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Case Report

Population Age Structure, Complex Socio-Demographic Systems and Resilience Potential: A Spatio-Temporal, Evenness-Based Approach

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Abstract: The present study illustrates an original approach grounded on entropy theory and complex system thinking with the aim to investigate changes over time and space in population structure by age in Italy, in light of socioeconomic resilience and post-crisis recovery potential. Assuming that population structure may reflect different levels of resilience to exogenous shocks, a Pielou J evenness index was calculated on census data made available every 10 years (1861–2011) with the aim to identify compositional homogeneity (or heterogeneity) in the age structure of the Italian population. Trends over time in the Pielou J evenness index were identified using descriptive statistics, comparison with ancillary demographic indicators and multivariate exploratory techniques including principal component analysis. The empirical results allowed the identification of multiple dimensions of demographic transition in Italy, distinguishing two phases, the former encompassing a relatively long time period between 1861 and 1936, and the latter covering a shorter period between 1936 and 2011. A spatially-explicit analysis of Pielou J evenness indices applied to the population age structure of each Italian municipality at the latest survey (2017) finally provided a comprehensive overview of the demographic characteristics likely influencing the resilience potential of local districts. The empirical evidence outlined the consolidation of a coastal–inland divide as a result of the complex linkage between demographic dynamics and local background contexts.

Keywords: population dynamics; age structure; spatial analysis; exploratory data analysis; Italy

1. Introduction

Despite the importance of the resilience dimension in social and economic disciplines, a partial consensus on definitions and assessment techniques has been reached, deriving concepts and basic approaches from the general notion of socio-ecological resilience [1–3]. Assuming that resilience is the ability of a local socioeconomic system to tolerate external disturbance without shifting to a state governed by different conditions, the amplitude of changes caused by disturbance and post-disturbance recovery dynamics is a pivotal issue when evaluating a system's resilience [4]. The assessment of resilience in systems transforming rapidly over time is key for advancing policies of local and regional development [5]. Holling [6] discussed the resilience concept within the broader notion of system stability, focusing on the level of disturbance that a system can face under pre-determined, self-organized processes [7]. By referring to the ability to respond to continuous changes, more recent studies re-framed the concept of resilience in the light of a multiple ensemble of opportunities that disturbances open up in terms of new structures and functions [5], system renewal [6], and the emergence of new developmental paths [4]. While being a relatively underexplored dimension in studies assessing local system resilience, demography is a key component of socioeconomic processes, expressing—likely better than other factors—local adaptation to new conditions [8].

Assessing the specific contribution of demography to socioeconomic resilience at different spatial scales (i.e., defining the importance of intrinsic system properties such as population structure by age) provides basic knowledge to develop a demographically-informed vision of a socioeconomic system's resilience, as an original contribution to integrated issues of sustainable development in advanced countries [9]. Assuming that resilience involves path-dependent, historical lock-in processes, a local system has multiple equilibria emphasizing the linkage between economic expansion and social transformation [10]. The low-level equilibrium of a given system depends on the related social structure, which can be stable or allow for transitions between different configurations [11–14]. Assuming that resilience implies (more or less rapid) recovery from external shocks to a system [15–17], population structure by age is considered a key variable contributing to system stability and leading to higher resilience [18–20]. In this regard, urbanization and population change are important factors shaping the resilience of local systems [21].

Demographic transitions (DTs) from high birth and death rates to low birth and death rates [22] take place in countries with marked socioeconomic transformations [23–25]. In Europe, reduced fertility was observed in the last century [26–30], with death rates levelling off at even lower rates [31]. Considering that a DT is a phenomenon shaping the resilience of local socioeconomic systems, the identification of the demographic dynamics resulting in specific population structures is key to a better understanding of local system's response to external shocks and recovery after crises [31–33]. Assuming a link between regional development and population dynamics [33,34], a refined understanding of DTs based on complex adaptive system theory may shed light on long-term socioeconomic transformations [34–36].

With the understanding that DT is a multidimensional process of change involving several dimensions of population structure and dynamics, the present study hypothesized that different population distributions by age reflect distinctive levels of resilience of a local system, underlying different responses to external shocks [37,38]. Based on these premises, a two-step exploratory analysis verifying (i) the temporal coherency of population structure indicators in Italy between 1861 and 2011; and (ii) the spatial coherence of population structures in Italian municipalities at the most recent time point was developed. This analysis defined homogeneous (i) time intervals and (ii) spatial districts with distinctive demographic contexts implying a variable level of local resilience. Step 1 involved a comprehensive analysis of an entropy-based indicator (the Pielou J evenness index) computed on aggregated census data for representative time points with the aim of assessing compositional homogeneity (or heterogeneity) in the age structure of the Italian population. Analysis was carried out using a multivariate technique (principal component analysis), with the objective of identifying latent relationships among input variables. Step 2 involves a spatially-explicit analysis of Pielou J evenness indices applied to the population age structure of each Italian municipality at the latest survey (2017), providing a comprehensive overview of the demographic characteristics affecting the resilience potential of local districts. A multi-stage approach investigating selected demographic attributes over time and space may reveal latent interactions between socioeconomic development, local system resilience and long-term demographic processes [39–42].

2. Materials and Methods

2.1. Study Area and Data Collection

This study investigated temporal and spatial patterns in selected demographic indicators, applying complex system theory and an evenness index to the analysis of changes in population age structures over a sufficiently long time period in Italy [43–45]. The study area coincided with the Italian borders and covered 301,330 km^2 of land (23% flat land, 42% uplands, 35% mountains). A map of Italy illustrating boundaries of administrative regions and municipalities is presented in Figure 1. The long-term population dynamics in Italy reflect the typical outcomes of a transitional demography in advanced economies. Until World War I, high fertility contributed significantly to natural population growth, and massive emigration to Northern Europe and North America allowed the balancing of socioeconomic disparities within the country, containing unemployment and rural poverty. During the inter-war period, fertility remained high and mortality increased slightly, despite a moderate increase in life expectancy.

Figure 1. Map of Italy illustrating the boundaries of administrative regions (and the official name) and municipalities (the insert indicates the geographical position of Italy within Europe and the Mediterranean basin).

In the post-war decades, fertility became more variable over time, with the highest peaks observed in the late 1950s and the early 1970s, corresponding to the so-called baby boom in Western Europe. Intense migration from Southern to Northern Italy reflected the economic backwardness of a relatively large part of the country south of Rome. At the same time, life expectancy increased more markedly, outlining an increasing divide between urban and rural areas. Since the late 1970s, the total fertility rates decreased continuously—although with a temporary recovery during the 2000s—and population aging consolidated in both urban and rural areas. Fertility decline and aging both contributed negatively to the natural population balance. The total population growth was (and still is) slightly positive thanks to the contribution of massive international migration from developing countries. Population trends in Italy were extensively discussed in Billari et al. [26], Vignoli et al. [28], Cazzola et al. [29] and Caltabiano et al. [33], among others.

The population structure by age (using homogeneous, 5-year age classes) was derived from time-series data (1861–2011) disseminated by the Italian National Institute of Statistics (ISTAT) at the national scale (www.istat.it/demo). These data refer to homogeneous geographical boundaries over time and were derived from the general census of the population and households held approximately every 10 years [46]. A specific focus on municipal data was also carried out considering the population structure by age for all Italian municipalities, using aggregated data from the national population register held by ISTAT referring to 2017. Indicators of population structure by age [47] (old age dependency index and structural dependency index) were also derived from the same dataset disseminated by ISTAT and supplemented the information derived from a multivariate analysis of population structure by age.

2.2. Methodology

The relative share of population by age class in the total resident population at each census year or spatial domain (municipality) was the input for the Pielou evenness J index [48,49]. The Pielou J index is a Shannon diversity function (the so-called H′ Shannon index) standardized to the level of diversification in a given spatial unit [50,51]. The Pielou J index ranges from 0 (complete homogeneity) to 1 (the highest heterogeneity according to the level of local-scale diversification), calculated as follows:

$$\mathrm{J} = \mathrm{H}'/\mathrm{H}_{\max} \tag{1}$$

where H' is the Shannon diversity index, calculated as:

$$H' = \sum_{i=1}^{n} p_i \ln p_i \tag{2}$$

where p_i is the proportion of observations falling in the *i*-th class on the total number of observations for each age class, and $\mathrm{H}_{\max}$ is the logarithm of the number of age classes with at least one observation. While Pielou's evenness functions were traditionally used in ecological applications, with the final objective of assessing the diversity of animal and plant communities, this index was more recently adopted in research dealing with, e.g., the related variety of economic activities, class diversification, social inequalities and compositional analysis of migrant communities by citizenship [6–8,47].

To assess changes over time in the age structure of the Italian population, a principal component analysis (PCA) was run on the matrix consisting of the relative proportions of population by age class in the total population on the country scale by year. The PCA is an exploratory approach selecting independent latent variables (components) from a given data set treating redundancy and serial autocorrelation in a multivariate distribution of observations [40,50,52,53]. Starting from elementary observations, a correlation matrix was adopted as the input of the PCA [54]. While being subjective and not based on hypothesis testing, the selection of relevant components was based on the a priori eigenvalue threshold [55]: components with an eigenvalue > 1 were retained and analyzed further [56]. Component loadings and scores were considered together when defining the independent dimensions of DT in Italy. The PCA was supplemented with three non-active indicators (old age dependency index, structural dependency index, and evenness J index of population structure) contributing to identifying time periods with homogeneous population dynamics. The spatial distribution of the Pielou J index applied to the population age structure in each Italian municipality at the last survey date (2017) was finally mapped using a shapefile of local administrative units provided by ISTAT.

3. Results

Changes in the age structure of the Italian population are shown in Figure 2, using 5-year age classes. The demographic structure observed for 1911 was particularly homogeneous, displaying a characteristic pyramidal shape. This form was a consequence of the high fertility and high mortality, typical of an early stage of a demographic transition. The distribution by age in the previous 50 years (from 1861) was instead more convoluted, with evident local peaks, likely the result of exogenous shocks (e.g., wars, diseases, famines, rural poverty) affecting the structure of the population in the past (e.g., in the early decades of the 19th century). With the rising life expectancy, the age structure of the Italian population in 1951 became more heterogeneous, with a progressive decrease in the younger segment (age classes up to 25–29 years) and a substantial stability of the population at older ages. The impact of World War I was particularly relevant in the 30–34 age group. The population structure in 1981 was even more heterogeneous, reflecting the increase in life expectancy in a context of stable (or slightly declining) fertility. Finally, the structure of the population in 2011 presented a particularly unbalanced age distribution, reflecting a marked decline in fertility, with an increasingly visible impact on younger age classes and showing an aging population. The changes over time in the old age dependency index reflected a substantial aging of the Italian population, accelerating since 1971. The structural population dependence showed a quite homogeneous trend, remaining substantially stable until 1936 and varying only moderately in subsequent decades. The Pielou J evenness index grew progressively over time, indicating a regime shift from a proportional structure by age class to a more heterogeneous, rectangular structure.

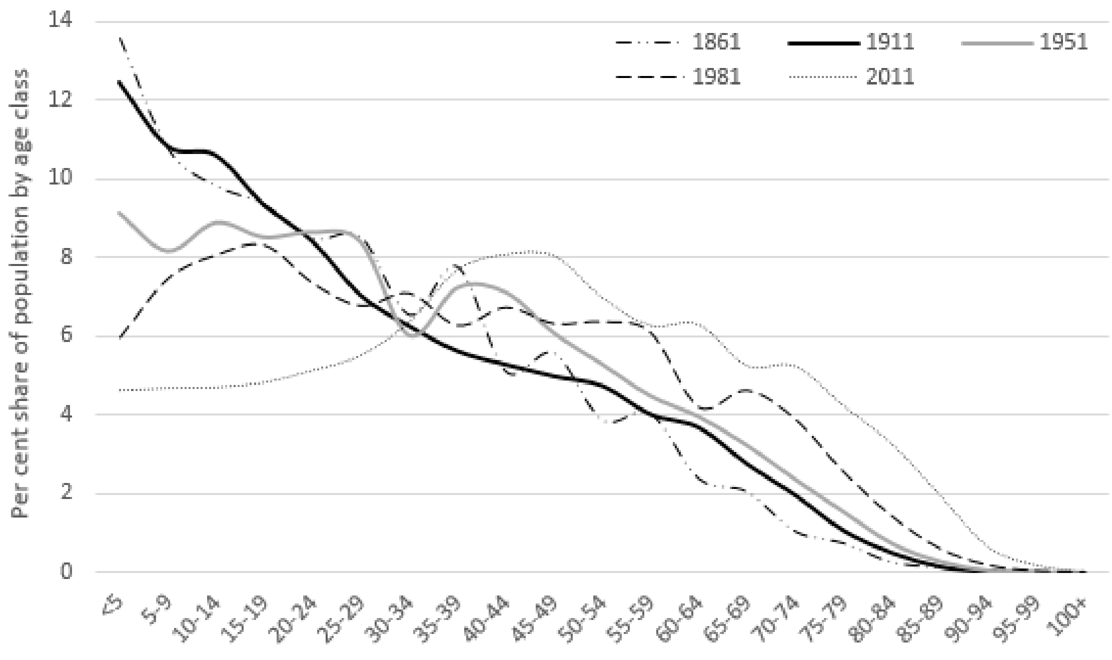

Figure 2. Per cent share of population by age class in the total resident population in Italy by year.

A descriptive analysis was carried out by computing two demographic indicators (the old age dependency index and structural dependency index) together with the Pielou J index (Table 1).

Table 1. The relationship between the Pielou J evenness index applied to population structure by age in Italy and supplementary demographic indicators over time, 1861–2011.

Year	Old Age Dependency Index	Structural Dependency Index	Evenness J Index
1861	12.2	62.3	0.854
1871	15.7	60.2	0.869
1881	16.0	59.5	0.870
1901	17.7	67.9	0.871
1911	20.2	67.9	0.871
1921	23.3	61.2	0.875
1931	24.7	58.8	0.881
1936	24.3	61.4	0.884
1951	31.4	52.3	0.895
1961	38.9	51.6	0.906
1971	46.1	55.5	0.914
1981	61.7	53.1	0.921
1991	96.6	45.3	0.930
2001	131.4	49.0	0.939
2011	148.7	53.5	0.945

A principal component analysis was carried out on the data matrix consisting of per cent shares of the population by age class in the total population, evidencing specific trends over time and links with supplementary indicators (the old age dependency index, structural dependency index, and the Pielou J evenness index). The first two components accounted for a cumulated variance larger than 85%, indicating multidimensional patterns for each analysis dimension, and the variables contributing the most to such trends (Table 2).

Table 2. Variable loadings (per cent share of population by age class in total population) of selected principal components (see also Figure 2). Bold indicates relevant loadings > |0.5|; Italics indicate a supplementary variable in the PCA.

Class (Years)	Axis 1	Axis 2
<5	**−0.93**	−0.19
5–9	**−0.97**	−0.15
10–14	**−0.93**	−0.10
15–19	**−0.90**	−0.03
20–24	**−0.89**	0.32
25–29	−0.46	**0.74**
30–34	0.30	**0.70**
35–39	**0.61**	0.27
40–44	**0.82**	−0.14
45–49	**0.89**	−0.10
50–54	**0.89**	0.11
55–59	**0.92**	0.03
60–64	**0.94**	−0.01
65–69	**0.94**	0.09
70–74	**0.97**	−0.05
75–79	**0.99**	0.01
80–84	**0.97**	−0.12
85–89	**0.97**	−0.15
90–94	**0.96**	−0.11
95–99	**0.86**	−0.24
Old age dependency index	*0.98*	*−0.06*
Structural dependency	*−0.77*	*−0.53*
Evenness J index	*0.97*	*0.09*
Expl. Var.	77.3	7.5

Component 1 extracted 77% of the overall variance in the data matrix and was associated negatively with younger population (age classes up to 20–24 years) and positively with the adult population (from 35 years onwards). The old age dependency index and Pielou J evenness index were positively associated with Component 1, while the structural dependency index was negatively associated with the same component. The age classes (25–29 years and 30–34 years) were positively associated with Component 2, which explains 7% of the overall variance. This component was also negatively associated with the structural dependency index. The temporal structure associated with the principal components 1 and 2 is illustrated in Figure 3. A moderate shift along Component 2 (from negative to positive values) was observed during the period 1861–1936, together with a more accelerated shift along Component 1 (1936–2011). Municipalities with the highest Pielou J evenness index (>0.98) were scattered in internal areas of the country, especially along the central and southern Apennines, and more occasionally along the Alps (Figure 4).

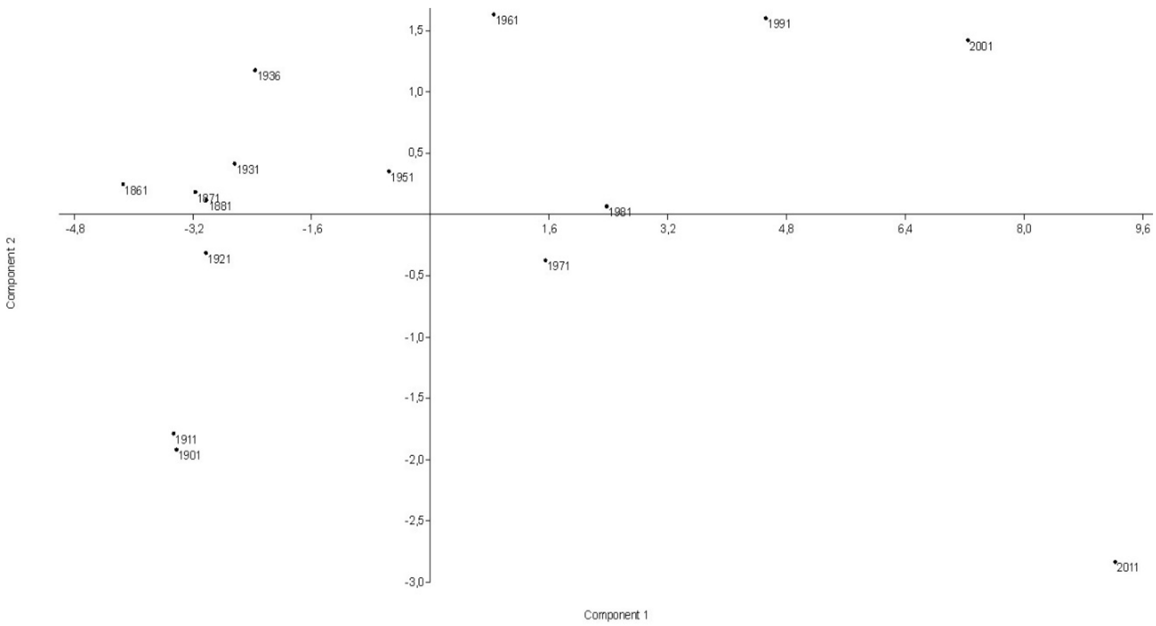

Figure 3. Biplot illustrating the year scores for principal components 1 and 2 (see Table 2).

Low fertility and population aging have characterized these districts in recent times [26,28,29]. Most of the Italian municipalities were classified in the range between 0.97 and 0.98: these territories—widespread throughout the country, both inland and along the coasts—displayed demographic dynamics associated with progressive aging and a moderate fertility decline. The J class between 0.96 and 0.97 identified municipalities with a mixed demographic structure basically found in coastal areas, especially in central and southern Italy. These municipalities are often situated at the border of large cities (e.g., Rome, Naples, Cagliari, Bari, Palermo) and display a relatively young population structure, with moderately high fertility rates and intense population growth thanks to immigration from abroad. Finally, municipalities with a Pielou J index lower than 0.96 present a particularly mixed demographic structure, dominated by a young population in some cases (urban areas of Rome, Naples and Cagliari), or by an adult and older population in other cases (rural and internal areas of the Northern and Central Apennines as well as economically-marginal areas of Piedmont and Friuli Venezia Giulia).

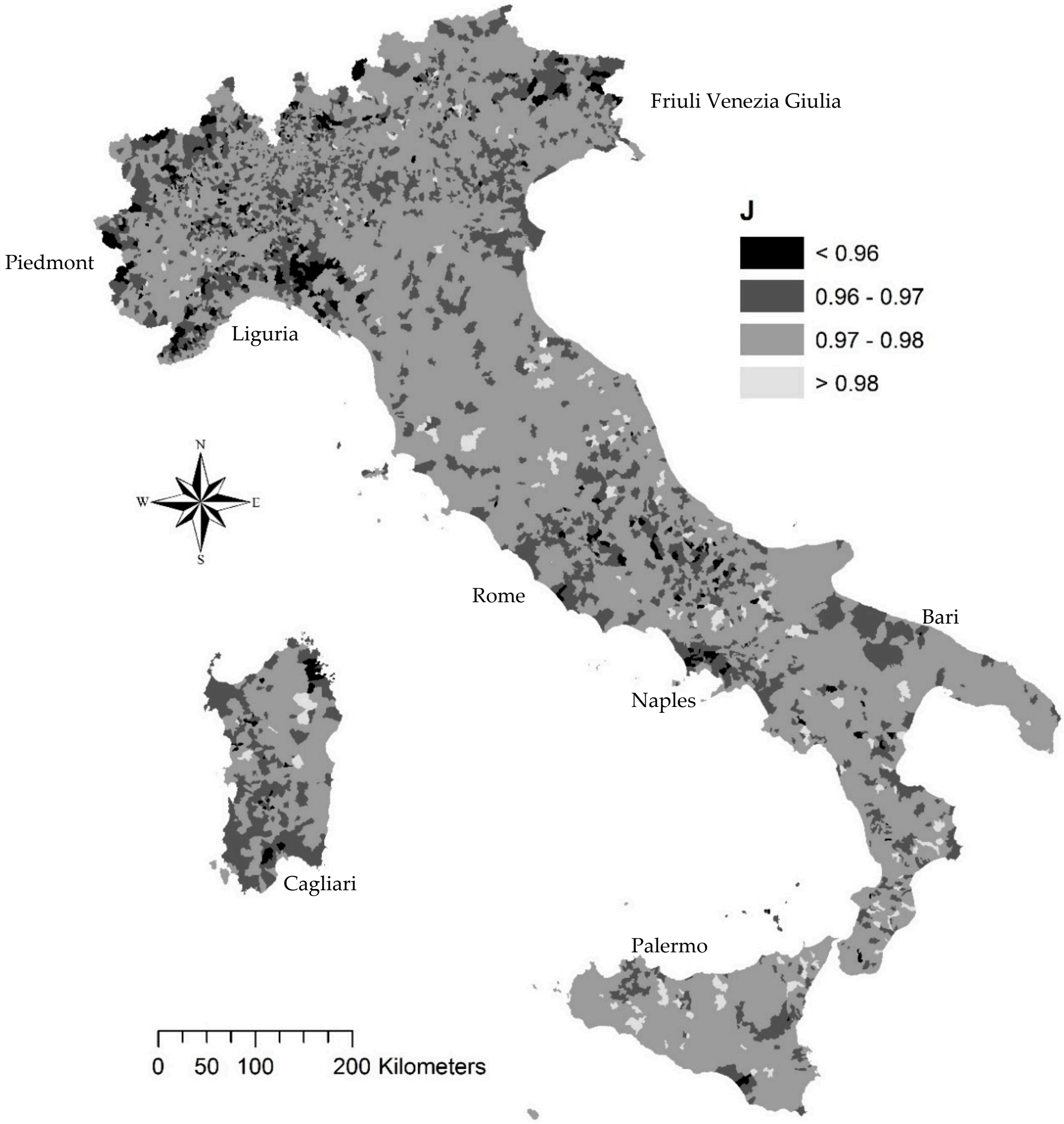

Figure 4. Spatial distribution of the Pielou J evenness index applied to population structure by age in Italian municipalities (2017).

4. Discussion

Under the assumption that economic development is a key component of a system's resilience, socio-demographic diversity makes local systems less vulnerable to external shocks with respect to lower-diversity contexts [1]. While greater diversity may reduce fluctuations and uncertainty in present and future growth, districts with high resilience are adapting more quickly to global challenges and external shocks [5–8]. Systems with low resilience may experience negative impacts from population aging, unemployment and emigration [57]. Analysis of the multifaceted dimensions of socio-demographic resilience contributes to estimating the adaptive capacity of local systems to external shocks [58,59]. In this regard, approaches evaluating the contribution of the population structure to the socioeconomic conditions of local systems are particularly appropriate for a comparative analysis of system resilience [60]. A comprehensive analysis of changes over time in population indicators during the Italian demographic transition contributes to identifying key components of socioeconomic resilience [61]. As it is grounded in a multivariate statistical approach, our study provides a conceptual and operational perspective for a renewed understanding of long-term population trends at the country and regional scale, focusing on the latent interplays between demographic patterns and processes [62]. The results of this study support the assumption that demographic transformations are linked with a broad spectrum of socioeconomic conditions influencing the resilience of local systems [48].

In line with previous works grounded on different disciplinary approaches [10,41,56], the empirical results of this study offer a reflection on the notion of regional resilience in advanced countries, reconnecting local systems to issues of territorial disparities and socioeconomic imbalances, considering a specific aspect of resilience resulting from the intimate characteristics of demographic structures [40]. Our work outlines the relevance of integrated assessment frameworks for spatial demography. In this regard, population structure by age—together with other socioeconomic aspects characterizing local systems—is a key variable when assessing the level of resilience at the local scale [39]. Demographic phases may reflect a dynamic balance between the population and the evolving socioeconomic context, highlighting latent system transitions [45]. Homogeneous time intervals featuring different demographic dynamics were identified as sequential developmental waves in Italy. These time intervals reflect conditions of dynamic equilibrium within specific socioeconomic contexts [15,16,43]. Population dynamics have contributed to this transition thanks to e.g., the inherent polarization of settlements in high-density and low-density areas [42].

As it involves socioeconomic dimensions that are hard to characterize as factors of change, the latent link between demographic structures and local development requires a more comprehensive analysis in economically-advanced countries [60]. A comparative investigation of population age structures over time and space can be extended to other countries in Mediterranean Europe with the aim of identifying common resilience trends, assuming that changes in vital rates are responsible for distinctive paths of population growth (or decline) in this region [39]. The operational framework proposed in this study outlines the importance of novel demographic indicators in a broader framework linking changes in population structure with the socioeconomic resilience of local systems (more or less rapidly) adapting to global change [17].

The approach proposed in this paper contributes to identifying specific demographic patterns and processes over time and space, in relation with the evolving socioeconomic context at different investigation scales. Based on a simplified indicator of evenness in the population structure by age, two homogeneous time intervals—corresponding to distinctive phases of demographic transition—were identified in Italy: a relatively long time period between 1861 and 1936, and a more recent phase between 1936 and 2011. Being characterized by different demographic conditions (birth and death rates, migration, aging), these stages may reflect a dynamic balance between the population and the evolving socioeconomic context, highlighting latent system transitions responding to specific drivers of change and shaping the overall resilience to external shocks. A spatial analysis of the evenness indexes applied to the population structure by age in Italian municipalities finally identified a gradient reflecting coastal–inland disparities consolidated over time.

5. Conclusions

An explicit analysis of demographic processes allows a more comprehensive definition of socioeconomic resilience, informing strategies aimed at stimulating the faster recovery of local systems from external shocks. Further investigation based on such observations should operationally focus on the (apparent and latent) effects of demographic transitions (considering together changes in population dynamics and structure) on regional resilience. As proposed in this study, indicators inspired to incorporate complex system thinking and renewed approaches grounded on entropy theory seem to be appropriate to unravel the latent link between spatial demography and resilience science, providing an improved characterization of the socioeconomic patterns and processes that underlie regional resilience.

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