**Network Connectivity and Regenerative Economic Capacity in the Western Balkans**

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## Abstract

*Long-term population dynamics in regenerative economic systems depend not only on a region's ability to absorb and adapt to structural pressures, but also on how interurban network connections transmit competitive and complementary effects across space. Using longitudinal census data (primarily 2011–2021) for 65 urban areas in the Western Balkans, we examine population change as an indicator of long-run regional development within a spatial interaction framework. Road-network accessibility is derived from OpenStreetMap, while contextual urban indicators—including infrastructure density, cultural, financial, child-oriented amenities, and regenerative economy capacities—are generated using GIS-based kernel density methods.*
*We estimate three weighted least squares regressions corresponding to alternative spatial interaction formulations (negative exponential, log-normal, and inverse distance decay), where origin–destination relationships are weighted by destination population size. Results show that the log-normal specification, emphasizing medium-distance interactions, provides the strongest explanatory power for cross-national population change. Local amenities and regenerative economy capacities at origin cities are associated with greater resilience, while destination-city characteristics exhibit mixed and often competitive effects. Shared language significantly moderates network effects by reducing spatial and institutional frictions. Overall, the findings highlight the importance of integrating regenerative economies, network connectivity, and spatial interaction into the analysis of long-term regional adjustment processes. The proposed approach offers a transferable framework for studying long-term regional dynamics in data-scarce international contexts.*

Keywords: Economic resilience, accessibility, network connectivity, depopulation, migration, Western Balkans, GIS, Services, Regenerative economy

## Introduction

In recent years, regenerative economics has become synonymous with a wholistic definition of economic systems where ecology, sustainability, and adaptive economic capacity are integrated in all actions from policy, to business (van der Laag, C., & Östh, J., 2025; Čegar et al., 2024; Sessa, 2025). This also means that there is potential for the use of a broader regenerative economic lens for the observation and study of regional economic performance and development processes. Literature suggests that there is a link between economic performance, demographic change, and regenerative economy where regenerative economies may support regional systems that are better equipped to mitigate depopulation and to facilitate rural development and economic development (Cave & Dredge, 2021; Ferreira, & Ferreira, 2023; Loza, 2025).

Regenerative economic capacity and network connectivity represent vital, interconnected amenities and potential for regional stability and growth. Connectivity and accessibility to jobs and services via transport networks enable access to opportunities within feasible times and distances. Conventional assessments of regional development prioritize regional assets like industrial diversity, human capital, infrastructure, innovation, health, and global integration, avoiding lock-ins. Yet, these often tally stationary factors within fixed boundaries, overlooking spatial interactions that integrate economies through flows of goods, labor, and ideas. More recently, place-based capacities related to environmental adaptation, circular resource use, and energy transitions, commonly discussed under the umbrella of regenerative economies. Therefore, to better understand long term regional development and adjustment processes, an understanding of the role of networks and accessibility is necessary (Östh et al. 2015; 2018; 2023).

Prior work has shown that network connectivity and accessibility critically modulate the propagation of shocks, see for instance (Östh et al. 2015; 2018; 2023), yet most studies remain confined to regions or single-country analyses due to data harmonization challenges. In this paper, we propose a novel methodology for studying long-term regional development patterns through regenerative economic capacity and transport networks across multiple countries also where detailed flow data are unavailable, and we do so for a region where comparable economic performance measures are difficult to obtain. Studying regenerative economic capacity and network connectivity between regions located in different countries is difficult regardless of countries involved but, in the Balkans, past and recent conflicts and political, cultural and religious tensions between East and West, makes access to data and comparable information almost impossible to obtain. Having that said, in the new era of open data and online data repositories, new options for data generation have emerged also in instances where official data is scarce. These developments also allow the incorporation of non-traditional indicators, including environmental and regenerative economy–related infrastructure, derived from open spatial data sources. In this study, we test if we can estimate long-term regional development patterns linked to regenerative capacity and network connectivity within and between the countries in Western Balkans, i.e., Slovenia, Serbia, Croatia, Albania, Bosnia-Herzegovina, Kosovo, North Macedonia and Montenegro.

Recent reports underscore the urgency: the region faces a projected 190,000 worker shortfall by 2030 due to ongoing emigration and aging populations (World Bank, 2025). However, the present economic status is not the inflection point of the regional economic shock in the Western Balkans, instead today is just another day in a process where the regional economy is under continuous pressure in several areas, and where this has been the case since at least the Balkan wars. We operationalize the slow changes in economic performance as percent population change over time where we use longitudinal census figures to capture regional development. This because there are strong links between negative population development, in particular when measured as loss of working aged individuals, and economic vulnerability (GMF, 2023; Östh et al., 2023; World Bank, 2025). Depopulation has no clear national pattern but responds to local and global events, and is also highly sensitive to urban-rural composition, demography and regional politics (Milijić et. al., 2025; Newsham & Rowe, 2023; Loras-Gimeno et al., 2025). Having that said, policy and actions dedicated to reduce net-migration loss seems to be effective in reducing depopulation (Loras-Gimeno et al., 2025), at the same time as poorer rural regions with a population dual deficit, i.e., net-outmigration and low nativity, have few policy tools available to mitigate losses. So, for regions with financial means to engage in costly strategies, population loss mitigation strategies may be effective, at the same time as the regions with few or no means consolidate as population loss regions (Loras-Gimeno et al., 2025).

To place these long-term development patterns in a broader conceptual context, it is useful to briefly reflect on how resilience has been understood in regional studies. Traditionally, the study of resilience in regional economies is often described differently depending on the temporal situating of the economic shock, and the view of how the economy has the capacity to bounce back or to develop into something different after the shock. Departing from Pimm's definition of resilience (1984), engineering resilience reflects an economy's capacity to bounce back after a shock, stressing the speed of return to its pre-shock state. In contrast, ecological resilience (see Holling, 1973) refers to the ability to absorb shocks with minimal structural change, maintaining an existing equilibrium until the magnitude of the shock exceeds a region's threshold and pushes it into a new, usually less favourable, state. Both engineering and ecological resilience refers to a near equilibrium state to which the impact of shocks is assessed (Sutton et al., 2023). Parallel to the near equilibrium studies of economic resilience, studies of economic resilience where there is no expectation of return to a near equilibrium state, or even stability, but rather the complex and diverse development of economies, governance and society are gaining popularity (see for instance Reggiani et al., 2002). This study belongs in many ways to the latter category, often referred to as evolutionary resilience, not only because of the lack of a near equilibrium state, but also since our means for studying long-term regional development through regenerative and network conditions in the Western Balkans doesn't include sudden shocks or changes to the economic system (as discussed by Rose, 2009), but rather describes long-term changes to the regional economic performance. Within this evolutionary perspective, regenerative economies can be interpreted as one mechanism through which regions adapt, reconfigure, or stabilize their development trajectories over time. Rather than returning to a prior condition, economies may bounce forward, adjusting structures and functions to sustain or improve their development path, but economies may also develop in a less favourable way. While this study is not centred on shocks, these perspectives help interpret long-term regional adjustment processes.

The processes studied in this paper are depicted in Figure 1., where regional shocks (depicted as rain) come with different intensity and angle but is persistent over time. Access-providing network connectivity and regenerative economies both provides support for long-term regional adjustment and stability over time.

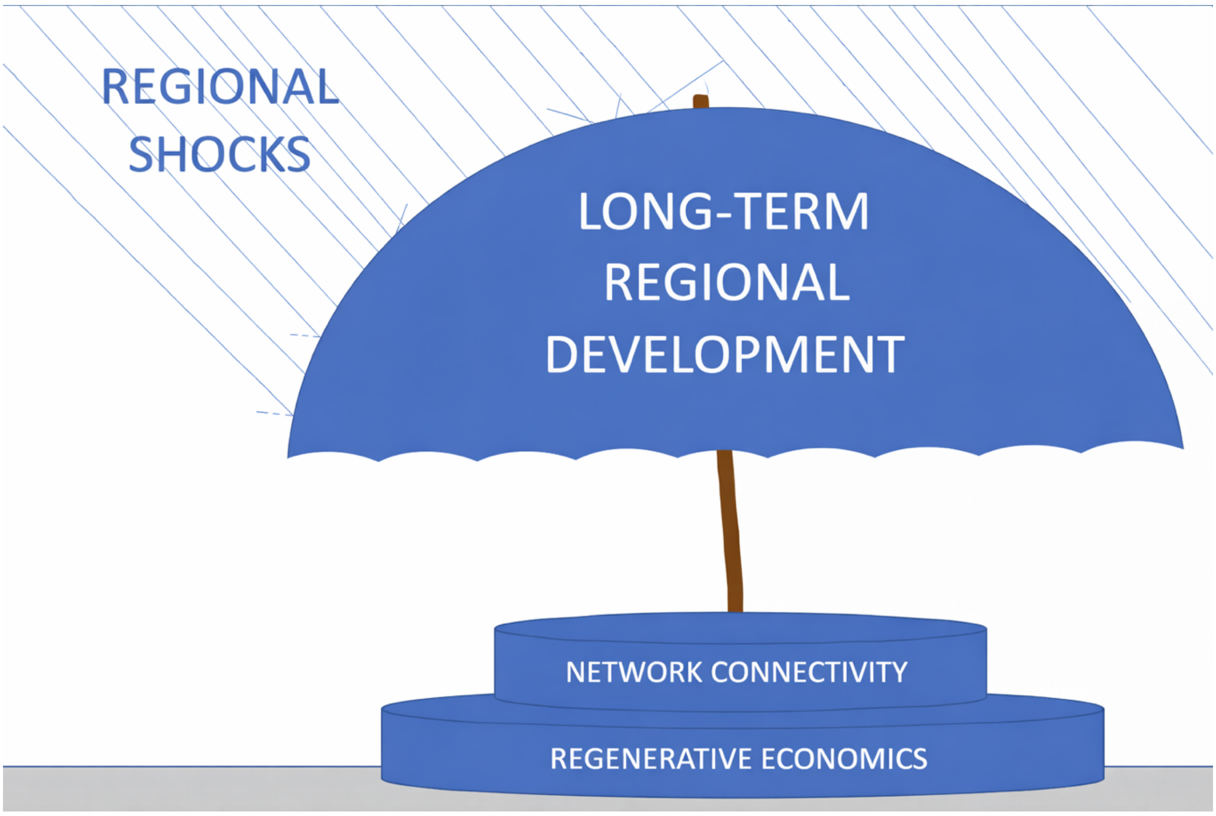


*Figure 1 Depiction of how network connectivity and regenerative economies provides support for long term regional development.*

Based on the literature we have developed two broad questions that we will seek to answer in this study:

1. To what extent can long-term population change be associated to varying levels of network connectivity and regenerative economies in evolutionary-type regional economies?
2. Can the lack of national and regional data on network connectivity, regenerative economics and related regional dynamics in the Western Balkans be substituted with data drawn or generated from Open international data repositories?

The latter question indicates that with no comparable measures of flows between urban areas in the Western Balkans, the role of networks in regional development processes could be questioned, however, there are established links between the magnitude and stretch of infrastructure and the degree of economic exchange (Limão & Venables, 2001; Anderson & van Wincoop, 2003). With this knowledge we have derived a comprehensive road-network from Open Street Map (OSM) where OD distances between nodes were estimated using network-distances. By combining potential-accessibility metrics with contextual variables drawn from open-source spatial data, including both conventional urban amenities and indicators related to regenerative economy capacity, our approach enables cross-national analysis of regional development patterns in data-scarce regions. We illustrate this method in 65 urban areas of the Western Balkans. The main objective is to develop a methodological approach for the estimation of regional development processes linked to regenerative economic capacity, including both local and interregional conditions in countries or regions where data is scarce.

In order to facilitate replication in other data scarce regions, we relied on three main open sources for data; 1) Eurostat population grid for year 2021 has been used to calculate population density throughout Balkans (Eurostat, 2025), 2) Open Street Map (OSM) was used to generate data describing the spatial distribution of road infrastructure, services and amenities related to culture, finance, childrearing, as well as regenerative economy–related infrastructure such as renewable energy facilities, environmental monitoring stations, and waste management sites, and finally 3) different national statistical agencies providing census-based population counts per cities over time. Similar variables could be generated for most regions worldwide.

In the reminder of the study, we will detail data and generation of variables, followed by a methods section where the analytical approach is specified. This is followed by a results section where regressions and an estimation of population change (i.e. the long term regenerative development trajectories) based on alternative network specifications are compared to observed population changes. Finally, we discuss findings, merits and weaknesses of using a simple setup as described in this paper.

## Data and Study Area

Studying long term regional development and within- and cross-border network connectivity is challenging in any multi-country setting. In the Western Balkans, however, the difficulty is greatly amplified by a legacy of conflict, persistent political frictions, and deep cultural and religious divides, all of which severely restrict access to harmonized, reliable, and comparable official data. Against this backdrop, the rise of open-data platforms and crowdsourced repositories offers a promising alternative for generating spatially detailed and temporally consistent indicators where traditional sources remain scarce or fragmented. This study therefore explores the feasibility of estimating regional regenerative economics and interregional network connectivity across the Western Balkans using reproducible data sources. First, we use population grid data, available for the EU+ countries at different time period (Eurostat, 2025). The data is available as geocoded grids, and could potentially also form the basis for the estimation of population change over time, however, in this study we have employed gridded data to establish population concentrations in different countries without being confined to different kinds of administrative delineations of urban areas but rather ensure that we had similar population counts throughout the studied region. Using a k-nearest neighbour/object algorithm, we defined rules to indicate areas (any grid unit and surroundings) that had least 50000 inhabitants within a radius of 20km from the km unit midpoint. The count was set to find all population centres from national to regional capitals, also allowing for inclusion of populations in neighbouring regions/countries. In figure 2, two maps are shown, where the left map shows the population densities through western and central Europe. In the right map, dark green dots indicate centres reaching a population concentration as indicated above, and the light green dots are showing the same for the included western Balkan region. In total, 65 urban areas were identified in the Western Balkans. The 65 urban areas included all regional and national capitals in all the Western Balkans. Selected urban areas were large enough to constitute regional centres where various societal activities and functions served local and surrounding populations and could act as attractors for populations in neighbouring regions.

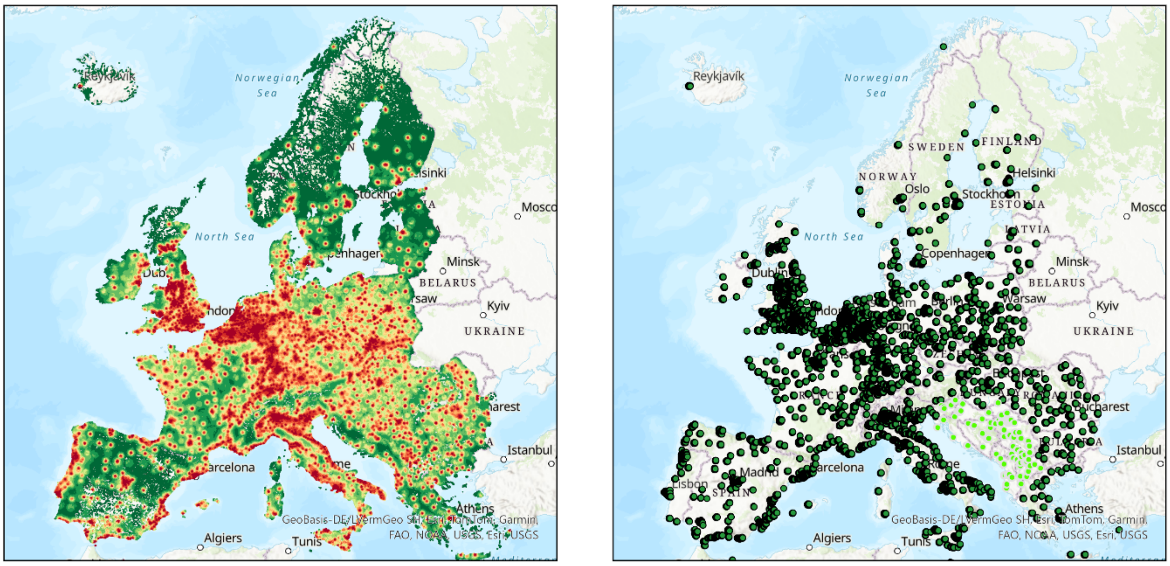


*Figure 2 Population density in Europe, Left map shows population density where green indicates low density, and red indicates high density of population, in the right map, urban areas reaching a population density of 50000 inhabitants within a 20km radius are shown as green (light green for Western Balkans, darker for the rest). Data source population grid for 2021, Eurostat.*

<u>Road Network and POIs</u>

Road-network geometry and points of interest (POIs) were extracted from OpenStreetMap (OSM) for the Western Balkans. The interurban road network was generated using a GIS-based network analysis, identifying the shortest road distance between all pairs of the 65 selected urban areas. The network was restricted to primary, secondary, and tertiary roads, excluding smaller rural roads and local streets with unknown speed limits or access restrictions. This procedure yielded a 65 × 65 origin–destination (OD) matrix representing likely interurban travel trajectories based on road distances.

Figure 3 illustrates the spatial distribution of the selected urban areas (left panel) and the resulting road network composed of primary, secondary, and tertiary roads (right panel). In addition to serving as input for the GIS-based network analysis, the road data were also used to derive a measure of infrastructure density. A line density function was applied, calculating the total length of roads within a 5 km radius of each 1 km² grid midpoint and dividing it by the corresponding area. For each city, the maximum line density value was retained to represent the intensity of road infrastructure within the urban area.

In addition to road infrastructure, OSM was used to extract approximately two million objects that can be classified as points of interest (POIs), representing services and amenities such as supermarkets, schools, monuments, and automated teller machines across the Western Balkans. For the analysis, three POI categories were selected to represent core urban functions associated with everyday life and economic activity. First, childrearing services, including schools, kindergartens, and playgrounds, were identified to capture family-oriented amenities that may mitigate population loss. Second, banks and ATMs were selected to represent financial and work-related services, which may also reflect the level of local economic performance. Third, cultural amenities, including theatres, museums, cinemas, and sports arenas, were included to capture cultural and social capital that may positively influence population development.

For each POI category, service density was estimated using a spatial kernel density function. Kernel densities were calculated for all 1 km² grid cells covering the Western Balkans, allowing services located in the immediate surroundings of each grid cell to contribute to the estimated density. For each city and POI category, the maximum kernel density value was retained as a composite measure capturing both the magnitude of service provision and the spatial concentration of amenities within the urban area. These measures were subsequently used as origin- and destination-specific variables in the spatial interaction models.

To extend the analysis beyond conventional urban amenities, additional POI categories were extracted from OSM to capture dimensions of regenerative economy capacity. These include renewable energy facilities such as solar, wind, hydro, and biomass installations; environmental monitoring stations; and waste management and recycling infrastructure. These POIs represent place-based investments related to ecological restoration, environmental governance, and circular resource use, and are interpreted as indicators of regenerative capacity supporting long-term regional adjustment and development.

As with conventional POIs, kernel density surfaces were generated for each regenerative economy category across the 1 km² grid. Maximum kernel density values were then extracted for each city and used to construct origin- and destination-level indicators of regenerative energy capacity, environmental monitoring capacity, and waste-related capacity. Owing to the sparse and spatially concentrated nature of these facilities, regenerative economy indicators were standardized prior to inclusion in the regression analysis, ensuring comparability across cities and specifications.

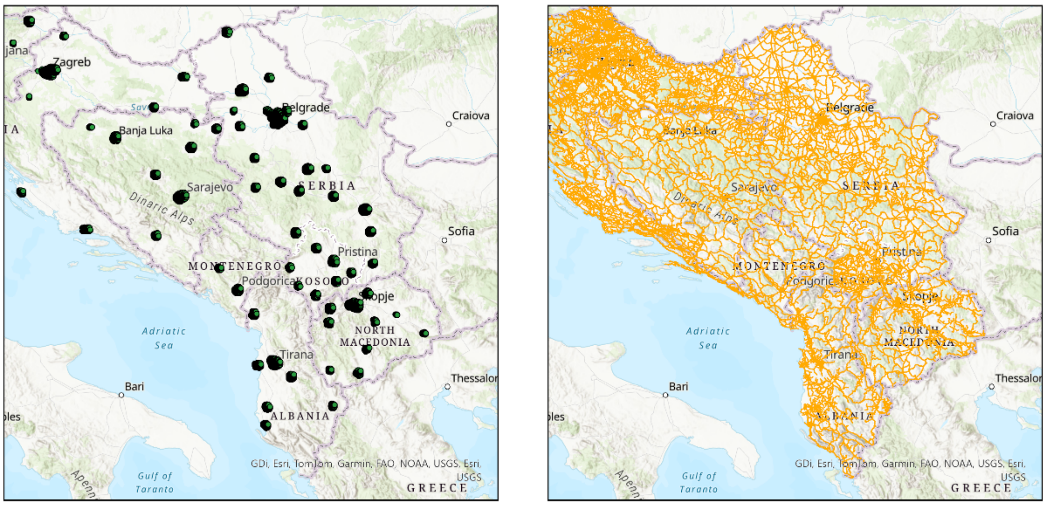


*Figure 3 shows the distribution of urban areas in the Western Balkans (left) and the distribution of roads (primary, secondary and tertiary) in the region (right).*

In addition to the network function, roads were also employed to estimate a magnitude of urbanity. Assuming that road density is an indicator of urban density, we estimated a line density measurement expressing the length of all roads within 5km from the identified urban cores, and expressed as meters per km.

Population Change and language

Population change (%) was calculated between the two most recent censuses per country (e.g., 2011–2021, or nearest available). This change serves as our dependent variable, used as a proxy for long-term regional development and adjustment processes. Since censuses are collected for different years in different countries, it has not been possible to generate a dataset with the exact same temporal settings. Finally, using a combination of census material and team experience, a matrix (65 x 65) of the main language spoken in each city was classified as the same or as different, for each pair of cities. The categorization *same=1* was applied to all languages being similar enough to enable easy communication between pairs of cities (i.e., Serbian and Croatian were considered as the same language) and *same=0* for cities were, for example, Slovenian and Albanian were spoken. In table 1, used variables, excluding spatial interaction, are presented. Variable Percchange Origin indicates the over-time population change in each city (the 4225 observations indicate the 65 x 65 occurrences of pairs of cities). For remaining variables ending with *origin*, reflects the values at the potential sending side, and similarly *dest*, indicate the potential receiving side in network derived spatial interaction models.

*Table 1 Descriptive statistics of variables included in the regressions.*

| **Variable** | **Obs** | **Mean** | **Std. Dev.** | **Min** | **Max** |
|---|---|---|---|---|---|
| Percent population change (origin) | 4,225 | −8.110 | 10.326 | −39.402 | 12.440 |
| Cultural amenities (origin) | 4,225 | 0.218 | 0.288 | 0.019 | 1.616 |
| Financial functions (origin) | 4,225 | 0.119 | 0.135 | 0.005 | 0.824 |

| Variable | Obs | Mean | Std. Dev. | Min | Max |
|---|---|---|---|---|---|
| Child-oriented amenities (origin) | 4,225 | 0.165 | 0.204 | 0.004 | 1.261 |
| Road density (origin) | 4,225 | 9.122 | 5.439 | 3.099 | 32.773 |
| Cultural amenities (destination) | 4,225 | 0.218 | 0.288 | 0.019 | 1.616 |
| Financial functions (destination) | 4,225 | 0.119 | 0.135 | 0.005 | 0.824 |
| Child-oriented amenities (destination) | 4,225 | 0.165 | 0.204 | 0.004 | 1.261 |
| Road density (destination) | 4,225 | 9.122 | 5.439 | 3.099 | 32.773 |
| Regenerative energy capacity (origin, z) | 4,225 | 0.000 | 1.000 | −0.393 | 5.731 |
| Regenerative monitoring capacity (origin, z) | 4,225 | 0.000 | 1.000 | −0.535 | 3.839 |
| Regenerative waste capacity (origin, z) | 4,225 | 0.000 | 1.000 | −0.448 | 5.375 |
| Regenerative energy capacity (destination, z) | 4,225 | 0.000 | 1.000 | −0.393 | 5.731 |
| Regenerative monitoring capacity (destination, z) | 4,225 | 0.000 | 1.000 | −0.535 | 3.839 |
| Regenerative waste capacity (destination, z) | 4,225 | 0.000 | 1.000 | −0.448 | 5.375 |
| Same language | 4,225 | 0.215 | 0.411 | 0 | 1 |
| Same country | 4,225 | 0.164 | 0.370 | 0 | 1 |
| Same religion | 4,225 | 0.356 | 0.479 | 0 | 1 |
| Road distance (OD) | 4,225 | 859,769 | 654,331 | 0 | 3,256,859 |

**Note:** Regenerative economy variables are reported in standardized (z-score) form due to their sparse and highly skewed raw distributions resulting from kernel-density construction.

**Methods**

The lack of commuting flow data in the western Balkans means that we must explore alternative specifications for spatial interaction. In this section we will first specify three alternative spatial interaction models as well as describe the regression used for the analysis. The choice of spatial interaction models is informed by a combination of common practice in GIS and geo-computation and previous research on the specification and use of spatial interaction models. The spatial interactions are used to weight the importance of destinations in three models where the OD relationship between 65 x 65 regions make up the population.

<u>Spatial Interaction Models</u>
In most cases, the known volume of commuting flows between any pair of locations is used to statistically determine the spatial interaction, but in absence of observed flow data, we applied three mathematical distance-decay functions as weight matrices in spatial interaction. The different spatial interaction models are multiplied with the most recent (year vary due to differences in national censuses) urban population, so that populous and/or near urban areas have greater influence. The formulations are listed below, where *d* represents distance in km,

and *i,j*, represents origin and destination. The first model, Inverse distance, is a common distance decay approach in geo-computation and is integrated in most GIS software. Inverse distance weights more distant attributes using a simple formula where decay is generated by dividing 1, with a value representing distance. In our model the distances are divided by 10, and a power value (common in most inverse distance formulations) are set to the default and non-affecting value of 1. The function is weighted with the destination population.

**Inverse distance:** $f_{ij} = \frac{1}{(d_{ij}/10)^\wedge 1} Pop_j$ Eq. 1

The second function, a negative exponential function, is specified in equation 2. Negative exponential functions have a functional form that closely mimics the friction of distance for daily mobility patterns (Östh et al., 2016) and is chosen to represent the daily interaction between close urban areas for commuting, recreation and service.

**Negative exponential:** $f_{ij} = exp(-\beta d_{ij}) Pop_j$ Eq. 2

The distance decay parameter in equations 2 and 5 (below), $-\beta$, is commonly estimated using regressions where information about time/distance or cost are regressed on flow counts. However, since flows are missing in our dataset, $-\beta$ is estimated using a mathematical formulation as suggested by Östh et al., (2014, 2016). The formula departs from the idea that a median distance (or value representing it) also represents a distance within which half of all trips ends, while the remaining half travels further; and by assigning ½ of the AUC of the functional form of different decay functions, it is possible to formulate a function that decays more distant urban areas in ways that are similar to commuting trips. For the negative exponential function, a beta value can be calculated as below:

**$-\boldsymbol{\beta}$, negative exponential**: $-\beta = \ln(1/2)/\mathrm{m}$ Eq.3

Where ½ represents half= i.e., median of the travelling population, and m represents the median distance.

For the log-normal functional form, the $-\beta$ calculation is more complex. The Log-normal function mimics the spatial interaction observed for migration which should have bearing for the interaction between cities across the Western Balkans. Normally, migration or longer-distance interactions are modelled using a power function using a regression. However, since no flow data is available, and since a power function $-\beta$ cannot be determined mathematically, we are employing the log-normal function that has *power-like* attributes.

**$-\boldsymbol{\beta}$** , Log-normal: $$\beta = \frac{\left(erf^{-1}(-0.5)\right)^2 \pm \sqrt{\left(erf^{-1}(-0.5)\right)^4 + 2\left(erf^{-1}(-0.5)\right)^2 \ln(m) + \ln(m)}}{2(\ln(m))^2}$$ Eq.4

Where $erf^{-1}$ represents an inverse error function. After determining the $-\beta$, a less complex formulation of spatial interaction is needed and expressed as shown in equation 5. It should be noted that a webpage designated to the calculation of $-\beta$ is available from (Östh, 2025).

**Log-normal:** $f_{ij} = exp(-\beta[ln d_{ij}]^2)\ Pop_j$ Eq. 5

In figure 4 below, the functional forms of the three spatial interaction models are shown in a plot where distances are shown on the x-axis, and the over-distance-reduction of opportunity are indicated on the y-axis. When a median distance of 50km is used to determine the halving of opportunity the results indicate that log normal has the lowest opportunity throughout the visible part of plot (at greater x, negative exponential will have lower opportunity), and negative exponential has the greatest values. Inverse distance holds an intermediate curve in the visible parts of the plot.

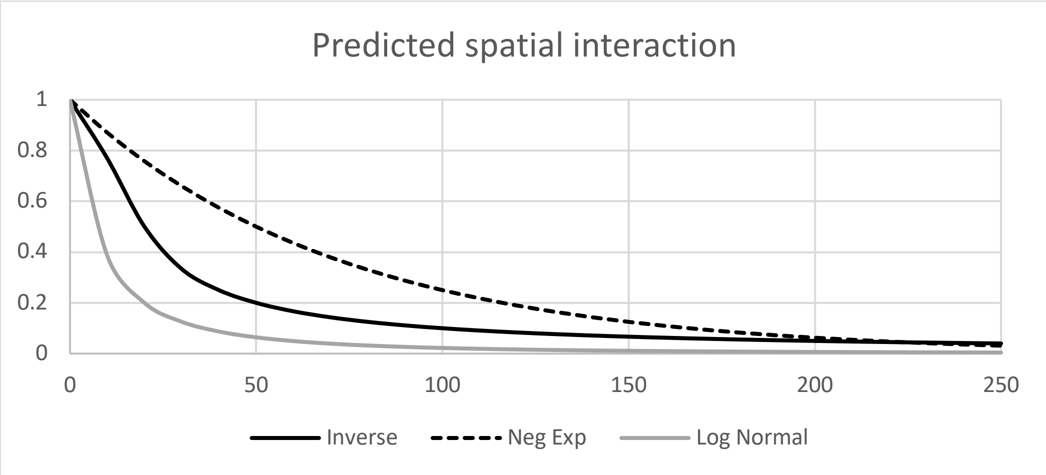


*Figure 4 example of functional form of spatial interaction models. For Negative exponential and log-normal functions a median replacement value of 50 (km) was employed.*

<u>Regression Framework</u>

Urban population change is increasingly shaped not only by traditional economic opportunities and accessibility, but also by cities' capacity to adapt to environmental constraints, resource scarcity, and long-term sustainability challenges. These adaptive capacities are closely related to long-term regional adjustment processes and are mediated through network connectivity linking cities across space. Within this broader framework, regenerative economies—understood as place-based systems that restore ecological functions, support circular resource use, and promote renewable energy transitions—represent one important, yet still under-quantified, dimension of regional development capacity.

To capture these interrelated dynamics, we embed regenerative economy capacity directly into a spatial interaction framework, alongside cultural, economic, infrastructural, and network-based variables. This approach allows us to assess how multiple dimensions of local conditions, regenerative capacity, and connectivity jointly shape population change across cities. We conceptualize population change at a given origin city $i$ as the outcome of three interacting forces.

First, local urban conditions at the origin, including amenities, infrastructure, and regenerative economy capacity, influence population retention and adaptive capacity.

Second, competitive and complementary effects from other cities, transmitted through spatial interaction and network connectivity, shape relative attractiveness and redistribution processes.

Third, spatial and institutional frictions, such as physical distance and cultural proximity, mediate the intensity of interurban adjustment.

Accordingly, population change is modelled as a function of both origin-specific characteristics and spatially weighted destination characteristics, allowing development-related factors—including regenerative economies—to operate through local stabilization, interurban competition, and network-mediated mechanisms.

Conceptual model

For each origin city $i$, population change $\Delta P_i$ is expressed as:

$$\Delta P_i = f\left(A_i^O, R_i^O, \sum_{j\neq i} w_{ij}\, A_j^D, \sum_{j\neq i} w_{ij}\, R_j^D, N_i^O, \sum_{j\neq i} w_{ij}\, N_j^D, C_{ij}, d_{ij}\right), \qquad Eq.6$$

where:

- $A$ denotes conventional urban amenities (cultural, financial, and child-oriented functions),
- $R$ denotes regenerative economy capacity,
- $N$ captures network accessibility (e.g., rail and road infrastructure),
- $C_{ij}$ represents cultural and institutional proximity (shared language, country, and religion),
- $d_{ij}$ denotes physical distance between cities $i$ and $j$, and
- $w_{ij}$ is a distance-decay weight governing the intensity of spatial interaction.

This formulation explicitly allows regenerative economies to influence population change both locally, through local stabilization and adjustment at the origin, and relationally, through competitive or complementary interactions across the urban network.

Estimable specification

The estimable linear form of the model is given by:

$$\begin{aligned}\Delta P_i = \quad & \alpha + \beta' A_i^O + \theta' R_i^O + \gamma' \sum_j w_{ij}\, A_j^D + \kappa' \sum_j w_{ij}\, R_j^D \\ & + \eta' N_i^O + \mu' \sum_j w_{ij}\, N_j^D + \lambda' C_{ij} + \phi d_{ij} + \varepsilon_i, \end{aligned} \qquad \text{Eq.7}$$

where $\varepsilon_i$ is an idiosyncratic error term.

Estimation strategy

We estimate the model using weighted least squares (WLS) under three alternative spatial interaction formulations: log-normal, negative exponential, and inverse distance decay. For each specification, the unit of analysis is the origin–destination (OD) pair, covering the full $65 \times 65$ interurban network.

The dependent variable is the percentage population change at the origin city, measured between the two most recent census periods. Regression weights $\omega_i$ are derived from destination population size, reflecting the role of larger cities as stronger gravitational attractors within the regional urban system.

The WLS estimator minimizes:

$$\min_{\theta} \sum_i \omega_i \left(\Delta P_i - \widehat{\Delta P_i}\right)^2, \ Eq.8$$

where the weights $\omega_i$ vary across the three decay specifications. The negative exponential formulation emphasizes nearby interactions, while the inverse distance specification places relatively greater weight on distant connections. The log-normal formulation lies between these two extremes. The implications of these functional differences are illustrated in Figure 4. Weighted least squares is employed to account for heteroskedasticity inherent in origin–destination data and to reflect the greater influence of larger destination cities within the interurban network, consistent with gravity-based spatial interaction theory.

**Results**

This study aims to analyse to which extent long-term regional development, in the form of local over-time population change, can be determined using GIS-networks, spatial interaction models and variables generated from open data sources and where commonly used OD-flow data or comparable economic and sociodemographic variables are missing. The results' output is partitioned into three parts, where we first present results from the regressions, thereafter correlate observed population change to predicted population change on regional level, and finally, generating and comparing population development ranks for the individual regions. Our findings indicate that across all three spatial interaction specifications, population change at the origin city is systematically related to both local conditions and spatially weighted characteristics of other cities, confirming the relevance of a network-based perspective.

Cultural amenities and financial functions at the origin exhibit strong positive associations with population change, while child-oriented amenities are negatively associated, suggesting differential life cycle and household sorting effects across the urban system. A potential explanation to the negative association is the pan-regional and massive decline in fertility in later decades where Total Fertility Rates (TFR) are well below population replacement rates (see for instance CRPM, 2025).

Spatially weighted destination characteristics also play a significant role. Cultural and financial functions in connected cities affect origin-level population change through competitive and complementary mechanisms, depending on the distance-decay formulation.

These results highlight that population dynamics are not driven solely by local attributes, but by cities' relative position within the interurban network.

Road infrastructure density is consistently significant at both origin and destination levels, underscoring the importance of physical connectivity in mediating population adjustment. Cultural proximity variables—shared language, country, and religion—are also robust predictors, confirming that institutional and social frictions shape interurban population responses beyond pure geographic distance. At the origin, regenerative energy capacity exhibits a strong and statistically significant association with population change, indicating that cities with greater renewable energy presence experience more favourable demographic trajectories. In contrast, regenerative monitoring and waste-related indicators show negative coefficients, suggesting that these dimensions may be associated with transitional adjustment costs or reflect compensatory investments in response to environmental stress.

Spatially weighted regenerative economy indicators at destination cities also matter, though with smaller magnitudes and more heterogeneous significance. This pattern suggests that regenerative economies operate primarily through local stabilization mechanisms, while also contributing to network-mediated competitive dynamics across cities. In other words, regenerative capacity supports local population stability, but its influence is partially redistributed through interurban interactions.

Table 2: Regression results. Population change at origin is used as dependent variable, independent variables are specified for both origins and destinations. The three models correspond to the three methods used for spatial interaction modelling.

| | Log-normal specification | Negative exponential specification | Inverse distance specification |
|---|---|---|---|
| CultKern (Origin) | 30.85*** (1.29) | 30.18*** (1.35) | 36.71*** (1.25) |
| FinanceKer (Origin) | 41.49*** (2.00) | 40.13*** (1.97) | 41.32*** (1.99) |
| KidsKern (Origin) | −44.35*** (1.72) | −41.77*** (1.75) | −55.04*** (1.64) |
| CultKern (Destination) | −6.77*** (1.31) | −11.13*** (1.35) | −6.66*** (1.21) |
| FinanceKer (Destination) | −2.56 (1.57) | −1.90 (1.54) | −3.33* (1.63) |
| KidsKern (Destination) | −1.69 (1.58) | 2.08 (1.57) | −7.36*** (1.54) |
| RegenEnergy (Origin, z) | 4.45*** (0.19) | 4.70*** (0.17) | 4.16*** (0.20) |
| RegenMonitoring (Origin, z) | −1.62*** (0.19) | −1.34*** (0.19) | −1.27*** (0.19) |

| | | | |
|---|---|---|---|
| RegenWaste (Origin, z) | −5.59*** (0.20) | −5.43*** (0.19) | −6.21*** (0.20) |
| RegenEnergy (Destination, z) | −0.92*** (0.18) | −1.07*** (0.17) | −1.36*** (0.18) |
| RegenMonitoring (Destination, z) | 0.42* (0.17) | 0.08 (0.17) | 0.75*** (0.17) |
| RegenWaste (Destination, z) | 0.84*** (0.17) | 1.07*** (0.16) | 0.86*** (0.17) |
| LineD5km (Origin) | 0.15** (0.06) | 0.04 (0.05) | 0.31*** (0.05) |
| LineD5km (Destination) | 0.51*** (0.05) | 0.62*** (0.05) | 0.77*** (0.05) |
| Same language | 5.01*** (0.60) | 3.66*** (0.59) | 5.38*** (0.63) |
| Same country | −5.27*** (0.48) | −5.17*** (0.46) | −6.00*** (0.46) |
| Same religion | −4.57*** (0.44) | −3.72*** (0.46) | −4.83*** (0.49) |
| Road distance | −5.15e−06*** (3.82e−07) | −1.30e−05*** (1.51e−06) | −5.58e−06*** (4.64e−07) |
| Constant | −11.78*** (0.45) | −10.92*** (0.42) | −13.88*** (0.37) |
| R-squared | 0.424 | 0.458 | 0.724 |
| Adjusted R-squared | 0.422 | 0.455 | 0.723 |
| Observations | 4,225 | 4,225 | 4,225 |

Notes:

Standard errors in parentheses.

Significance levels: * p < 0.05, ** p < 0.01, *** p < 0.001.

All models estimated using weighted least squares, with weights derived from destination population accessibility under the corresponding decay function

**4.2 Specification Comparison**

Results are consistent across the log-normal, negative exponential, and inverse distance formulations. While coefficient magnitudes vary, the signs and relative importance of key variables remain stable, indicating that the main conclusions are not sensitive to the choice of distance-decay function.

The negative exponential specification places greater emphasis on nearby interactions and therefore amplifies localized competitive effects, while the inverse distance specification highlights the influence of long-range connections within the urban network. The log-normal specification lies between these two extremes. Despite these differences, regenerative economy indicators remain significant across specifications, reinforcing their relevance as a structural component of long term regional development processes.

Correlation analysis between predicted and observed city-level population change shows comparable performance across all three models, with Pearson correlations ranging from approximately 0.43 to 0.49. Thus, this approach picks up part of the pattern, but a lot of city population change is still driven by factors not in the model, such as employment availability. Predicted values are highly correlated across specifications, exceeding 0.93 in all cases, indicating strong robustness of the spatial interaction framework.

Table 3. Specification comparison: Pearson correlations

| | **Predicted Log-normal** | **Predicted Negative Exponential** | **Predicted IDW** | **Observed population change** |
|---|---|---|---|---|
| **Predicted Log-normal** | 1.000 | 0.937*** | 0.998*** | 0.494*** |
| **Predicted Neg. Exp.** | 0.937*** | 1.000 | 0.931*** | 0.434*** |
| **Predicted IDW** | 0.998*** | 0.931*** | 1.000 | 0.482*** |
| **Observed change** | 0.494*** | 0.434*** | 0.482*** | 1.000 |

City-level ranking comparisons in Table 4. and 5 further illustrate the stability of results. Cities experiencing the highest observed population growth—such as Pristina, Durres, Novi Sad, and Skopje—are consistently identified among the top performers across all specifications. Conversely, cities with declining or stagnating populations—such as Shkoder, Zenica, Bitola, and Leskovac—remain clustered at the bottom of predicted rankings. Also, some cities exhibit divergence between observed and predicted ranks, which reflect the interaction between local conditions, regenerative capacity, and different network dynamics or other drivers of population change not in the model (e.g., employment, policy, housing, conflict history, external migration).

Table 4. Top-ranking cities by population development

| **City** | **Rank (observed)** | **Rank (log-normal)** | **Rank (neg. exp.)** | **Rank (IDW)** |
|---|---|---|---|---|
| Pristina | 1 | 3 | 4 | 2 |
| Podgorica | 2 | 27 | 26 | 32 |
| Durres | 3 | 1 | 2 | 1 |
| Novi Sad | 4 | 2 | 1 | 3 |
| Bijeljina | 5 | 41 | 46 | 44 |
| Novi Pazar | 6 | 36 | 39 | 36 |
| Ljubljana | 7 | 61 | 61 | 61 |
| Skopje | 8 | 4 | 5 | 4 |

| City | Rank (observed) | Rank (log-normal) | Rank (neg. exp.) | Rank (IDW) |
|---|---|---|---|---|
| Belgrade | 9 | 5 | 6 | 5 |
| Kranj | 10 | 7 | 9 | 8 |
| Vlore | 11 | 6 | 3 | 6 |
| Maribor | 12 | 9 | 8 | 10 |
| Tirana | 13 | 12 | 18 | 13 |
| Ferizaj | 14 | 23 | 40 | 23 |
| Celje | 15 | 47 | 49 | 48 |
| Niš | 16 | 49 | 43 | 49 |

**Table 5.** Bottom-ranking cities by population development

| City | Rank (observed) | Rank (log-normal) | Rank (neg. exp.) | Rank (IDW) |
|---|---|---|---|---|
| Shkoder | 64 | 59 | 59 | 59 |
| Zenica | 63 | 28 | 34 | 27 |
| Sarajevo | 62 | 14 | 11 | 15 |
| Bitola | 61 | 46 | 45 | 46 |
| Prizren | 60 | 10 | 10 | 9 |
| Gjakova | 59 | 60 | 60 | 60 |
| Mostar | 58 | 8 | 7 | 7 |
| Rijeka | 57 | 13 | 14 | 12 |
| Tuzla | 56 | 39 | 37 | 43 |
| Slavonski Brod | 55 | 16 | 36 | 16 |
| Zrenjanin | 54 | 52 | 48 | 52 |
| Peja | 53 | 63 | 63 | 63 |
| Leskovac | 52 | 40 | 30 | 39 |
| Subotica | 51 | 32 | 41 | 34 |
| Kraljevo | 50 | 53 | 51 | 54 |
| Shtip | 49 | 57 | 56 | 56 |

## 5. Discussion

This study examined how long-term population change in the Western Balkans is shaped by the interaction of (1) local urban conditions, (2) interurban network connectivity, and (3) regenerative economic capacity. By embedding regenerative economy indicators within a spatial interaction framework, the analysis extends conventional approaches to regional development analysis, which often remain confined to static regional attributes or single-country settings.

The results confirm that local urban amenities remain are central to population retention and long-term adjustment. Cultural and financial functions in origin cities are consistently associated with more favourable population trajectories, indicating that places with stronger service-based and institutional capacity are better positioned to adapt to prolonged demographic and economic pressures. This finding aligns with evolutionary interpretations of resilience, where adaptation and reconfiguration, "bounce forward", rather than recovery to a pre-shock equilibrium, shape long-term outcomes.

At the same time, the analysis reveals that destination-city amenities do not uniformly generate positive spillovers. Network position matters and can be competitive. Spatially weighted destination characteristics are systematically related to origin population change, confirming that population dynamics are not only "local". In several specifications, highly concentrated cultural and financial functions in destination cities are associated with negative effects on origin population change. This suggests that interurban interaction may operate through competitive and displacement mechanisms, whereby stronger urban centres draw resources, labour, or opportunities away from neighbouring cities rather than generating complementary growth. Such dynamics are particularly relevant in polycentric but economically uneven regions such as the Western Balkans (e.g., with strong core–periphery patterns), where intercity competition may dominate positive spill-overs.

The negative association between child-oriented services and population change is also noteworthy, whether a sign of the fertility drop or something else, the negative coefficient for child-oriented services should not be read as evidence that schools or playgrounds reduce population stability but that population decline is a real thing. Rather than signalling declining urban quality, this pattern may reflect life-cycle and residential sorting processes, where families with children relocate toward lower-density or peri-urban areas. In this sense, child-rearing amenities may capture demographic transitions rather than direct development-related effects. This interpretation is consistent with broader evidence that population change in the region is shaped by selective migration rather than uniform decline.

Infrastructure plays a dual role. Road-line density at the origin strengthens local population stability by improving accessibility and internal connectivity, supporting population retention. However, the presence of modest negative spillover effects suggests that improved infrastructure can also intensify spatial competition by lowering barriers to out-migration or enabling redistribution toward stronger nodes in the network. This finding reinforces the need to interpret infrastructure not only as a growth-enhancing asset but also as a mechanism that reshapes interurban hierarchies. This reinforces the idea that infrastructure is not automatically growth-producing for all places, rather its effects depend on where connectivity gains accrue within the network.

Soft connectivity moderate population redistributions. Cultural and institutional proximity, particularly shared language, emerges as a robust moderator of interurban interaction. Shared language reduces spatial and institutional frictions, amplifying the effects of network connectivity and facilitating population redistribution across borders. This result is especially salient in a cross-national context marked by historical, political, and cultural fragmentation, underscoring the importance of soft connectivity alongside physical infrastructure.

Crucially, the inclusion of regenerative economy indicators provides new insight into long-term regional adjustment dynamics. Regenerative economy indicators add explanatory power but are heterogeneous. Origin-level renewable energy capacity is positively associated with population change, suggesting that visible investments in energy transition may align with more favourable trajectories (eg. through local jobs, improved reliability, or signalling effects), contributing to stabilization and adaptive capacity rather than short-term attraction. In contrast, monitoring and waste-related indicators are negative at the origin in these models, which may reflect transitional adjustment costs, siting patterns (eg facilities located in weaker areas), or compensation investment responding to stress rather than driving decline. Destination-level regenerative indicators show smaller and more mixed associations, consistent with the idea that regenerative capacity operates mainly through local stabilisation while also interacting with network competition and complementary dynamics depending on the type of regenerative activity. These findings support the view that regenerative economies operate not merely as isolated environmental assets but as components of broader development systems embedded within interurban networks.

Signs and key variables are stable across the three distance-decay formulations, and predicted values are highly correlated across specifications, indicating that conclusions are not driven by one modelling choice. Across the three spatial interaction specifications, the log-normal decay function consistently delivers the strongest explanatory power. This suggests that medium-distance interactions, rather than purely local or long-distance effects, are most relevant for understanding population change in cross-national, data-scarce regions. inverse distance produces the highest in-sample fit in the regression. Taken together, this points to robustness rather than a single dominant decay form, and also highlights the importance of considering intermediate spatial scales, where competition, adaptation, and network-mediated spillovers intersect.
The results have two practical implications:

- Policy should treat regional development as relational, not purely local. Investments that strengthen local amenity base (culture, finance, services) may support retention, but the same investments concentrated in nearby hubs can intensify outflows from smaller cities. Regional strategies should therefore combine place-based investments with network-aware planning that avoids reinforcing only the strongest nodes.
- Regenerative transitions can be part of demographic stability, but effects differ by domain. Renewable energy presence aligns with better outcomes at the origin, while monitoring and waste indicators may proxy for stress, adjustment burdens, or facility siting. Planning should separate investments that strengthen a place from infrastructure that mainly imposes costs and support the latter with compensatory development measures.

Overall, the findings demonstrate that population change in the Western Balkans reflects a complex interplay between local development capacities, interurban competition, and network connectivity. Regenerative economies contribute meaningfully to this process, not as isolated drivers of growth, but as part of an adaptive system that conditions how cities respond to long-term demographic and economic pressures. Methodologically, the study shows that meaningful insights into long-term regional development patterns can be generated even in data-scarce regions by combining open spatial data with spatial interaction modelling.

Limitations

The main limitation of this study is data availability. Population change is a useful but imperfect proxy for long-term regional development dynamics because it mixes migration, fertility, mortality, and administrative effects and does not directly measure jobs, productivity, or income. Key variables such as employment opportunities at origins and destinations could not be included. Census years also differ across countries, adding timing noise that can weaken predictive accuracy. Because observed commuting or migration flows data are missing, spatial interaction weights must be assumed rather than estimated, so the model can represent plausible interaction intensity but cannot validate flows directly. Results should be interpreted as associations rather than causal effects, since amenities and regenerative infrastructure may reflect earlier growth or decline and unobserved factors may confound estimates. Using road-network distance instead of travel time ignores variability in border delays, congestion, and service frequency. OSM coverage varies by country/settlement type, which may bias POI and infrastructure measures and overemphasise well-mapped areas. OD-pair observations are not fully independent, which can understate uncertainty. Future work could improve robustness by using travel-time networks, explicit border-friction measures, remotely sensed indicators, more harmonised socio-economic covariates, flow data to calibrate decay parameters, and alternative POI summaries beyond kernel-density maximum. However, this study paves the road by demonstrating a replicable approach for analysing long-term regional development patterns in data-scarce, cross-national settings. Across alternative distance-decay specifications, the main conclusions are stable, supporting the use of spatial interaction modelling as a practical tool for development analysis where conventional flow data and harmonised socio-economic indicators are unavailable.

## 6. Conclusion

We present a replicable method for analysing long-term regional development and transport-network effects in regions lacking detailed flow data, by combining open-source spatial datasets (OSM and population grids) with transport-network modelling and spatial interaction frameworks. In the Western Balkans, population change is systematically associated with both local conditions and network-mediated effects, indicating that long-term population development is shaped by cities' attributes and their relational position within the interurban system. Regenerative economy indicators contribute additional insight, especially for origin-level renewable energy capacity, while other regenerative proxies show patterns consistent with stress, siting policies, or transition burdens. Our study in the Western Balkans demonstrates the importance of both origin- and destination-level factors and highlights the suitability of the log-normal spatial-interaction specification. This framework can be extended to other international contexts, informing regional development and infrastructure planning.

If we revisit the two questions from the introduction:

1. To what extent can long-term population change be associated to varying levels of network connectivity and regenerative economies in evolutionary-type regional economies?
2. Can the lack of national and regional data on network connectivity, regenerative economics and resilience in the Western Balkans be substituted with data drawn or generated from Open international data repositories?

We can conclude that international and open data repositories are fundamental in the sense that they make it possible to conduct a larger regional study, but that data limitations makes it difficult to validate the trends. Having that said, the generated results suggest that network connectivity and regenerative economics reduce the long-term population losses, thereby contributing to more stable long-run regional development trajectories.

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