Case Study

Spatial Autocorrelation Analysis for New FUA Inner Strategic Asset: A Case Study of the Metropolitan City of Milan, Italy

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Abstract: Functional urban areas represent integrated urban contexts whose territories are economically interconnected. They, therefore, include a central city and all the municipalities that make up the commuting area for work reasons. The economic energies and settlement transformations that characterize these territories have been consolidated over time. The current geographic conformation, as defined today, does not provide information on each municipality's rank (role) in the overall functioning. In this perspective, the work presented examines the demographic and urban dynamics that have affected the FUA of Milan in the last 60 years and then evaluates the presence of possible homogeneous geographic clusters (hot and cold spots) through spatial correlation techniques. Statistic validation was performed through the ANOVA and subsequent posthoc analysis (Tukey–Kramer method). Results show a new configurational asset within the FUA of Milan, which could provide a new key to interpreting the territory, aimed at identifying homogeneous areas to adopt new and more effective forms of strategic planning. **DOI:** 10.1061/(ASCE)UP.1943-5444.0000860. © *2022 American Society of Civil Engineers.*

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Introduction

This study represents the first analysis to identify homogeneous territorial areas for demographic and settlement conditions as possible geographical elements for applying new forms of management and control of anthropic transformations. This analysis has a twofold purpose: on the one hand, to identify possible municipal aggregations to optimize urban development processes and the management of public services; on the other hand, to facilitate new forms of planning more closely linked to the territory's characteristics rather than to administrative limits. Indeed, the high urbanization that can be seen today in Italy has a partial origin related to the particular geological and landscape conformation that substantially contributed to the construction of the historical parts of the settlement. The other cause is the high administrative fragmentation and the weak cogency of strategic planning. This substantially generated the high settlement dispersion that characterizes the entire Italian territory (Martellozzo and Clarke 2011; Romano et al. 2017a, b).

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As highlighted by several international papers (Squires 2002; Carruthers and Ulfarsson 2003; Ewing 2008; Patacchini et al. 2009; Jaeger et al. 2010; Barrington-Leigha and Millard-Ballb 2015; Oueslati et al. 2015), this particular conformation of the settlement is highly energy-intensive, consumes a vast amount of soil, and has several negative impacts on the ecosystems and the services they provide. The essential objectives of the 2030 Agenda, together with the zeroing of land consumption set for 2050 and the alignment of this aspect to real population growth by 2030, entail the adoption of territorial policies that must necessarily decouple land consumption from economic growth (Colantoni et al. 2016; Sapena and Ruiz 2019; García-Coll and López-Villanueva 2018; Salvati 2019). Therefore, this is a significant turning point, not only in economics that sees the construction industry as one of its main pillars but also in the procedures for governing the territory and reducing the number of municipalities, the main actors in settlement transformation processes. The latter is a process that has already been underway for some time. The last 20 years have led to a reduction in the number of municipalities from 8,101 in 2001 to the current 7,903, an average of 10 fewer municipalities every year. This reduction did not significantly change the average size of these administrative entities that, in essence, increased by only 1 km^2 going from 37.3 km^2 in 2001 to 38.2 km^2 in 2020. Furthermore, these mergers are much localized along the Italian peninsular arc because most of these occurred in the northern regions (mainly Trentino Alto Adige, Lombardy, and Piedmont). At the same time, very few are recorded in central and southern Italy. The techniques used in this work for the Milan FUA prove to be very effective in identifying homogeneous territorial areas that could represent the geographical basis for the appropriate application of careful policies aimed at achieving the previously discussed objectives. These techniques could undoubtedly also be applied to other national and European contexts.

Study Area

The analyses carried out in this study concern the Functional Urban Area (FUA) of Milan. The OECD defined FUA in 2012:

a functional urban area consisting of a city and its commuting zone (OECD 2012). Therefore, functional urban areas consist of a densely inhabited city and a less densely populated commuting zone whose labor market is highly integrated with the one of the city (L. Dijkstra, H. Poelman, and P. Veneri. "The EU-OECD definition of a functional urban area," working papers, OECD Publishing, Paris.). It is, therefore, a strictly interconnected territorial context from an economic standpoint. The FUA of Milan indeed represents one of the most important metropolitan systems both at the national and European levels. This area extends over an area of just under 3,900 km^2 (1.3% of the Italian territory), where about 5,200,000 inhabitants currently reside (about 9% of the national total) with a population density equal to more than six times the national average (200 inhabitants/km^2). Three hundred fifty-two municipalities are part of the FUA, the average size of which (11 km^2) is less than a third of the Italian value (38 km^2).

Therefore, given the high economic interests linked to the territory in question, there is a solid administrative subdivision. These municipalities affect the limits of 10 provinces, which substantially involve the part of the Lombardy region except for two cities (Cerano and Trecate), which instead fall within the geographical limits administered by Piedmont (Fig. 1). From an economic standpoint, this area produces 12% of the total taxable income recorded in Italy in 2018 (the latest available data from the Ministry of Economy and Finance—MEF). Therefore, it is an urban system of fundamental importance for various aspects at the national level.

Materials and Methods

The data used in this work come from various sources. The data relating to the FUA of Milan were downloaded from the European project Urban Atlas 2018 (Copernicus-Land Monitoring Service 2018), from which the related urbanized surfaces were then extracted for the analysis of the settlement dynamics. These data derive from photo-interpretation processes of satellite images with geometric resolution between 2 and 4 m/pixel. The minimum mapping unit (MMU) is equal to 0.25 ha for Class 1 and 1 ha for Classes 2–5, while the minimum mapping width is equal to 10 m. The data relating to the urban geography of the second postwar period and the urban planning forecasts in the current plans derive from the respective regional Geoportals (Lombardy Geoportal 2021 and Piedmont Geoportal 2021). The data concerning the demographic aspects have been extrapolated from the Italian National Institute of Statistics (ISTAT 2021). The settlement and demographic dynamics that affected the study area between the Second World War and 2018 were first reconstructed and analyzed. Then, the spatial distribution of values was studied for both periods through the

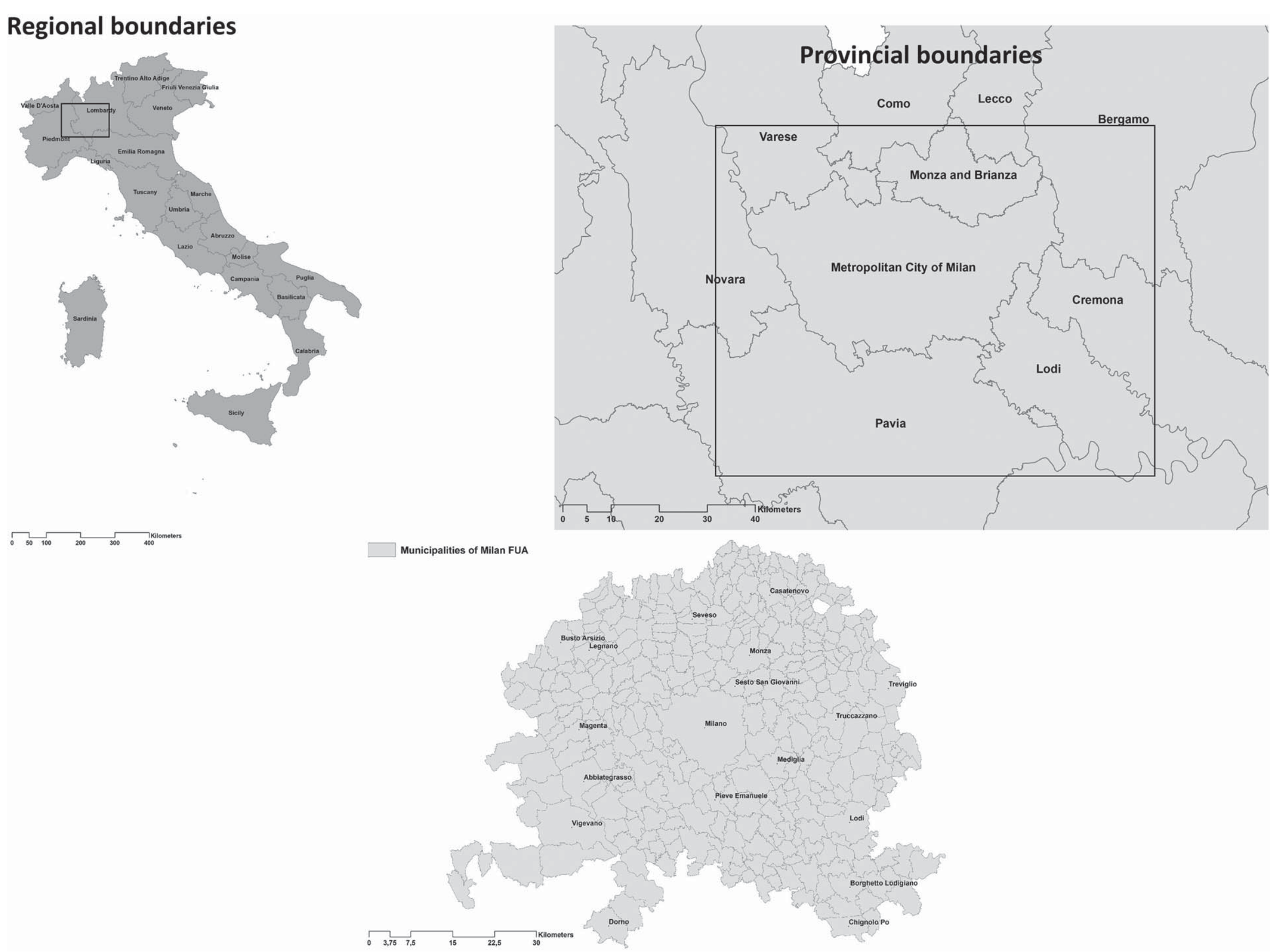


Fig. 1. Study area. Our elaborations. (Data from Italian National Institute of Statistics 2021.)

spatial autocorrelation performed on specific indicators using the municipalities of the FUA as geographical units (Fig. 2). The local spatial autocorrelation is used to analyze, describe, and visualize the spatial distribution and continuity of the investigated phenomenon (Tobler 1970, 2004; Goodchild 1986) and, specifically, it was performed using the local indicators of spatial association (LISA) index. There are various indicators of spatial autocorrelation divided into two global and local macrocategories. In the first category, it is possible to find the presence or absence of autocorrelation; while in the second category, it is possible to understand where the autocorrelation is more concentrated. This analysis, especially in diachronic form, helps in investigating local effects and potential clusters on a geographical basis about the evaluated parameter (Scardaccione et al. 2010; Murgante and Borruso 2012; Nolè et al. 2019). Specifically, this work used the LISA index, highlighting areas where the spatial autocorrelation is more accentuated, reporting its significance from a statistical standpoint. It is configured as a Moran index (Moran 1948), a global indicator of spatial autocorrelation, on a local scale as defined by Anselin (1995, 1988):

$$\sum_i Ii = \gamma \times I \tag{1}$$

Eq. (1) shows how in the LISA formulation, the sum of all the local indices is directly proportional to the value of the Moran index, whose equation is the following:

$$Ii = \frac{Xi - \bar{X}}{Sx^2} \sum_{j=1}^{n} (W_{ij}\,(X_j - \bar{X})) \tag{2}$$

The index then compares the data of the variable considered in a given position (in this case, the municipality) with the values of the neighboring territorial entities. The parameter weight, W_{ij}, was defined based on the contiguity of administrative boundaries. The result is a Moran Scatterplot where it is possible to analyze the statistical trend of the variable concerning the same spatialized variable, a map with all the I_i calculated for every single geographical entity studied, an information layer containing the significance of the results, and a cluster map containing five combinations defined as follows:

- Hot spots (High-High H-H): Areas where high values of the investigated phenomenon and a high level of similarity with the values found in the neighboring territory are found;
- Cold spots (Low-Low L-L): Areas where low values of the investigated phenomenon and a low level of similarity with the values found in the neighboring territory are found;
- Potentially spatial outliers [High-Low (H-L) or Low-High (L-H)]: Areas where high (or low) values of the investigated phenomenon and a low (high) level of similarity with the values of the surrounding areas are found;
- Lack of a significant correlation.

The interesting characteristic of LISA is in providing an adequate measure of the degree of relative spatial association between each territorial unit and its neighboring elements, thereby highlighting the type of spatial concentration and clustering. The neighborhood property is analyzed using the parameter weight, W_{ij} (Cliff and Ord 1969), whose values indicate adjacent spatial units' presence or absence to a given one. The neighborhood is computed in contiguity, such as areal units sharing a common border of nonzero length (O'Sullivan and Unwin 2010). It has a range of values between −1 and 1 where −1 indicates a negative autocorrelation and therefore a dispersed distribution of data, the 0 value indicates no-autocorrelation corresponding to random distribution, and the 1 value indicates a positive autocorrelation that is a clustered distribution. The spatial autocorrelation through the LISA index was therefore performed for both chronological sections investigated by analyzing both the demographic aspect through the population density (PD—number of resident inhabitants compared with the surface of the municipality expressed in km^2) and the settlement aspect through the urbanization density (UD—the percentage of municipal territory covered by urbanized surfaces). Queen contiguity was applied.

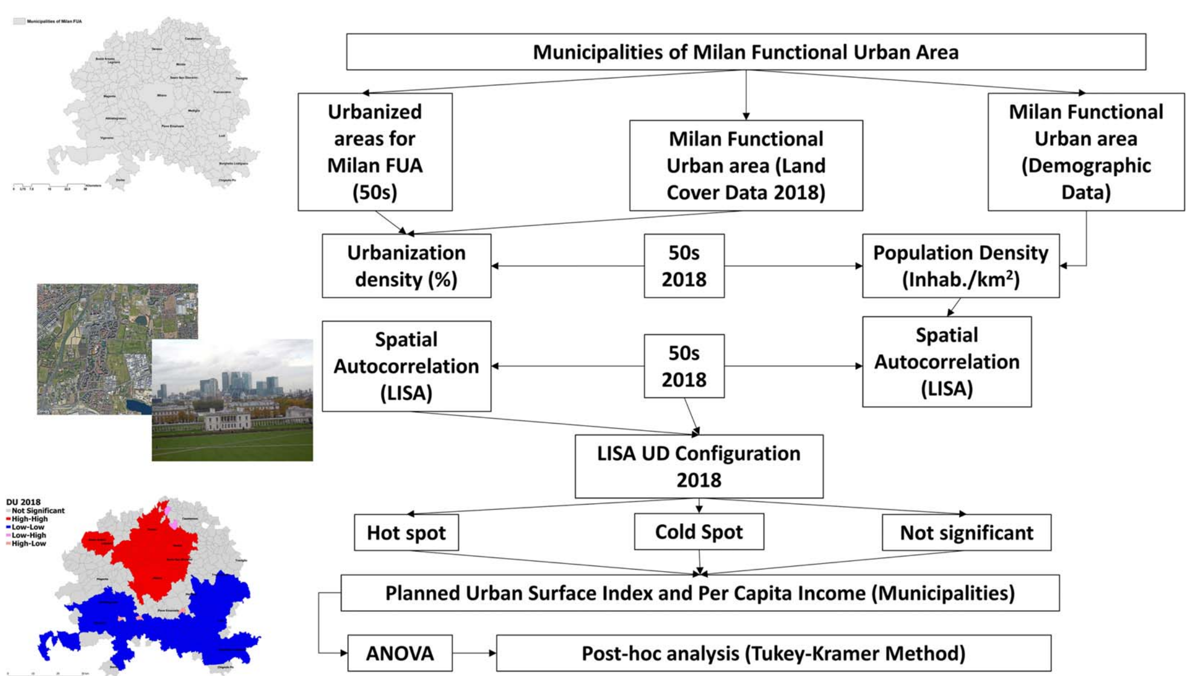


Fig. 2. Flowchart of used methods. Our elaborations. (Image © Google, Image © 2022 Maxar Technologies; Image by Francesco Zullo.)

Results

Situation in the 1950s

After World War II, the territory of the Milan FUA already showed a significant level of urbanization compared with the national context. Indeed, the UD was close to 10% compared with the 2% recorded in Italy. At the municipal level, it is important to note that only 25% of the municipalities of the examined area had an urbanization density value similar to the national average value of the period, while already 80 cities had an urbanization value that was at least equal to today's national one (10%). The regional capital and the conurbation that reached the Monza area and the urban area of Busto Arsizio and Legnano in the western region of the FUA already showed UD values exceeding 25% in the period. On the other hand, at the demographic level, the detected situation showed a PD value (755 inhabitants/km^2) higher than the national average of the period (120 inhabitants/km^2) with a resident population of approximately 3,000,000 units corresponding to 6.2% of the national total.

Fig. 3 shows the results obtained through the spatial autocorrelation analysis performed through the LISA index. The values measured globally for the area show a positive autocorrelation for both variables analyzed with values, respectively, equal to 0.41 (PD) and 0.62 (UD). This indicates a clustered distribution of the values of the indices found in the municipalities, as clearly shown in the provided maps. In particular, it is interesting to note how the geographic location of these detected clusters is quite similar for the variables considered. Two important hot spots have been highlighted already in the 1950s: the first, less extensive, is represented by the municipalities of Busto Arsizio and Legnano and the neighboring municipalities, while the second is the one that extends northward from Milan, involving the territories of the province of Monza up to the municipality of Seveso. The geographical extension of the only cold spot present substantially crosses the entire area investigated in the southern part of the Lombard capital, from Vigevano to Lodi, two important local urban polarizers. It is a territory with an economy with a robust agricultural vocation that directly influences the values of the two indexes analyzed, which show significantly lower values than the two areas previously described, where the economy already had a solid industrial connotation. However, it should be noted that the municipality of Lodi represents an outlier (H-L) for both analyzed indexes.

In contrast, the municipality of Vigevano shows it only for the PD index. Fascinating is the L-H condition for the PD index found in the municipalities of the hinterland of Milan and, in particular, in the south of the regional capital. The PD values in these areas are significantly lower than Milan's (over 7,000 inhabitants/km^2). Still this condition is not evident in the municipalities of the northern hinterland of the capital, which also have similar territorial dimensions. Furthermore, the statistical significance highlighted for this group of municipalities for the PD index is absent about the UD values except in two municipalities (Settimo Milanese and Buccinasco).

Current Situation

In the period under investigation, approximately 750 km^2 of territory were converted to urban use at a rate of 1,170 ha/year, corresponding to 3.2 ha/day. Vigevano (12 km^2) and Milan (31 km^2) consumed the most land. At the same time, there was a noticeable increase in the number of residents, equal to over 2,200,000 units, most of whom were mainly in the municipalities of Milan, Monza, and Cinisello Balsamo. In the investigated period, the urban area available for each resident inhabitant almost doubled, from 120 m^2/inhab. the 1950s to about 210 m^2/inhab. today. This value is lower than the national average of the period (about 360 m^2/inhab.). The UD of the area is approximately three times the national value, with around 70 municipalities having over 50% of their territory occupied by urban surfaces. Only 50 municipalities remain below the national value, equal to less than a seventh of the total of those that make up the study area. The correlation diagram between the values of the two variation rates (demographic and urban) recorded for the period investigated shows a not very high level of correlation ($R^2 = 0.4$), highlighting how, in essence, the urban growth of the studied area shows a certain degree of linear relationship with the demographic growth while remaining substantially influenced by various kinds of economic and social factors (Fig. 4).

The spatial autocorrelation analysis shows extremely interesting results. First of all, it is necessary to highlight the net increase of the LISA (for both indices, the value reaches 0.79) over the entire area,

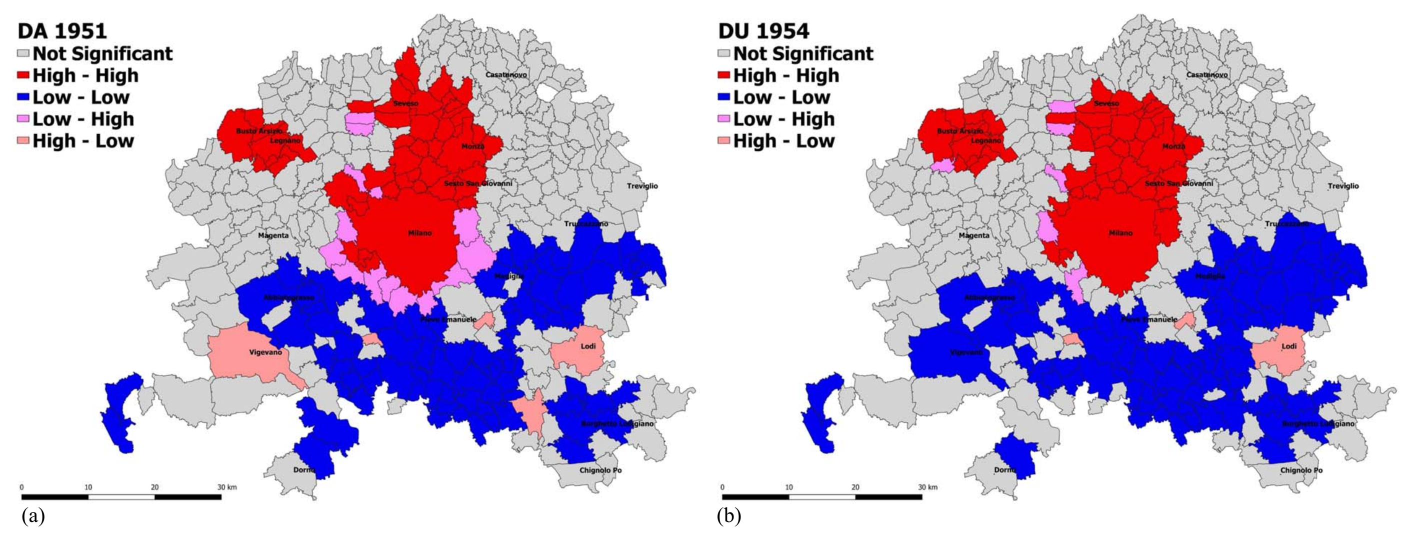


Fig. 3. LISA map on population density: (a) urbanization density; and (b) in study area municipalities. Our elaborations. (Data from Italian National Institute of Statistics 2021.)

underlining a robust clustering of the FUA municipalities, clearly distinguishable in Fig. 5.

In particular, regarding the PD, the two hot spots remain, but while the one located in the west area has substantially reduced, the other relating to the central polarity has widely extended its borders both to the north and to the south of Milan, incorporating the municipalities detected as outliers (L-H) in the 1950s. A significant role in this context was undoubtedly played by the construction of the A50 west ring road in 1968 that, starting from the Rho junction, joins the A1 at the level of the hamlet of Viboldone in the municipality of San Giuliano Milanese. The cold spot present in the southern area since the 1950s now involves a more significant number of municipalities, effectively becoming a single area extended along with the entire lower limit of the FUA. The situation reported by the geography of the LISA results regarding UD is substantially similar to that described previously, with the extensions of the two clusters, H-H and L-L, which involve a more significant number of municipalities. In particular, the two hot spots identified in the first analysis now become a single area, underlining the intense, transformative process undergone by this area that, as evidenced in Fig. 4, had greater energy in the north and west than in the south. From the new geographic configuration identified through LISA, very few outliers are found in addition to the two major clusters described previously.

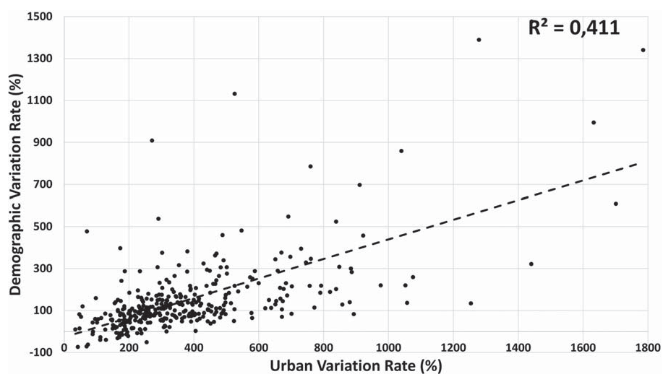


Fig. 4. Correlation between the urban and demographic variation rates for each FUA municipality in the analyzed period. Our elaborations.

New Definition of Municipalities Asset

The results, deriving from the spatial autocorrelation, clearly show how the evolution of settlement phenomena, together with demographic ones, have created three large areas in the municipalities of the FUA that show different conditions concerning the surrounding territory regarding the investigated parameters (Fig. 5). Therefore, this spatial configuration originated from demographic, economic, and settlement dynamics that had different roles and energies in the 60 years analyzed. Then, starting from the geographical configuration identified by the LISA performed for the UD (2018), the urban growth forecasts of the current plans in the three sets of municipalities surveyed were analyzed, using the data on the PGT available on the geoportal (data for the municipalities of Massolengo and Zerbolò are missing). This is because the urban growth dynamics certainly had a powerful effect on this arrangement. Therefore, the forecasts of the current urban planning instruments could design a different functional system in this geographical context.

Furthermore, it could be interesting to understand if this subdivision shows significant differences in the settlement increases envisaged individually by each municipality about the three identified areas. The plan forecasts have been extracted from the database of the plans for the government of the territory (PGT), which contains the data relating to the territorial areas involved in transformation interventions, that is, parts of the region, already built and/or otherwise, in which construction and/or urban planning interventions are planned aimed at a functional transformation. Starting from this information layer, the areas destined for new urbanization have been obtained differently from the current urbanized surfaces. The following index was therefore implemented for each municipality:

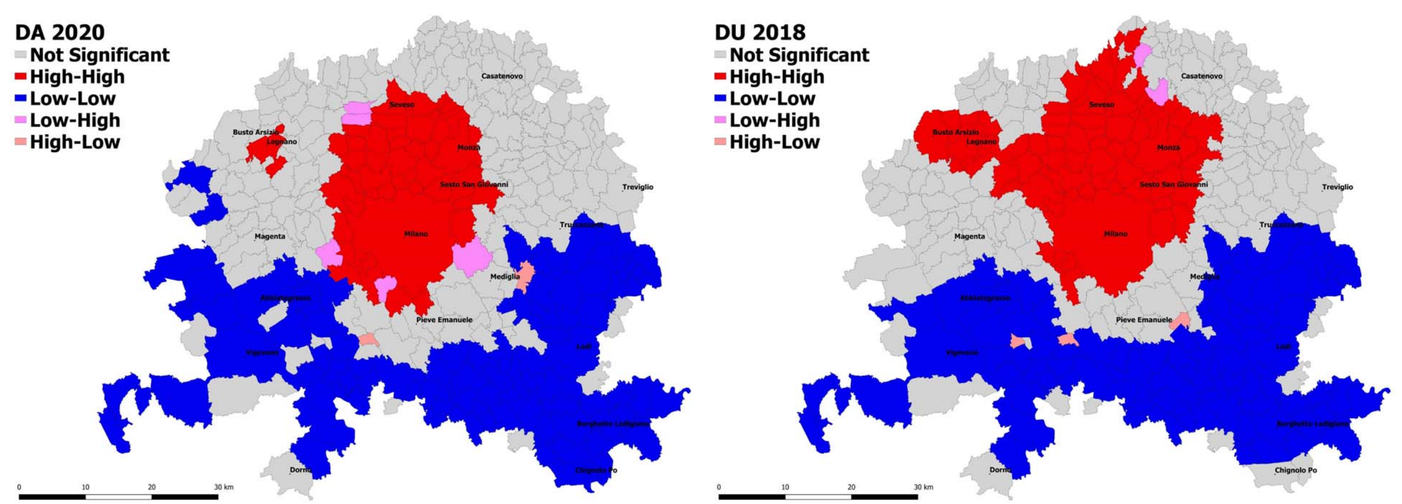
$$\text{Planned Urban Surfaces Index (PUSI)} = \text{Ap}/\text{Aurb}\ (\%) \quad (3)$$

where

Ap = urbanized area foreseen in the urban planning tools currently in force [sum of areas destined for residential use (expansions, developments, and land parceling), areas destined for services (social, cultural, and technological), and regions destined for productive activities (craft and industrial)].

$$\text{Aurb} = \text{Urbanized areas}$$

PUSI index represents a typical settlement behavior index. It shows the number of times that the transformation projections of



(a) (b)

Fig. 5. LISA map on Population density: (a) urbanization density; and (b) in study area municipalities. Our elaborations. (Data from Italian National Institute of Statistics 2021.)

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Table 1. Main statistical parameters for the PUSI index regarding the three macro areas identified

Spot areas	Number of municipalities	Minimum value	Mean value	Maximum value	Median value	Standard deviation	Coefficient of variation	First quartile	Third quartile
Hot spot	77	2.4	12.3	32.55	10.82	6.78	0.55	6.8	14.83
Cold spot	101	3.21	20	163.08	14.83	21.86	1.09	9.21	23.16
Not significant	166	1.26	16.98	199	11.39	22.81	1.34	7.39	16.35

Table 2. Posthoc analysis with the Tukey–Kramer method for PUSI

Comparison of spot areas	Difference	Count group 1	Count group 2	SE	q	Q score Tukey $\alpha < 0.05$ (3.31)	Q score Tukey $\alpha < 0.01$ (4.12)
Cold–hot	8.096	101	77	2.155	3.7561	Yes	No
Cold—not significant	3.410	101	166	1.798	1.8965	No	No
Hot—not significant	4.686	77	166	1.964	2.3856	No	No

Table 3. Main statistical parameters for PCI index regarding the three macro areas identified

Spot areas	Number of municipalities	Minimum value	Mean value	Maximum value	Median value	Standard deviation	Coefficient of variation	First quartile	Third quartile
Hot spot	77	18,869.59	24,504	34,878	23,797	2,996.95	0.12	22,669	25,107
Cold spot	103	18,180.6	22,265	26,754.31	21,833	1,674.46	0.07	21,094	23,150
Not significant	166	19,755.61	24,258	48,186.206	23,737	3,150.38	0.13	22,628	24,838

Table 4. Posthoc analysis with Tukey–Kramer method for PCI index

Comparison of spot areas	Difference	Count group 1	Count group 2	SE	q	Q score Tukey $\alpha < 0.05$ (3.31)	Q score Tukey $\alpha < 0.01$ (4.12)
Cold–hot	2,239.145	101	77	296.107	7.562	Yes	Yes
Cold—not significant	1,993.946	101	166	246.993	8.073	Yes	Yes
Hot—not significant	245.199	77	166	269.866	0.909	No	No

the current urban planning tool multiply what has been achieved within the surveyed municipality. Table 1 shows the principal statistical parameters for the PUSI index for each of the macro areas identified.

In the area investigated, the index value is equal to 16%, with an amount of new urbanized surfaces equal to about 185 km^2, an area as large as the entire municipality of Milan. It is interesting to note how the average values measured in these three areas are different: they range from a minimum of 12.3% for the municipalities of the hot spot to a maximum of 20% for those belonging to the cold spot. An ANOVA test was performed to assess their statistical significance ($p < 0.05$). A posthoc analysis was then performed using the Tukey–Kramer method ($K = 3$ df > 120) to compare the averages found in these three territorial configurations. The Tukey–Kramer test (controls Type I error rate) is a conservative post hoc test used when the sample sizes for each level are unequal. This operation allowed paired comparisons between the PUSI and PCI average values observed in three defined geographic clusters of municipalities (hot spot, cold spot, and not significant). This comparison indicates significant statistical differences between the observed average indexes values in the three groups of municipalities identified. Two significance levels were considered ($\alpha < 0.05$ and $\alpha < 0.01$). The results are shown in Tables 2 and 4.

While there are no significant differences, from a statistical standpoint, between the urban planning forecasts of the plans of the municipalities in the *Not Significant* area and those of the two different spots, the analysis highlights how the differences detected in the forecasts of the plans in the municipalities of the hot spot are statistically significant ($\alpha < 0.05$) compared with those of the plans of the cold spot municipalities. The same type of statistical analysis was performed using an economic indicator such as the per capita income, calculated for each municipality using the taxable income data available on the website of the Ministry of Economy and Finance (n.d.). Tables 3 and 4 show the results.

The results of the posthoc analysis show how the differences between the average values of per capita income are statistically significant between the municipalities belonging to the hot spot and those relating to the cold spot (about € 2000/taxpayer) and between the latter and those belonging to the *Not Significant* area identified by the LISA, while there are no significant differences in the average values of the municipalities in the hot spot compared with those belonging to the *Not Significant* area.

Discussion

The analysis conducted in this work has shown how the urban dynamics that have taken place in the last 60 years have led to the formation of homogeneous and perfectly distinguishable territorial areas within the 3,900 km^2 of the territory of this functional unit. The current geography of the structures detected through spatial autocorrelation derives from the convergence of transformative events that occurred over a significant period, leading to the establishment of relationships between the settlement systems involved. The subsequent elaborations on these diversified sets of municipalities have shown statistically significant differences in income, and the forecasts of new urbanization envisaged in the current urbanization planning instruments. About this last point, it should be emphasized that these are recent planning instruments, many of which are after the date of issue of the regional law to reduce land consumption (RL no.31/2014). Still, they, in any case, forecast significant increases in terms of the occupation of free land for urban use, even if decidedly lower than the values recorded for other Italian municipalities (Romano et al. 2019).

Furthermore, considering that each administrative unit is substantially autonomous in planning its urban policy within its borders and that forms of intermunicipal planning are rarely applied, these detected differences acquire a further and vital significance. The convergence toward a greater endowment of settled spaces of the municipalities in the cold area seems almost aimed at filling the apparent gap with the municipalities of the hot area where, however, urban space is used in a much more efficient way (urban area per capita equal to 128 sqm/inhabitant versus 350 sqm/inhabitant) also due to a much higher resident population. Even excluding the municipality of Milan from the calculation, the per capita urban area of the municipalities in the hot area is always lower (203 sqm/inhabitant). In absolute terms, in the municipalities of the hot area, there are about 80 km^2 (PUSI 16%) of land destined for new urbanization. In contrast, these are 33 km^2 with a PUSI of 18% in those of the cold area. By maintaining these standards of surface area per capita, these urban planning forecasts would lead to an overall population increase over the next 10–20 years equal to 720,000 units, of which 625,000 are in the municipalities of the hot area and the remaining 95,000 in those of the cold area. Let us analyze these areas' demographic dynamics recorded in the last 10 years. It is immediately evident that these expansion forecasts are oversized concerning this aspect and in clear contrast to the European intention of linking land consumption to real population growth. In fact, between 2010 and 2020, the municipalities of the hot area recorded an increase of 152,000 units, while those of the cold area are only 16,300. Furthermore, further alarming data derive from the intersection between the new expansion forecasts and the current land use: 80% of these concerned territories are now destined for grazing or crops, with significant losses in food production and essential ecosystem services.

Conclusions

The study of settlement phenomena, and those connected to them over significant periods together with the adoption of spatial autocorrelation techniques, could provide a new key to interpreting the territory, aimed at identifying homogeneous territorial areas within which to adopt new and more effective forms of strategic planning. In the current Italian governance system, such an approach, at least at a provincial level, could lead to a better distribution of the areas to be allocated to urban uses or those dedicated to public utility services, effectively restoring the cogency of strategic planning. Such an approach could simultaneously improve the effectiveness in the management of soil transformations, also taking into account issues (e.g., planning of ecological networks and ecosystem services) that, due to their characteristics, require broader territorial scales and forms of planning working in synergy. Finally, the increasingly pervasive forms of settlement dispersion (sprawl and sprinkling) that characterize the Italian soil could be better controlled.

Data Availability Statement

All data, models, and code generated or used during the study appear in the published article.

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