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Toward Sustainable Development Trajectories? Estimating Urban Footprints from High-Resolution Copernicus Layers in Athens, Greece

Alessia D'Agata [1], Daniele Ponza [1], Florin Adrian Stroiu [1], Ioannis Vardopoulos [2], Kostas Rontos [3], Francisco Escrivà [4], Francesco Chelli [5], Leonardo Salvatore Alaimo [6], Luca Salvati [1,*] and Samaneh Sadat Nickyain [7]

1 Department of Methods and Models for Economics, Territory and Finance, Faculty of Economics, Sapienza University of Rome, Via del Castro Laurenziano 9, I-00161 Rome, Italy; alessia.dagata@uniroma1.it (A.D.); ponza.1792885@studenti.uniroma1.it (D.P.); stroiu.1743606@studenti.uniroma1.it (F.A.S.)
2 Department of Regional and Economic Development, School of Applied Economics and Social Sciences, Agricultural University of Athens (AUA), 33100 Amfissa, Greece; ivardopoulos@post.com
3 Department of Sociology, University of the Aegean, 81100 Mitilini, Greece; k.rontos@soc.aegean.gr
4 Soil Erosion and Degradation Research Group, Department of Geography, University of Valencia, Blasco Ibàñez, 28, ES-46010 Valencia, Spain; francisco.escriva@uv.es
5 Department of Social and Economic Science, Polytechnic University of Marche, Piazzale Martelli 8, I-60121 Ancona, Italy; f.chelli@univpm.it
6 Department of Social Sciences and Economics (DISSE), Faculty of Political Sciences, Sapienza University of Rome, Piazzale A. Moro 5, I-00185 Rome, Italy; leonardo.alaimo@uniroma1.it
7 Planning and Design Faculty, Agricultural University of Iceland, Hvanneyri, 311 Borgarbyggð, Iceland; samaneh@lbhi.is
* Correspondence: luca.salvati@uniroma1.it; Tel.: +39-06-4976-6418

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Abstract: Land imperviousness reflects settlement growth and urban sprawl. Grounded on a comparative approach, a set of multidimensional statistical techniques were adopted here to quantify the evolution of land imperviousness from Copernicus High-Resolution Layers (HRLs) in a representative case study of Southern Europe (Athens, Greece). A two-way data matrix reporting the percent share of the surface land exposed to different sealing levels (101 classes ranging continuously from 0% to 100%) in the total municipal area was computed for two years (2006 and 2018) individually for 115 municipalities in metropolitan Athens. This matrix represented the information base needed to derive place-specific urban footprints and a comprehensive (global) profile of land imperviousness. Results of a Detrended Correspondence Analysis (DCA) delineated a metropolitan structure still organized along the density gradient, moving from dense settlements in central locations with dominant land classes sealed for more than 90% of their surface area to completely pervious land (0%) typical of rural locations. While the density gradient became less steep between 2006 and 2018, it continued to aliment a socioeconomic polarization in urban and rural districts with distinctive profiles of land imperviousness. Intermediate locations had more mixed imperviousness profiles as a result of urban sprawl. Differential profiles reflect place-specific urban footprints with distinctive land take rates.

Keywords: urban sprawl; soil sealing; urban planning data mining; indicators; sustainable urban development; Mediterranean Europe

1. Introduction

As a result of economic development, urban expansion rates in recent times have accelerated in both intensity and spatial coverage, exerting impacts on both ecosystems and societies [1–3]. Being structurally different from the abrupt growth of cities in emerging economies [4–7], European urban regions expanded at a more regular pace, while altering (more or less rapidly) the surrounding (natural and cultural) landscapes, thus creating mixed and indistinct metropolitan continuums [8–10]. The rapid expansion of Mediterranean cities after World War II aroused much interest in this perspective, being interpreted as a mixed socioeconomic process [11–13], sharing functional traits with both classical (North)European development paths and the more intense growth processes typical of emerging economies [14–16]. For such reasons, urban expansion in Mediterranean Europe requires continuous monitoring [17,18], since an increasing amount of agricultural and forest lands have been converted to (residential and industrial) settlements in both central and peripheral locations [19–22].

This process pushed traditional urban–rural gradients toward a more complex spatial organization reflecting polycentric (or scattered) settlements [23–25]. Economic growth—with the progressive restructuring of the production base taken as a response to population concentration and compact urbanization [26]—was demonstrated to fuel the expansion of low-density, spatially discontinuous settlements as a result of urban sprawl [27–29], leading to accelerated rates of soil consumption [30–32]. In this perspective, the sprawl caused a latent restructuring of metropolitan regions [33–35], reshaping the traditional polarization in urban and rural areas typical of Mediterranean Europe [36–39]. Urban sprawl has often been related to the development of second homes—thanks to an increasing preference for suburban areas—and strip expansion of industrial (or service) settlements—thanks to accessibility gains and an increasing preference for suburban areas [40–42]. While allowing people more living space and enterprises more spacious working places, the growth of discontinuous settlements had negative impacts for sustainable development [43], determining a sudden increase in energy demands, human health issues, a latent (quantitative and qualitative) decline of soil resources, and socioeconomic inequalities at large [44–47]. Based on its complexity, the sprawl requires additional investigation of the corresponding land imperviousness profiles, as a peculiar trait of the joint expansion of residential and industrial settlements [48–50].

It is widely recognized how 'patterns' and 'processes' of sprawl have been increasingly analyzed in a mostly decoupled manner, pointing out the inherent diversity in the underlying ecological and economic approaches [51–54]. However, recomposing the disciplinary divide in functional and structural issues [55–57] is necessary to re-comprise morphological dynamics and the related socioeconomic processes into a broader 'holistic' perspective able to understand the role of different economic and social agents at the base of urban expansion [58–60]. As a result of such complex dynamics [61], place-adapted profiles of land imperviousness derived from high-resolution, remotely sensed thematic layers of land-use were considered an appropriate information base to (i) estimate (global and local) urban footprints, (ii) quantify the net land consumption rate over given time intervals, and (iii) evaluate the intrinsic sustainability of recent development paths in a given metropolitan area [60–64]. Direct and indirect measures of urban footprints and a renewed estimation of land take, as well as specific insights into the sustainable development path of metropolitan regions, are demanding research tasks that are particularly relevant and urgent in light of the Agenda 2030 Sustainable Development Goals (SDGs), with a focus on SDG11 (safe, inclusive, resilient, and sustainable cities) [65–67].

Based on these premises, the present work has two basic motivations: the first is methodological and proposes an exploratory data mining strategy for the analysis of place-specific land imperviousness profiles [68]. This objective is based on a sequence of (parametric and non-parametric) multivariate statistical techniques interpreting the complex and latent relationships between input variables, namely, the share of impervious classes in total municipal area [69]. Revealing such relationships—both linear and non-linear—will enhance the information content of the (two-way) input data matrix from a space-time perspective [70]. The second motivation is conceptual and suggests an interpretation of the characteristic footprint of each municipality from a sustainability perspective [71]. Starting from the results of the multivariate statistical technique which presents the maximum goodness-of-fit to input data, changes over time in urban footprints have also been read as a proxy for land consumption [72]. On the basis of this preliminary evidence, and considering the exploratory vision of the statistical analysis adopted in our study, we have finally distinguished local-scale settlement structures on the basis of specific land imperviousness profiles [73–75]. The discrimination between vertical settlements, dominated by scale economies and governed by agglomeration factors [76], and horizontal ones, reflecting the intense suburbanization of recent decades [77], is a particularly deserving issue that merits further investigation.

2. Methodology

2.1. Study Area

Our investigation adopts metropolitan Athens (3000 km^2) as the study area, whose physical boundaries were delineated in line with the definition of cities in Urban Atlas, a major initiative of the European Environment Agency (EEA). The study area encompasses the major part of Attica, a NUTS-2 (Nomenclature of Statistical Territorial Units from Eurostat) administrative region in Central Greece, including Athens, the Greek capital city, and its surroundings [78]. The Greater Athens' area (nearly 400 km^2 classified as the first conurbation of Greece, as far as both population and area are concerned) was included in this definition, together with its peri-urban and rural surroundings (2600 km^2) [79]. Population density was above 10,000 inhabitants/km^2 in central locations and decreased to 2000–5000 inhabitants/km^2 in suburban districts [80]. Rural locations had up to 1000 inhabitants/km^2, on average [32]. City growth was continuous and particularly intense for the whole of the last century [22]. More recently, suburban development fueled the expansion of spatially discontinuous settlements into agricultural and natural land, determining an accelerated rate of soil loss [24]. During economic crisis (2008–onwards), building activity decreased markedly in the area. However, this decrease was more intense in downtown Athens and Piraeus, and in other dense municipalities with less availability of free spaces to develop. The number of building permits released in the Greater Athens' area, in both downtown and the surrounding municipalities, documents the intensity of building activity during the entire study period. While the crisis depressed building activity especially between 2010 and 2014, the previous years (2006–2009) and the following years (2015–2018) were characterized by a moderate construction rate. This includes both new buildings and enlargement of existing buildings, which is an important component of Athens' growth, especially in the context of limited available buildable spaces. In several municipalities around downtown Athens and belonging to the Greater Athens' area, however, settlement growth was rather evident also during the crisis.

2.2. Data Sources and Elementary Variables

We used High-Resolution Layers (HRLs) of soil sealing released by the European Environment Agency (EEA) under the main initiative of Land Copernicus within the Global Monitoring for Environment and Security (GMES) framework [79]. Raster HRLs with complete European coverage have been produced every three years since 2006 (i.e., 2006, 2009, 2012, 2015, 2018), and, in the last release (2018), they were fully harmonized in both time and space and freely available in GeoTiff format [79]. We assumed two raster files from the Fast Track Service on Land Monitoring as the reference geo-spatial database elaborated in the present study [81]. More specifically, we considered the maps available at the first (2006) and last (2018) production waves as a basic information source for mapping impervious surfaces, defined as pavement structures (roads, sidewalks, driveways, and parking lots) covered by asphalt, concrete, brick, stone, and rooftops [82]. These layers are geo-referenced binary raster files, including sealed and non-sealed pixels, derived from multi-sensor ortho-rectified satellite imagery. We considered only two comparable layers with 100 m spatial resolution (regular grid) for both 2006 and 2018. We avoided using more detailed rasters (20 m grid for 2006 and 10 m for 2018) for the sake of full comparability over time. Spatially detailed Google Earth imagery was taken as a supplementary data source validating HRLs [83]. Classification accuracy was tested considering estimates of omission error, commission error, and overall accuracy [84]. Classification accuracy of sealed and non-sealed land resulted in much higher than 85% per hectare, with both omission and commission errors remaining systematically below 15% [37]. In each map, non-sealed pixels were representative of completely pervious (i.e., natural) soils [85]. Sealed pixels were in turn classified according to with the intensity (namely level) of soil sealing at the local scale [86], expressing a continuous degree of land imperviousness ranging from 0% to 100% in a 100 m regular grid [87].

2.3. Indicators of Land Imperviousness

With the aim of delineating soil sealing spatial patterns and trends on the municipal scale in metropolitan Athens, a comprehensive investigation of local profiles of land imperviousness was based on a multidimensional analysis of indicators derived from the aforementioned HRLs (2006 and 2018). More specifically, the composition of sealed land in each municipality was delineated considering 101 classes of land imperviousness (0%, and from 1% to 100%) estimated as the percent surface area of each class in the total municipal area [79]. To achieve this objective, we used the 'Tabulate area' tool provided with ArcGIS (ESRI Inc., Redwoods, Redlands, CA, USA) after the overlap between each land imperviousness raster map and the shapefile containing the municipal boundaries [78]. The 'Tabulate area' procedure computed selected statistics, including the count of the raster values recorded on the 100 m grid and belonging to a given (vector) spatial unit [79].

2.4. Statistical Analysis

To illustrate (global and local) profiles of soil sealing in metropolitan Athens, descriptive statistics were run with the aim of providing a coherent delineation of the spatial degree of land imperviousness using tables, graphs, and maps [54]. Additionally, a multivariate strategy based on a composite chain of five separate techniques was adopted here to summarize the complex relationship at the base of land imperviousness profiles in Athens as a contribution to planning design and policy implementation for urban footprints' containment and metropolitan sustainability at large [49]. More specifically, the (multivariate) latent relationship between the spatial extent of the different soil sealing classes in each municipality (namely, the local-scale 'footprint profile') of metropolitan Athens was studied over time (2006 and 2018, see Figure 1) considering the results of five statistical analyses run sequentially. Techniques included a Principal Component Analysis (PCA), a Principal Coordinate Analysis (PCoA), a non-metric Multidimensional Scaling (n-MDS), a Correspondence Analysis (CA), and a Detrended Correspondence Analysis (DCA). All these techniques were aimed at decomposing complex data matrices by variable, using criteria oriented toward the 'correlation' notion (PCA and, in part, PCoA), the 'similarity' notion (nMDS), or the association notion (CA, DCA).

2.4.1. Principal Component Analysis (PCA)

Principal Component Analysis (PCA) identifies hypothetical variables (namely, components) that account for the largest proportion of the variance in a given (input) matrix organized as a two-way, multivariate dataset with variables by column (namely, the percent share in total municipal area by land imperviousness class) and observations by row (namely, municipalities) [88]. Components were algorithmically constructed as linear combinations of the original variables, maximizing the individual information from the input matrix [50,52]. PCA was frequently used with the aim of reducing a given dataset into a small number of components for plotting purposes under the assumption that the most important components (usually the first two) are correlated with other underlying variables [88]. Eigenvalues, reflecting the variance associated with each component extracted, were determined from the spectral decomposition of the correlation matrix using the Singular Value Decomposition (SVD) algorithm [25]. The use of a correlation matrix (instead of a variance-covariance matrix) guarantees an implicit standardization of the input variables [68]. The percentage of variance accounted for by each extracted component was, thus, derived from the respective eigenvalue [45]. Optimal PCA representations of a given data matrix imply that the first extracted components account for the largest proportion of variance compared with the remaining components [89]. In this study, components with eigenvalues > 1 were selected and analyzed by computing loadings (that reflect the intrinsic correlation between variables—land imperviousness classes—and components) and scores (that reflect the intrinsic linkage between units—municipalities—and components) [56]. A biplot summarizing the position of loadings and scores in the same factor plane was finally adopted to illustrate the outcome of this multivariate analysis [58].

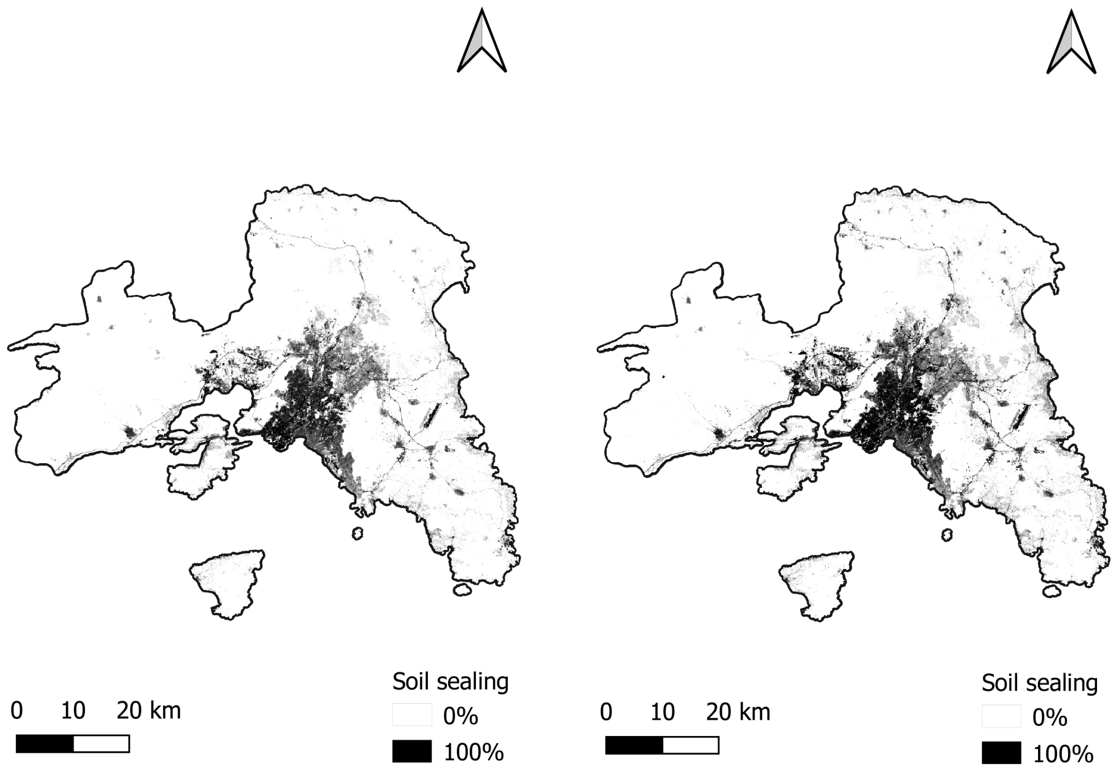

Figure 1. Maps of land imperviousness (**left**: 2006; **right**: 2018) in metropolitan Athens, Greece, derived from HRLs of soil sealing; the degree of land imperviousness was represented with a grey tone ramp, from 1% (soft grey) to 100% (black) (Source: own elaboration on basic, geo-referenced raster files disseminated by European Environment Agency, GMES Copernicus Land Map System).

2.4.2. Principal Coordinate Analysis (PCoA)

PCA results were coupled with those from a Principal Coordinate Analysis (PCoA), another ordination method (also known as Metric Multidimensional Scaling) that extracts both eigenvalues and eigenvectors from a matrix containing correlations, distances, or similarities between all data points [80]. Many correlation, distance, or similarity metrics were frequently adopted when running PCoAs [52]. Using Euclidean distances gives outcomes similar to those from a PCA. In this study, we checked the results of four metrics (Euclidean, Manhattan, parametric Pearson correlation, and non-parametric Spearman Rho co-graduation) reflecting both correlation and similarity approaches [56]. Eigenvalues giving a measure of the variance accounted for by the corresponding eigenvector (i.e., coordinate) were calculated separately for each coordinate, giving in turn the percentages of variance accounted for by these components [90]. The 'metric' values have been raised to the power of c (the 'transformation exponent') before eigenanalysis is fixed to 2, a standard coefficient in most quantitative exercises [91]. A scatter plot was drawn to project each variable in the coordinate system given by the PCoA [92]. Each axis was scaled using the square root of the eigenvalue, and a minimum spanning tree option was performed on the base of the selected metric in the original space [93].

2.4.3. Non-Metric Multidimensional Scaling (n-MDS)

Paralleling the experimental design adopted above (Section 2.4.2), an n-MDS using Euclidean, Manhattan, correlation, and rho metrics was adopted here as an assumption-free and flexible exploratory technique evaluating the overall similarity in the spatial distribution of land imperviousness classes in Athens [92]. More specifically, n-MDS identified meaningful (latent) dimensions explaining the observed similarities between input variables [93]. Irrespective of the similarity metric, n-MDS arranges the investigated variables in a geometrical space with a (particularly low) number of dimensions (usually two) so as to reproduce the observed distances over space based on a similarity matrix [85]. In this perspective, n-MDS is considered a multivariate analysis that provides an implicit assessment of the role of space in the geometrical configuration of observations [86]. By 'rearranging' objects in an efficient manner, n-MDS provides a geometrical configuration that best approximates the observed distances based on similarity metrics [90]. The analysis verifies 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 minimizing the so-called 'lack of fit' [91].

2.4.4. Correspondence Analysis (CA) and Detrended Correspondence Analysis (DCA)

To corroborate the results of previous analysis' steps, Correspondence Analysis (CA), another ordination method somewhat similar to PCA and specifically addressing the issue of compositional data [91], was run in our study. CA is especially suitable when observations are expected to show unimodal responses to the underlying parameters, which become rare for lower and higher values. This is in contrast to PCA, which assumes a linear response across the whole range of values [94,95]. Following Greenacre [90], the CA algorithm finds the eigenvalues and eigenvectors of a matrix containing the Chi-squared distances between all columns based on SVD [96]. Eigenvalues, giving a measure of the association accounted for by the corresponding eigenvector, were given for each eigenvector [92]. The percentages of similarity accounted for by these components were also provided [93]. A scatter plot visualized all data points (both variables and observations) within the coordinate system given by the CA [97].

It is important to note that compositional data that sum to a constant by design, such as proportions summing to 1 or percentages summing to 100, may contain 'spurious' correlations because as one value increases, the others may have to decrease [91]. As a consequence, some multivariate analyses can be negatively affected by this serial autocorrelation structure. By analyzing observations in rows and imperviousness classes in columns, a Detrended Correspondence Analysis (DCA) following the algorithm proposed by Decorana [97], with modifications according to Oxanen and Minchin [90], was implemented here with the aim of overcoming (or, at least, mitigating) the compositional issue introduced above. Similarly to a classical CA, eigenvalues for a maximum of four ordination axes were extracted and indicate their relative importance in explaining the observed spread in the raw data [88]. Detrending is a sort of normalization procedure carried out in two steps. The first step involves an attempt to 'straighten out' points lying in an arch, which is a common occurrence in the compositional issue illustrated above [86]. The second step involves a sort of 'spreading out' the points to avoid clustering of the points at the edges of the plot [85]. While seeming like a sort of arbitrary procedure, we assume DCA represents a meaningful support for compositional data interpretation over both time and space.

3. Results

Using boxplots, Figure 2 outlines the statistical distribution of the degree of soil sealing for each municipality in the study area, separately for 2006 (left) and 2018 (right). These plots illustrate the average level of land imperviousness and its (statistical) deviation along the urban–rural gradient in metropolitan Athens as a function of the municipal area. Heterogeneity was a systematic characteristic of the sample in both 2006 and 2018, preventing the use of parametric/inferential statistical methodologies based on the normality assumption and sophisticated econometric techniques aimed at specifying the main determinants of land imperviousness all over the study area. The use of exploratory multivariate techniques, as extensively illustrated in the following paragraphs, was aimed at interpreting such heterogeneity over time and space. Generally speaking, the largest heterogeneity in the statistical distribution of municipal area was found for the highest classes of land imperviousness, namely between 90% and 100%. Additionally, urban expansion in metropolitan Athens was visible when comparing data between 2006 and 2018 since classes between 80% and 100% of land imperviousness experienced a moderate increase in their average surface area and the related dispersion around the mean. This sort of latent densification was observed (more or less intensively) irrespective of the distance from the inner city; however, the densest neighborhoods of downtown Athens were rather stable in their soil sealing profile (see also the diachronic maps in Figure 1), likely because of the chronic shortage of buildable land in a landscape traditionally saturated by buildings since the 1950s. This evidence was not completely true for the surrounding (urban) municipalities, having dense settlements and some free space (vacant land) that were developed even during the crisis (2007–onwards). Moreover, the steepness of the (decreasing) gradient of municipal area moving from classes that reflect a low intensity of soil sealing (e.g., <20%) to classes that reflect a medium-high intensity of soil sealing (e.g., >50%) intensified in 2018 compared with 2006.

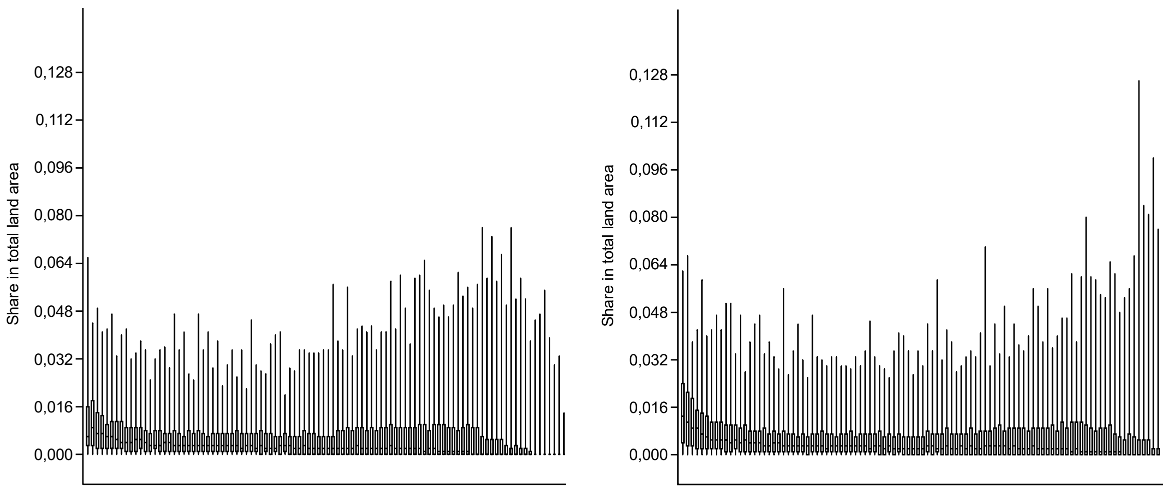

Figure 2. Statistical distribution of land imperviousness in Athens' municipalities (n = 115; the two boxplots (**left** 2006; **right**: 2018) illustrate the relative share of municipal area covered by each class of soil sealing (moving from 0% to 100% from the left to the right of the horizontal, *x* axis)).

Taken together, these results suggest a particularly complex (spatial) configuration of land imperviousness across the study area and heterogeneous profiles of soil sealing at the scale of municipalities. In this direction, Figure 3 provided some additional diagnostics (histograms and normal probability plots) indicating the substantial deviation of the elaborated data from a normal statistical distribution, thus suggesting the use of specific (exploratory) techniques.

By fulfilling the specific characteristics of the input data, the results of five exploratory techniques of multivariate statistics were proposed in Table 1, considering the first three latent dimensions extracted in each run. Results indicate how the variance explained in each extracted dimension (from one to three) increases moving from a simplified multivariate technique (PCA) decomposing the correlation matrix (based on linear Pearson coefficients) of input variables to more flexible techniques (namely PCoA, n-MDS, and CA) adopting similarity metrics—a less precise approach that is revealed to be more robust when complex data patterns are analyzed. The visual clarity of the outcomes of all the statistical techniques mentioned above seems to have moderately improved from 2006 to 2018. DCA finally provided a more appropriate extraction of the most relevant analysis' dimensions. This finding seems to be fully in line with the technical properties of this technique, appropriately treating compositional data and intrinsically removing the serial autocorrelation eventually occurring in the input variables.

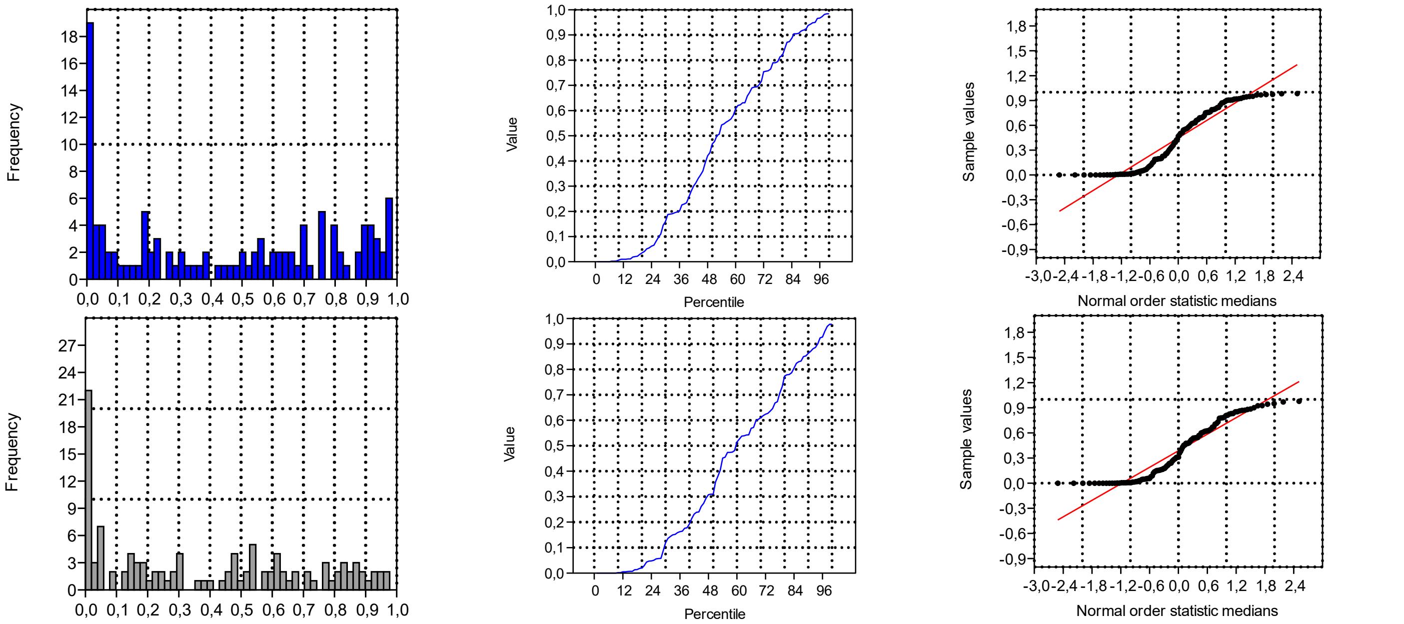

Figure 3. Visual diagnostics illustrating the intrinsic characteristics of the statistical distribution of land imperviousness degree in metropolitan Athens.

Table 1. Basic results of the multivariate extraction of the first three latent dimensions of soil sealing spatial complexity from the input data matrix by year and statistical technique (PCA: Principal Component Analysis, PCoA: metric multi-dimensional scaling, n-MDS: non-metric multidimensional scaling, CA: Correspondence Analysis, DCA: Detrended Correspondence Analysis).

Axis	PCA	PCoA	n-MDS	CA	DCA
			2006		
1	28.3	39.4	39.9	38.4	52.5
2	24.7	10.3	11.4	17.4	9.4
3	10.1	5.0	6.1	9.5	4.1
			2018		
1	32.0	41.7	41.3	41.0	55.0
2	24.2	18.7	18.9	18.8	7.9
3	10.1	9.1	8.8	8.5	4.3

Figure 4 illustrates the most relevant findings obtained from the multivariate techniques described above. All findings clearly indicate the presence of peculiar, and possibly complex, latent data structures that require a specific analysis in order to remove the influence of compositional issues, as the 'horseshoe' distribution of the observation cloud projected along axes 1 and 2 clearly outlines, irrespective of the applied technique. These visual results, together with the numerical outcomes reported in Table 1, suggest the use of Detrended Correspondence Analysis as an exploratory technique appropriate to treat the latent complexity in the dataset, providing a coherent description of columns/cases (localities) and rows (land imperviousness classes) from the input matrix. Additionally, in line with the classical results of a PCA, a biplot of DCA will provide a more complete representation of the intimate relationship between cases (municipalities) and rows, contributing to the delineation of a more defined (local) profile of land imperviousness.

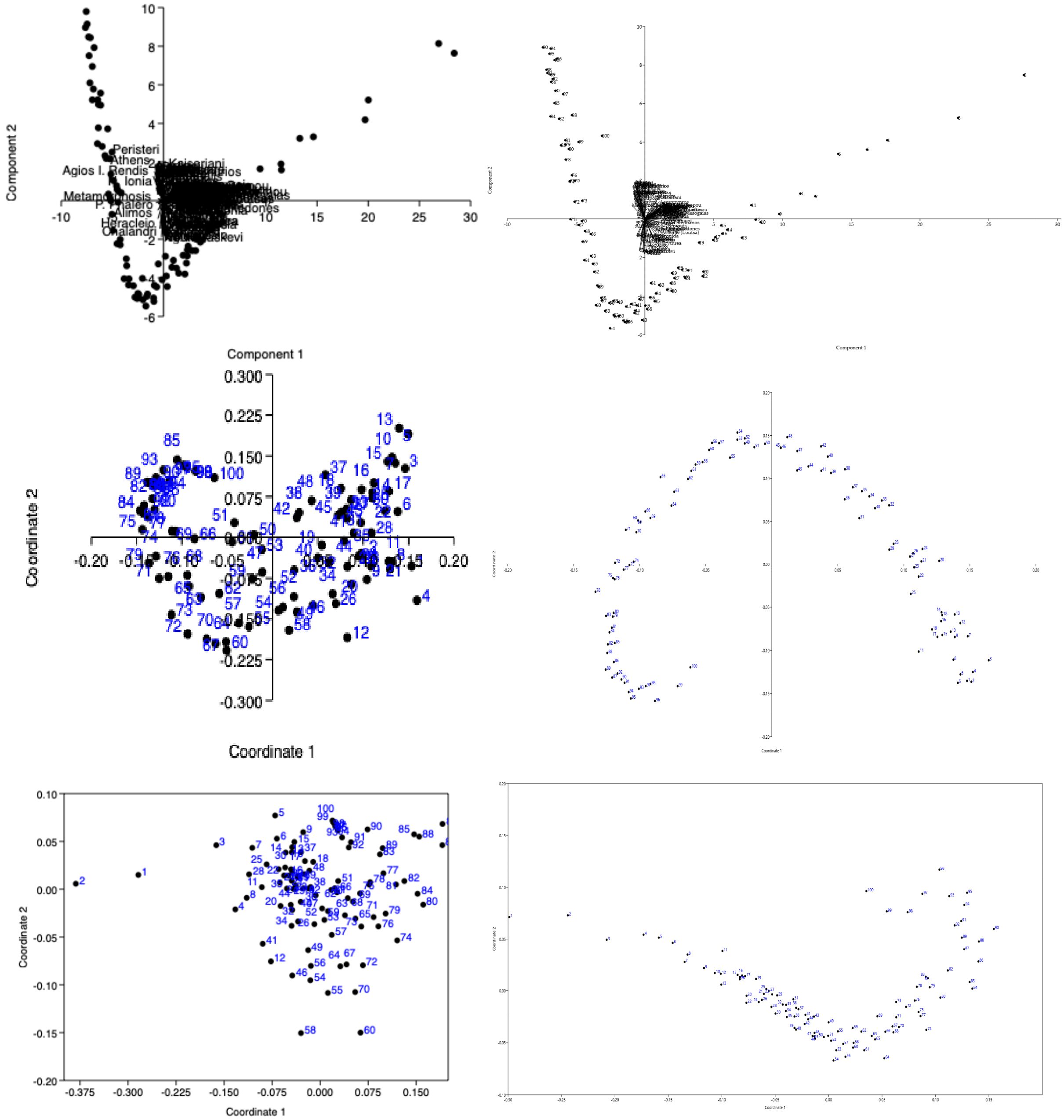

Figure 4. Selected outputs of the multivariate analyses presented in Table 1: (**upper panel**) biplot (land imperviousness classes vs. municipalities) of Principal Component Analysis (Axis 1 vs. Axis 2); (**middle panel**) dimensional plot (coordinate 1 vs. coordinate 2) illustrating the position of land imperviousness classes using non-metric Multidimensional Scaling (comparable results obtained from Principal Coordinate Analysis, not shown here); (**lower panel**) component plot (coordinate 1 vs. coordinate 2) illustrating the position of land imperviousness classes using a Correspondence Analysis (left graphs' line: 2006; right graphs' line: 2018); numerical labels indicate the ELSTAT (Hellenic Statistical Authority) code uniquely associated with each municipality in the study area for census purposes.

By illustrating a large part of the total matrix variance along dimensions 1 and 2, the results of a Detrended Correspondence Analysis (Figure 5) provided the necessary explanation of the complex relationship between locations and the spatial distribution of soil sealing, delineating place-specific profiles of land imperviousness in metropolitan Athens. Small changes in the biplot (locations vs. imperviousness degree) were visually identified when comparing the results of the 2006 and 2018 runs. Generally speaking, DCA identified two main axes, possibly corresponding to distinctive geographical gradients in the study area, which basically explained more than 80% and more than 10% of the total variance, respectively.

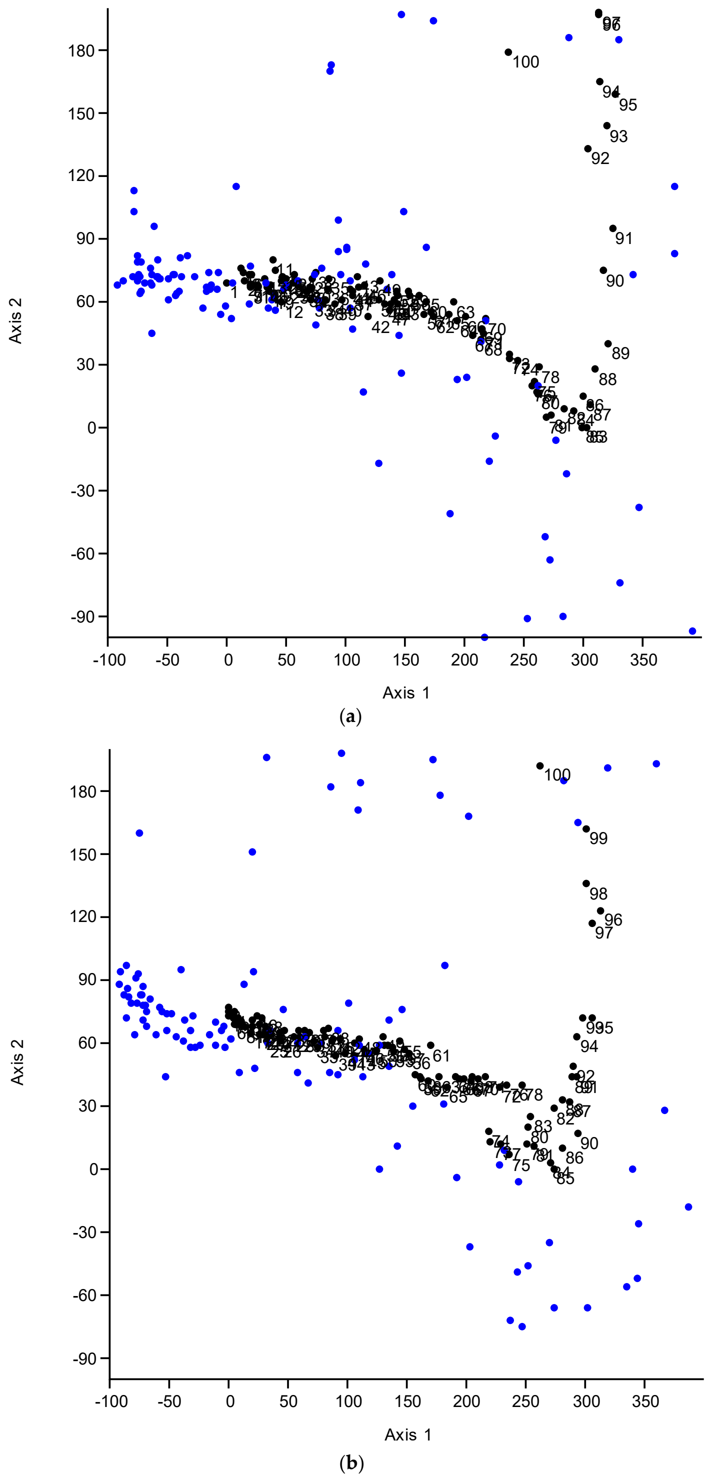

Figure 5. Results of a Detrended Correspondence Analysis showing the relationship between cases (municipalities) and rows (land imperviousness classes) in the input data matrix of metropolitan Athens; 2006 (**a**) and 2018 (**b**); numerical labels (from 1 to 100) indicate each individual class of soil sealing as DCA projection on Axes 1 and 2; the position of municipalities was projected with blue dots in the same graph (see also Figure 4 for numbering explanation).

By providing a complete description of data complexity, Dimension 1 delineated a gradient of soil sealing from low to medium-high intensities of land imperviousness (from 0% to nearly 80% in 2006, from 0% to nearly 85% in 2018), which was in turn associated with rural municipalities (placed on the left side of the horizontal axis) or peri-urban (or moderately urban) municipalities (projected on the right side of the axis). In other words, rural municipalities were associated with a systematically low degree of land imperviousness, while peri-urban and moderately urban municipalities reflected the dominance of intermediate classes of soil sealing (namely, between 50% and 80%).

The moderate differences found between 2006 and 2018 biplots (namely, the gradient associated with Dimension 1 and spanning from 0% to 80% in 2006 and to 85% in 2018) reflect the latent trend toward settlement expansion in the Greater Athens' area, more recently associated with mixed compact-dispersed urban growth especially in the municipalities surrounding Athens and Piraeus. This result indicates how settlement growth in metropolitan Athens determined a slow but progressive expansion of high imperviousness classes, thus consolidating a mono-centric, dense structure typical of large Mediterranean cities. Despite accounting for a restricted proportion of variance compared with Dimension 1, Dimension 2 delineated a different gradient moving from medium-high to very high degrees of soil sealing in the study area (namely, from 80% to 100% in 2006 or from 85% to 100% in 2018). Urban municipalities with compact and hyper-dense settlements were appropriately ordered along this axis, up to the most concentrated (based on both buildings and population) municipalities in central Athens (e.g., Piraeus, Dafni, Agios Ioannis Rendis, Keratsini, Drapetsona, Nikea). Downtown Athens was projected in an intermediate position because of the large surface area devoted to urban gardens, parks (Ethnikos Kipos, Likavitòs, Archaelogical area of Akropolis-Filopappos, Pedion ton Areos, Singrou grove, Acadimia Platonos, Attiko Alsos, and the central cemetery), and other natural/cultural amenities that intrinsically reduced the average level of soil sealing at the municipal level. The spatial organization of both rows' and columns' points projected along the two axes (basically illustrating two orthogonal gradients of soil sealing) may confirm that the two latent dimensions represent distinctive settlement structures likely associated with distinctive socioeconomic processes at the base of a classical rural–urban gradient (Dimension 1) and a strictly urban gradient benefiting from scale economies (Dimension 2) generated by agglomeration, concentration, and activity diversification.

4. Discussion

Causing departures from a purely radio-centric expansion path, metropolitan transformations have determined—especially in Europe—a shift from traditional mono-centric structures (with characteristic, high-density settlements) toward a (more or less marked) shift to spatially discontinuous, low-density morphologies [98–100]. With this perspective in mind, comparative and diachronic analyses of land imperviousness profiles may delineate a simplified, rough measure of urban footprints, estimating the intrinsic sustainability of a given development path [101]. The data mining strategy implemented in this work proved useful when decomposing the intrinsic complexity of a compositional data matrix that illustrates the local profile of land imperviousness [102]. In particular, the sequence of multivariate analyses we have used in the present work exercise highlights the usefulness of a DCA for the extraction of latent dimensions of soil sealing spatio-temporal complexity [103]. The first two dimensions identify, in both 2006 and 2018, two local profiles of 'land imperviousness', the one characterized by the dominance of settlement typologies with a medium-low percentage of soil sealing, the other grounded on systematically higher percentages of soil sealing [104]. The level of soil sealing discriminating between the two dimensions was visually estimated at around 79% imperviousness degree in 2006 and 84% in 2018. The first typology, associated with Dimension 1 (which explains the maximum variability extracted from the input data matrix), included rural, peri-urban, and quasi-urban contexts, with highly variable settlement density ranging from 100 inhabitants/km^2 to nearly 5000 inhabitants/km^2. This dimension ordered municipalities from left to right according to a density gradient, which reflects settlement compactness [105]. The municipalities on the left side of the axis are markedly rural, economically marginal, and geographically peripheral [106]. The municipalities on the right side of the axis are, on the contrary, typically urban, economically dynamic, and geographically accessible [107]. Unlike Dimension 1, which included a large number of municipalities, a smaller number of municipalities were associated with Dimension 2. A similar structure of municipalities was observed in 2006 and 2018, and the soil sealing classes were ordered from the bottom (lowest values around 80–85%) to the top (highest values up to 100%). Municipalities associated with Dimension 2 were ordered according to a settlement concentration gradient, from the bottom to the top of the axis. Municipalities with denser settlements and more concentrated populations were clustered towards the top side of the axis. Conversely, the less concentrated (urban) municipalities (with a density always higher than 5000 inhabitants/km^2) were grouped downwards.

The two dimensions were rather stable over time and highlighted two specific settlement types characteristic of large metropolitan areas. In particular, the local land imperviousness profile indicates the coexistence of two distinctive morphologies: (i) a vertical city, typically compact and hyper-dense, which corresponds to the central localities of the respective mono-centric model (Athens, Piraeus) and the surrounding municipalities, even denser than the respective centers; (ii) a horizontal city, with a more pronounced settlement diffusion and a land-use mix oriented along the density gradient [108]. The two dimensions resulted in being non-additive since they were not oriented along the same multivariate gradient, being instead orthogonal and, thus, associated with different economic processes [109]. Based on these premises, it is possible to argue how agglomeration factors in the study area have fueled the formation and consolidation of horizontal cities along a gradient oriented from rural areas to quasi-urban locations, according to purely additive socioeconomic processes [80]. The advantages of scale economies acting at higher densities underlie the formation and consolidation of a vertical city profile typically associated with central locations [106], which benefited from population concentration and in turn experiencing negative externalities (e.g., congestion). The empirical results of this analysis relate morphological dynamics to the socioeconomic dimension of metropolitan transformations [30], revealing the usefulness of exploratory approaches that can be reproduced in profoundly different territorial contexts [110], decomposing ‘horizontal’ and ‘vertical’ dimensions of urban growth [111]. In this direction, future studies should focus on novel indicators [112] of soil sealing, considering multiple sets of local attributes, not only dealing with municipal size (i.e., surface area or population) but also extended to other socioeconomic and ecological characteristics of the specific territory under investigation. Our study definitely clarifies how soil sealing appears with very different profiles at the local scale, resulting in heterogeneous geographies of land imperviousness that change over time, mostly revealing place-specific development patterns.

5. Conclusions

Underlying different mechanisms of urban growth, metropolitan regions in advanced economies experienced functional and structural transformations that reflect new socioeconomic trends impacting (directly or indirectly) urban footprints and environmental sustainability. Taken as a direct manifestation of sprawl, discontinuous settlements were frequently associated with heterogeneous land-use patterns, spatially variable urban footprints, and accelerated land take rates, leading to unsustainable development. Based on these assumptions, breaking down the latent dynamics of urban growth into differentiated (e.g., vertical and horizontal) components is a significant contribution to regional science and spatial planning. By reflecting distinctive economic and social conditions, the decomposition of urban growth into separate (vertical and horizontal) components is particularly appropriate when designing policies for the containment of urban sprawl and a more sustainable metropolitan development. More precisely, the notion of (local) land imperviousness profiles allows for an adequate representation of urban footprints and an indirect estimation of metropolitan sustainability. In this sense, a comparison of local footprints with a broad socio-spatial analysis of municipalities may delineate the main socioeconomic determinants of soil sealing at an appropriately operational spatial scale for both regional/urban planning and local developmental policies.

An additional methodological improvement for future studies—especially dealing with urban densification—is associated with the improvement of higher resolution layers of land imperviousness within the Copernicus Land initiative. Despite the fact that some more detailed geo-referenced layers of soil sealing exist, especially for 2018, we considered a 100 m grid as the elementary layer from the EEA Copernicus initiative to allow a full comparison between the two years investigated in this study. A 100 m grid appears to be the appropriate spatial resolution in this kind of study, considering also the necessity of obtaining a full harmonization of geo-spatial layers of soil sealing over time (during the whole extent of the time series, e.g., between 2006 and 2018) and space (e.g., all over the European continent). A multidimensional analysis of Copernicus HRLs finally demonstrated that they were a coherent tool for estimating urban footprints and quantifying spatial patterns (and short-term trends) of land take. The use of more detailed layers (e.g., with a spatial resolution between 10 m and 20 m) should be evaluated in further studies documenting explicitly the homogeneity and comparability of geo-spatial datasets of soil sealing with slightly different resolution grids, as routinely offered by GMES Copernicus Land Initiative. The empirical results of this study suggests the importance of two releases of soil sealing layers, the first at less powerful spatial resolution but fully comparable over the whole time series investigated (e.g., 100 m grid between 2006 and 2018) and the second at a more powerful resolution (10 m grid) and available only for the most recent years (e.g., 2012 and 2018). Irrespective of the disseminated variable, future releases of spatial rasters of GMES Copernicus Land Initiative should take into account both time and space dimensions, providing the appropriate layer for any research and planning need.

Author Contributions: The research project discussed in this article involved a collective endeavor where multiple authors collaborated and made distinct contributions. These contributions encompassed a wide range of aspects, such as offering different viewpoints, sharing unique insights, providing valuable feedback, and offering guidance throughout the process. However, it is important to note that these contributions may not be easily quantifiable or easily categorized in a definitive manner. Despite this challenge, an effort has been made to comprehend and summarize the authors' contributions. Conceptualization, L.S.A. and A.D.; methodology, L.S.A. and I.V.; software, A.D.; validation, K.R. and L.S., formal analysis, D.P., F.A.S. and A.D.; investigation, I.V. and L.S.A.; resources, K.R. and L.S.A.; data curation, A.D.; writing—original draft preparation, L.S. and S.S.N.; writing—review and editing, F.C. and F.E.; visualization, A.D.; supervision, F.E.; project administration, F.C.; funding acquisition, F.E. and I.V. All authors have read and agreed to the published version of the manuscript.

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