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Mixed Land Use as an Intrinsic Feature of Sprawl: A Short-Term Analysis of Settlement Growth and Population Distribution Using European Urban Atlas

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Abstract: This study investigates the land-use/population mix over time as the base to derive an indicator of urban sprawl. Land-use individual patches (provided by Urban Atlas, hereafter UA, with a detailed spatial geometry at 1:10,000 scale) were associated with the total (resident) population based on official statistics (census enumeration districts and other public data sources), providing a comprehensive mapping of the spatial distribution of population density by land-use class in a representative case study for the Mediterranean region (metropolitan Athens, Greece). Data analysis adopted a mix of statistical techniques, such as descriptive statistics, non-parametric curve interpolation (smoothing splines), and exploratory multivariate statistics, namely hierarchical clustering, non-metric multi-dimensional scaling and confirmative factor analysis. The results of this study indicate a non-linear gradient of density decline from downtown (dominated by compact settlements) to peripheral locations (dominated by natural land). Population density in agricultural land was locally high and increasing over time; this result suggests how mixed land use may be the base of intense sprawl in large metropolitan regions. The methodology implemented in this study can be generalized over the whole sample of European cities included in Urban Atlas, providing a semi-automatic assessment of exurban development and population re-distribution over larger metropolitan regions.

Keywords: metropolitan expansion; residential settlements; density curve; Urban Atlas; Southern Europe

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1. Introduction

Sprawl, a process of latent urban diffusion over progressively larger regions, is a heavily debated issue in the disciplinary fields of Urbanism, Planning, Applied Economics, Geography, Sociology, Demography, and Environmental Sciences [1–8]. As sprawl involves multiple subjects of study, the phenomenon is fascinating while being, in turn, hard to analyze [9–13]. For such reasons, sprawl has been the subject of a plethora of research, with the objective of defining the nature, impacts, and consequences of low-density settlement growth on local territorial systems—both urban and rural—all over the world [14–18]. Sprawl dynamics accompanied and, in some ways, determined the most recent evolution of urbanization patterns and processes in advanced economies, both in the 'old' and in the 'new' world, creating a mixed landscape dominated by discontinuous and low-density settlements [19–23]. Moreover, sprawl, initially defined with regards to the North American context, has been demonstrated to be connected with the environmental, political, social, cultural and economic characteristics of any region, justifying the adoption of ad-hoc approaches that give value to the peculiarities of the local context [24–28]. Thus, the investigation of sprawl, universally performed using building, land-use and demographic indicators, and thus considering together form (i.e., morphology) and functions (i.e., developmental dynamics) of representative human settlements [29–33], could receive further value with the introduction of spatially explicit approaches.

In many contexts, sprawl appears subtly mixed with other forms of urban expansion, including compact and dense growth [34–37]. Land scarcity, agglomeration and scale factors, economic downturns, social permeability of fringe districts, a strong urban ideal of rural populations, spatially imbalanced demographic dynamics and international migration are some elements at the base of this mixed pattern of metropolitan expansion, which is even more difficult to define and quantify operationally than the 'pure' urban sprawl [38–42]. Making the intrinsic, mutual linkage between urban and rural areas particularly complex [43–47], sprawled or mixed (compact-dispersed) patterns of settlement expansion have also affected, at least indirectly, the social composition of central locations in recent times [48–52]. This process has determined a sort of spatial rebalance of population, settlements and land use along metropolitan (i.e., density) gradients. As a matter of fact, it was demonstrated—especially in the Old World—how the formation of metropolitan continuums and polycentric settlements was progressively altering the traditional compact structure of mono-centric cities [49,53,54].

Being connected with sprawl, the reduction in density spans regions thus became a challenging issue that needs further investigation, comparing different disciplinary approaches, analysis perspectives, socioeconomic contexts, and policy frameworks [55–59]. The role of rural spaces surrounding cities as a land stock for the sprawled expansion of settlements has also been largely differentiated on the base of local factors [60–64], and the definition of 'rural space' is still a matter of intense debate, since multiple operational criteria were proposed depending on the place identity of non-urban districts [65–69]. With this perspective in mind, the aim of this contribution is to provide a detailed picture on the nature of urban sprawl using a multivariate exploratory analysis of high-resolution morphological and demographic indicators, based on easily available and free data, focusing on its short-term dynamics, and discussing selected effects on social and landscape systems.

The analysis of urban sprawl was focused on the Mediterranean region, investigating land-use, settlement, and population indicators that may scrutinize morphological and functional dynamics of metropolitan development together. Based on a geo-spatial perspective, the empirical results of this analysis contribute to verify the intimate characteristics of the dominant urban trend observed in the most recent period. Assuming the appropriateness of a mixed model alternating compact growth and subtle sprawl of metropolitan expansion [70], the empirical results of this study are summarized and discussed in light of the debate on future developmental paths of Mediterranean cities. Considering land scarcity, heterogeneous economic impulses, social permeability, and the strong urban ideal associated with (long-term) urbanization processes as powerful drivers of metropolitan change in Southern Europe, the final aim of this study re-orients conceptual frameworks interpreting the newly emerging settlement models in the old continent.

2. Methodology

2.1. Study Area

This work investigates a large part of the administrative region of Attica coinciding with metropolitan Athens, the capital city of Greece (Figure 1). Extending more than 3000 km^2, nearly 400 km^2 were classified as strictly urban and correspond with the Greater Athens area, the largest conurbation in Greece [71]. In the Greater Athens area, population density surpassed 5000 inhabitants/km^2, declining in rural locations to values between 300 and 500 inhabitants/km^2 on average [72]. This area has been chosen as paradigmatic of the urban development of a traditionally mono-centric settlement gradually shifting towards a more disperse and irregular settlement structure. Athens' urban expansion has been continuous and intense since the last century, determining the highest population concentration in the 1970s (nearly 20,000 inhabitants/km^2 downtown, on average) [70,73]. In the most recent decades, suburbanization fueled the creation of spatially discontinuous (and often isolated) settlements in correspondence with agricultural land-use, especially in accessible locations [74], progressively destroying the traditional landscape characteristic of rural Attica [60,75–77].

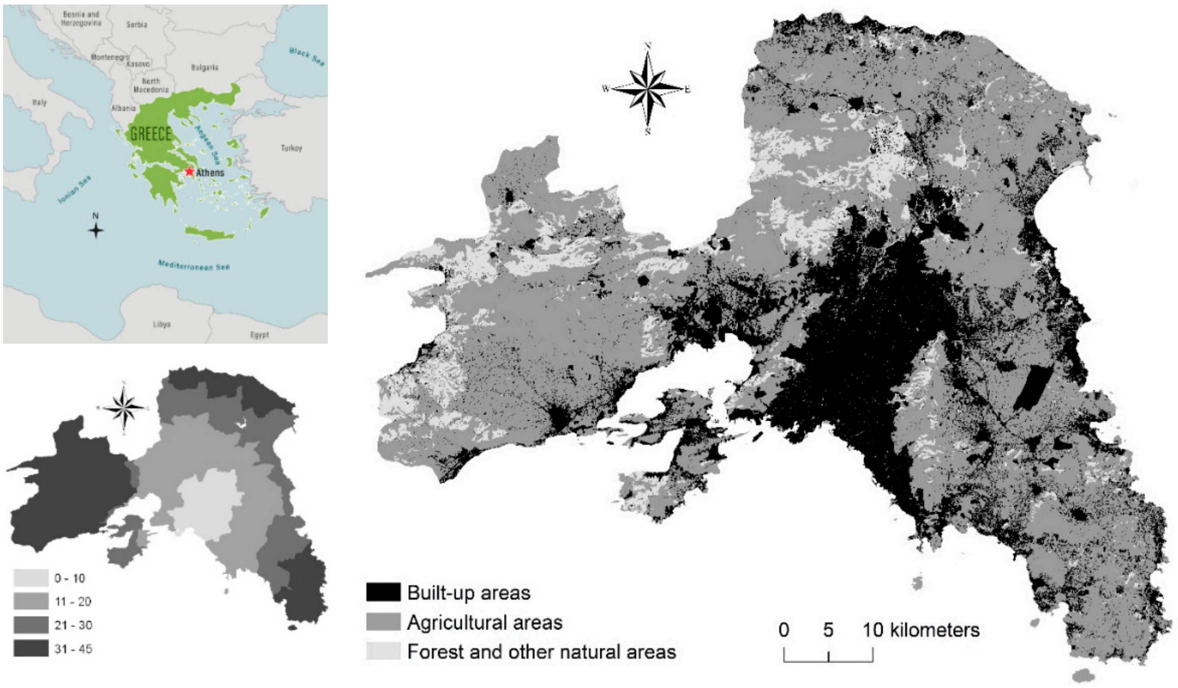

Figure 1. Spatial coverage of the study area and its location in Greece and the Eastern Mediterranean basin; (**upper left**): the position of Athens (red star) in the country; (**lower left**): the boundaries of the study area and the average distance from downtown (km); (**right**): the spatial distribution of different land uses (built-up, agriculture, forests) in metropolitan Athens based on high-resolution urban atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System).

2.2. Data and Variables

This work involves the integrated use of geo-spatial data sources provided by the European Environment Agency initiative, in order to achieve a more refined interpretation of short-term settlement patterns in the study area, also considering the related population dynamics [78,79]. This initiative, called Copernicus, was taken under a program managed by the European Union Maritime Safety Agency (EMSA) and the European Space Agency (ESA), with the support of other European and international organizations. The program bases its work on six thematic services: land, marine, atmosphere, climate change, emergency management, and security and develops free data openly accessible by all users. The local component of the land service is represented by the 'Urban Atlas' product which provides detailed information on urban characteristics and useful data for different fields of study [50,80–82]. The product, thanks to the use of high-resolution satellite images and advanced analysis techniques, provides in its most recent versions related to the years 2012 and 2018 land-use data for more than 780 Functional Urban Areas (FUA) and the estimate of total population residing in each part of the investigated areas [83]. The amplitude of both the geographic coverage and the dashboard of elementary data makes this source extremely valuable, even if its use constraints the time horizon of the empirical analyses.

The Urban Atlas land-use nomenclature based on 27 classes established by EEA [82] was adopted here, and the list of classes, with extensive description, is reported as follows: Continuous Urban Fabric with sealed land > 80% (1110), Discontinuous Dense Urban Fabric with sealed land between 50% and 80% (1121), Discontinuous Medium-Density

Urban Fabric with sealed land between 30% and 50% (1122), Discontinuous Low-Density Urban Fabric with sealed land between 10% and 30% (1123), Discontinuous Very Low-Density Urban Fabric with sealed land <10% (1124), Isolated Structures (1130), Industrial, commercial, public, military and private units (1210), Fast transit roads and associated land (1221), Other roads and associated land (1222), Railways and associated land (1223), Port areas (1230), Airports (1240), Mineral extraction and dump sites (1310), Construction sites (1330), Land without current use (1340), Green urban areas (1410), Sports and leisure facilities (1420), Arable land with annual crops (2100), Permanent crops, basically vineyards, fruit trees, and olive groves (2200), Pastures (2300), Complex and mixed cultivation patterns (2400), Orchards at the fringe of urban classes (2500), Forests (3100), Herbaceous vegetation associations including natural grassland (3200), Open spaces with little or no vegetation such as beaches, dunes, or bare rocks (3300), Wetland (4000) and Water bodies (5000).

2.3. Statistical Analysis

Tables, graphs, and maps were used to illustrate the statistical distribution of land use, settlement, and population in the study area. The resident population (absolute number and density) was provided for each land-use patch, irrespective of class typology. To compute morphological and demographic descriptors specific to each land use, we have worked on the geo-spatial database (dbf tabular format) associated with each Urban Atlas shapefile. Descriptive statistics were calculated with the aim of providing a coherent (aggregate) description of the landscape matrix by land-use class, considering six indicators (both morphological and demographic). These descriptors were selected with the aim at assuring a comprehensive (functional) interpretation of heterogeneous landscape matrices characteristic of metropolitan regions, containing—at the same time—the risk of redundancy related to the use of multiple input variables. Descriptors include (i) mean patch size (Area) and (ii) a measure of statistical variability of the mean patch size (coefficient of variation) both calculated by land-use class (AreaSD), (iii) percentage areal share in total landscape by land-use class (%Area), (iv) mean edge density (ED) by class, a landscape metric that estimate the morphological convolution of patches, (v) per cent population share (%Pop) in total population (metropolitan Athens) by class, and finally (vi) the average population density by class (Den).

2.3.1. Modeling Density/Land-Use Gradients through Smoothing Splines

Smoothing splines, basically a sequence of third-order polynomials continuous up to the second derivative [84] were adopted in this study to estimate a smooth curve that best fit the land-use specific relationship between population density and its rank. This exercise was run separately for the two observation years (2012 and 2018) using average population density (log-transformed) by land-use type, considering only classes with non-null population density. Smoothing splines were used to explore non-linear, complex forms in the relationship between population density and land-use. Based on the sample size considered in this study (n = 14 classes with non-null population), an optimal smoothing run by a cross-validation procedure allows performing an estimation of the land-use/population relationship adopting a third-order moving average as an appropriate indicator function for both observation years. To gain an indirect confirmation of the result of smoothing splines, the same relationship was tested with more conventional methodologies including a pair-wise parametric correlation analysis (based on Pearson moment-product coefficients and the related statistical inference testing at $p < 0.05$ against the null hypothesis of no correlation between population density and land-use rank) and a linear regression fitting land-use rank against log-transformed population density.

2.3.2. Delineating Landscape-Population Characteristics under Compact Growth and Sprawl

The latent relationship between the spatial distribution of resident population across land-use classes in metropolitan Athens was studied over time (2012 and 2018) considering two basic approaches grounded on the analysis of the six (morphological and demographic) descriptors illustrated above (Section 2.3). More specifically, two criteria identifying the latent relationship between population distribution and land use were adopted, considering separately (i) similarity in the statistical distribution of morphological and demographic descriptors across land-use classes and (ii) the intrinsic (multivariate) correlation between descriptors across the land-use nomenclature (n = 27 land-use classes) adopted in Urban Atlas. The empirical analysis related to issue (i) was run adopting Hierarchical Clustering (HC) and non-metric MultiDimensional Scaling (n-MDS) as a multivariate exploratory strategy for input data with some deviations from normality, while analysis related to issue (ii) was realized using a generalized, three-way (years x descriptors x land use) factor decomposition of dynamic correlation matrices (namely, a confirmative factor analysis).

HC—based on Euclidean distances with Ward's agglomeration rule—and n-MDS—based on Manhattan distances—were adopted here as assumption-free and flexible exploratory techniques aimed at evaluating the overall (multivariate) similarity among (morphological and demographic) descriptors. The two distance metrics (Euclidean and Manhattan) were extensively adopted in earlier works analyzing demographic and landscape phenomena [85,86]. More specifically, HC provided an aggregate (graphical) representation of descriptors' similarity based on dendrograms; n-MDS was used to delineate the intrinsic, overall similarity among land-use classes, based on the multivariate statistical distribution of the descriptors. n-MDS is a valid alternative to principal component analysis (or generalized factor techniques) when considering similarity patterns among input variables. In brief, the aim of the analysis was to detect meaningful (latent) dimensions that allow explaining observed similarities or dissimilarities (distances) between the investigated objects. Irrespective of the input variables' metric, n-MDS attempts to arrange the investigated 'objects' (land-use class in our case) in a geometrical (latent) space with a particular number of dimensions (e.g., two-dimensional) so as to reproduce the observed distances based on a similarity matrix. As a result, similarities and differences between land use classes were summarized in terms of the few underlying dimensions extracted and plotted in a specific scatterplot.

n-MDS is thus an approximate procedure 'rearranging' objects in an efficient manner, so as to arrive at a geometrical configuration that best approximates the observed distances based on similarity metrics. It actually moves objects around in the space defined by the requested number of dimensions and checks how well the distances between objects can be reproduced by the new configuration, using a function minimization algorithm that evaluates different configurations with the goal of maximizing the goodness of fit (or, more specifically, minimizing the 'lack of fit'). In this perspective, 'stress' is the most common measure evaluating how well (or poorly) a particular configuration reproduces the observed distance matrix. In this study, the raw stress value 'Phi' of a given configuration was adopted as defined by

$$\mathrm{Phi} = [d_{ij} - f(ij)]^2$$

where d_{ij} stands for the reproduced distances, given the respective number of dimensions, and f_{ij} stands for the input data (i.e., observed distances); f(ij) indicates a non-metric, monotone transformation of the observed input data (distances) and attempts to reproduce the general rank ordering of distances between the objects in the analysis. The smaller the stress value, the better the fit of the reproduced distance matrix to the observed distance matrix. The reproduced distances for a particular number of dimensions against the observed input data (distances) were finally illustrated using a scatterplot called the 'Sheppard diagram'. This plot shows the reproduced distances plotted on the vertical (Y) axis versus the original similarities plotted on the horizontal (X) axis. Deviations from the step-line indicate lack of fit.

2.3.3. Exploring the Evolution of Land-Use and Population Distribution over Metropolitan Athens, 2012–2018

To corroborate the results of HC and n-MDS, a dynamic factor analysis was run on a three-dimensional matrix (descriptors × land-use class × year) with the aim of decomposing latent correlation patterns among the most important (morphological and demographic) dimensions of landscape change [87]. Results of the analysis were presented separately by year ('partial analysis') and overall ('global analysis'). In both cases, factors with eigenvalue >1 were analyzed for the structure of loadings (morphological and demographic descriptors) and scores (land-use classes) providing a biplot, namely a graphical representation of the multivariate relationship between cases (land-use) and variables (descriptors). Global analysis evaluated a multivariate measure of rapidity-of change (2012–2018) separately for land uses and descriptors [54]. Changes over time across the selected axes (see above) and the global change overall were reported in a table considering a standardized measure of change. Higher values of this metric indicate a more dynamic context as far as the given variable is concerned.

3. Results

3.1. A Descriptive Analysis of Land-Use and Population Dynamics

Figure 2 outlines a possible representation of the urban–rural gradient in metropolitan Athens based on population density as a function of land-use class. Considering the absolute value of population density by land use derived as spatial overlap and intersection of high-resolution information layers from the European Urban Atlas, results of this graph represent an innovative contribution to urban science. The gradient illustrated in Figure 2 reflects agglomeration and scale factors and is based on two coexisting trends: (i) a rapidly decreasing vertical axis that moves from compact residential land use (code 1110) to discontinuous residential land use (code 1130) and (ii) an almost horizontal branch moving from low-density to null-density (land-use) classes representing non-urban, natural land, mainly forests, rocks, and wetlands. These trends are similar in the two years studied. A slight increase in individual land-use density values was observed in 2018 compared to 2012 primarily for non-residential urban land use (1230 and 1420).

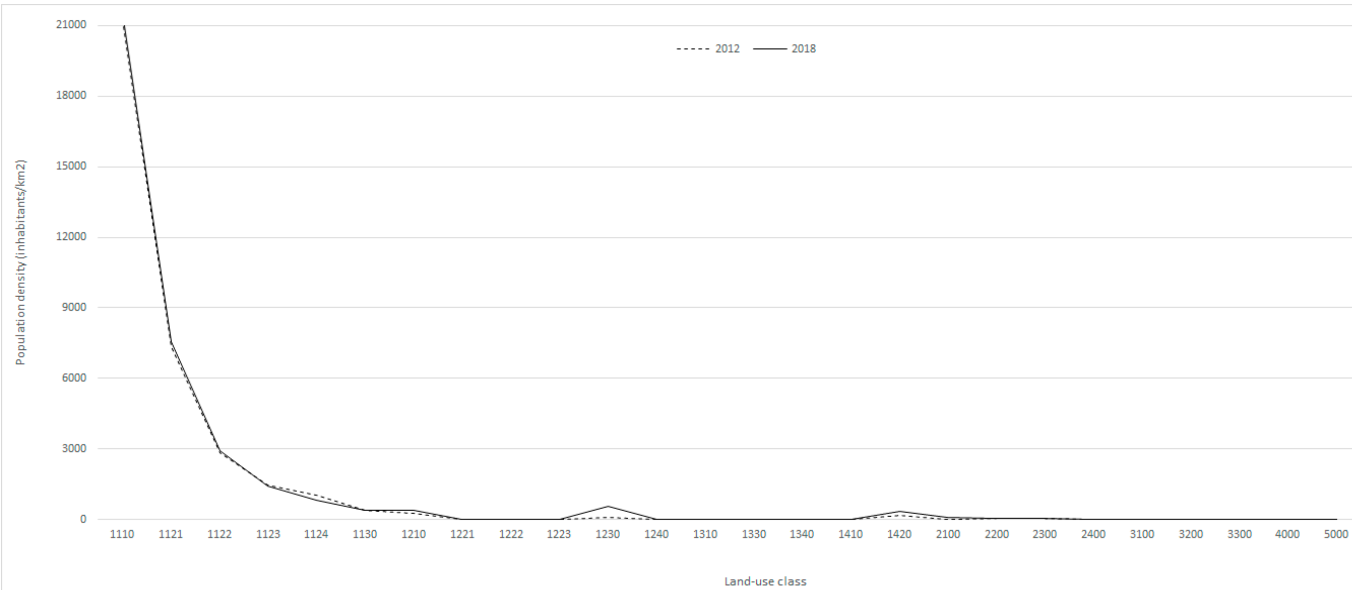

Figure 2. Population density (inhabitants/km^2) by year and land-use class (Urban Atlas nomenclature, see Section 2.2) in metropolitan Athens based on high-resolution Urban Atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System).

Figure 3 illustrates the spatial distribution of population density in metropolitan Athens separately for 2012 and 2018, representing the intimate geography of individual landscape patches that discriminate between different land uses as elementary analysis' units. Taken together, these maps highlight the heterogeneous distribution of the resident population in the study area. Despite the persistent concentration of population in downtown Athens, a progressive settlement de-concentration was observed moving at greater distances from the inner city, indirectly confirming the existence of a mono-centric model explaining past evolution and recent metropolitan growth in Athens. Recent trends towards dispersed (or mixed) urban growth can be thus interpreted as a radio-centric and additive expansion towards the most peripheral areas of Greater Athens.

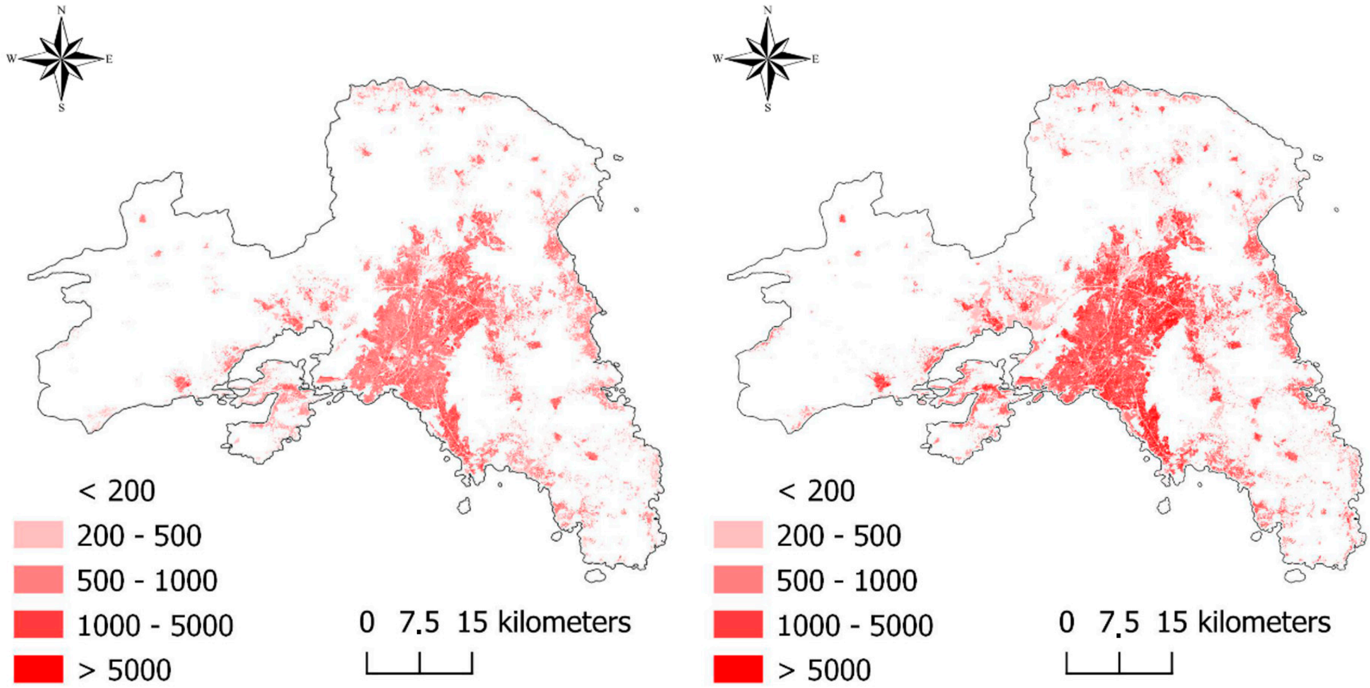

Figure 3. The spatial distribution of population density (inhabitants/km^2) in metropolitan Athens by year ((**left**): 2012; (**right**): 2018) based on high-resolution urban atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System).

Tables 1 and 2 illustrate selected statistics regarding a selection of relevant variables in the analysis of landscape and the spatial distribution of resident population, distinguishing the respective values for 2012, 2018 and the absolute variation in the related time interval. The 1110 class, which represents compact settlements, includes 62.8% of the total population of the Athens metropolitan area, dominating the mono-centric, dense, and additive structure that still characterizes downtown Athens and Piraeus, the third city (after Thessaloniki) and the main port of Greece. A quarter of the population resided in dense, discontinuous areas (1121), and only 7.4% settled in areas with medium-density discontinuous settlements (1122). Finally, areas with low-density residential settlements hosted only 3% of the total population. These four classes of land use concentrate almost all the population residing in Attica.

Table 1. Basic land-use attributes (mean patch area and its coefficient of variation, average edge density of patches, total area of patches, percentage share of patches in total landscape, mean population density, and percentage share of population in total population by class) in metropolitan Athens (2012) based on high-resolution urban atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System; nomenclature codes reported in Section 2.2).

Class	Mean Area (ha)	Coeff. Variation	Edge Density	Total Area (km^2)	Area Share (%)	Popul. Density	Popul. Share (%)
110	0.38	0.69	0.013	109	3.51	21,258	62.8
1121	0.64	0.88	0.016	125	4.05	7327	24.9
1122	0.85	0.97	0.017	96	3.10	2845	7.4

Table 1. *Cont.*

Class	Mean Area (ha)	Coeff. Variation	Edge Density	Total Area (km^2)	Area Share (%)	Popul. Density	Popul. Share (%)
1123	1.01	1.00	0.018	76	2.44	1474	3.0
1124	0.80	1.04	0.017	13	0.43	1040	0.4
1130	0.47	0.54	0.015	22	0.70	402	0.2
1210	1.68	2.46	0.022	128	4.14	274	1.0
1221	8.41	2.04	0.019	7	0.22	0	0.0
1222	158.7	8.84	0.004	141	4.56	0	0.0
1223	9.93	1.50	0.013	4	0.13	0	0.0
1230	13.15	2.55	0.034	12	0.40	71	0.0
1240	199.4	1.61	0.145	20	0.64	0	0.0
1310	4.98	3.00	0.031	18	0.58	2	0.0
1330	1.07	1.50	0.017	2	0.05	0	0.0
1340	0.71	3.18	0.015	10	0.32	4	0.0
1410	1.74	2.94	0.020	30	0.97	0	0.0
1420	2.80	3.35	0.026	20	0.64	184	0.1
2100	9.13	2.46	0.038	37	1.18	1	0.0
2200	5.16	1.95	0.031	62	2.02	24	0.0
2300	4.50	1.75	0.031	152	4.91	30	0.1
2400	5.95	2.22	0.032	281	9.08	0	0.0
3100	16.34	3.38	0.043	295	9.51	0	0.0
3200	18.04	7.38	0.031	1303	42.1	0	0.0
3300	5.49	4.15	0.028	58	1.88	0	0.0
4000	25.80	1.39	0.066	5	0.17	0	0.0
5000	127.1	4.69	0.038	71	2.30	0	0.0

Table 2. Basic land-use attributes (mean patch area and its coefficient of variation, average edge density of patches, total area of patches, per cent share of patches in total landscape, mean population density, and percentage share of population in total population by class) in metropolitan Athens (2018) based on high-resolution urban atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System; nomenclature codes reported in Section 2.2).

Class	Mean Area (ha)	Coeff. Variation	Edge Density	Total Area (km^2)	Area Share (%)	Popul. Density	Popul. Share (%)
1110	0.38	0.69	0.013	109	3.51	21,572	61.9
1121	0.64	0.88	0.016	125	4.05	7573	25.1
1122	0.85	0.97	0.017	96	3.10	2926	7.4
1123	1.02	1.00	0.018	76	2.45	1438	2.9
1124	0.81	1.13	0.017	13	0.43	834	0.3
1130	0.47	0.54	0.015	22	0.70	403	0.2
1210	1.67	2.44	0.022	132	4.26	407	1.4
1221	8.41	2.04	0.019	7	0.22	0	0.0
1222	155.5	8.95	0.004	142	4.57	0	0.0
1223	9.44	1.57	0.012	4	0.14	0	0.0
1230	13.44	2.63	0.034	13	0.41	558	0.2
1240	181.3	1.72	0.134	20	0.64	0	0.0
1310	5.21	3.00	0.031	18	0.57	0	0.0
1330	1.36	1.25	0.023	0	0.01	0	0.0
1340	0.68	3.17	0.015	10	0.31	0	0.0
1410	1.74	2.94	0.020	30	0.97	0	0.0
1420	2.83	3.34	0.026	20	0.65	365	0.2

Table 2. *Cont.*

Class	Mean Area (ha)	Coeff. Variation	Edge Density	Total Area (km^2)	Area Share (%)	Popul. Density	Popul. Share (%)
2100	8.62	2.52	0.036	36	1.15	106	0.1
2200	5.15	1.95	0.031	62	2.01	62	0.1
2300	4.47	1.75	0.030	151	4.87	53	0.2
2400	5.93	2.23	0.031	281	9.05	0	0.0
3100	16.34	3.38	0.043	295	9.51	0	0.0
3200	18.01	7.39	0.031	1303	42.0	0	0.0
3300	5.49	4.15	0.028	58	1.89	0	0.0
4000	25.80	1.39	0.066	5	0.17	0	0.0
5000	126.7	4.68	0.038	71	2.29	0	0.0

Residual areas with discontinuous and dispersed settlements (1124 and 1130 codes) hosted only 0.5–0.6% of the resident population. Urban areas with non-residential settlements (macro-classes 1.3 and 1.4) concentrated nearly 1% of the total population. The population associated with agricultural areas amounted to less than 1% in both periods, while the areas with land use classified as macro-classes 3, 4, and 5 (non-urban and non-agricultural land use) were found to have no population at all, both in 2012 and 2018.

Table 3 highlights the main landscape changes between 2012 and 2018. Considering the short-term time horizon, modest changes were expected both regarding the possible re-distribution of the population and land-use modifications. The resident population decreased, slowly but steadily, in all classes of residential urban land use (1110–1124 codes), albeit with rather different proportions, while rising in some non-residential urban classes (1210 and 1230 codes), in parallel with the increase in population density. Conversely, population density increased markedly in central areas with more dense settlements, while decreasing slowly in areas with discontinuous settlements. The slow increase in the share of population among the total resident population in metropolitan Athens was observed in correspondence with agricultural land use, confirming the expansion of discontinuous low-density or spatially isolated settlements in accessible rural areas.

Table 3. Basic land-use attributes (mean patch area and its coefficient of variation, average edge density of patches, total area of patches, per cent share of patches in total landscape, population density (differential value per km^2) and percentage share of population in total population by class) in metropolitan Athens calculated as absolute difference between 2012 and 2018 data based on high-resolution urban atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System; nomenclature codes reported in Section 2.2).

Class	Mean Area (ha)	Coeff. Variation	Edge Density	Total Area (km^2)	Area Share (%)	Popul. Density	Popul. Share (%)
1110	0.0	0.0	0.0	0.0	0.0	314.4	−0.9
1121	0.0	0.0	0.0	0.0	0.0	245.8	0.1
1122	0.0	0.0	0.0	0.2	0.0	81.6	0.0
1123	0.0	0.0	0.0	0.4	0.0	−35.9	−0.1
1124	0.0	0.1	0.0	0.1	0.0	−205.7	−0.1
1130	0.0	0.0	0.0	0.1	0.0	0.5	0.0
1210	0.0	0.0	0.0	3.8	0.1	132.4	0.5
1221	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1222	−3.2	0.1	0.0	0.3	0.0	0.0	0.0
1223	−0.5	0.1	0.0	0.3	0.0	0.0	0.0
1230	0.3	0.1	0.0	0.3	0.0	487.1	0.2
1240	−18.0	0.1	0.0	0.0	0.0	0.0	0.0

Table 3. *Cont.*

Class	Mean Area (ha)	Coeff. Variation	Edge Density	Total Area (km^2)	Area Share (%)	Popul. Density	Popul. Share (%)
1310	0.2	0.0	0.0	−0.3	0.0	−1.8	0.0
1330	0.3	−0.2	0.0	−1.3	0.0	0.0	0.0
1340	0.0	0.0	0.0	−0.4	0.0	−4.4	0.0
1410	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1420	0.0	0.0	0.0	0.3	0.0	181.2	0.1
2100	−0.5	0.1	0.0	−0.9	0.0	104.9	0.1
2200	0.0	0.0	0.0	−0.2	0.0	38.2	0.1
2300	0.0	0.0	0.0	−1.0	0.0	22.7	0.1
2400	0.0	0.0	0.0	−0.9	0.0	0.0	0.0
3100	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3200	0.0	0.0	0.0	−0.5	0.0	0.0	0.0
3300	0.0	0.0	0.0	0.1	0.0	0.0	0.0
4000	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5000	−0.4	0.0	0.0	−0.2	0.0	0.0	0.0

3.2. Depicting the Metropolitan Gradient with Joint Land-Use and Population Dynamics

Figure 4 offers a graphical representation of the urban–rural gradient based on the distribution of population density according to the different land-use classes, ordered according to an increasing naturalness gradient from macro-class 1 (urban) to macro-class 5 (water bodies). In Figure 4, however, only land-use classes associated with non-zero values of population density have been reported and analyzed. Moving from macro-class 1 to macro-class 2, a constant decrease in population density was observed with a scaling leap in 2012, which distinguished strictly urban areas (residential/productive) from transitional (urban-rural) areas. On the contrary, the same analysis carried out in 2018 shows a more balanced, logarithmic distribution of population density in space. The density values decreased progressively and almost linearly with the increase of the urban–rural rank, outlining a very sharp metropolitan density gradient. This gradient underlies a process of progressive redistribution of the population towards areas with mixed urban–rural land use, a characteristic attribute of recent sprawl dynamics. The shift towards a linear transformation of the relationship between urban ranking and population density was evident in the non-parametric estimation presented in Figure 4 (making use of smoothing splines). The increase over time in a parametric pairwise correlation index (Pearson) from 2012 ($r = -0.944$, $p < 0.001$, $n = 14$) to 2018 ($r = -0.994$, $p < 0.001$, $n = 14$) gave intrinsic ground to such findings. A regression analysis finally confirmed the strength of this relationship over time (2012: $y = 4.67 - 0.30x$, $R^2 = 0.892$; 2018: $y = 0.457 - 0.32x$, $R^2 = 0.988$).

Assuming the dashed line as the condition for stability over time in both settlement growth and landscape change, the relationship between population density (log-transformed) and land-use classes in 2012 and 2018 in metropolitan Athens was illustrated in Figure 5a. The analysis highlights how the most marked variations in population density (deviations upwards or downwards from the dashed line) were observed in correspondence with some urban non-residential (1210, 1230, 1420) and agricultural (2100, 2200, 2300) land-use classes. These deviations were systematically located upwards and indicate increasing population density between 2012 and 2018. This trend was seen as a result of short-term sprawl processes affecting fringe areas that were not yet fully urbanized, with the progressive conversion of non-urban patches into settlements and the consequent increase in the density of the resident population (e.g., local phenomena of compaction and densification).

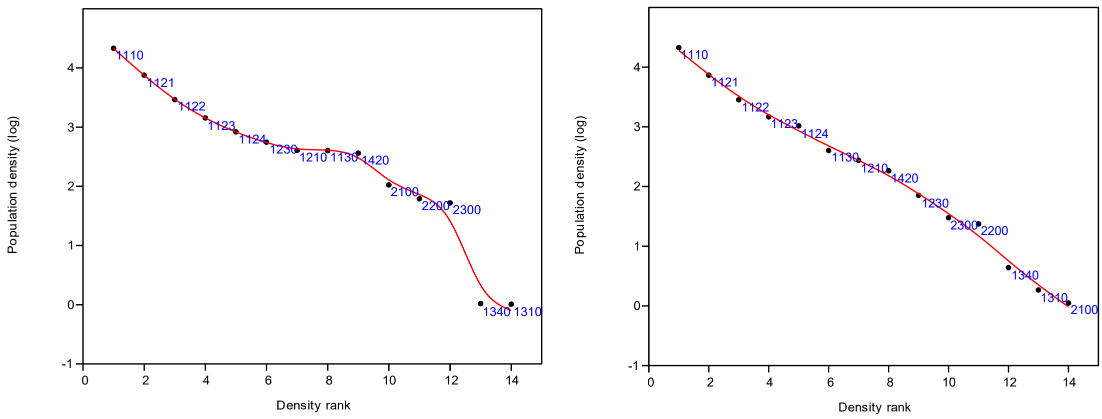

Figure 4. Results of a smoothing spline analysis (red line) of the population/land-use density gradient in metropolitan Athens separately for 2012 (**left**) and 2018 (**right**) based on elaboration of high-resolution urban atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System; nomenclature codes reported in blue and described in Section 2.2).

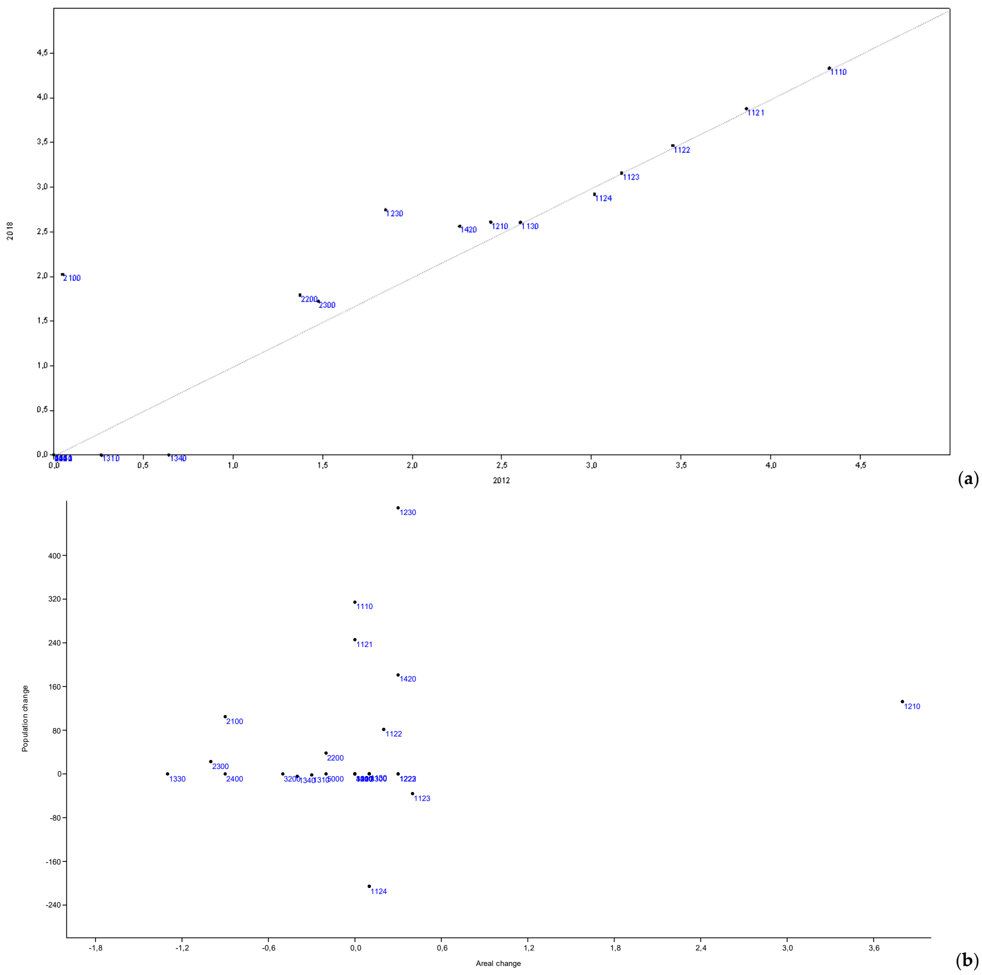

Figure 5. (**a**) The relationship between population density (log-transformed) by land-use class in 2012 and 2018 in metropolitan Athens (dashed line delineates the assumption of landscape–settlement stability over time, see Section 3.2); (**b**) a scatterplot confronting areal change and population change (2012–2018) in metropolitan Athens by land-use class based on elaboration of high-resolution urban atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System; nomenclature codes reported in Section 2.2).

These processes have been monitored more closely in Figure 5b, where the percentage of changes over time (2012–2018) in population density and land-use area have been compared. Although it is not possible to define an explicit relationship between the two variables, it can be stated that only a small number of land-use classes were located around the center of gravity of the scatterplot (approximately zero values for both variables). On the contrary, many land-use classes have experienced a (more or less) modest acreage reduction following a stable population (3200, 1340, 1310, 5000 codes) or a slow rise in population density (2300, 2400, 1330, 2100, 2200). In correspondence with these land-use classes, settlement phenomena have occurred despite the related areal contraction. In other cases, the growth in population density was more evident, both in a context of geographical stability that characterizes the most consolidated urban settlements (1110, 1121), and in a context of moderate expansion of settlements (1230, 1420, 1122, 1210, 1223).

3.3. Similarity in the Spatial Distribution of Population and Land-Use

Figure 6 illustrates the empirical results deriving from the application of two statistical techniques (hierarchical clustering and non-metric multidimensional scaling), considering six morphological and demographic descriptors (Area, Area(SD), ED, %Area, %Pop, Dens) made available for each land-use class (see Tables 1 and 2). The spatial distribution of the descriptors proved to be similar and stable when comparing 2012 (left) with 2018 (right) data. Compared with the demographic descriptors, the morphological descriptors reflected more heterogeneity, even if a marked similarity has been observed between Edge Density (ED) and the percentage of area associated with each land use. The average size of patches, regardless of land use, appears to be a particularly heterogeneous descriptor decoupled from the other descriptors, both morphological and demographic.

Non-metric multidimensional scaling outlined similarities and divergences in the distribution of the 27 land-use classes, according to the values of the six (morphological and demographic) descriptors in each class. Some differences were found between 2012 and 2018, likely associated with the progressive spatial rebalancing of the population towards areas with mixed urban–rural land-use. In 2012, quadrant III of the n-MDS scatterplot highlighted a cluster of land-use classes characterized by similar morphological and demographic traits (from 1110 to 2300) as opposed to transitional, mixed land use (1340, 1330, 1410)—mainly positioned in quadrant IV—and rural land-use (except 1240) with zero-population located in quadrant I. The scatterplot referring to 2018 highlighted the existence of two groups stretched along the Dimension 1 (urban land use and rural, transitional land use oriented towards the negative values of the axis; rural land use with zero population oriented towards the positive values of the axis). The Sheppard plots illustrated in Figure 6 below (2012: left; 2018: right) also indicate a satisfactory representation of the real data matrix in the first two non-metric coordinates of the MDS, with a stress index of 0.032 (2012) and 0.042 (2018) and an R^2 value reflecting the quality of data representation on Dimension 1 equal to 0.983 (2012) and 0.993 (2018).

3.4. The Spatio-Temporal Correlation in the Distribution of Population Density and Land-Use

The latent relationship between the distribution of the resident population and the prevailing land use in a given area was assessed running a multi-way factor analysis of short-term dynamics (2012–2018) in both analysis' dimensions (population and land-use). The results of a partial factor analysis (i.e., per year) were reported in Figure 7, starting from the same data matrix used in the non-metric MDS (consisting of six descriptors and 27 land-use classes). Two main factor axes were extracted that explained more than 60% of the overall variance in both years (about 64% in 2012, about 63% in 2018). Factor 1, which explained more than 40% of the overall variance, represented a morphological-demographic gradient which opposed negative values associated with urban concentration (population density) to positive values associated with patch size, irrespective of land-use class. These results suggest the existence of a latent correlation between population concentration and landscape fragmentation, in line with the assumption that sees urban contexts associated with the highest level of landscape fragmentation on a metropolitan scale. On the basis of this gradient, Factor 1 discriminated urban land use with higher density (negative factor scores) from pristine, natural land use with null population density (positive factor scores). Factor 2, explaining less than 20% of the total variance, delineated an areal gradient: the dominant land uses in metropolitan Athens were oriented towards the positive values of the axis, while land uses with more shaped morphologies (Edge Density) were associated with the negative axis values. This gradient discriminated land use types with high naturalness (3200, 5000) or with little fragmentation (1222) from urban and rural land use with structural and functional fragmentation (4000, 1240).

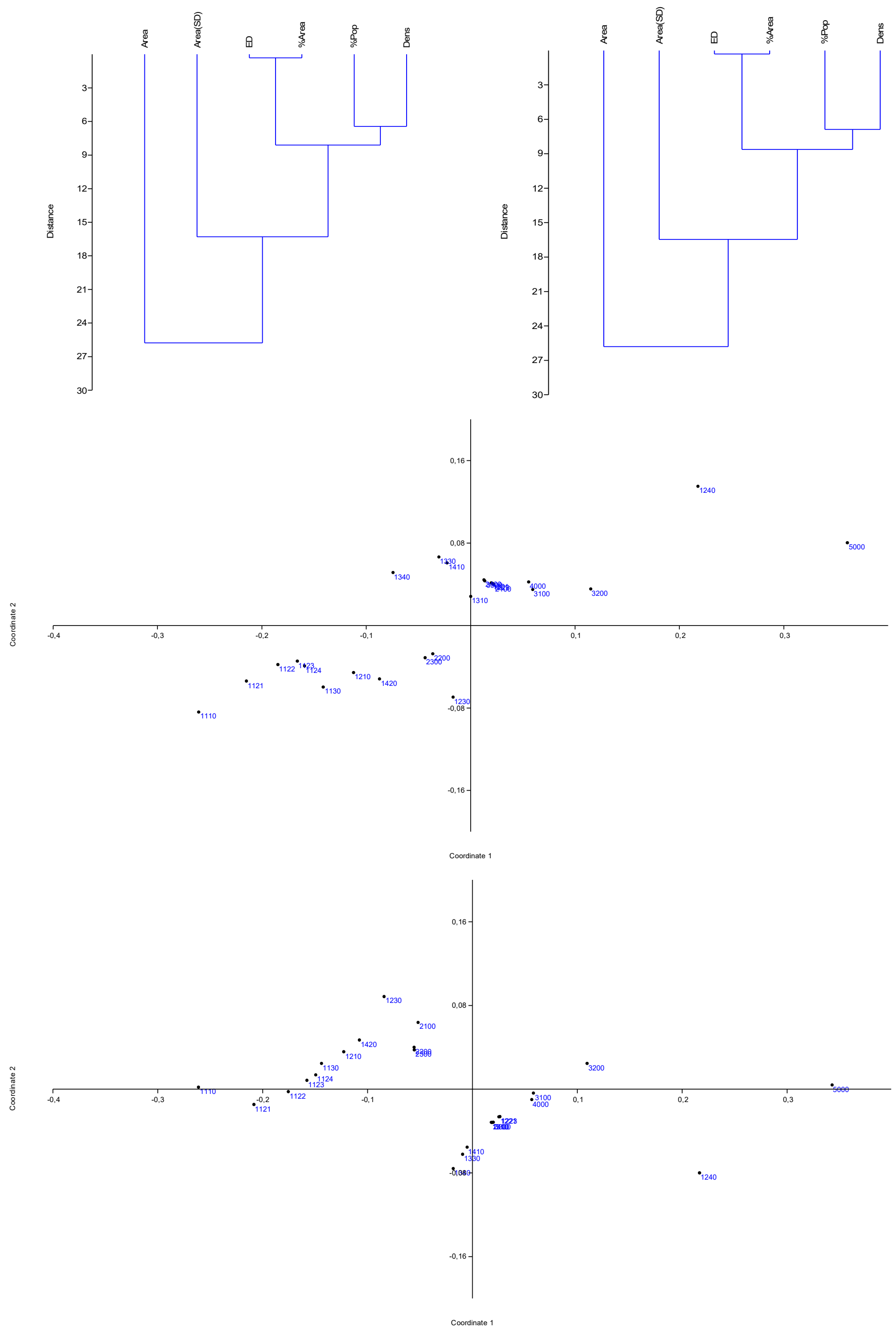

Figure 6. *Cont*.

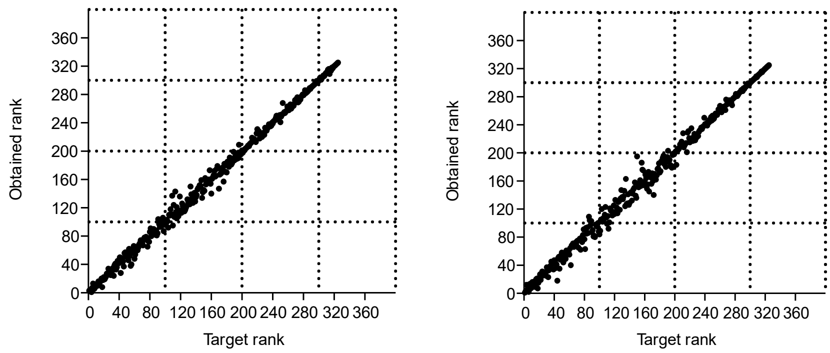

Figure 6. (**upper panels**) Dendrograms resulting from Hierarchical Clustering: indicators' proximity outlines similarity in their spatial distribution within metropolitan Athens; (**intermediate panels**) Dimensions extracted through non-metric-Multidimensional Scaling (n-MDS) delineate similarities in land-use classes according to the values of the indicators; (**lower panel**) Sheppard graphs (**left**: 2012; **right**: 2018) showing the quality of data representation in n-MDS (Source: elaborations on high-resolution urban atlas cartography data from European Environment Agency, GMES Copernicus Land Map System; nomenclature codes reported in Section 2.2).

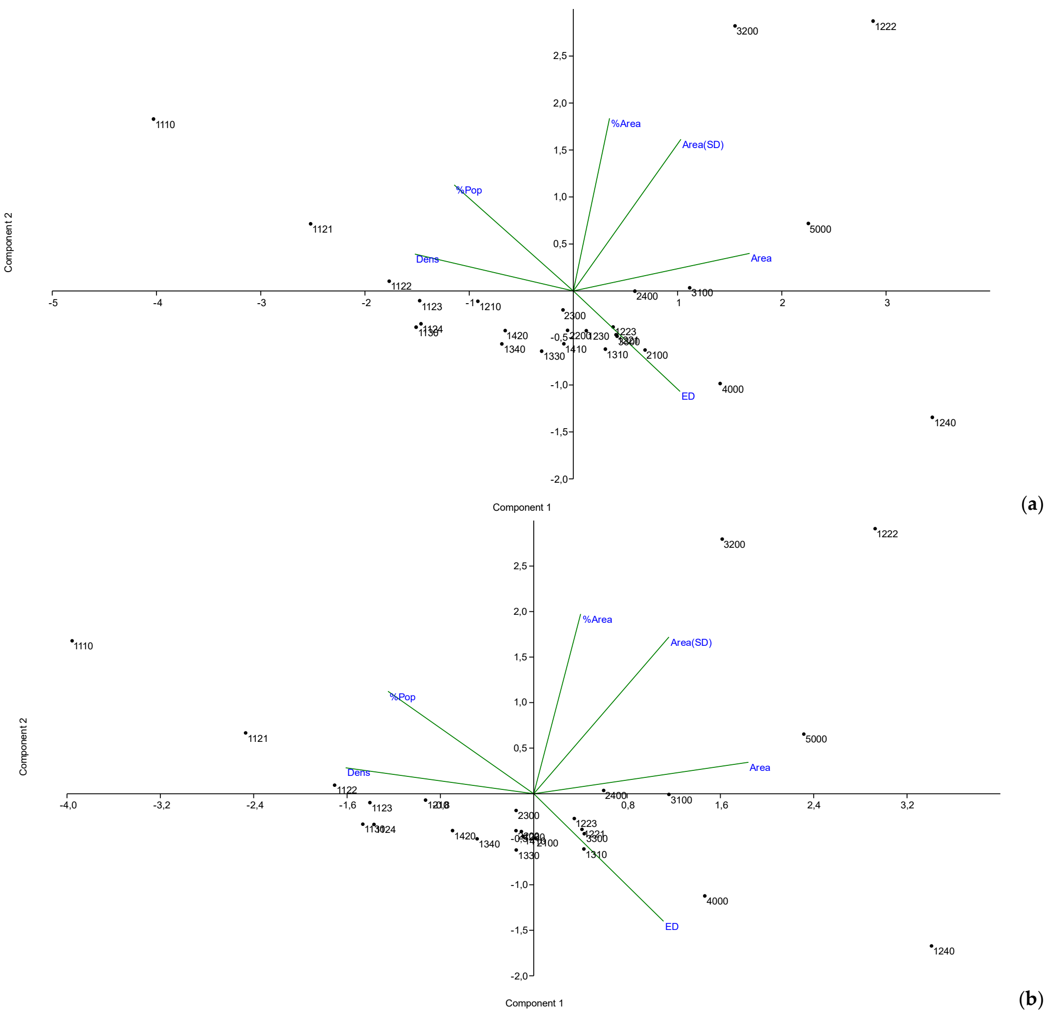

Figure 7. A factor analysis of land-use classes and landscape–settlement attributes in metropolitan Athens by year ((**a**): 2012; (**b**): 2018), based on elaboration of high-resolution urban atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System; nomenclature codes reported in Section 2.2).

The multi-way global analysis (Table 4) makes it possible to identify the morphological–demographic descriptors and land-use classes that have shown the greatest dynamism over time (higher values in the 'overall' column). Among the descriptors, the rapidity of change associated with both edge density and population density was particularly evident. Land uses showing accelerated temporal dynamics included both non-residential urban typologies (e.g., 1230, 1240 codes) and rural typologies with agricultural use (e.g., 2100 code). In both cases, these typologies have experienced a growth in the resident population over time, regardless of the corresponding areal growth or decline.

Table 4. Aggregate results of a multi-way factor analysis of land-use classes and landscape–settlement attributes in metropolitan Athens, quantifying rapidity of change over time along the selected axes and overall (namely, global analysis), based on elaboration of high-resolution urban atlas cartography (Source: European Environment Agency, GMES Copernicus Land Map System; land-use nomenclature codes reported in Section 2.2).

Variable	Axis 1	Axis 2	Overall
Area	−0.16	−3.43	0.03
Area(SD)	0.36	−0.30	0.02
ED	−0.17	3.44	0.08
%Area	0.93	−0.17	0.01
%Pop	−0.09	−1.36	0.03
Density	−0.59	−5.52	0.05
Land use class (nomenclature code explained in Section 2.2)			
1110	−0.3	−1.4	0.17
1121	−0.3	−1.1	0.07
1122	−0.6	−1.7	0.06
1123	−0.8	−0.8	0.07
1124	−1.1	−0.6	0.09
1130	−0.5	−2.2	0.07
1210	0.2	−5.9	0.04
1221	0.1	−2.6	0.07
1222	0.3	0.2	0.06
1223	−1.5	−4.8	0.12
1230	−30.9	−0.3	0.23
1240	−0.2	4.1	0.33
1310	6.7	−0.3	0.12
1330	−8.5	−0.6	0.16
1340	−4.9	−2.0	0.21
1410	0.1	−2.8	0.09
1420	1.1	−0.7	0.04
2100	−16.3	−3.7	0.69
2200	28.9	−0.5	0.10
2300	8.6	−1.4	0.05
2400	0.3	−279	0.04
3100	0.6	−20.5	0.06
3200	0.7	−0.1	0.07
3300	0.5	−1.5	0.04
4000	0.7	2.3	0.15
5000	0.4	−1.5	0.09

4. Discussion

Urban sprawl has marked the process of urban change all over the world; however, the formulation of effective indicators for sprawl is still an open issue. Sprawl has progressively altered the most consolidated (e.g., compact and dense) settlements models in Southern Europe, re-shaping the implicit relationship between central and peripheral locations [88–90]. Looking at sprawl as the low-density expansion of residential settlements and spatial relocation of population in originally non-urban places, a complete assessment of this phenomenon requires high-resolution mapping of land use and resident population over broad geographical coverage. Based on these premises. The empirical results of our study have documented the appropriateness of a short-term analysis of urban sprawl based on high-resolution spatial geo-databases [91–95].

In particular, this work highlights the operational opportunities in environmental monitoring and spatial planning linked to the use of GMES Land Copernicus products, especially the Urban Atlas geo-database, which homogeneously covers more than 700 metropolitan areas in the old continent. The urban atlas maps were updated approximately every six years, providing sufficient historical depth and full comparability thanks to the adoption of the same nomenclatural system. In fact, land use was classified according to a Corine Land Cover system into more than 20 different types, both urban and rural, thus providing a complete description of the landscape. These mapping characteristics allow outlining the extreme fragmentation of land-use patches in consolidated urban contexts, thanks to the high resolution of the geo-spatial survey. Moreover, the adopted Urban Atlas classification proved to be effective in delineating the characteristic of metropolitan gradients based on population concentration and agglomeration factors, as clearly shown in the smoothing spline analysis of density gradients from urban to rural locations in Athens.

Despite the limited duration of the study period (2012–2018), the results of exploratory data analysis—based on descriptive, correlation and multivariate statistics—highlighted the enormous potential of a systematic use of the European Urban Atlas for environmental monitoring and as an information tool of spatial planning. Based on the information available in Urban Atlas, our work has highlighted the relationship between land-use, settlement types and resident population, portraying urban sprawl as associated with a greater mix between urban and rural land use. Being associated with increasingly scattered settlements, the reference population grew in correspondence with agricultural land-use. Despite the low building activity that characterized the study period—coinciding with slow economic recovery after the intense recession that hit Greece starting from 2007—landscape transformations and population redistribution in metropolitan Athens were evident between 2012 and 2018 [94,95].

Recently, Athens' growth has outlined an articulated relationship between morphology and functions at the base of urbanization dynamics. The shift toward low-density residential settlements was rather evident, despite being associated with a slow process of settlement compaction and spatial redistribution of population across residential land-use classes. Total population also increased in correspondence with non-residential land use (commercial, industrial, services), confirming the land use mix characteristic of the real estate/housing dimension in Greece. Given the multiplicity of territorial contexts and driving forces, such findings delineate the dominant role of a mixed compact–dispersed model of urban expansion in Athens' recent development instead of a purely 'sprawled' path, despite differentiated spatial regimes potentially existing locally [96–98].

Mixed models of urban growth have demonstrated a reduction in the pre-existing density divide in compact urban fabric and accessible rural spaces [99–101]. Experiencing intrinsically complex (and progressively diverging) stimuli toward dispersion and densification, metropolitan systems became more chaotic as far as the internal structure is concerned, in turn undergoing uncertain development paths in the short term [102]. Being a specific trait of 'urban sprawl' in the study area—and likely in other metropolises of the Northern Mediterranean basin—such dynamics require a comprehensive interpretation of short-term development paths based on more effective integration of morphological (e.g., land-use) and functional (e.g., socioeconomic) indicators [103–105]. Assumed to exert an influential effect on both central cities, suburban locations, and rural districts [106–108], such dynamics should be governed with a truly holistic spatial perspective [109], regulating the latent interaction between land-use patterns, agglomeration forces, and socio-demographic trends [110–112].

According to our results, sprawl in Athens' recent growth manifested primarily in (i) a spatial rebalance of resident population across land-use classes (based on the results of smoothing splines that indicate a more homogeneous density gradient from urban to rural areas in 2018 than in 2012), (ii) a moderate increase in the resident population in urban (non-residential) land use types (based on the results of descriptive statistics that outlined the increasing economic mix and social permeability of fringe land), and (iii) a weak increase in the resident population in correspondence with specific agricultural land use in turn associated with sparse settlements [113–115]. Such evidence suggests that (i) an increasing proportion of the population moved toward isolated settlements when suburbanizing and that (ii) production and commercial settlements became increasingly heterogeneous, hosting resident population e.g., in mixed-use buildings [116–118]. These two faces of a complex restructuring of metropolitan structures highlight diverging trends respectively toward settlement dispersion and moderate densification of already urbanized locations.

5. Conclusions

In the light of defining the nature of short-term sprawl evolution in Mediterranean cities, metropolitan Athens was envisaged as an appropriate example for performing a quantitative, high-resolution analysis of densification vs. dispersion patterns considering morphological indicators derived from a representative geo-spatial data source such as the Copernicus Land Urban Atlas, covering more than 700 metropolitan regions all over Europe. Sprawl assessment in metropolitan Athens has been performed using different sprawl indicators. Due to the nature of the adopted variables, these will evidence characteristics regarding the anatomy (physical features) and the essence (conceptual elements) of the phenomenon being investigated. Although mixed processes of settlement densification and diffusion seem to be dominant in recent paths of city growth in Southern Europe, understanding the short-term evolution of population, residential/production settlements and land use, requires an enhanced landscape classification with a specific (morphological) focus, as illustrated in the present study. Given the multiplicity of territorial factors involved in land use transitions, metropolitan development was demonstrated to adapt to differentiated territorial regimes, in turn requiring specific and spatially explicit planning measures. These actions have to effectively contain land take, by reorienting settlement expansion toward more sustainable (environmentally friendly, socially cohesive and economically viable) paths.

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Data Availability Statement: Data derived from European Environment Agency, GMES Copernicus Land Map System were freely downloadable and workable through a Geographic Information System (GIS) software from https://www.eea.europa.eu/data-and-maps/data/copernicus-land-monitoring-service-urban-atlas (accessed on 25 January 2023).

Conflicts of Interest: The authors declare no conflict of interest.

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