1 years to assess the convergence or divergence in the studied variable over time. A regression model with the slope and intercept respectively equal to 1 and 0 indicates stability among the two studied spatial data series. A slope equal to 1 and an intercept >1 (or <1) indicate a generalized increase (or decrease) of the variable (with no convergence) in all of the spatial units investigated. An intercept equal to 0 and a slope >1 (or <1) indicate a convergence (or divergence) process. A positive (or negative) intercept with a slope >1 (or <1) indicates a convergence (or divergence) process with a net increase (or decrease) of the studied variable. Adjusted R^2 was used as a diagnostic to assess the goodness-of-fit of each regression model. Convergence analysis was carried out for the whole study area (n = 114 municipalities) and separately for urban municipalities (n = 58) and rural municipalities (n = 56), as described in Section 2.1.

2.4.3. Profiling Municipalities for Urban Land Use Efficiency

Municipalities were classified into low and high urban land use efficiency types according to four criteria and related thresholds: (i) positive (LUE(−)) or negative (LUE(+)) variation in per-capita built-up area between 1960 and 2010; (ii) the time trend in per-capita built-up area observed by decade during 1960–2010 (L− = linear, negative trend; L+ = linear, positive trend; U = U-shaped square trend; inv-U = inverse U-shaped square trend; ?− = non-linear, non-square negative trend; ?+ = non-linear, non-square positive trend); (iii) absolute per-capita built-up area measured in each municipality for 1960 (LUE60) and for 2010 (LUE10); municipalities were classified as low land use efficiency when encompassing the threshold of 500 m^2 developed area per inhabitant. The 500 m^2 threshold was chosen according to the inspection of the statistical distribution of the LUE indicator for both 1960 and 2010.

2.4.4. Exploring Land Use Efficiency along the Urban-Rural Gradient Using Principal Component Analysis

A multivariate framework has been further developed on the same data matrix considering together the LUE indicator observed at any year of study (1960, 1970, 1980, 1990, 2000 and 2010) in a principal component analysis (PCA). The PCA aimed at classifying municipalities into a few homogeneous groups according to the latent LUE spatial patterns [32]. Significant components with an eigenvalue > 2 were analyzed [31]. Component loadings > |0.5| were considered significant. A score plots was prepared for significant components with the aim of highlighting the spatial distribution of each municipality over the factorial plain.

2.4.5. Investigating the Relation between Land Use Efficiency and Socioeconomic Variables

A Spearman rank analysis identifying both linear and non-linear pair-wise correlations was carried out between LUE and each of the 23 indicators, testing for significance at $p < 0.05$. Bonferroni's correction for multiple comparisons was also applied. The analysis was developed for each year of study (1960, 1970, 1980, 1990, 2000 and 2010) with the aim of assessing significant relations between territorial indicators and land use efficiency.

2.4.6. Exploring Changes over Time in the Spatial Determinants of Urban Land Use Efficiency

A forward step-wise multiple regression model was performed using LUE as the dependent variable and the 23 indicators for each year of study. The analysis is aimed at identifying long-term changes in the most relevant factors associated with urban land use efficiency at the local scale. The analysis also ranks the selected territorial indicators on the basis of their influence on land use efficiency in each municipality of the study area. Variables were standardized prior to regression analysis. Independent variables have been selected, fixing F-to-remove and F-to-enter thresholds respectively to 3 and 1.5. The results include slope coefficient estimates and the associated significance level (testing for the null-hypothesis of the non-significant regression coefficient) based on the Student's t statistics at $p < 0.05$. The overall goodness-of-fit estimate for each regression model was measured using adjusted R^2 and tested for significance (against the null hypothesis of the non-significant model) through a Fisher–Snedecor F-test with $p < 0.001$. A Durbin–Watson statistic was applied separately to the residuals from the six least squares regressions, testing for serial correlation in the residuals. Values of Durbin–Watson statistics close to 2 (e.g., in the range between 1.5 and 2.5) indicate negligible auto-correlation.

2.4.7. A Summary Analysis of Urban Growth and Change between 1960 and 2010

A multiple factor analysis (MFA) combining LUE with the 23 territorial indicators at each studied point in time was finally developed with the aim of assessing the patterns and processes underlying the changes in urban land use efficiency along different expansion waves of Athens and to identify latent relationships among per-capita built-up area and relevant morphological/functional variables over time. The general objectives of the MFA are: (i) to explore the relationship among variables; (ii) to analyze diachronically the whole dataset, as projected into a unique matrix, called the 'compromise' matrix; and, finally; (iii) to assess the communalities and discrepancies of the resulting 'compromise' [31]. The weights used to compute the compromise matrix are chosen in order to make it representative of all datasets. The MFA allows one: (i) to evaluate whether the positions of the indicators on the factorial plane are changing over time; and (ii) to determine the joint time path of indicators and municipalities through the analysis of factor loadings and scores. A spatial association is indicated by the points (*i.e.*, indicators or municipalities) placed close to each other in the factorial plane, while points placed far from each other indicate spatial segregation.

3. Results and Discussion

3.1. Descriptive Analysis of Land Use Efficiency in Attica

Selected statistics describing the temporal evolution of per-capita built-up area in Attica are reported in Table 2 by decade and computed using municipalities as the elementary spatial domain. Statistics indicate a progressive decrease in developed land per inhabitant between 1960 and 2010, but with distinct trends between decades. Median per-capita built-up area decreased by 73 m^2 from 429 m^2 in 1960 to 356 m^2 in 2010, with a non-linear trend showing a moderate increase in 1960–1980 up to a peak of 452 m^2 per inhabitant. This preceded a considerable decrease (1980–2000), in turn followed by a moderate increase in the last decade. Taken together, this pattern highlights the complex urban path observed in the last 50 years in Attica, with distinct expansion waves, alternating settlement densification, sprawl and urban re-polarization. The arithmetic mean of per-capita built-up area at the municipal scale was systematically higher than the median value with an increasing median-to-mean ratio (from 0.44 in 1960 to 0.59 in 2010).

Table 2. Descriptive statistics on per-capita built-up area (m^2) in mainland Attica by year.

Statistic	1960	1970	1980	1990	2000	2010
Median	429	435	452	280	249	356
Arithmetic mean	965	1013	936	475	394	604
Median/mean	0.44	0.43	0.48	0.59	0.63	0.59
Coefficient of variation	1.85	1.57	1.41	1.36	1.18	1.02
Geometric mean	424	434	395	258	236	322

This evidence highlights a deviation from normality in the statistical distribution of per-capita built-up area in Attica and reflects the polarization into distinct urban and rural regions, especially in the earliest decades studied. The coefficient of variation of per-capita built-up area decreased continuously from 1.85 in 1960 to 1.02 in 2010. This indicates the increased homogeneity and spatial balancing of human settlements promoted by the recent urban expansion.

The spatial distribution of per-capita built-up area has been mapped in Figures 1 and 2 by study year together with the absolute difference between 1960 and 2010. In 1960, LUE was relatively low in the whole of Attica apart from some municipalities located in the northern part of the region, totaling more than 1500 m^2 of developed land per inhabitant (Figure 2). Per-capita built-up area increased on Athens' fringe in 1970 and 1980 following a wave of suburbanization with low- and medium-density settlements and house speculation, especially along the coasts. The municipalities with the highest value of developed land per inhabitant were concentrated in the northern and eastern side of the region. In the remaining fringe areas, a moderate process of urban concentration has been observed.

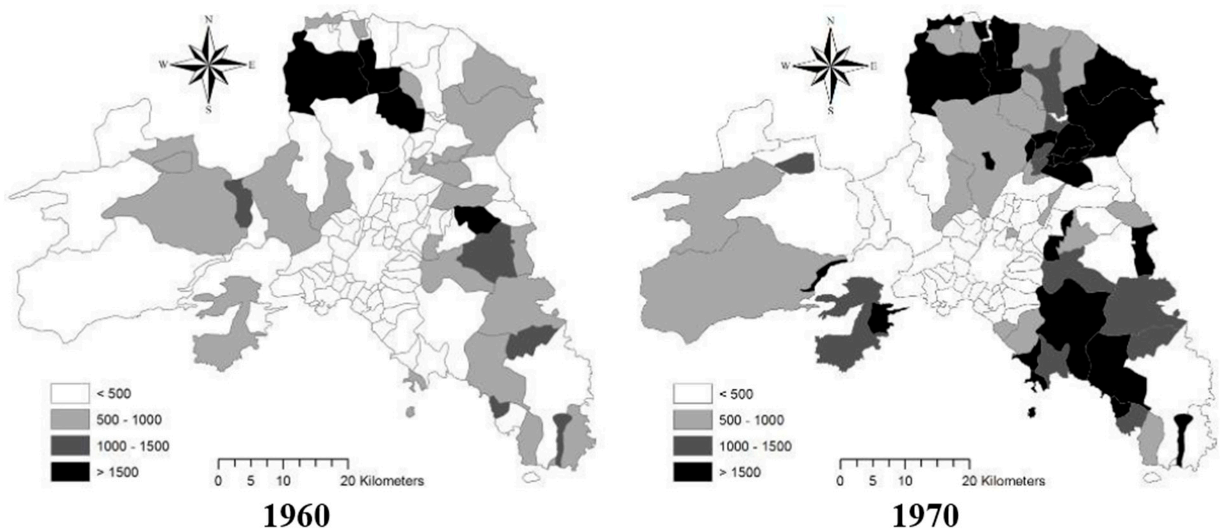

Figure 2. *Cont.*

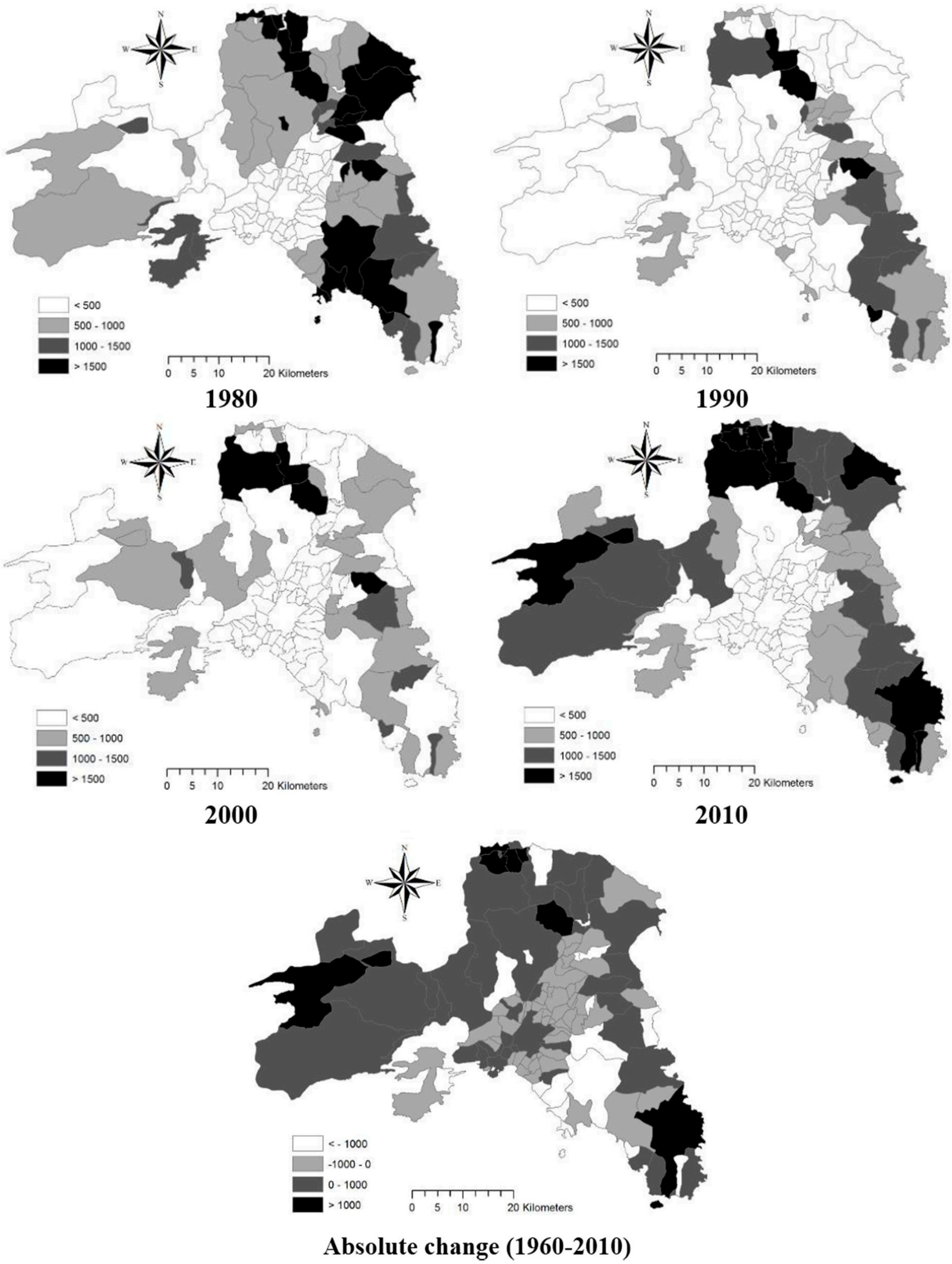

Figure 2. Per-capita built-up area (m^2) by decade and municipality in Athens' metropolitan area.

In 2000, high per-capita built-up areas were concentrated in northern Attica and in the eastern side of the region (Mesogaia Plain). Following the wave of urban re-polarization and sprawl occurring in the last decade encompassing the 2004 Olympic Games, a typical urban-rural gradient in per-capita built-up area was observed in 2010, with the highest values in coastal municipalities. At the same time, urban consolidation occurred in the central area (inner Athens, Piraeus, Maroussi and the surrounding northern suburbs) with developed land systematically <500 m^2 per inhabitant. The spatial distribution of the absolute difference of the LUE indicator in each municipality indicates the distinct urbanization waves (concentration, sprawl, re-polarization) observed in the region between 1960 and 2010 well. The municipalities with the largest LUE increase were concentrated along the coast. Conversely, the largest decrease was found in fringe municipalities around Athens with a remarkable population increase. This pattern determined the alteration of the original urban form at the local scale: the strict urban area showed mixed trends with a moderate LUE increase in the inner cities of Athens and Piraeus, mainly driven by population de-concentration and a moderate decrease in the medium-density municipalities in northern Attica (primarily caused by settlement densification).

3.2. Spatial Convergence in Land Use Efficiency over Time

A spatial convergence analysis in LUE by decade (Table 3) was carried out at the municipal scale. Linear models are significant for all decades, although the highest R^2 was observed for 1960–1970 (0.72) and 1990–2000 (0.86). This result indicates the decades with the largest homogeneity in the spatial distribution of LUE. This evidence is confirmed by non-parametric convergence analysis using Spearman rank correlation tests, identifying 1960–1970, 1970–1980 and 1990–2000 as the most homogeneous decades. Equation slopes (1 indicates a similar spatial distribution between decades) were largely variable over time, with the highest values observed for 1960–1970 (0.76) and 2000–2010 (0.88). The lowest slope coefficients were observed for the decades with relevant changes in the spatial distribution of LUE (see Figure 2). Based on these findings, the decade 1980–1990 was considered the most heterogeneous decade, possibly representing the shift from compact growth to a more dispersed settlement expansion mode.

Table 3. Convergence analysis of urban land use efficiency (LUE) observed in each Attica municipality by decade (^{ns} not significant, * significant at $p < 0.05$; ** significant at $p < 0.001$).

Parameter	1960–1970	1970–1980	1980–1990	1990–2000	2000–2010	1960–2010
Mainland Attica						
Intercept	280.0 **	398.6 *	172.7 *	77.4 **	256.9 *	549.6 ^{ns}
Slope	0.760 **	0.531 *	0.323 *	0.667 **	0.881 *	0.162 ^{ns}
R^2	0.722 **	0.411 *	0.431 *	0.864 **	0.438 *	0.026 ^{ns}
Spearman ρ	0.900 **	0.936 **	0.867 *	0.929 *	0.831 **	0.631 *
Z sign test	1.12 ^{ns}	3.91 *	4.66 *	2.90 *	2.80 *	2.05 *
Urban municipalities						
Intercept	11.2 **	30.8 **	43.3 **	28.9 **	11.7 **	
Slope	0.806 **	0.581 **	0.552 **	0.737 **	0.860 **	
R^2	0.872 **	0.961 **	0.869 **	0.903 **	0.961 **	
Rural municipalities						
Intercept	598.1 **	932.5 *	326.8 *	141.4 **	736.8 *	
Slope	0.709 **	0.415 *	0.271 *	0.629 **	0.502 *	
R^2	0.687 **	0.280 *	0.284 *	0.825 **	0.224 *	

Intercept coefficients indicate the average net increase in LUE, which is not attributable to spatial convergence processes. The highest value was observed for the 1970–1980 decade (399 m^2), which represents the time period with the most evident settlement growth in Attica. Decades 1960–1970 and 2000–2010 showed a moderately high coefficient (respectively 280 and 260 m^2), while 1980–1990 and 1990–2000 decades were characterized by the lowest net increase. The results of a non-parametric inference (Z sign) testing for significant differences in the statistical distribution of LUE between decades finally suggests that changes between 1960 and 1970 are not significant, with the largest variation being observed between 1980 and 1990. Convergence analysis between 1960 and 2010 indicates a diverging spatial pattern with non-significant R^2 coefficient (the absence of a linear correlation between the two years), a weakly significant Spearman ρ coefficient (moderate non-linear correlation) and a high Z sign statistic. All together, these results suggest that a change in the spatial distribution of LUE occurred along the last 50 years in Attica reflecting the two urbanization phases described above.

By classifying municipalities into two homogeneous groups (urban *vs.* rural), urban municipalities showed higher convergence than rural municipalities with very high R^2 (from 0.87 to 0.96) and the slope coefficients (from 0.55 to 0.86) for all decades analyzed (Figure 3). Low intercept coefficients indicate that the average net increase in LUE is moderate and ranges between 11 m^2 and 43 m^2. By contrast, rural municipalities showed a modest convergence between decades, since they experienced more rapid changes in land use efficiency than urban municipalities. Moderate convergence was observed for 1960–1970 and 1990–2000 decades. In the remaining decades, convergence is low or negligible, indicating substantial changes in the structure of settlements at the local scale. Figure 4 clearly distinguishes urban municipalities from rural municipalities. The former class is more homogeneous than the latter class, confirming the previous results.

3.3. Profiling Attica Municipalities for Urban Land Use Efficiency

Attica municipalities were classified into homogeneous classes of land use efficiency using four criteria and thresholds (Table 4). The first criterion discriminates municipalities with an increase in per-capita built-up area (LUE+) between 1960 and 2010 from municipalities with decreasing LUE (LUE−). A total of 46 municipalities (69.5% of the total investigated land) showed decreasing land use efficiency during the last 50 years (+519 m^2 per inhabitant on average), while 69 municipalities (30.5% of the total investigated land) showed increasing land use efficiency (−947 m^2 per inhabitant on average). Municipalities with decreasing LUE administer a bigger surface area than municipalities with increasing LUE and host a less dense population, increasing moderately between 1951 and 1981 (from 509 inhabitants/km^2 to 837 inhabitants/km^2) and decreasing slightly between 1981 and 2011 (from 837 inhabitants/km^2 to 799 inhabitants/km^2). By contrast, the share of population residing in LUE(−) municipalities to the total population living in the study area decreased from 70.5% to 44.5%. LUE(−) spatial units are more likely coastal municipalities and are more distant from Athens (+10 km), Piraeus (+7 km), Maroussi (+10 km) and Markopoulo M. (+11 km) than LUE(+) units. This finding reflects the territorial implications of the suburbanization process observed in Athens in the last few decades well.

Table 4. Basic characteristics of Attica municipalities according to four distinct classification criteria using defined thresholds for the LUE indicator.

Variable	LUE Variation		Trend in Per-Capita Built-Up Area						LUE 1960 (m^2)		LUE 2010 (m^2)	
	(+)	(−)	L−	L+	U	inv-U	?−	?+	<500	>500	<500	>500
No. of municipalities	69	46	33	4	31	11	13	23	63	52	66	49
Surface area (%)	30.5	69.5	10.0	3.5	17.9	11.3	9.1	48.2	53.0	47.0	21.6	78.4
Average municipal size (km^2)	13.4	45.7	9.1	26.2	17.5	31.1	21.2	63.4	25.4	27.4	9.9	48.4
Resident population 1951 (%)	29.5	70.5	14.6	2.1	72.5	2.3	3.6	4.9	93.3	6.7	92.1	7.9
1981 (%)	47.2	52.8	25.9	1.7	59.1	4.2	3.9	5.2	90.5	9.5	93.5	6.5
2011 (%)	55.5	44.5	32.4	1.7	45.5	5.6	6.3	8.4	81.8	18.2	88.5	11.5
Population density 1951 (/km^2)	484	509	733	302	2028	101	199	51	883	71	2137	50
1981 (/km^2)	1707	837	2857	534	3640	410	471	120	1883	223	4773	91
2011 (/km^2)	2270	799	4056	612	3172	618	867	218	1928	482	5112	184
Elevation (m)	229	298	210	70	209	268	294	394	221	300	208	323
Coastal municipalities (%)	23.2	37.0	24.2	75.0	16.1	27.3	23.1	47.8	28.6	28.8	19.7	40.8
Distance from Athens (km)	13.0	22.5	12.1	19.5	12.0	17.6	15.2	30.0	13.4	21.0	9.1	27.3
Distance from Piraeus (km)	18.1	25.2	17.0	20.3	16.1	23.3	19.8	32.8	16.6	26.2	13.2	31.4
Distance from Maroussi (km)	12.6	22.8	12.2	23.1	13.3	16.1	13.6	28.6	15.2	18.6	10.5	25.0
Distance from Markop. M. (km)	23.7	34.5	23.4	23.4	28.3	18.8	24.2	41.5	29.0	26.8	24.9	32.2

Legend: LUE variation (absolute change in per-capita built-up area between 1960 and 2010): (−) and (+) respectively indicate negative and positive changes over time. Trend in per-capita built-up area (temporal pattern in per-capita built-up area measured every decade from 1960 to 2010): L− = linear, negative trend; L+ = linear, positive trend; u = U-shaped square trend; inv-U = inverse U-shaped square trend; ?− = non-linear, non-squared negative trend; ?+ = non-linear, non-squared positive trend. LUE 1960 (the absolute per-capita built-up area measured in each municipality for 1960): <500 and >500 respectively indicate municipalities classified below and above the threshold of 500 m^2 developed area per inhabitant. LUE 2010 (the absolute per-capita built-up area measured in each municipality for 2010): <500 and >500 respectively indicate municipalities classified below and above the threshold of 500 m^2 developed area per inhabitant.

The second criterion discriminates municipalities into six homogeneous trends in per-capita built-up area over 1960–2010 (linear positive or negative trend: L+ or L−; U-shaped and inverse U-shaped square trend: U or inv-U; non-linear, non-square positive or negative trend: ?+ or ?−). The most populated classes are L− and U (respectively 33 and 31 municipalities covering 10% and 18% of the total investigated area). The class occupying the largest surface area is ?+ (48%), including municipalities administering, on average, more than 63 km^2 of land each. This class is typically mixed and heterogeneous with low-density municipalities (from 51 inhabitants/km^2 to 218 inhabitants/km^2) concentrated in both hilly and coastal areas far away from Athens and the other urban sub-centers (Figure 3). The heterogeneous territorial profile of the municipalities belonging to the six trend classes may indicate the complex relation existing between long-term urban growth and changes in land use efficiency at the local scale.

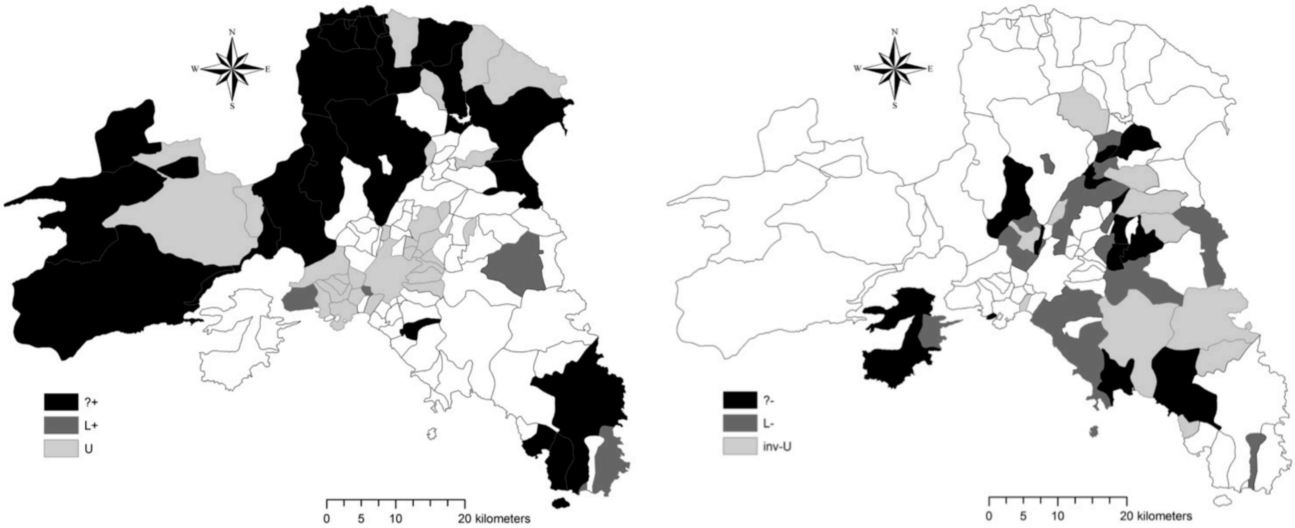

Figure 3. Classification of Attica municipalities based on long-term trends in per-capita built-up area ((**left**) increasing LUE trend classes; (**right**) decreasing LUE trend classes).

Urban municipalities, characterized by high density levels, populated mainly L− and U clusters and host an increasing proportion of resident population. The L+ group includes coastal municipalities with dispersed urbanization, house speculation and second-home settlements. Finally, the inv-U group is interesting from the urban containment perspective: the municipalities belonging to this group experienced a moderate increase in LUE until the 1980s, followed by a rapid decrease in the two most recent decades. These municipalities are examples of urban re-polarization after sprawl, determining a moderate increase in population density.

The last two criteria identify a critical threshold evaluating selected territorial and socioeconomic characteristics of municipalities with low and high urban LUE in both 1960 and 2010. High LUE municipalities increased from 63 to 66 over the study period, administering 53% of the total investigated area in 1960 and only 22% in 2010. Consequently, municipalities classified at low LUE covered 78% of the total investigated area in 2010 with a net increase by 56% during 1960–2010. Comparing 1960 with 2010 figures, the low efficiency class shows a lower population density, higher elevation and a marked increase in the percentage of coastal municipalities and a higher distance from all urban centers (Athens: +6.3 km between 1960 and 2010; Piraeus: +5.2 km; Maroussi: +6.4 km; Markopoulo M.: +5.4 km).

This suggests the importance of low-density, sparse settlements determining the increasingly lower land use efficiency observed in several municipalities during the study period.

3.4. Exploring Land Use Efficiency along the Urban-Rural Gradient

The PCA carried out on the spatial distribution of the LUE indicator in the six decades studied was aimed at extracting the most relevant analysis' dimensions and identifying homogeneous groups of municipalities based on land use efficiency. Component 1 explains 59% of the total variance and may be regarded as an 'urban land use efficiency' gradient, with compact and dense urban municipalities clustered on the positive scores of the axis and rural municipalities with sparse settlements clustered on the negative scores. Component 2 explains 24% of the total variance with scores segregating two distinct groups (Figure 4): municipalities with low efficiency in the use of land in the earliest observation decades (1960 and 1970) and municipalities with low efficiency in the use of land in the most recent decades (2000 and 2010).

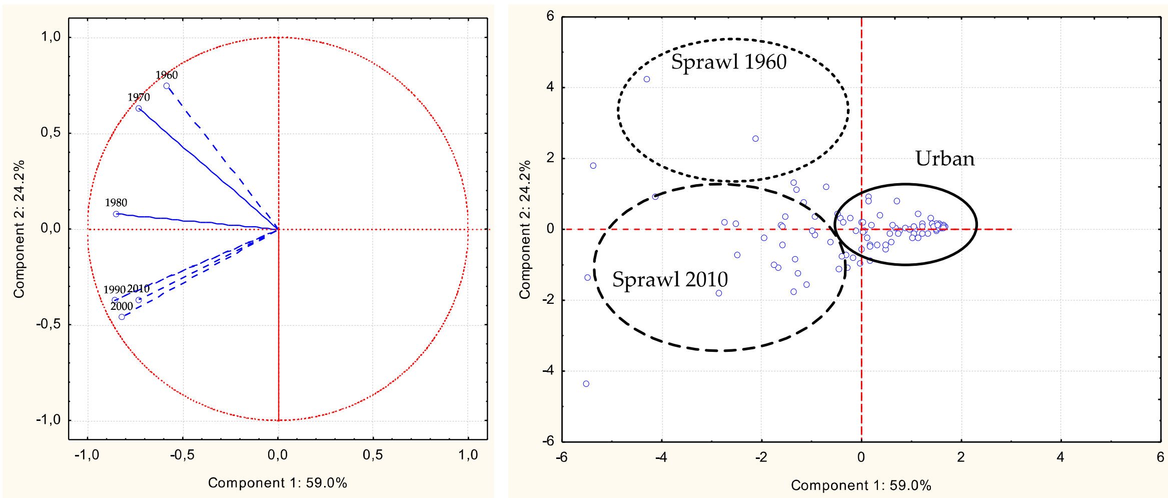

Figure 4. Principal component analysis applied to the spatial distribution of per-capita built-up area in Attica municipalities by year: (**left**) component loadings; (**right**) component scores.

The former group is formed by fringe municipalities surrounding Athens and experiencing the first wave of urban expansion during 1960–1980 and then (re)compacting as a consequence of economic polarization processes. The latter group is formed by rural, remote municipalities with (expanding) sparse settlements and isolated buildings on free land, especially forest areas.

3.5. The Relation between Land Use Efficiency and Socioeconomic Variables

Spearman rank correlations carried out on a decadal scale identified few indicators significantly correlated with per-capita built-up area (Table 5). As expected, LUE decreased with indicators of urban centrality and settlement compaction, such as building height, population density and diversity in urban land uses. This result reflects the mono-centric structure typically observed in Attica up to the 1980s and the concentration of mixed economic functions in the inner cities of Athens and Piraeus [30]. Interestingly, correlation intensity (measured by Spearman coefficients) increased for the three indicators, confirming the important role of compact morphologies for urban containment. The proportion of buildings with multiple use, taken as an additional indicator of land use diversification and urban primacy, correlated negatively with LUE, but with stable (or slightly decreasing) Spearman coefficients over time.

Table 5. Pair-wise Spearman non-parametric correlation analysis between each of the selected indicators and per-capita built-up area (LUE) in six decades between 1960 and 2010 (bold indicates significant correlation at $p < 0.05$ after Bonferroni's correction for multiple comparisons).

Variable	LUE					
	1960	1970	1980	1990	2000	2010
Population density	**−0.71**	**−0.79**	**−0.84**	**−0.78**	**−0.79**	**−0.95**
Annual population growth rate	−0.27	−0.22	0.34	0.59	0.51	0.20
Sparse population	0.20	0.34	0.45	0.51	0.52	**0.74**
Agricultural area	0.35	0.47	0.56	0.54	0.56	**0.77**
Forest area	0.28	0.39	0.40	0.37	0.37	0.47
Protected land	−0.22	−0.20	−0.19	−0.07	0.03	0.05
Municipal surface area	0.30	0.35	0.44	0.43	0.51	**0.64**
Inhabitants per building	−0.45	**−0.62**	**−0.81**	**−0.76**	**−0.68**	**−0.87**
Average building height	−0.50	**−0.62**	**−0.68**	**−0.68**	**−0.70**	**−0.85**
Self-contained settlements	−0.03	−0.40	−0.42	−0.17	−0.20	0.06
One-dwelling buildings	0.56	**0.75**	**0.81**	**0.71**	**0.70**	**0.68**
Diversity in urban land use	−0.54	−0.58	**−0.66**	**−0.63**	**−0.68**	**−0.83**
Residential buildings	0.04	−0.03	0.17	0.36	0.37	0.49
Industrial buildings	−0.36	−0.23	−0.13	−0.14	−0.07	−0.15
Hotel use buildings	−0.19	−0.04	−0.04	−0.04	−0.06	0.09
Service/commerce buildings	−0.32	−0.23	−0.25	−0.44	−0.25	−0.40
Multiple usage buildings	−0.58	**−0.74**	**−0.79**	**−0.74**	**−0.68**	**−0.66**
Elevation	0.40	0.40	0.39	0.35	0.39	0.38
Coastal municipality	0.06	0.14	0.16	0.14	0.11	0.17
Distance from Athens	0.54	**0.68**	**0.75**	**0.69**	**0.67**	**0.87**
Distance from Piraeus	0.56	**0.69**	**0.74**	**0.68**	**0.66**	**0.84**
Distance from Maroussi	0.20	0.31	0.40	0.37	0.36	**0.61**
Distance from Markopoulo M.	−0.09	−0.01	0.02	−0.06	−0.01	0.22

The proportion of one-dwelling buildings and the distances from Athens and Piraeus are the indicators showing a significant positive correlation with LUE. This intuitive result confirms that areas with low land use efficiency are concentrated in rural municipalities at distances progressively higher from the inner city. At the same time, the distance from Markopoulo M., the center of Mesogaia Plain (considered as the best example of Athens' sprawl [28]), became significant in 2010. This suggests that the Mesogaia area is re-configuring itself through urban polarization and densification (according to [30]), and low efficiency areas are progressively moving out of Athens' fringe. In this sense, LUE can be considered an anticipatory variable for spatially-complex urban dynamics moving from compaction to sprawl and back again (but, see also [14]). Figure 5 illustrates the indicators with the most changing correlation intensity with LUE between 1960 and 2010. The population growth rate and the proportion of sparse residential settlements are the variables with the highest net increase in the Spearman coefficient over time. This finding suggests that a lower land use efficiency is mainly caused by low-density, discontinuous expansion fuelled by real-estate speculation and increased demand for specific residential house typologies [23].

Figure 5. Change in Spearman non-parametric rank coefficients (1960–2010) for the pair-wise correlation between the LUE indicator and each of the socioeconomic and territorial variables * considered in this study (dotted lines indicate the confidence threshold). * s, sparse population; g, annual population growth rate; r, residential buildings; a, agricultural area; dMar, distance from Maroussi; Area, municipal surface area; dAth, distance from Athens; dPir, distance from Piraeus; t, hotel-use buildings; p, protected land; i, industrial buildings; f, forest area; n, one-dwelling buildings; Lit, closeness to the sea; c, self-contained buildings; Ele, mean elevation; m, multiple usage buildings; e, service/commerce buildings; d, population density; u, diversity in urban land use; h, average building height; b, inhabitants per building.

3.6. Changes over Time in the Spatial Determinants of Urban Land Use Efficiency

A step-wise multiple regression analysis (Table 6) identified the variables impacting LUE levels most in Attica. Taken together, our results reflect a substantial divergence in the urban structure between 1960 and 2010. This allows identifying the different expansion waves in Attica and evaluating their impact on urban land use efficiency. The model's performance increased over time, passing from 0.13 adjusted R^2 in 1960 to 0.74 in 2010. This may indicate a polarization in areas with high and low efficiency in the use of urban land. In 1960, only the percentage of buildings with multiple uses impacted the LUE distribution negatively. The number of significant predictors increased over time. In 1970, LUE decreased with both the percentage of buildings with multiple uses and the area of self-contained urban expansion.

In 1980, the percentage of one-dwelling buildings was the predictor that impacted the LUE indicator positively with the largest intensity. Lower intensities were observed for the concentration of tourism activities (positive) and agricultural area (negative). Our findings reflect the dominant sprawl model observed in Athens in the late 1970s and the early 1980s. This settlement model was characterized by residential (sometimes informal) urban expansion, creating low-density suburban districts dominated by detached houses, mainly along coastal areas [4]. The proportion of sparse settlements was the most relevant variable determining higher LUE values also for 1990. In that period, the proportion of residential buildings was negatively correlated with LUE. This pattern was associated with massive industrial re-location from the central city on fringe land typically observed in the 1980s [36]. This process resulted in the overall decline of land use efficiency in suburban municipalities.

Interestingly, LUE decreases with the distance from Markopoulo Mesogaia. This reflects the intense sprawl observed in Mesogaia Plain since the early 1980s [28], and it is in line with previous findings indicating urban re-polarization, following dispersed expansion, in the last decade. In 2000, the proportion of sparse settlements is the variable with the highest positive coefficient for LUE and contrasts the negative impact of population density. In 2010, the distance from inner Athens is the variable associated with the most rapid variation in the LUE spatial distribution. However, sparse settlements remain an important variable for LUE together with the extension of forest land. The high vertical profile of buildings, and, thus, settlement compactness/density, is the only variable negatively correlated with LUE. In summary, the multiple regression outputs distinguish among the most relevant socioeconomic and territorial characteristics of the different expansion models in Attica: settlement compaction and population densification in the 1960s; more dispersed expansion along the coasts and on Athens' fringe in the 1970s; urban consolidation on Athens' fringe in the 1980s; a moderate re-polarization in peri-urban areas together with a more diffused; discontinuous urban expansion in the 1990s; and finally, urban sprawl in rural areas in the 2000s.

Table 6. Results of the forward stepwise multiple regression analysis with the LUE indicator as the dependent variable (* indicates a significant coefficient at $p < 0.05$; ** indicates a significant coefficient at $p < 0.0001$; see Table 1 for the abbreviations).

Variable	1960	1970	1980	1990	2000	2010
Population density					−0.31(0.09) **	
Sparse settlement					0.35(0.09) **	0.25 (0.06) **
Agricultural areas			−0.29 (0.10) *			
Forest areas						0.19 (0.05) **
Average building height						−0.17 (0.07) *
Self-contained buildings		−0.26 (0.09) *				
One-dwelling buildings			0.74 (0.10) **	0.62 (0.09) **		
Residential buildings				−0.23 (0.09) *		
Hotel-use buildings			0.29 (0.07) **			
Multiple usage buildings	−0.37 (0.09) *	−0.34 (0.09) **				
Dist. Athens						0.49 (0.08) **
Dist. Markopoulo				−0.26 (0.08) **		
Adjusted R^2	0.13	0.23	0.40	0.27	0.31	0.74
Fisher-Snedecor F	17.7	18.3	25.8	15.2	26.4	82.2
Degrees of freedom	*1113*	*2112*	*3111*	*3111*	*2112*	*4110*
Durbin-Watson test	2.05	2.08	2.14	2.07	1.99	1.89

After the first period (1960, 1970) dominated by the dichotomy between urban areas (with mixed economic functions, dense population and settlement compactness) and rural areas, land use efficiency declined (1980, 1990), with discontinuous, low-density residential settlements along coastal areas surrounding Athens and in 'sprawl' districts (such as Mesogaia). In the last two decades (2000, 2010), land use efficiency was shaped by the expansion of sparse (or even isolated) buildings in forest areas at increasing distances from inner Athens. These results also highlight the importance of semi-dense and spatially balanced morphologies, as revealed by the positive impact of the vertical profile of buildings on LUE [31].

3.7. A Summary Analysis of Urban Growth and Changes in Attica over 1960–2010

Changes in the spatial distribution of land use efficiency and in selected socioeconomic factors were assessed using a multiple factor analysis (Table 7). The analysis illustrates the expansion waves and the progressive restructuring of the spatial structure of Athens' metropolitan region by decade. The analysis extracted two factors with an eigenvalue >2 explaining, respectively, 31.7% and 12.2% of the total variance. Factor 1 identifies the urban-rural gradient with the (progressively increasing) opposition between dense municipalities (population density, settlement compactness, building height, diversity in urban land use, buildings with multiple use, density of services) and rural municipalities with sparse settlements (Figure 6, upper panel). The distribution of loadings along Factor 1 indicates an increasing polarization between urban and rural municipalities over time. In particular, the loadings of urban concentration indicators, such as population density, inhabitants per building and building's vertical profile, increased continuously over time. The concentration of service activities correlated with Factor 1 in 1990 only.

Table 7. The multiple factor analysis (MFA) indicator's loading by factor and year (bold indicates loadings >|0.5|; see Table 1 for the abbreviations).

Variable	1960		1970		1980		1990		2000		2010	
	1	2	1	2	1	2	1	2	1	2	1	2
Population density	**0.71**	0.28	**0.74**	0.29	**0.78**	0.28	**0.81**	0.27	**0.83**	0.25	**0.84**	0.24
Pop. growth	**0.55**	−0.10	**0.53**	−0.15	0.09	−0.36	−0.29	−0.28	0.01	−0.45	0.11	**−0.58**
Sparse settl.	**−0.62**	0.00	**−0.66**	−0.04	**−0.65**	0.00	**−0.71**	−0.05	**−0.65**	−0.20	**−0.53**	−0.24
Agriculture	−0.45	**−0.56**	−0.49	−0.50	−0.51	−0.45	**−0.77**	−0.31	**−0.82**	−0.27	**−0.81**	−0.11
Forests	−0.34	**0.54**	−0.37	**0.51**	−0.37	**0.53**	−0.26	**0.51**	−0.27	**0.60**	−0.34	**0.64**
Protected land	0.21	0.14	0.16	0.24	0.13	0.22	0.16	0.22	0.17	0.21	−0.09	0.21
Inhab/building	0.32	0.17	**0.51**	0.26	**0.78**	0.39	**0.82**	0.37	**0.83**	0.34	**0.86**	0.33
Building height	**0.78**	0.25	**0.80**	0.29	**0.84**	0.28	**0.88**	0.22	**0.86**	0.18	**0.86**	0.16
Self-containm.	−0.50	0.08	−0.10	0.42	0.23	0.30	0.18	−0.08	0.17	−0.11	−0.10	0.10
One-dwell. buil.	**−0.62**	−0.32	**−0.80**	−0.36	**−0.86**	−0.32	**−0.90**	−0.28	**−0.83**	−0.27	**−0.66**	−0.27
Diversity land use	**0.66**	0.07	**0.69**	0.05	**0.69**	0.03	**0.66**	0.02	**0.67**	0.02	**0.70**	0.04
Residential buildings	−0.04	0.01	0.08	−0.18	−0.11	−0.27	−0.36	−0.32	−0.45	−0.34	−0.46	−0.37
Industrial buildings	0.28	0.11	0.20	0.02	0.19	−0.02	0.08	0.05	−0.02	0.14	0.11	0.09
Hotels	0.26	0.05	−0.12	0.21	0.07	−0.04	0.05	0.22	−0.09	0.23	−0.05	0.26
Service/commerce	0.33	−0.02	0.18	0.05	0.47	−0.02	**0.64**	0.11	0.42	0.16	0.40	0.08
Multiple-usage buil.	**0.55**	0.18	**0.66**	0.32	**0.78**	0.40	**0.80**	0.36	**0.76**	0.32	**0.65**	0.16
Municipal area	−0.19	0.32	−0.30	0.31	−0.29	0.36	−0.25	0.34	−0.22	0.40	−0.22	0.40
Elevation	−0.46	**0.64**	−0.46	**0.64**	−0.46	**0.64**	−0.46	**0.64**	−0.46	**0.64**	−0.46	**0.64**
Closeness to the sea	−0.21	−0.45	−0.21	−0.45	−0.21	−0.45	−0.21	−0.45	−0.21	−0.45	−0.21	−0.45
Dist. Athens	**−0.88**	0.26	**−0.88**	0.26	**−0.88**	0.26	**−0.88**	0.26	**−0.88**	0.26	**−0.88**	0.26
Dist. Piraeus	**−0.81**	0.07	**−0.81**	0.07	**−0.81**	0.07	**−0.81**	0.07	**−0.81**	0.07	**−0.81**	0.07
Dist. Maroussi	**−0.73**	0.32	**−0.73**	0.32	**−0.73**	0.32	**−0.73**	0.32	**−0.73**	0.32	**−0.73**	0.32
Dist. Markopoulo	−0.45	**0.70**	−0.45	**0.70**	−0.45	**0.70**	−0.45	**0.70**	−0.45	**0.70**	−0.45	**0.70**
LUE indicator	−0.07	−0.39	−0.19	−0.39	−0.23	−0.35	−0.17	−0.23	−0.23	−0.14	**−0.79**	0.09

By contrast, indicators of discontinuous urban expansion (one-dwelling buildings and sparse settlements) showed negative loadings, with peak values observed for 1990. Taken together, these results confirm that the most relevant changes in the morphological structure of the Attica region (influencing land use efficiency at the local scale) occurred primarily in the 1980s. Interestingly, LUE was associated (negatively) with Factor 1 for 2010 only. This indicates that spatial transformations in Attica are shaping the spatial distribution of land use efficiency along the urban-rural gradient.

Factor 2 loadings illustrate the regional polarization into agricultural and forest (natural) land. Forest areas showed an increasingly negative loading over time, while the agricultural areas' loading decreased in absolute terms. Factor 2 represents a typical (non-urban) land use gradient shaped by elevation: forests are associated with hilly and mountain areas, and the reverse pattern is observed for agricultural areas. Only the distance from Markopoulo M. correlated with Factor 2, indicating that agricultural areas were concentrated in Mesogaia in the first decades and then disappeared progressively due to urban sprawl (Figure 6, lower panel). This result is in agreement with previous studies dealing with land use changes in Attica [31].

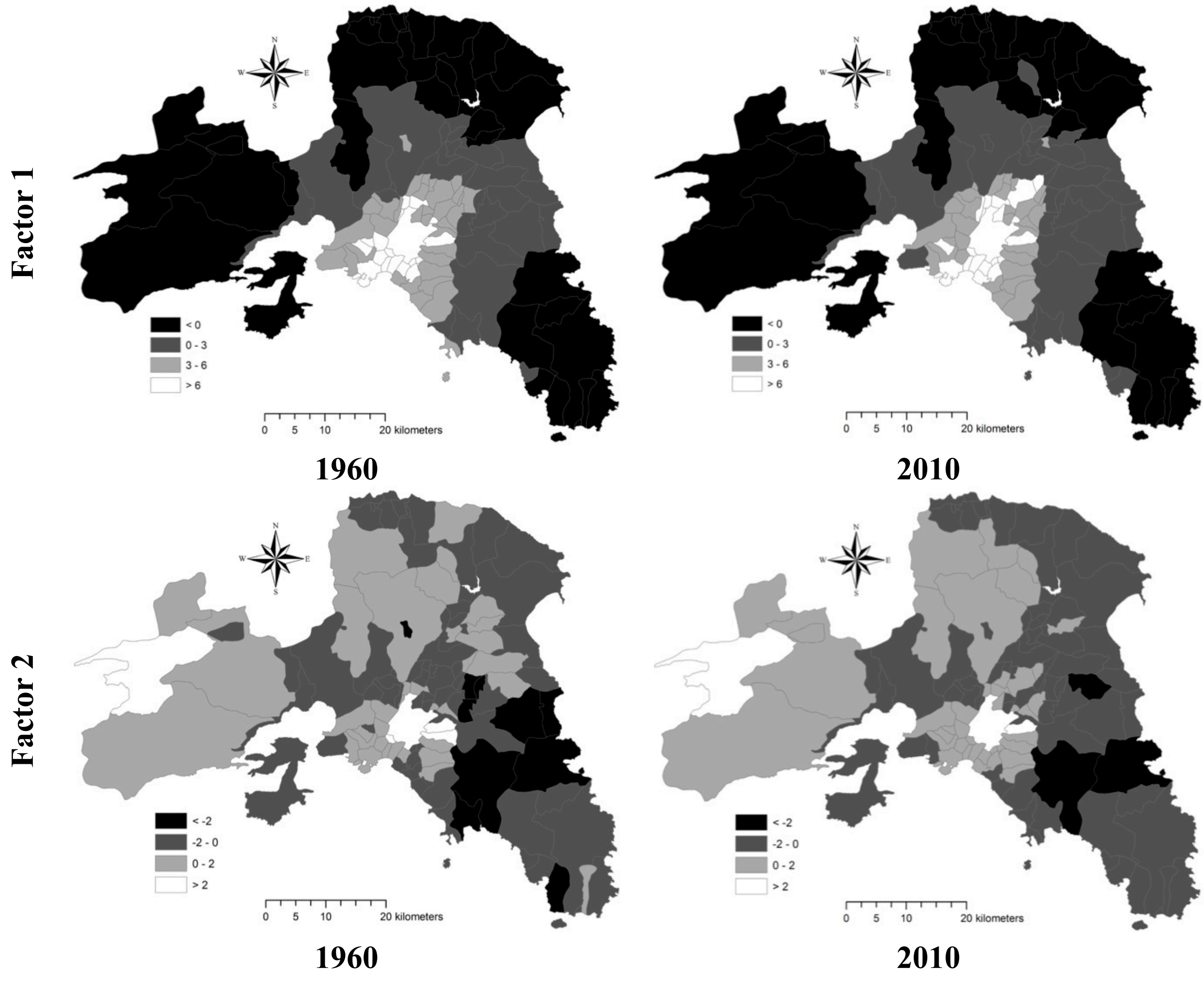

Figure 6. MFA score map by component and year.

4. Discussion

This study proposed an original framework to assess spatio-temporal changes in urban land use efficiency. An evaluation exercise through quantitative indicators and multivariate statistical approaches was carried out in Attica, a southern European region characterized by consecutive phases of compact and dispersed urban expansion [29]. Athens' development did not benefit from an integrated planning of the metropolitan area, being instead influenced by successive waves of de-regulated urban growth characterized by different morphological characteristics and mixed functions [30]. How urban growth and change influence the efficiency in the use of land at the local scale can be an example for other Mediterranean cities undergoing similar expansion processes, spanning from post-war compact expansion to the sprawled development of recent years [4,37–39]. The novelty of this study is in introducing an operational framework aimed at verifying if and how different urban phases (assessed through a large set of contextual indicators) may affect the efficiency in the use of land at both the local and regional scale. Our work clarified the relation between an efficient use of urban land and the local socioeconomic context, identifying the contextual variables most associated with low soil consumption or, conversely, low urban containment [40–42].

The results presented in this paper, based on long-term analysis encompassing the last 50 years of urban growth and change in Athens, indicate the non-linearity in the settlement dynamics and expansion patterns at the local level and the important changes in the urban structure observed at the regional scale. These processes were mainly related to the polarization in areas of low and high efficiency in the use of land along the urban gradient [31]. Based on these results, multi-scalar sustainable land management policies are particularly important for curbing sprawl in peri-urban contexts [43]. At the same time, it seems clear that strategies that re-direct urban expansion towards self-contained development, particularly required in Mediterranean contexts featuring traditionally compact urban morphologies, should be based on the promotion of semi-dense, continuous settlements [44]. This can be done by facilitating the processes of urban consolidation on the fringes developed informally after World War II, as observed in Athens, especially during 1970–1980 and 1980–1990 decades. Mixed urban-rural fringe land is mostly made up of heterogeneous and fragmented areas, which can be converted to urban functions through densification processes, while maintaining a balanced socioeconomic structure and moderate environmental quality [45]. At the same time, a more effective protection of natural and agricultural land from scattered urban expansion is required for rural districts, which were identified in Attica as the places of the most recent sprawl processes [32].

Notably, the present study assesses urban land use efficiency in Athens up to the beginning of the economic and political crisis that struck Southern Europe deeply [46]. It is not yet clear what might be the outcome of these changes in the structure and functions of originally compact, but recently sprawling, regions, such as Attica [47]. The urban transformations observed in the last decade are characterized by a higher land consumption rate at the local scale and reflect a progressive re-polarization of population, settlements and economic activities along the urban gradient at the regional scale. If this condition continues in the coming years, or conversely, if the economic crisis spurs a more efficient use of urban land, depends on many factors combined [48], some of which have been analyzed in this work. Every decade that we have analyzed, in fact, was the result of a dynamic equilibrium between settlement patterns and urban functions. As the convergence analysis applied in this study shows, equilibrium conditions have been altered by (more or less marked) social and economic changes. One case is represented by the transition from a compact expansion to a more dispersed growth observed in the 1980–1990 decade, as the regression analysis indicates. Since the socioeconomic changes observed in the most recent years could drive a new turning point in the development path of several Mediterranean cities, further studies are required to ascertain the possible changes in the relation among urban growth, socioeconomic contexts and land use efficiency at the present time.

Evidence suggests how a balanced local context is a key element when promoting an effective and sustainable use of land resources ([1,4,25] among others). This may depend on the fine-tuning among the different components of the system (e.g., social, economic, territorial, environmental), as was sometimes observed in past waves of Athens' development [30]. These results have important implications when designing policies for sustainable urban form and promoting the containment of sprawl in de-regulated urban contexts [18].

5. Conclusions

Although a general agreement has been reached on the causes of unsustainable urban growth from the perspective of land use efficiency, urban expansion reflects the outcome of a complex interplay between market forces and the, often unintended, consequences of a mix of sectoral policies and practices, as illustrated in the present study. Especially in the actual socioeconomic context, the processes (especially market-driven) through which urban land becomes vacant and is then re-used should be investigated further with the aim of informing more effective policies for self-contained urban expansion. At the same time, greater emphasis should be given to questions of the density and character of development, as well as to location, whether on greenfield or on brownfield land. Long-term joint monitoring of urban growth and land use efficiency proved to be an essential informative tool when designing policies capable of promoting a truly sustainable use of land.

Author Contributions

Marco Zitti and Carlotta Ferrara carried out the statistical analysis and wrote the methodological chapter. Luigi Perini prepared maps and figures' outputs. Margherita Carlucci wrote the introduction. Luca Salvati wrote the remaining part of the manuscript. The original idea of the study is by Luca Salvati.

Conflicts of Interest

The authors declare no conflicts of interest.

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