

Research Article

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Functional transformation of settlements in coal exploitation zones: A case study of the municipality of Stanari in Republic of Srpska (Bosnia and Herzegovina)

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Abstract: This study explores how long-term surface coal exploitation has affected the distribution of economic functions and contributed to hierarchical changes within the settlement network of the municipality of Stanari. The aim of this study is to contribute to a broader understanding of the spatial consequences of intensive resource exploitation on settlement systems. Using the case study of Stanari, the analysis focuses on changes resulting from ongoing mining activities. The most pronounced transformations occurred in settlements near the mine, where exploitation led to increased employment in industry and services, while more distant settlements retained their functional type with minor modifications. Centrality analysis indicates shifts in the hierarchical position of settlements. The geographic information system was utilized as a key analytical

tool for spatial modeling and visualization of functional transformations within the settlement network, providing deeper insight into the spatial-functional changes caused by coal exploitation. To assess future transformation, a survey was conducted, examining the relationship between place of residence and attitudes toward potential relocation and employment. The results show a statistically significant association between these decisions and respondents' spatial affiliation, suggesting possible future changes in the functional structure and hierarchy of the settlement network. The findings of this study offer a broader contribution to the understanding of spatial and functional dynamics in areas affected by intensive resource exploitation. They provide important insights for planning strategies aimed at supporting the local population and guiding decision-making processes in Stanari and similar regions, which may be valuable to local governments and relevant ministries, by informing spatial planning and management of resource exploitation. Furthermore, the study highlights the importance of employment dynamics and workforce retention as critical factors for ensuring both demographic and economic sustainability in areas affected by mining-induced transformations. The ultimate goal remains maintaining demographic stability and preserving the long-term functional integrity of the settlement network.

Keywords: settlement network, settlement functions, functional shifts, hierarchy of settlements, coal exploitation, surface mining, GIS, municipality of Stanari, Republic of Srpska, Bosnia and Herzegovina

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1 Introduction

Mining activities, along with their related processes, necessitates the construction of large-scale infrastructure systems that, in a short period of time, change the quality,

spatial form, and functioning of existing spatial structures. In addition to the immediate and visible impacts, mining activities also generate effects that may intensify or become more evident over time. These include the degradation of natural resources, environmental changes, relocation of population, households, and entire settlements, disruption of everyday life in surrounding communities, and socioeconomic transformation [1–3]. These effects intensify the socioeconomic transformation in mining basins, as well as changes in the distribution and functions of settlement centers [4].

In areas where mining activity occurs, the development of other sectors is generally focused only on those that are complementary to mining, resulting in a mono-functional economic development of the region [3,5,6] and economic dependence on the exploited natural resource. The socio-geographical characteristics of settlements are closely linked to the work function and changes in employment by sectors of activity, and thus the structure of economic activities is considered an important indicator of the socio-geographical transformation of settlements [7]. Productive activities, especially industry, have larger gravitational areas than service activities [8], which suggests that they also possess a higher degree of centrality. Due to their strong attractive effects, mining and industry dictate the balance in the distribution of economic activities, leading to changes in the functional structure and centrality of settlements within the settlement network.

The issue of functional transformation is being examined in countries undergoing dynamic changes driven by processes such as urbanization and energy transition, including Western Australia, the Czech Republic, Hungary, Iran, Poland, Romania, and Slovakia [9–15]. Functional transformation and changes in the hierarchy of the settlement network have also been studied with particular attention given to various regions of Serbia, including the Toplica District, the Mačva and Srem regions, the municipalities of Prijepolje, Loznica, Indija, Čačak, and Sokobanja, as well as areas such as Vojvodina, Central Serbia, and the Belgrade metropolitan region [16–47]. The process of exploitation affects both the economic and demographic base in mining zones [9,48–50]. The local population is gradually leaving settlements that are losing functional strength and centrality. In addition to this form of spontaneous outmigration, organized relocation is also taking place as an integral part of the land expropriation process for the expansion of mining zones [51,52].

In their study, Pasqualetti and Frantál [53] cite examples of the displacement of more than 100 villages and the forced migration of around 100,000 residents in Czechoslovakia between 1978 and 1989, for the purpose of opening

surface coal mines. The relocation of the local population further undermines the functional capacity and centrality of settlements, often leading to long-term socio-spatial consequences. In this context, growing attention has been directed toward understanding how communities perceive and respond to mining-induced displacement, with studies documenting these processes in mining regions across the world [54–57].

As a result, the exploration of potential forms of socio-ecological transformation has become increasingly relevant within social and spatial sciences [58] emphasizing the need for new spatial-functional relationships aimed at strengthening territorial cohesion [59]. The disproportion in functional development, manifested through the transformation of functions and the monofunctional development of mining regions, and later in the post-industrial phase through the loss of functions, has been recognized as a significant issue. Such a loss of functions, especially in the post-mining period, is frequently accompanied by significant demographic challenges, most notably depopulation and increased emigration from affected areas.

In the Republic of Srpska (RS), surface coal mining takes place in three major basins Ugljevik, Gacko, and Stanari primarily to support electricity production in thermal power plants (TPP) [60]. Despite the scale and intensity of these activities, the functional transformation of settlements located within mining zones has not yet been the subject of scientific inquiry. More broadly, research on the impact of mining on the transformation of the settlement network in both the RS and Bosnia and Herzegovina (B&H) remains scarce.

Although the transformation of settlement hierarchies and functional roles in mining regions remains underexplored in academic literature, processes such as industrial expansion, urban restructuring, and energy sector development have elsewhere been associated with spatial-functional changes. However, studies that specifically address changes in the functional type and centrality of settlements within active mining zones are rare. This gap highlights the need for targeted research in regions undergoing intensive resource exploitation, where settlement systems may be particularly vulnerable to transformation.

This study focuses on the Stanari municipality – one of the three key surface coal mining basins in the RS – where mining and energy production represent the dominant pillars of local development. According to the official classification, Stanari is categorized as a developed local self-government unit [61]. However, this formal developmental status conceals underlying vulnerabilities in the spatial and functional structure of its settlement network. Given the heavy reliance on mining, there is a tangible risk that

certain settlements may undergo shifts in functional type, experience a reduction in centrality, or ultimately lose their role within the regional hierarchy.

In view of the broader relevance of functional transformation processes and the lack of previous studies in the RS, this study poses the following research questions:

- Have the settlements located within the surface mining zone undergone a change in functional types, specifically a transformation from predominantly agricultural to industrial types?
- What spatial patterns of functional transformation have emerged so far within the settlement network of the Stanari municipality?
- To what extent has mining activity influenced changes in the hierarchical structure and the centrality of settlements within the settlement network?
- What future spatial pattern of functional transformation may be anticipated in light of the projected expansion of surface mining and its long-term effects on the settlement network?

The results of this study provide a more detailed insight into the ongoing functional transformation of settlements driven by the expansion of surface coal mining. They point to spatial patterns and changes in the hierarchical position of settlements within the network, contributing to a better understanding of how resource-based development influences socio-geographical structures over time.

The purpose of this research is to analyze the existing trends and spatial patterns of functional transformation within the settlement network of the Stanari municipality – as a representative example of a mining zone in the RS – and to project possible future directions of change. This type of analysis aims to offer research-based insights that may also be applicable to other mining areas with similar structural and developmental characteristics.

The findings may serve as a basis for planning interventions aimed at mitigating the impacts of mining during the exploitation phase, as well as for informing rational planning of changes in the post-mining period. By identifying settlements exposed to transformation and considering potential trajectories of their development, the study may contribute to the formulation of measures directed toward preserving spatial cohesion, demographic stability, and the functional role of settlements in the future. Given that employment opportunities and economic stability play a key role in residents' decisions to relocate or remain, the study also emphasizes the need to integrate workforce management strategies into spatial planning processes. At the same time, this research seeks to address a gap in the existing literature on settlement transformation in

mining regions, where such processes have often remained underexplored. Accordingly, the remainder of this work is structured as follows. The subsequent section delineates the study area and outlines the methodological framework adopted. This is followed by a presentation of empirical findings, which address both historical (1971–2013) and anticipated functional and hierarchical transformations of the settlement network. The analysis then turns to residents' perceptions regarding relocation and changes in employment. The study concludes with a discussion of policy implications, consideration of study limitations, and recommendations for future research.

2 Study area

The study area is defined by the settlement network of the Stanari municipality (from 44°67'39"N to 44°84'27"N and from 17°73'85"E to 17°93'19"E) located in the northeastern part of the RS, within B&H (Figure 1). The municipality is situated in the Stanari mining basin, which contains some of the most significant lignite deposits in B&H [60] and whose exploitation serves as the foundation for the planned development of the thermal power sector [62]. The geological base of the Stanari municipality is highly diverse, with deposits ranging from Triassic sediments, including various limestones, sandstones, and clays, to much younger Quaternary alluvial and proluvial sediments [63]. This lithological diversity is particularly significant because the coal deposits that underpin current and planned mining activities are associated with these sedimentary rock formations. Coal mining in the Stanari municipality has a tradition spanning more than a century. Since 1974, extraction has been conducted through surface mining at the "Raškovac" open pit, which remains active to this day [64]. The current concession for coal exploitation in the Stanari basin has been granted for a period extending until 2035 [65]. Intensive coal exploitation in the municipality began in 2016 with the privatization of the mine and the opening of the "EFT Stanari Mine and Thermal Power Plant" in the settlement of Dragalovci. Based on calculations by the Ministry of Mining and Energy [66], this TPP ranks as the leading electricity producer in the RS, contributing 25.08% to the overall production. The Stanari municipality was established in 2014, 2 years before the TPP began operating, following its separation from the administrative territory of the City of Dobož. According to the most recent census conducted in 2013, the Stanari municipality had a population of 6,958 [67] distributed across 13 settlements (Brestovo, Dragalovci, Jelanjska,

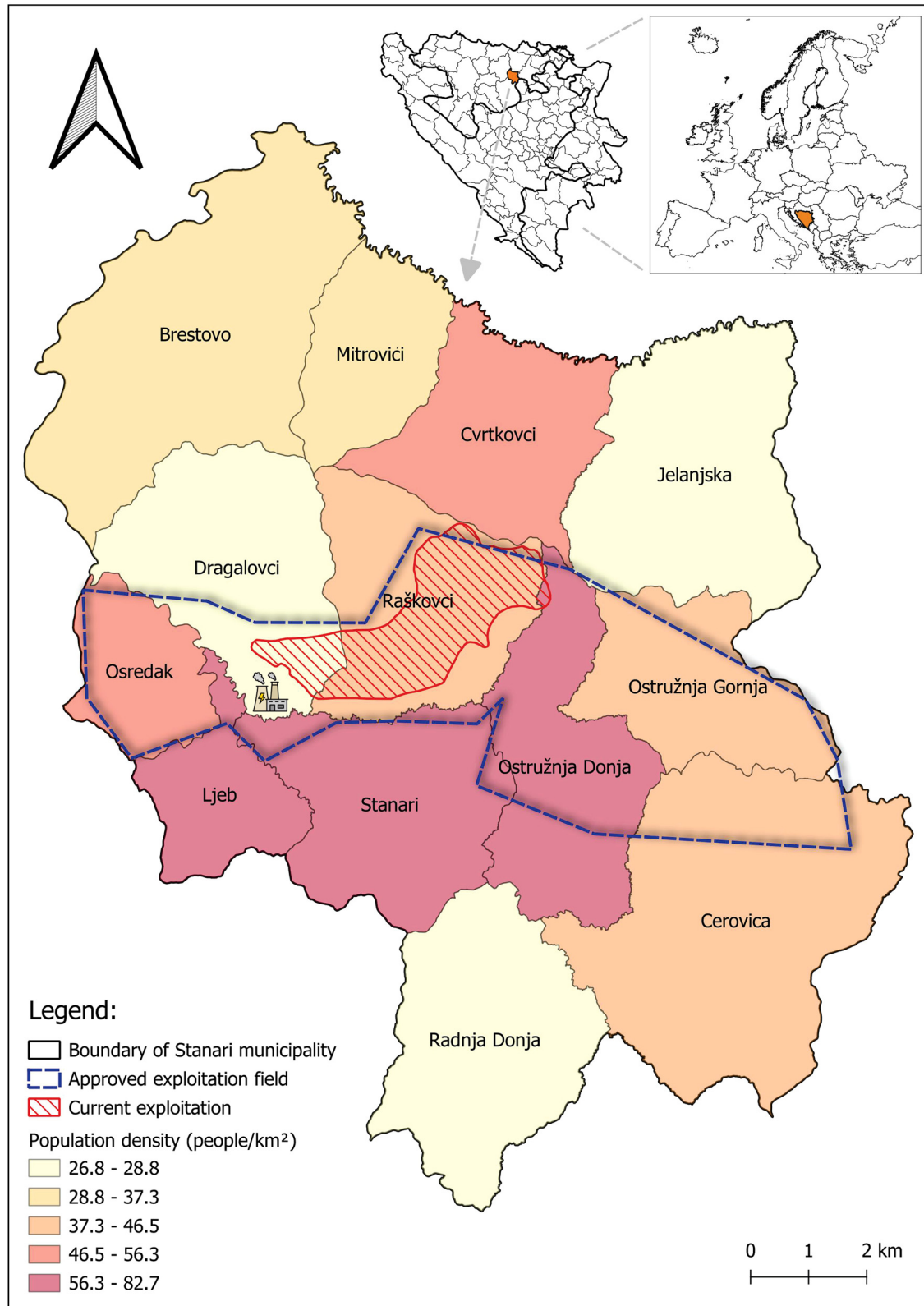


Figure 1: The study area.

Ljeb, Mitrovići, Osredak, Ostružnja Gornja, Ostružnja Donja, Radnja Donja, Raškovci, Stanari, Cvrtkovci, and Cerovica) (Figure 1).

With the exception of the central settlement, all other settlements are rural in character. Stanari, as the central settlement, assumed the function of the municipal administrative center after the municipality was established. Although it had a rural character prior to the establishment of the municipality, over time it has acquired characteristics of an urban settlement, marked by the highest population density within the settlement network and the concentration of central functions. Data from the 2013 census indicate that the majority of the employed population in the municipality worked in the secondary (38.44%) and primary (25.84%) sectors of the economy, with 18.73% engaged specifically in mining and electricity production activities [67]. According to estimates by the Institute of Statistics of the RS for 2024 [68], 71.10% of the employed population in the Stanari municipality worked in the secondary economic sector, while only 0.06% were employed in the primary sector. Compared to 2013, the share of

employment in the secondary sector increased (+32.66%), whereas the share in the primary sector declined (−25.78%). Within the secondary sector, employment in mining and electricity production accounted for 63.46% in 2024, indicating a notable increase (+44.73%) compared to 2013. Coal exploitation is currently taking place in three settlements – Dragalovci, Ostružnja Donja, and Raškovci – with varying intensity. Field research confirmed changes in land use caused by the direct impact of surface mining (Figure 2a–c). In addition, locations of population displacement within active exploitation zones were identified (Figure 2d–f). Previous research by Sabljic et al. [63] highlighted land use change, deforestation, and erosion as either direct or indirect consequences of mining activities. These effects of surface exploitation are presumed to contribute to shifts in the functional structure and the hierarchical arrangement of the settlement network.

Through the digitization of satellite imagery of the study area and the coordinates of the approved exploitation field [65], it was determined that surface mining is currently most extensive in the settlement of Raškovci,



Figure 2: Impact of surface exploitation in the area of the Raškovci surface mine on land cover change (a)–(c) and emigration (d)–(f).

Table 1: Characteristics of the settlement network in the context of current and planned coal exploitation

Settlement name	Total area	Area of current coal exploitation		Area of the approved coal exploitation field		Distance from the border of the current exploitation	Population (2013 Census)	
	km ²	km ²	%	km ²	%	m	Number	Density
Brestovo	21.52	0.00	0.00	0.00	0.00	5343.05	644	29.93
Dragalovci	13.06	0.99	7.55	3.51	26.87	1275.79	367	28.10
Jelanjska	15.73	0.00	0.00	0.04	0.25	3016.48	435	27.66
Ljeb	5.63	0.00	0.00	0.51	9.02	2325.99	325	57.70
Mitrovići	7.12	0.00	0.00	0.00	0.00	3326.96	233	32.72
Osredak	5.58	0.00	0.00	4.84	86.72	1976.27	282	50.52
Ostružnja Gornja	9.34	0.00	0.00	7.73	82.76	2716.05	380	40.69
Ostružnja Donja	11.62	0.39	3.34	7.66	65.91	458.89	838	72.14
Radnja Donja	13.72	0.00	0.00	0.00	0.00	4182.88	368	26.83
Raškovci	11.98	5.55	46.37	8.13	67.89	0.00	460	38.41
Stanari	12.27	0.00	0.00	1.62	13.21	1811.26	1,015	82.72
Cvrtkovci	10.70	0.00	0.00	0.00	0.00	1656.27	581	54.29
Cerovica	22.69	0.00	0.00	4.35	19.16	3711.16	1,030	45.40
Municipality total	160.96	6.93	4.30	38.38	23.85	—	6,958	43.23

where 46.37% of the settlement's territory has been affected by exploitation. The approved exploitation field also includes the settlements of Jelanjaska, Ljeb, Osredak, Stanari, and Cerovica, where coal mining is expected to take place in the future, to varying extents. In contrast, only four settlements are expected to remain unaffected by future exploitation, namely: Brestovo, Mitrovići, Radnja Donja, and Cvrtkovci. This means that, ultimately, 69.23% of the settlements within the network will be affected by mining activities, which will occupy 23.85% of the municipality's total area. The territories of Ostružnja Donja and Raškovci are projected to be affected by mining operations by more than 60%. In Osredak and Ostružnja Gornja, the proportion of land subject to exploitation is expected to exceed 80% (Table 1, Figure 1).

3 Data and methods

3.1 Methodology for monitoring previous functional transformation

The data used for the analysis of functional transformation within the settlement network were obtained from the population censuses of 1971 [69] and 2013 [67]. These sources include data from the time before surface mining began, as well as data from the most recent census conducted in B&H. The functional transformation of the settlement network at the municipal level was assessed using the ternary diagram method – Fehre's triangle [70]. The

ternary diagram method has been employed in earlier research examining functional transformation processes at the level of both local self-government units and settlements [11,14,20,21,29,32,34,42,44,70]. Changes in settlement functional types were monitored through the application of the settlement functional typology developed by Tošić [38], while a more detailed classification was carried out using the typology developed by Grčić [24,25]. The aforementioned typologies have been used in numerous studies on the functional structure and transformation of the settlement network in Serbia [16–18,20,21,23,28,32–34,36,39–42,44–46], but have not previously been applied to the territory of B&H. Their methodological foundation and relevance within a similar spatial and socio-economic context indicate the applicability of these typologies within the framework of this research. Both typologies are based on the method of calculating the share of employed persons by economic sector, with specific conditions regarding the relationships between these shares. Tripartite division into primary, secondary, and tertiary sectors has been widely used due to its analytical simplicity and historical prevalence in employment structure analysis. But, the model does not separately recognize the increasingly important quaternary sector, which encompasses knowledge-intensive activities such as scientific research, information technologies, and advanced services in education, culture, and management. However, for the purposes of this research, the quaternary sector has been integrated into the broader tertiary sector, in line with standard statistical classifications. This integration enables the application of previously established typologies and ensures comparability

across datasets. In this way, 9 (Figure 3a) and 11 (Figure 3b) functional settlement types are distinguished, respectively.

To assess the spatial distribution of functional transformation, the results obtained through the application of selected typologies were mapped using the geographic information system (GIS). GIS plays a central role in geospatial analysis, enabling the integration, visualization, and spatial modeling of complex environmental processes [71–76,63,77,78]. As an essential tool for geospatial analysis, GIS not only supports the systematic examination of spatial patterns and relationships, but also demonstrates remarkable applicability.

For the purposes of the analyses conducted in this study, QGIS 3.28 “Firenze” software (<https://qgis.org/>) was used. The impact of surface exploitation on the functional transformation of settlements was analyzed by considering each settlement’s distance from the current surface mine, as well as the proportion of its area currently affected by exploitation.

For this analysis, vector data representing settlements and exploitation zones in polygon geometry were used as input. The polygon layer of settlements was converted into point geometry (centroids) using the Centroids geometry tool in QGIS. Subsequently, the spatial relationship between settlement centroids and the surface mine was examined through vector-based proximity analysis. The shortest Euclidean distance between each centroid and the boundary of the mining polygon was computed using the Distance to Nearest Hub (points) algorithm, which enabled the identification of the closest point of contact between settlements and the exploitation zone.

Additionally, the extent to which each settlement is currently affected by surface exploitation was assessed through overlay analysis using the intersection geoprocessing tool. This procedure spatially intersected the settlement boundary polygons with the digitized footprint of the active surface mine, enabling the calculation of the affected area per settlement. The mine footprint was manually digitized from a Sentinel-2 satellite image (granule ID: S2C_MSIL2A_20250406T095051_N0511_R079_T33TYK_20250406T151618), acquired on April 6, 2025, and visualized using true color composite (Red [B4], Green [B3], and Blue [B2] – RGB), allowing for precise delineation of surface mining activities.

3.2 Methodology for monitoring hierarchy shifts in the settlement network

The data used for analyzing changes in the hierarchy of the settlement network were also obtained from the 1971 [69] and 2013 [67] population censuses. These sources include

data from the period before the onset of surface mining, as well as from the most recent census conducted in B&H. The hierarchical transformation within the settlement network was tracked by analyzing changes in settlement centrality through the application of Schmook’s index [79] (1). This index calculates the degree of deviation in the share of employees in the tertiary–quaternary sector in a specific settlement compared to the regional average. One of the main advantages of this approach lies in its ability to enable a targeted analysis of individual central functions within each settlement. It also allows for the assessment of the specific capacity of other functional sectors, providing more detailed insights into the settlement’s role and overall functional structure. However, a notable limitation of this method is the potential distortion of centrality values, as the calculation includes the regional average – which also reflects the concentration of tertiary and quaternary functions in major central settlements. These often exceed the minimum needed to meet the population’s basic needs, thus inflating centrality values in comparative terms. Despite this limitation, Schmook’s index was selected for its practicality and alignment with the objectives of this study, having been successfully applied in previous analyses of hierarchical shifts within settlement networks [19,22,47,80,81]. The formula for calculating the centrality index (C) is as follows [79]:

$$C = A_s \times \frac{TQ_s}{A_s} - \frac{TQ_m}{A_m}, \quad (1)$$

where A_s represents the total employed population in the settlement, TQ_s is the number of people employed in the tertiary–quaternary sector within the settlement, TQ_m refers to the number of people employed in the tertiary–quaternary sector at the municipal level, and A_m denotes the total employed population in the municipality. Positive values derived from this calculation point to the significance of centrality within the settlement [82]. In addition, the significance of secondary sector activities (SSA) was assessed using a modified version of Schmook’s index (2), which has been employed in comparable research contexts [22,81]. The secondary sector includes activities associated with the mining and processing of ores, energy production, and the manufacturing of material goods [7]. The SSA index was computed for both 1971 and 2013 to identify settlements where the importance of SSA either increased or decreased over time. Due to differences in sectoral classification between the 1971 and 2013 census methodologies, a harmonization process was conducted based on the classification of activities provided by the Institute of Statistics of the RS [83]. In the 1971 census, the secondary sector included the following activities: industry, mining, and

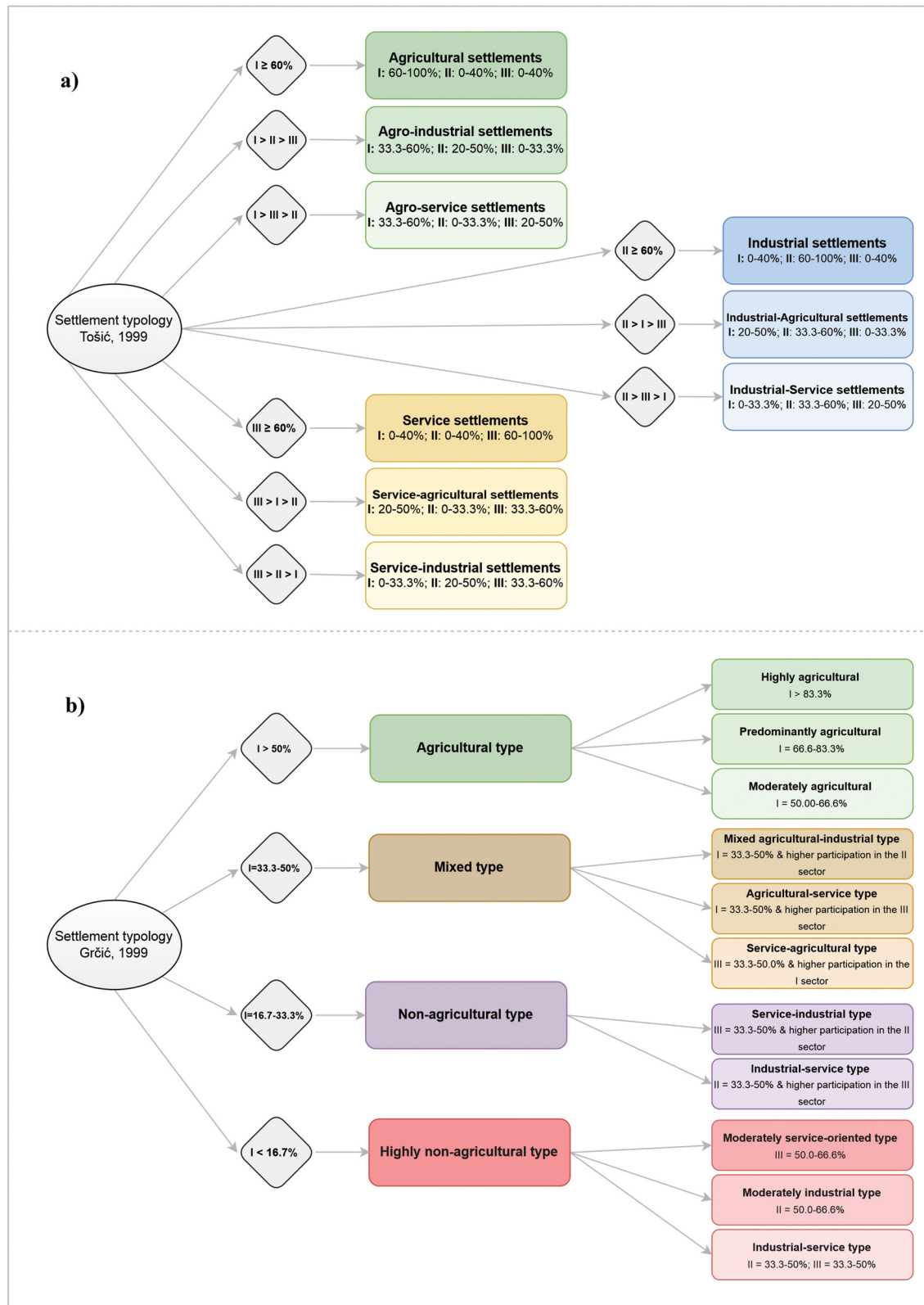


Figure 3: Functional typology of settlements according to Tošić from 1999 [37] (a) and Grčić from 1999 [23] (b).

construction. In the 2013 census, it comprised: mining and quarrying, manufacturing, electricity supply, water supply, and construction. SSA was determined using an adjusted formula:

$$SSA = A_s \times \frac{SS_s}{A_s} - \frac{SS_m}{A_m}, \quad (2)$$

where A_s represents the total employed population in the settlement, SS_s is the number of people employed in SSA within the settlement, SS_m refers to the number of people employed in SSA at the municipal level, and A_m denotes the total employed population in the municipality. Given the spatial and economic specificity of the study area, special emphasis was placed on the analysis of mining activities as a key component of the secondary sector. In line with the aim of this research, a modified Schmook's index was also applied to examine the significance of mining and related activities (SMA), in order to identify settlements where the mining function plays a dominant role (3). To assess whether the importance of these activities has increased or declined across individual settlements, the SMA index was computed for both 1971 and 2013. The data for its calculation were derived by extracting mining-related activities from the overall secondary sector. For the year 1971, mining activities included those directly or indirectly related to mining operations, namely, industry and mining. In the 2013 classification, they encompassed mining and quarrying, manufacturing, and electricity supply. The adjusted formula for determining SMA is as follows:

$$SMA = A_s \times \frac{MA_s}{A_s} - \frac{MA_m}{A_m}, \quad (3)$$

where A_s represents the total employed population in the settlement, MA_s refers to the number of people employed in mining activities within the settlement, MA_m denotes the number of people employed in mining activities at the municipal level, and A_m is the total employed population in the municipality.

The graphical interpretation of changes in the settlement network hierarchy based on C, as well as SSA and SMA, was conducted using Rochefort method [84], which has also been applied in similar studies [19,81]. The formula for determining the position of a settlement based on the centrality (4) within the coordinate system (X and Y coordinates) is as follows [84]:

$$X = \frac{TQ_s}{A_m}, \quad Y = \frac{TQ_s}{TQ_m}, \quad (4)$$

where TQ_s represents the number of people employed in the tertiary–quaternary sector within the settlement, A_m denotes the total employed population in the municipality,

and TQ_m refers to the number of people employed in the tertiary–quaternary sector at the municipal level.

The formula for determining the position of changes in the settlement network hierarchy based on SSA (5) within the coordinate system (X and Y coordinates) is as follows:

$$X = \frac{SS_s}{A_m}, \quad Y = \frac{SS_s}{SS_m}, \quad (5)$$

where SS_s is the number of people employed in SSA within the settlement, A_m denotes the total employed population in the municipality, and SS_m refers to the number of people employed in SSA at the municipal level.

The formula for determining the position of changes in the settlement network hierarchy based on SMA (6) within the coordinate system (X and Y coordinates) is as follows:

$$X = \frac{MA_s}{A_m}, \quad Y = \frac{MA_s}{MA_m}, \quad (6)$$

where MA_s refers to the number of people employed in mining activities within the settlement, A_m is the total employed population in the municipality, and MA_m denotes the number of people employed in mining activities at the municipal level.

3.3 Methodology for assessing future functional transformation

In order to anticipate the potential directions of future functional transformation within the settlement network, the results obtained through the application of functional typologies and the calculation of settlement centrality indices were compared with the spatial extent of the approved exploitation field. As for the projected impact of future surface exploitation on settlements, it was evaluated using the intersection geoprocessing tool in QGIS software, by overlaying the polygon boundaries of settlements with the vector layer representing the approved exploitation field. This vector layer was digitized based on publicly available coordinates from the Cadastre of Approved Exploitation Fields, published by the Ministry of Energy and Mining of the RS. The resulting intersection enabled the calculation of the proportion of each settlement's area expected to be affected by future surface mining.

The prediction of potential functional transformation within the settlement network was methodologically enriched by an analysis of survey data on residents' intentions regarding relocation and changes in employment. These indicators were selected for analysis because intentions to relocate and change employment directly affect the

potential destabilization of the existing functional structure within the settlement network. For this purpose, a survey was conducted in the territory of the Stanari municipality during 2024, among the local population, employees of public institutions (municipal administration, primary school, health center), and workers employed at the TPP. The survey was anonymous and included 373 adult respondents. Given that the focus of the analysis is the functional transformation of settlements, only the responses of employed individuals were considered relevant. Accordingly, the dataset was filtered by excluding the responses of unemployed and retired participants. Following this procedure, the final sample consisted of 261 respondents, representing 16.08% of the employed population in the Stanari municipality [68]. In order to identify the spatial pattern of potential settlement transformation in the future, respondents' answers regarding their place of residence were analyzed in relation to their stated intentions concerning relocation and the retention of their current job after relocation. All responses were digitized and processed using IBM SPSS Statistics 23, through the application of Crosstabulation and the Pearson Chi-Square (χ^2) test, with Monte Carlo simulations. The results were mapped at the level of settlements within the municipality of Stanari using QGIS software.

4 Results and discussion

4.1 Previous functional transformation

In order to analyze the general functional transformation of the settlement network, and in accordance with the

previously described methodology, a ternary diagram of the functional structure for the year 1971 was created, illustrating the functional orientation of settlements prior to the opening of the surface coal mine (Figure 4a), as well as a ternary diagram of the functional structure for the year 2013, showing the contemporary functional orientation of settlements (Figure 4b). Each corner of the triangle corresponds to the proportion of the employed population working in the primary (A), secondary (B), and tertiary (C) sectors, respectively. In 1971, the majority of settlements were oriented toward the primary sector. More than half of the settlements (Brestovo, Mitrovići, Radnja Donja, Cvrtkovci, Jelanjaska, Cerovica, and Dragalovci) had an exclusively agrarian function. The remaining settlements (Ostružnja Gornja, Raškovci, Ostružnja Donja, Ljeb, Osredak, and Stanari) were mostly slightly oriented toward activities in the secondary sector. The only settlement that deviated from this pattern was Stanari, which showed a noticeable share of employment in the secondary sector, indicating early industrial or mining activities. Overall, the functional structure of the municipal settlement network exhibited a monofunctional agrarian character. The current functional orientation of the settlement network reflects a more complex and diversified structure. All settlements underwent a decline in employment in the primary sector and a rise in the secondary and tertiary sectors. Settlements such as Raškovci and Dragalovci exhibit a stronger industrial orientation, which can be explained by the presence of coal exploitation in these areas. The settlement of Stanari stands out in particular, as it was positioned in 2013 along the axis between the secondary and tertiary sectors, with minimal employment in the primary sector.

This structure indicates the development of industrial, mining, and service functions. The functional transformation

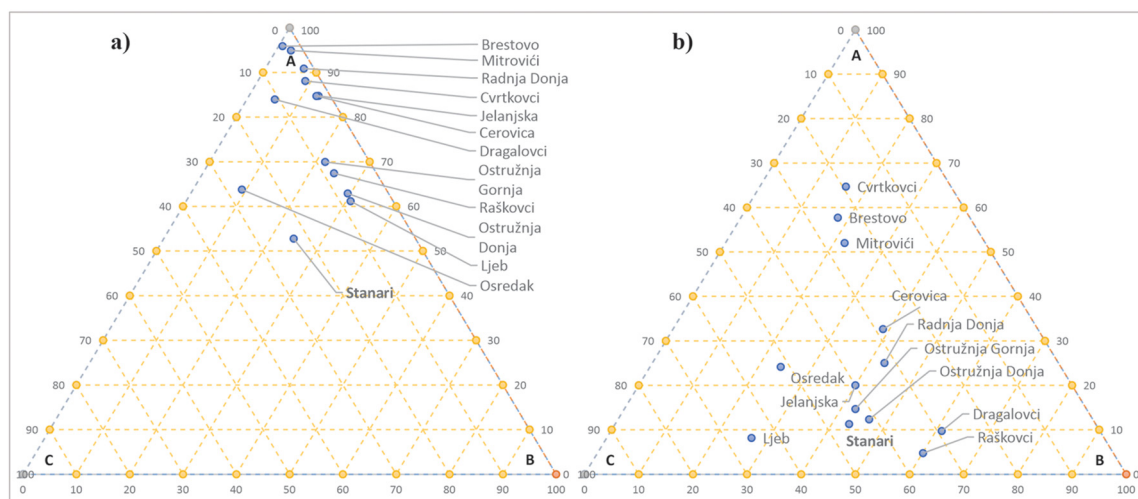


Figure 4: Ternary triangle of the functional orientation of the settlement network in 1971 (a) and 2013 (b).

of the settlement network during the observed period points to a process of deagrarianization, i.e., a declining role of agriculture within the overall economic structure. The results indicate that the diversification of traditional rural economies has been driven by an increase in the share of service-sector activities, as well as energy production – both of which represent ongoing trends in rural areas of Central and Eastern Europe [13]. An example of this broader trend of economic restructuring from agriculture to mining is found in the town of Boddington, Australia [10] which illustrates the shift observed in many rural communities worldwide. The study by Kerker and Vogel [15] highlights new functions of rural areas in Germany, including, among others, the function of energy production. A similar pattern of functional transformation toward deagrarianization within the settlement network has been observed in Serbia as well [20,21,29,32,34,42,44].

In order to determine the impact of mining activities and surface exploitation on parts of the settlement network, and in accordance with the previously described methodology, the functional type of each individual settlement was identified for the years 1971 and 2013. Two functional typologies were applied: the first, developed by Tošić [38], classifies settlements based on sectoral dominance

($\geq 60\%$) in the employment structure into nine types (Figure 3a); the second, developed by Grčić [24], classifies settlements based on the share of the primary sector in employment, resulting in 11 settlement types (Figure 3b). According to Tošić's typology, in 1971 the entire settlement network exhibited an agricultural character (Figure 5a), with the exception of the settlement of Stanari, which, although still agricultural, was classified as an agro-industrial settlement due to its modified structure. According to the same typology, the settlement network in 2013 displayed a more complex functional structure (Figure 5b). All settlements, except for Cvrtkovci, underwent changes in their functional type, to varying degrees. Settlements located in the immediate exploitation zone (0–1,500 m), whose territory overlaps with the active surface mine, were classified as industrial settlements. Settlements within the medium-distance zone from current surface mining (1,501–3,000 m) were reclassified into transitional types – such as industrial-agricultural, industrial-service, or service-industrial settlements – except for Cvrtkovci, which retained the agricultural type. The most distant settlements from the current exploitation area ($>3,000$ m) were functionally transformed into transitional types, most often industrial-agricultural or agro-industrial. The

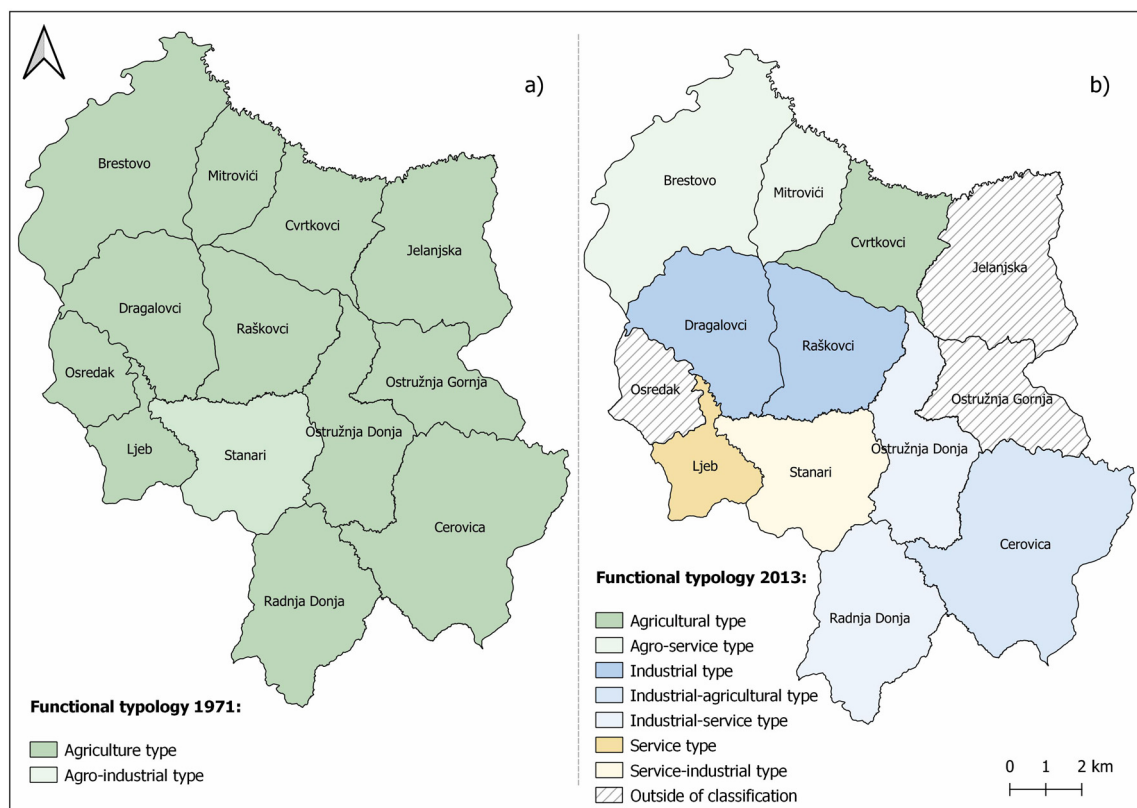


Figure 5: Functional typology of settlements in the municipality of Stanari according to Tošić's methodology from 1999 [37] in 1971 (a) and 2013 (b).

settlements of Osredak, Jelanska, and Ostružnja Gornja could not be precisely assigned to any single category from the typology, as their employment structures reflected relatively balanced shares across all three sectors. However, these settlements recorded higher proportions of employment in the secondary and tertiary sectors, indicating a departure from their 1971 agricultural orientation.

On the other hand, according to Grčić's typology, the functional structure of the settlement network in 1971 was entirely agrarian in character, with over 60% of the population employed in the primary sector (Figure 6a). More than half of the settlements in the network were classified as highly agricultural, while the remaining settlements exhibited modified agricultural functional types. Settlements located in the most distant zone from the area of current exploitation (Jelanska, Mitrovići, Cerovica, Radnja Donja, and Brestovo) showed a distinctly agrarian character, whereas those situated closer to the mining zone were categorized as modified agricultural types. According to the same typology, the functional structure of the settlement network in 2013 became significantly more complex (Figure 6b). Only three settlements retained to some extent their former 1971 functional character – Brestovo (which shifted from a highly agricultural type to a moderately

agricultural type), Mitrovići (also from highly to moderately agricultural), and Cvrtkovci (from highly agricultural to predominantly agricultural type). All other settlements in the network underwent a functional transformation. Settlements in the immediate vicinity of surface mining activities (0–1,500 m) transitioned into industrial types, with the most notable example being Raškovci, which shifted from a predominantly agricultural type in 1971 to a moderately industrial type in 2013. This settlement is the most affected by surface coal mining, with 46.37% of its territory under exploitation (Table 1). The population of settlements closest to the exploitation area moved away from employment in the primary sector and reoriented toward the secondary sector, indicating an intensive process of deagrarianization. Settlements located in zones further away from the mine (1,501–3,000 m and >3,000 m) show varying patterns of functional transformation, with a general tendency to abandon agricultural activities in favor of secondary or tertiary sector employment. These more distant zones also include the few settlements that experienced minimal functional transformation – namely, Brestovo, Mitrovići, and Cvrtkovci. The presence of coal exploitation has had a significant impact on the transformation of the functional structure of settlements, with the

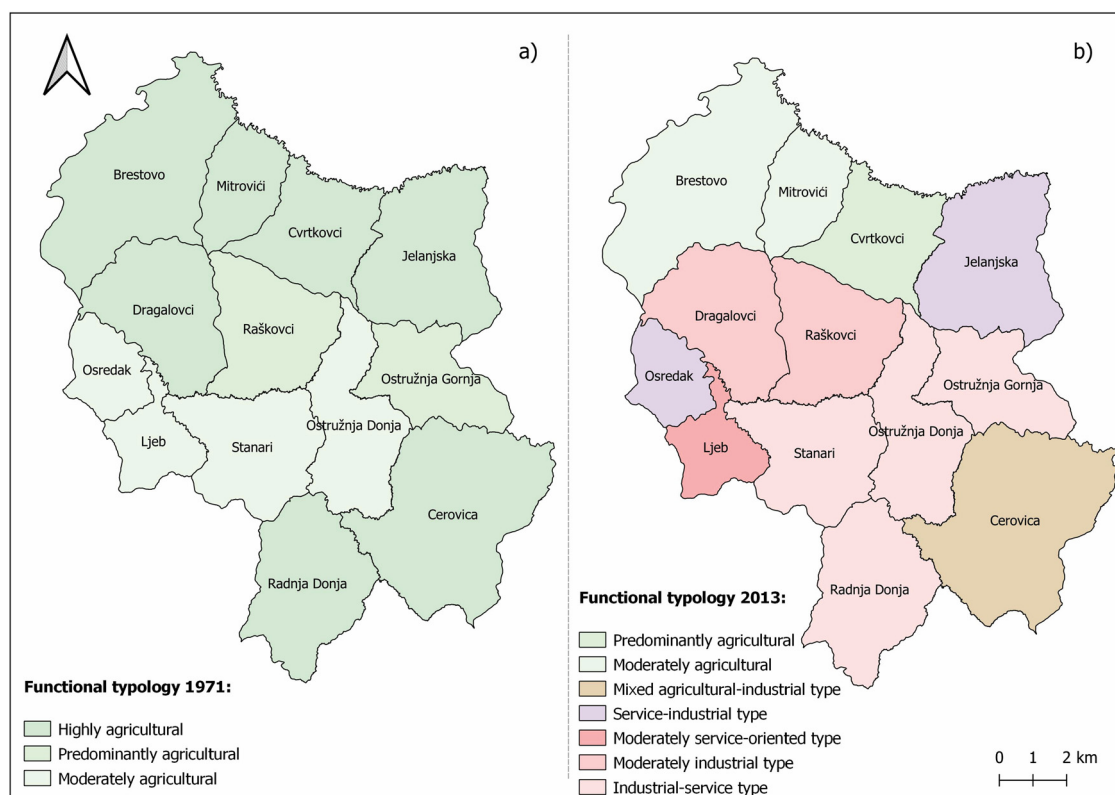


Figure 6: Functional typology of settlements in the municipality of Stanari according to Grčić's methodology from 1999 [23] in 1971 (a) and 2013 (b).

most pronounced changes occurring in those nearest to the surface mine. The spatial decline in influence reveals a clear gradient in the process of deagrarianization and a gradual industrialization of the affected areas.

4.2 Hierarchy shifts in the settlement network

In accordance with the previously described methodology, centrality was analyzed in order to gain insight into the hierarchical relationships within the settlement network during the observed period (Figure 7). In 1971, the centrality values (C) for most settlements were close to 1 or negative, indicating that these settlements lacked characteristics of centrality and had little to no central function. The settlements that stood out with high centrality values were Stanari (69.56) and Osredak (42.50), indicating the development of tertiary–quaternary sector activities in settlements located near the former mining site. The structure of centrality in the network exhibited a polarized character, with a pronounced hierarchy dominated by only two settlements. By 2013, centrality values increased in most settlements, suggesting a greater dispersion of

tertiary–quaternary activities throughout the settlement network. However, despite the overall increase, centrality values were not positive in all settlements. The most significant decline in centrality and the lowest recorded value was observed in Cvrtkovci (−32.80). The most intensive increase and the highest positive centrality values were registered in the settlements of Ljeb (25.28) and Ostružnja Donja (13.05). Although Stanari – the central settlement – maintained a positive centrality value (25.19), it experienced a noticeable decline. These findings indicate that service functions are increasingly developing outside the central settlement, contributing to a reduction in hierarchical imbalance within the network.

The analysis of the graphical interpretation of centrality provides insight into the position of each settlement within the network hierarchy, as well as changes in their relative position during the observed period (Figure 8). In 1971, most settlements occupied a low position in the hierarchy in terms of both the relative share of employment in the tertiary–quaternary sector compared to total municipal employment (X-axis) and the relative share of employment in the tertiary–quaternary sector compared to total employment in that sector at the municipal level (Y-axis) (Figure 8a). The settlement of Stanari stood out with a particularly high position relative to other settlements,

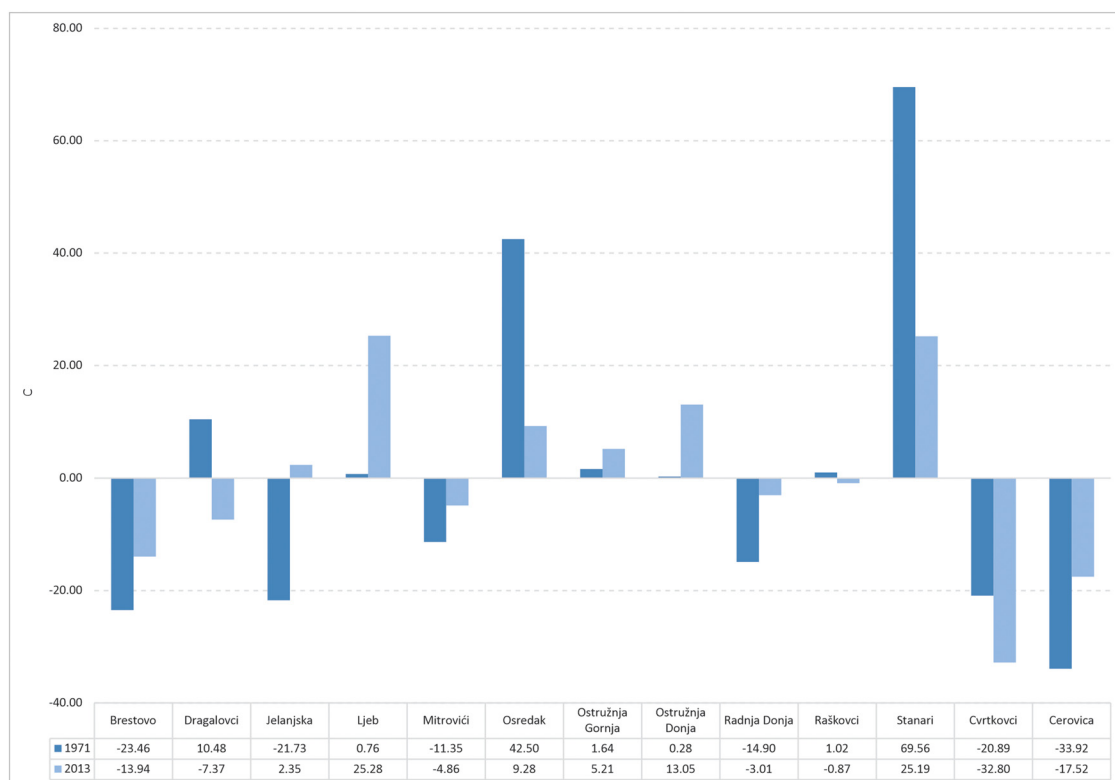


Figure 7: C index scores for settlements in Stanari municipality in 1971 and 2013.

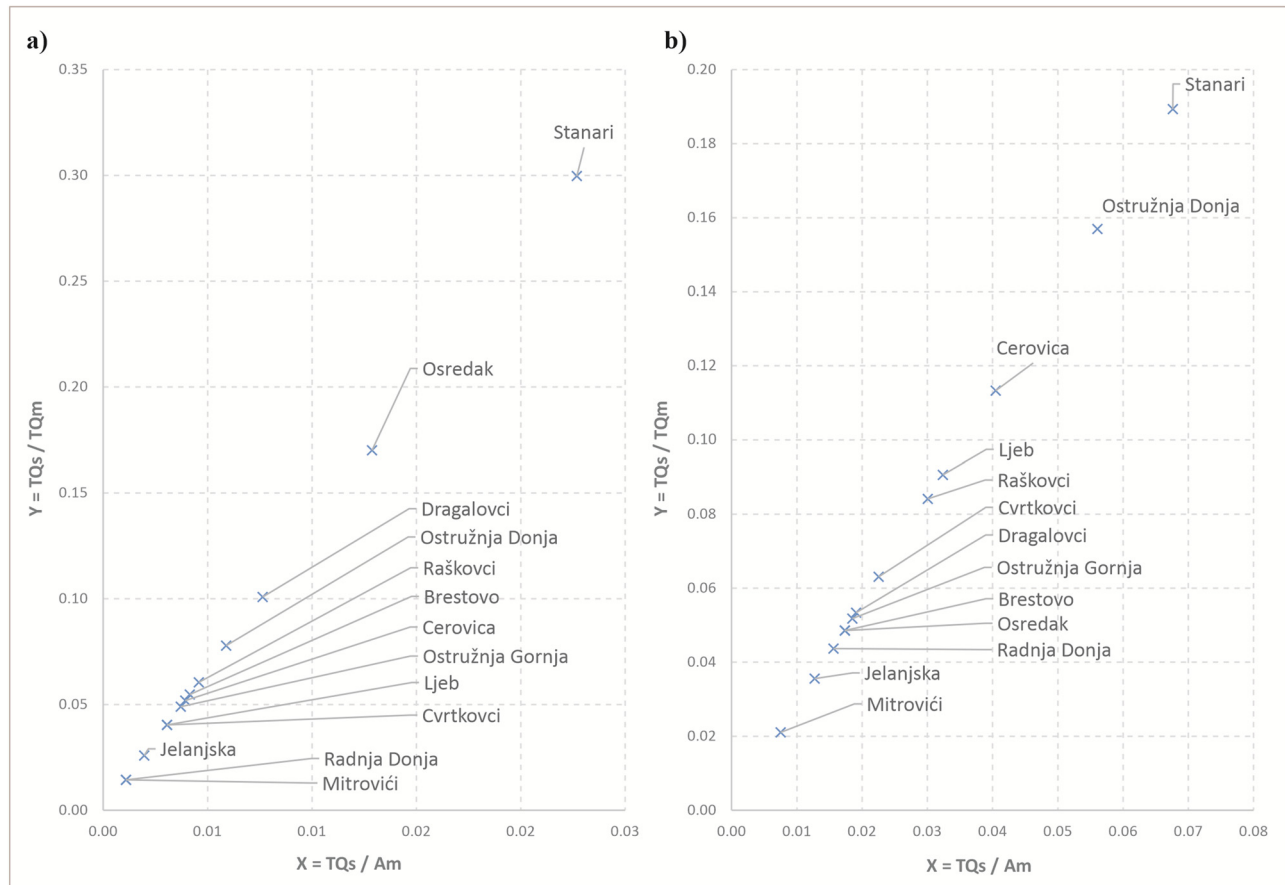


Figure 8: Settlement hierarchy according to centrality in 1971 (a) and 2013 (b).

suggesting that it already performed the role of a central settlement prior to the onset of intensive surface mining. Osredak also occupied a high position, but with lower values along the X-axis, implying a degree of specialization in the tertiary–quaternary sector, yet lacking a strong economic base. The hierarchy within the settlement network based on centrality in 2013 exhibited a more balanced character compared to 1971 (Figure 8b). In most settlements, the number of people employed in the tertiary–quaternary sector increased relative to the total employment in the municipality. Furthermore, there was a shift in the position of certain settlements in terms of the share of employment in the tertiary–quaternary sector relative to the total employment in this sector at the municipal level (Y-axis); these include Ljeb, Raškovci, Cvrtkovci, and Dragalovci. A significant shift in the hierarchical structure occurred in the settlements of Ostružnja Donja and Cerovica, indicating a diversification of functions and a strengthening of the economic base in these settlements. The settlement of Stanari continues to occupy the highest position in the hierarchy, thereby retaining its role as the central settlement.

The settlements that experienced a shift in their position within the settlement network hierarchy also changed their functional type from agricultural to various forms of industrial type. For this reason, it is important to analyze employment patterns in the secondary sector as well. Using the same methodology applied for calculating centrality (i.e., the concentration of employment in the tertiary–quaternary sector), the significance of secondary sector activities (SSA) was calculated. In 1971, the settlements with the highest SSA values were Ostružnja Donja (55.88) and Stanari (48.98), indicating their importance in terms of secondary sector employment (Figure 9). Relatively high SSA values were also recorded in the settlements of Ljeb (30.15) and Raškovci (29.01). In other settlements, the SSA values were not significant. By 2013, evident changes occurred in employment within the secondary sector (Figure 9). In Stanari, although the SSA value remained positive (12.21), a significant decrease was observed. In contrast, other settlements experienced an increase in SSA, indicating moderate industrial activity. Dragalovci recorded a substantial increase in SSA (from –27.17 to

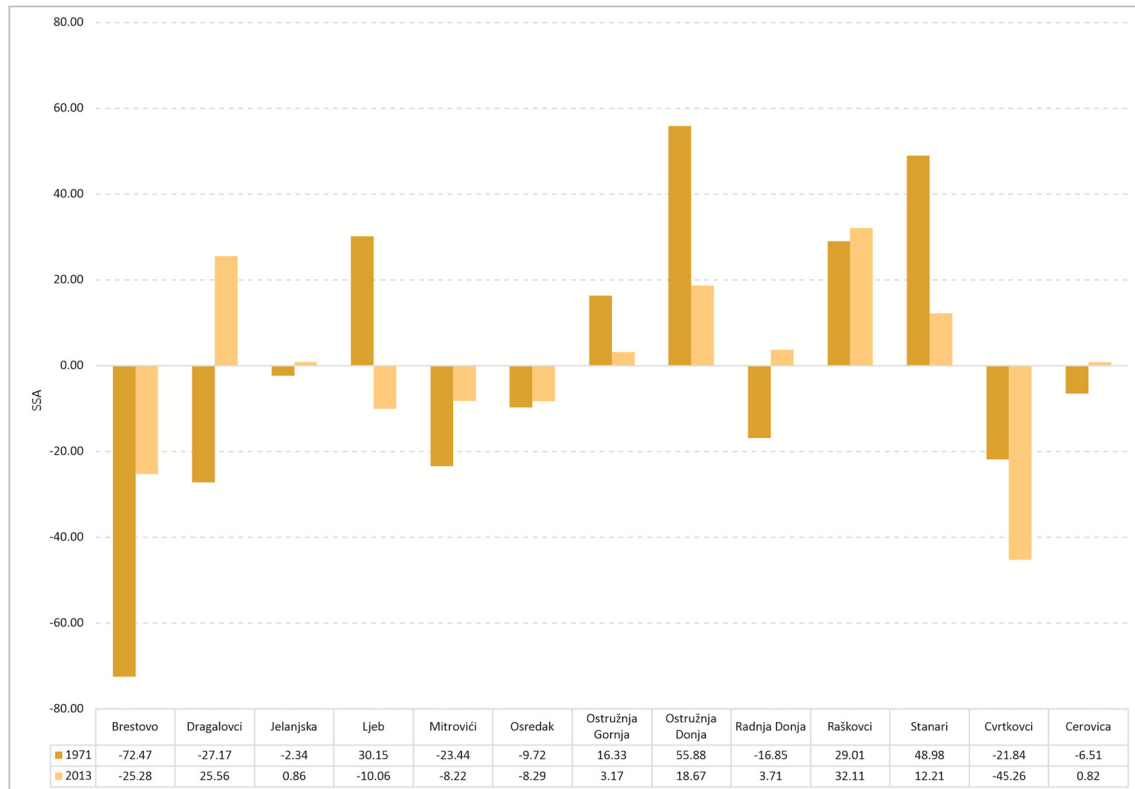


Figure 9: SSA index scores for settlements in Stanari municipality in 1971 and 2013.

25.56), pointing to a strengthening of the role of SSA. Notably, in 2013, the construction of the TPP began in this settlement. The plant's location corresponds to the area showing the greatest positive change in SSA, suggesting a direct impact of this economic facility on the transformation of the local functional structure through the pronounced concentration of labor.

The hierarchy within the settlement network based on SSA in 1971 was relatively balanced (Figure 10a). The settlements that occupied dominant positions within the network hierarchy were Stanari, Ostružnja Donja, and Cerovica. In other settlements, both the size of the economic base (X-axis) and the share of employment in SSA relative to total employment in that sector at the municipal level (Y-axis) were considerably lower. Settlements that exhibited a relatively higher concentration of employment in SSA included Raškovci, Ljeb, and Jelanjaska. By 2013, the SSA-based hierarchy within the settlement network showed clear positional shifts among settlements (Figure 10b). Growth was observed both in terms of the strengthening of the economic base (Y-axis) and the increased share of employment in SSA (X-axis). There were also notable changes in the relative positions of individual settlements within the network. In addition to settlements that were

already highly positioned in 1971, Raškovci and Dragalovci joined the group of settlements with high SSA values, indicating the development of SSA in these areas. Other settlements that had been marginalized in terms of SSA in 1971 now show moderate upward movement in the hierarchy, pointing to a gradual establishment of spatial balance and the decentralization of secondary sector functions within the settlement network.

Within the scope of further analysis, the results of the SMA index within the structure of the secondary sector stand out, as they allow for the assessment of the impact of mining on the economic base of settlements and their position within the network hierarchy. In 1971, the highest SMA values were recorded in the settlements of Ostružnja Donja (54.06), Stanari (43.43), and Raškovci (23.84) (Figure 11). Other settlements displayed lower or negative SMA values, indicating that mining and related industries had a strong influence on only a few settlements. The SMA values for 2013 (Figure 11) show that the settlements which played a leading role in 1971 largely retained their position, although the SMA values declined in Stanari and Ostružnja Donja. However, the SMA value increased in the settlement of Raškovci (35.30), positioning it as the most significant settlement within the network in terms of the role of

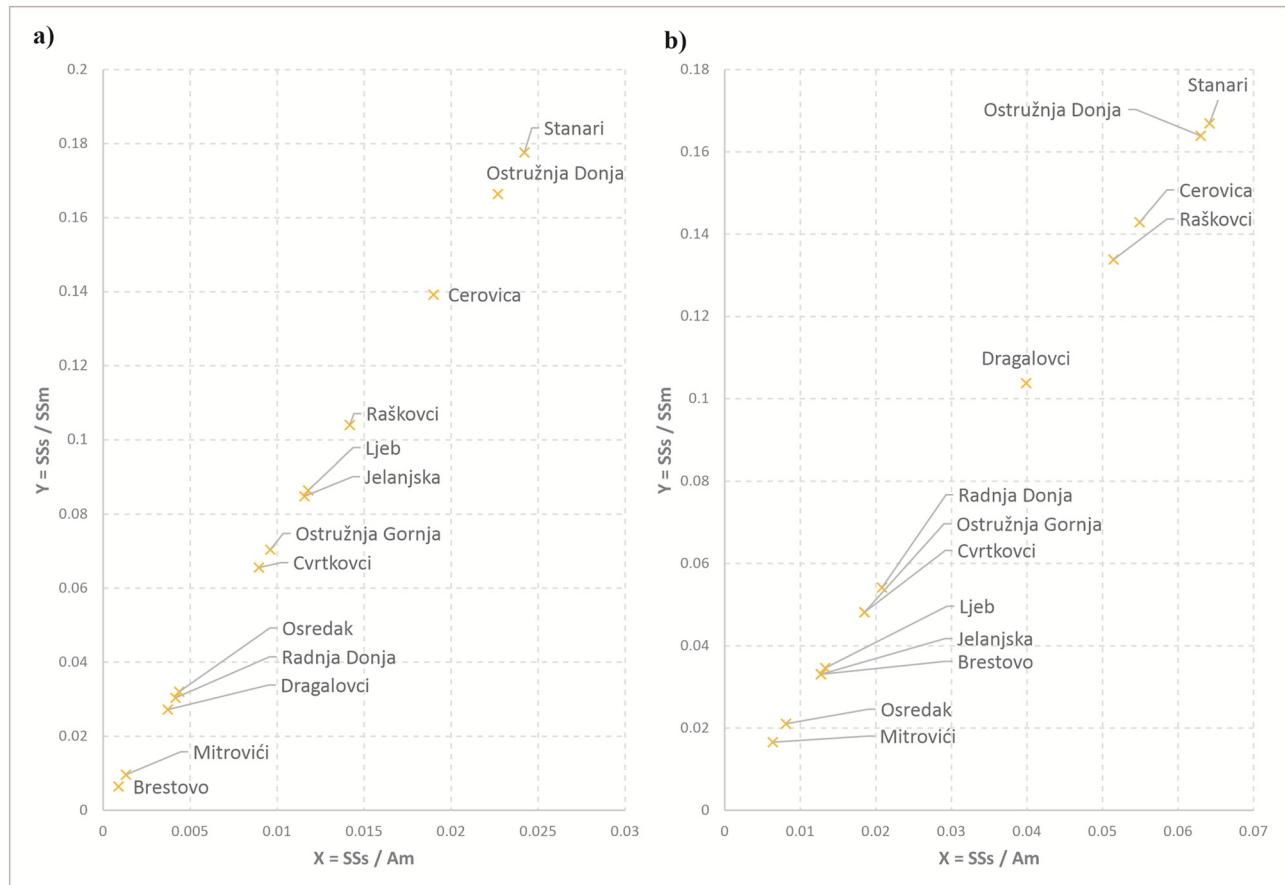


Figure 10: Settlement hierarchy according to SSA in 1971 (a) and 2013 (b).

mining and associated activities. Some settlements that had low SMA values in 1971 experienced a slight increase, while others continued to record negative values. These results point to a partial decentralization of mining and industrial activities within the settlement network.

The settlement network hierarchy based on SMA in 1971 reveals a clear dominance of two settlements – Ostružnja Donja and Stanari (Figure 12a). These two settlements stood out with the highest significance of mining activities, both in terms of the share of mining-related employment in total local employment (X-axis), and in terms of their contribution to overall municipal employment in the mining sector (Y-axis). Their position in the diagram (Figure 12a) indicates a high level of specialization and concentration of labor in mining and industrial activities. Raškovci also displayed a relatively prominent position within the hierarchy, although considerably lower than the two leading settlements. Other settlements such as Ostružnja Gornja, Cerovica, Ljeb, Jelanska, Osredak, and Radnja Donja were positioned in the lower portion of the graph, with low values on both axes, suggesting a

marginal role of mining activities in their economic structure. At the lowest positions in the settlement hierarchy were Brestovo, Dragalovci, Mitrovići, and Cvrtkovci, indicating a complete absence of mining activities in their economies. By 2013 (Figure 12b), significant changes occurred in the SMA-based hierarchy. Although Stanari and Ostružnja Donja retained their leading positions, the gap between them narrowed, suggesting a reduced difference in the intensity of mining and industrial activities between these key settlements. Raškovci showed a clear upward shift on both axes, thus joining the group of mining-significant settlements. Settlements that had played a marginal role in mining in 1971 now show moderate growth, although they still occupy lower positions in the hierarchy. Increases in both X and Y-axis values are evident in settlements such as Ostružnja Gornja, Cerovica, and Cvrtkovci, indicating a mild decentralization of mining functions. Nevertheless, the majority of settlements – including Brestovo, Mitrovići, and Dragalovci – maintain low values, reflecting the limited spatial extent of mining and industrial activities. Overall, the SMA-based hierarchy

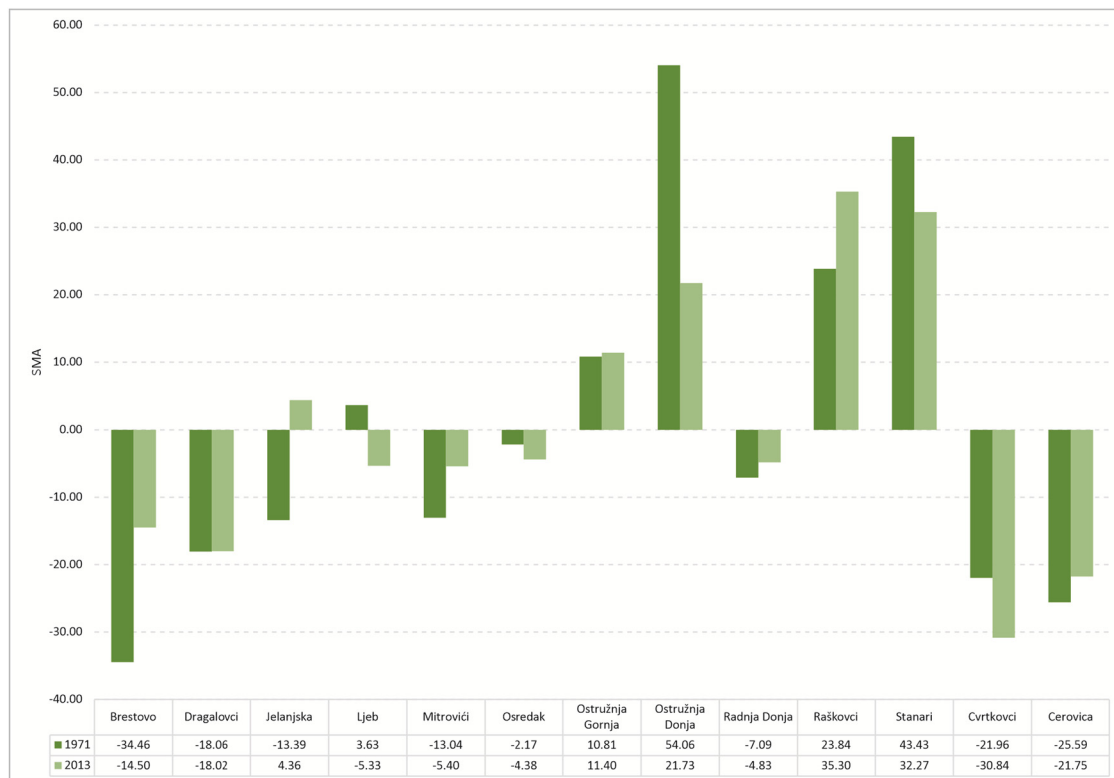


Figure 11: SMA index scores for settlements in Stanari municipality in 1971 and 2013.

in 2013 exhibits a softer polarization compared to 1971, but two dominant mining centers – Stanari and Ostružnja Donja – continue to prevail. The repositioning of other settlements within the network indicates a gradual upward movement in the hierarchy with respect to mining activity.

Overall, the results highlight the far-reaching impacts of coal mining on the functional and hierarchical structure of settlements within the municipality. Beyond economic restructuring and changes in employment patterns, these processes have triggered complex demographic, spatial, and environmental transformations.

In the context of ongoing and future coal exploitation, the application of sustainability principles is crucial for establishing a balance between economic development, environmental protection, and social welfare. While coal mining is an important driver of local economic growth and employment, it also brings significant challenges in terms of land degradation, loss of agricultural function, and population displacement [1]. These aspects become particularly prominent when considering the future functional transformation of the settlement network, which will be directly shaped by the continuation and expansion of mining activities in the coming period.

4.3 Future functional transformation

By comparing the functional typology of the settlement network with the spatial extent of the designated mining concession area, it is possible to identify settlements that are likely to undergo a functional transformation as a result of future coal exploitation. Analysis of the approved concession field reveals that mining activities will continue in settlements where exploitation is already underway and will expand to include additional settlements to varying degrees. Three groups of settlements can be distinguished based on the percentage of their territory projected to be affected by future exploitation: the first group will not be affected; the second group will be affected up to 30%; and the third group will be affected by more than 60%, with some exceeding 80%. Settlements that will not be affected by mining activities (Table 1, Figure 1) include Brestovo, Mitrovići, Radnja Donja, and Cvrtkovci. It can be concluded that these settlements are unlikely to experience significant changes in their functional types and that coal exploitation will not directly impact their functional structure. However, due to their relative proximity to the mining zone, indirect impacts are possible – particularly with

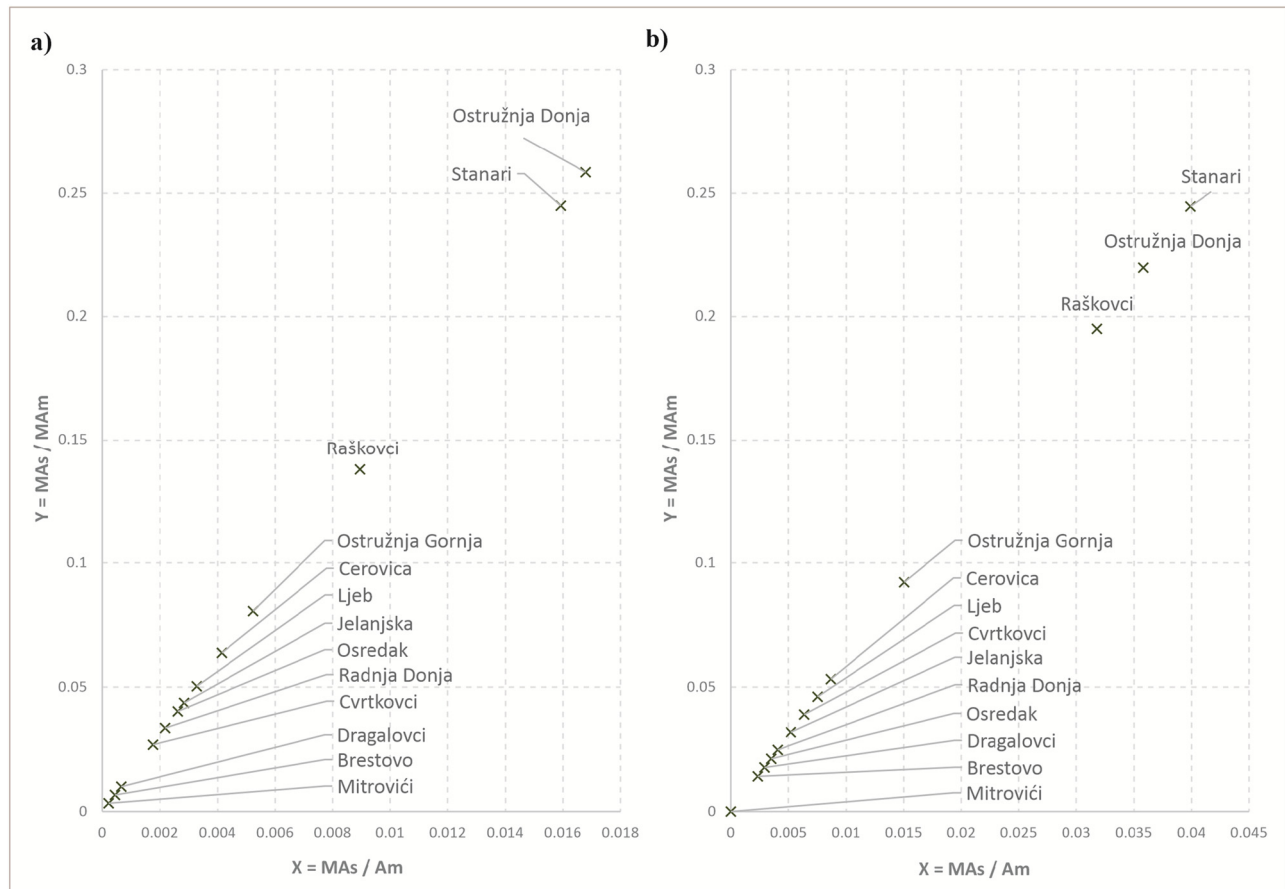


Figure 12: Settlement hierarchy according to SMA in 1971 (a) and 2013 (b).

regard to migration flows, labor redistribution, and the potential for the development of service or auxiliary activities. In this regard, moderate increases in the values of indicators C, SSA, and SMA may occur, potentially resulting in a slight upward shift of these settlements within the hierarchical structure of the settlement network. New settlements projected to be partially included in future surface mining – up to 30% of their territory – include Jelanska, Ljeb, Stanari, and Cerovica, along with Dragalovci, where exploitation is already taking place. It is expected that mining activities will influence the functional types of these settlements to varying extents, depending on the speed and direction of expansion. In terms of indicators, an increase in SSA is anticipated, particularly in those settlements with an already established industrial base. Likewise, the SMA indicator is expected to rise as a result of direct engagement in mining and industrial activities. The C indicator may also increase if the development of service functions accompanies industrial growth. However, if service sectors are neglected, a stagnation or even decline in centrality could occur. These

settlements will therefore be subject to varying degrees of functional transformation, influencing their position within the settlement network. The group of settlements projected to be affected by more than 60% includes those where mining is already active – Raškovci and Ostružnja Donja – as well as Osredak and Ostružnja Gornja, where mining has not yet started (expected to exceed 80% of the territory). Given the nature of surface mining, this group is likely to undergo a complete functional transformation and experience significant population displacement, which may ultimately result in demographic destabilization and the loss of both function and centrality. A considerable increase in the SMA indicator is expected due to the intensification of mining and industrial activity. However, if service and support functions collapse, the values of the C and SSA indicators may stagnate or decline. Moreover, a decline in the hierarchical structure of the network is possible if these settlements are reduced to purely technical exploitation zones without stable tertiary sector functions. The realization of the projected mining scenario, in line with the approved concession area (Table 1, Figure 1),

will lead to complex functional and hierarchical changes across the settlement network. Given the spatial effects and dynamics of surface mining, as well as the extended time required for land reclamation, a shift of the demographic and economic base toward the northern part of the municipality can be anticipated. Settlements not affected by mining may become relocation destinations for populations displaced through expropriation of land and property. This scenario is also envisioned in the current spatial plan of the municipality [85] and could be implemented through the targeted relocation of residents to other settlements within the municipal settlement network.

4.4 Residents' perceptions of relocation and employment change

In order to estimate the potential spatial patterns of future population relocation, responses from local residents who participated in the survey were analyzed. The first step in the survey involved examining the relationship between place of residence and the decision to relocate under different coal exploitation scenarios in the municipality. The analysis included 260 respondents (99.6%), while one response was missing (0.4%). A cross-tabulation and Chi-square test were conducted. The results of the cross-tabulation indicate that residents of certain settlements exhibited distinct patterns in their relocation decisions, depending on the scenario (continuation or permanent cessation of coal exploitation). The highest number of respondents who stated that they would not leave their settlement under either scenario came from Stanari ($n = 62$), accounting for 42.8% of all respondents in this category. Conversely, respondents from Ostružnja Gornja were more likely to relocate only in the event of a permanent cessation of mining activities (27.3% of that category). Similarly, residents of Ostružnja Donja and Cvrtkovci showed a greater tendency to relocate in both scenarios, suggesting a higher sensitivity of certain settlements to the continuation or termination of mining activities. The Chi-square test revealed a statistically significant association between place of residence and the decision to relocate ($\chi^2 = 82.998$; $df = 48$; $p = 0.001$). Given that 80% of the cells in the table had an expected frequency of less than 5, a Monte Carlo simulation with 10,000 samples was performed, confirming statistical significance ($p = 0.008$; 99% CI: 0.006–0.011). This indicates that the decision to potentially relocate is significantly influenced by the place of residence. Although the likelihood ratio was at the threshold of significance ($p = 0.057$), the Monte Carlo estimate in this case also confirmed statistical significance ($p = 0.030$). Fisher's Exact

Test yielded a p -value close to the conventional significance threshold ($p = 0.053$). The linear-by-linear association test did not show a significant relationship ($p = 0.576$), which is expected given the categorical nature of the variables. These findings suggest that respondents' spatial affiliation (i.e., the specific settlement in which they reside) influences their perceptions of the future under different exploitation scenarios. This may reflect varying degrees of exposure to the negative effects of coal exploitation, the duration of mining activity in certain settlements, and the degree of local economic dependence on mining-related employment.

Relocation from the current place of residence entails not only a shift in the demographic structure, but also a transformation of the economic base. To estimate the potential spatial pattern of changes in the economic base – i.e., the functional type – an analysis was conducted to examine the relationship between the place of residence and the intended employment solution after potential relocation. A total of 255 respondents with valid responses were included in the analysis. The potential association between these two variables was examined using the Chi-square test of independence. The results of the cross-tabulation revealed significant differences among settlements in terms of respondents' preferred employment solutions. In the settlement of Stanari, the highest number of respondents stated they would seek new employment in the new place of residence ($n = 26$; 47.3%). Settlements such as Ostružnja Donja and Ljeb recorded a relatively higher percentage of respondents who would look for new employment after relocating, while settlements like Osredak and Mitrovići showed an increased share of “no answer” responses. The Chi-square test confirmed a statistically significant association between place of residence and employment solution ($\chi^2 = 60.221$; $df = 36$; $p = 0.007$). Given that 76.9% of cells had an expected frequency below 5, the results were additionally verified using a Monte Carlo simulation with 10,000 replications. The resulting p -value ($p = 0.012$; 99% CI: 0.010–0.015) confirmed the statistical significance of the findings. The likelihood ratio test also showed significance ($p = 0.033$), while Fisher's Exact Test was on the threshold of statistical significance ($p = 0.050$). The linear-by-linear association test did not show a significant relationship ($p = 0.898$), indicating that there is no gradual or predictable trend between settlements and employment choices. Rather, differences in responses occur without a clear pattern and independent of one another. These findings suggest that the place of residence significantly influences how respondents perceive their employment future in the context of potential relocation – whether by retaining their current job or seeking new employment. Spatial affiliation plays an important role in

shaping decisions related to the economic stability of the population within the zone affected by coal exploitation.

In order to explore spatial differences in relocation intentions and potential employment changes, a summary analysis was conducted of respondents who expressed both a willingness to relocate under any scenario and to change jobs following relocation. Responses concerning relocation intentions were classified into four categories: very low willingness to relocate (0–25.1% of respondents willing to relocate), low to moderate willingness (25.1–41.0%), moderate willingness (41.0–61.0%), and high willingness to relocate (>61.0%) (Figure 13a). Very low willingness to relocate was recorded in the settlements of Brestovo, Mitrovići, and Osredak. On the other hand, settlements whose populations showed high willingness to relocate under at least one exploitation scenario include Jelanska (64.3%) and Raškovci (76.9%), where surface coal mining is currently ongoing. In the settlement of Stanari, the central settlement of the municipality, 43.6% of respondents indicated willingness to relocate under one of the scenarios. The survey results point to

dynamic changes in the demographic base across the settlement network. Only three settlements are likely to maintain demographic stability without migration caused by surface mining, while in all other settlements, mass outmigration may occur – including the settlement of Stanari, which serves as the central settlement of the municipality, where a moderate level of willingness to relocate was recorded (Figure 13a).

Regarding respondents' attitudes toward changing employment after relocation, the choice of this response implies not only the departure from current employment but may also reflect the potential loss of the settlement's existing employment function. Responses regarding willingness to change employment were classified into four categories: no change (0% of respondents who would change jobs), very low willingness to change jobs (0.01–15.0% of respondents who would change jobs), moderate willingness to change jobs (15.01–31.0% of respondents who would change jobs), and high willingness to change jobs (>30.01% of respondents who would change jobs) (Figure 13b). Survey

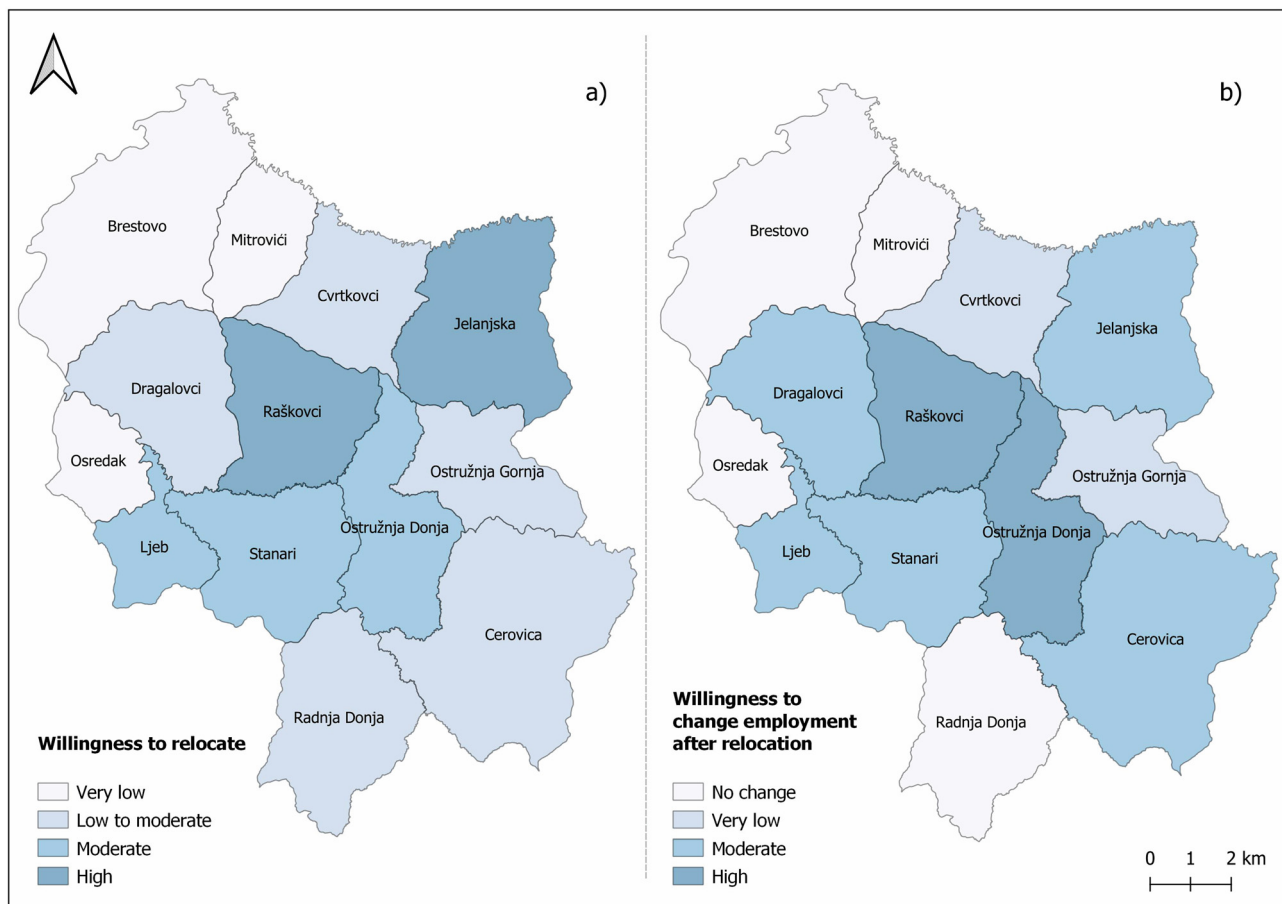


Figure 13: Attitudes of the local population in the settlements of Stanari municipality regarding willingness to relocate (a) and change employment (b).

results indicate a high willingness to change employment in the settlements of Raškovci (41.7%) and Ostružnja Donja (36.8%). In this context, settlements with a higher proportion of residents expressing an intention to change employment may be exposed to processes of functional destabilization, which could have potential consequences for the sustainability of their existing functional structure. A scenario of potential functional transformation caused by employment change following relocation is also anticipated in settlements with a moderate level of willingness to change employment, including Ljeb (26.7%), Jelanjska (21.4%), and the Stanari (24.1%), central settlement of municipality (Figure 13b).

Relocation will be inevitable in settlements located within the boundaries of the approved exploitation field. The displacement caused by mining activities, in addition to requiring the development of exit strategies for relocation and employment, may also lead to psychological challenges among the local population [86,87]. Physical displacement, relocation, and resettlement have been recognized as processes carrying substantial risks for communities directly affected by mining operations [88]. Given the complexity of mining-induced processes, future research should focus on exploring local residents' perceptions of quality of life in the immediate vicinity of mining activities, as well as their relocation strategies. In their study of the relationship between households, livelihoods, and resettlement caused by mining, Adam et al. [89] emphasized the importance of policy-makers ensuring transparency in handling the material aspects of resettlement and highlight the value of household-level research. The results of such studies can provide decision-makers with valuable guidance for aligning mining operations – imperative as an economic driver – with the needs of the local population. Research on mining-induced resettlement in Sierra Leone also underscores the necessity of developing legal frameworks that ensure alternative sources of livelihood for displaced persons [54]. Additionally, educating residents of mining communities about relocation-related legal provisions is essential [57]. The implementation of targeted strategies can help prevent homelessness and unemployment [56], and contribute to the establishment of mechanisms for long-term demographic stability and a balanced functional structure within the settlement network.

5 Concluding remarks

The research findings indicate that mining activity has had a significant impact on the functional and hierarchical transformation of the settlement network in the municipality of

Stanari. A comparative analysis of the years 1971 and 2013 points to a process of deagrarianization and industrialization, particularly in settlements located in close proximity to surface coal mining operations. This shift underscores the critical need for targeted spatial policies aimed at balancing industrial development with social sustainability.

Settlements such as Raškovci and Ostružnja Donja have undergone the most substantial functional changes and shifts within the hierarchy, accompanied by increases in the SMA and SSA indicators, confirming their new role within a mining-industrial structure. This is particularly significant when considered within the context of the broader socio-economic transitions occurring in the region. At the same time, the hierarchical structure of the settlement network shows signs of decentralization, with an increase in the centrality index (C) recorded in several peripheral settlements. This suggests a shift in the urban-rural dynamics, indicative of a trend toward more distributed service and infrastructure systems.

Notably, Ljeb, Ostružnja Donja, and Cerovica experienced a significant rise in centrality during the observed period. However, all three of these settlements are projected to be directly affected by the future expansion of surface mining operations, making them particularly vulnerable in terms of maintaining service functions and demographic stability. This vulnerability calls for urgent action in terms of both preservation of local functions and long-term demographic planning. The potential loss of their central roles could disrupt the functional structure of the entire network, necessitating timely planning and interventions to preserve their roles within the settlement system.

Special attention should also be given to settlements with moderate to high willingness to relocate (e.g., Jelanjska, Raškovci, Stanari) and to change employment (e.g., Ostružnja Donja, Ljeb), as these are the most sensitive to functional and demographic disturbances. These settlements should be considered priority areas in the development of exit strategies – by providing sustainable conditions for relocation, retaining the workforce, and preserving demographic cohesion. Conversely, settlements that will not be directly affected by exploitation, such as Brestovo, Mitrovići, Radnja Donja, and Cvrtkovci, should be recognized as key destinations for targeted internal relocation within the network. In the absence of an organized relocation model, local authorities must guide spatial policy toward retaining the population within the municipality and preventing out-migration to neighboring municipalities, which would jeopardize the economic and demographic base of the entire local government unit.

Experiences from mining communities around the world show that functional and demographic transformations, if not accompanied by adequate policies, often result in long-term spatial imbalances. Therefore, the analysis of spatial and functional changes should not be viewed as an end in itself, but as a foundation for developing targeted policies rooted in the real needs of local populations and the spatial capacities of the settlement network.

This research represents one of the first in-depth studies to examine the functional transformation of a settlement network affected by mining in the RS. By exploring the case of Stanari, the study contributes to filling existing research gaps and provides practical insights that may be applicable to other similarly affected regions. The results serve as a solid basis for understanding the spatial and functional dynamics of mining zones and for formulating targeted interventions that promote functional stability and territorial cohesion. Such interventions are necessary not only during active exploitation but also in the post-mining phase, ensuring long-term socio-economic sustainability.

Despite these valuable insights, several limitations must be acknowledged. The analysis relies on census data from only two time points (1971 and 2013), which limits the ability to capture finer temporal dynamics or intermediate changes, especially considering that the most recent census in B&H was conducted in 2013. Furthermore, projections of future transformation are informed by resident survey responses, which, while valuable, reflect subjective perceptions that may be influenced by changing political, economic, or institutional conditions over time. These limitations should be taken into account when interpreting the results. Still, the study offers a good starting point for understanding the spatial and functional dynamics of mining zones and provides a foundation for further research.

In addition, the study highlights the urgent need for more comprehensive and methodologically robust research on the socio-economic resilience of mining communities. Particular attention should be given to understanding household perceptions, the challenges of relocation, and the integration of displaced populations. Expanding such research – especially through longitudinal and mixed-method approaches – can provide deeper, more reliable insights to inform effective strategies for managing demographic shifts and preserving the functional roles of settlements.

The broader relevance of this study lies in its potential to inform planning in mining regions worldwide. By addressing critical gaps in the literature and underscoring the importance of proactive, locally tailored planning, it lays the groundwork for future policies that are responsive to the socio-environmental realities of mining areas. Future

research should increasingly focus on evaluating the long-term socio-economic resilience of post-mining communities, paying particular attention to both environmental degradation and economic restructuring.

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