

## Research Article

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# Impact of the agri-geographical transformation of rural settlements on the geospatial dynamics of soil erosion intensity in municipalities of Central Serbia

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**Abstract:** The aim of study is to analyze the agri-geographical transformation of rural settlements on changes in the intensity of soil erosion and the geospatial differentiation of soil erosion intensity according to the specificities of rural settlements. The study area included 349 rural settlements in 14 municipalities of Central Serbia. The shift-share analysis method was applied to identify four types of rural settlements: progressive, stagnant, regressive, and dominantly regressive types. An erosion potential model was used to estimate the soil erosion in 1971 and 2011. Cluster analysis (CA) was used to differentiate rural areas of municipalities based on selected indicators. The highest rates of soil erosion intensity reduction were found in the regressive and dominantly regressive types (average specific gross erosion 1971:  $W_{S_1} = 980 \text{ m}^3/\text{km}^2/\text{year}$ ; 2011:  $W_{S_2} = 587 \text{ m}^3/\text{km}^2/\text{year}$ ). The lowest reduction in erosion intensity was observed in the progressive and stagnant types (average specific gross erosion in 1971:  $W_{S_1} = 1,214 \text{ m}^3/\text{km}^2/\text{year}$ ; 2011:  $W_{S_2} = 936 \text{ m}^3/\text{km}^2/\text{year}$ ). The spatial differentiation of municipalities through CA revealed a clear pattern: the risk of soil erosion decreases along a north-south gradient. Also, the results of CA showed that natural conditions (forest cover, mean altitude, sediments of Neogene) are the most significant in the differentiation of the rural space of Central Serbia. The

multidisciplinary approach used in this study enables a holistic understanding of erosion processes, supports the identification of spatial patterns, and facilitates the formulation of targeted and region-specific land management strategies.

**Keywords:** agri-geographical transformation, rural settlements, soil erosion intensity, geospatial dynamics, the shift-share analysis, cluster analysis, sustainable environmental resource management

## 1 Introduction

Spatial patterns of land use are highly complex and heterogeneous [1], and changes in land use over time are not a linear process, but rather manifest in waves or cycles [2]. Studies have shown that the period from 1960 to 2005 was characterized as a phase of global acceleration, followed by the period from 2006 to 2019, which was marked as a phase of global deceleration [3]. Recent research results indicate that land use change has affected one-third of the global terrestrial surface over the past six decades [3]. Land use changes in accordance with the evolution of multiple simultaneous and interconnected factors [4]. Economic (changes in global and local markets, incentives for rural development, subsidy policies), technological (modernization of equipment and biotechnological innovations), political (legislative regulations, political approaches), ecological (climate change, biodiversity, and the protection of natural resources), and demographic factors (migration, urbanization, population aging) are the primary drivers of land use change [1,4–6]. These changes may result from long-term trends (e.g., population aging and climate change) or short-term decisions (e.g., subsidies or price fluctuations on the market) [5].

Data on the extent, patterns, and trends of land use are crucial for supporting global and national priorities and for sustainable development [7]. Some regions are more

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stable in terms of land use, while others experience rapid changes caused by urbanization, mining, and the intensification of agriculture [8,9]. In certain parts of the world, an increase in agricultural land has been recorded [6,9]. Sub-Saharan Africa is the region with the highest human pressures on agricultural land [10]. On the other hand, there are regions that have been marked for decades by the abandonment of agricultural land and the spontaneous expansion of forested areas [11–17]. The phenomena of abandonment and expansion of agricultural land are not opposite aspects of the same process, as the factors influencing them may differ [18].

Nevertheless, the global dynamics of agricultural land are moving toward the optimization of land use, with a tendency toward increasing the efficiency of production on existing land [19–21]. This means that for agricultural production, increasing productivity and intensifying agricultural practices are key, rather than expanding agricultural areas [22].

The role of agriculture in the context of soil erosion is becoming increasingly significant, due to growing challenges in sustainable development and environmental protection. The geomorphological response to land use change is nonlinear: a small change in the percentage of arable land leads to relatively large changes in erosion risk and sediment transport [23].

On a global scale, human activities such as deforestation, intensive agriculture, and urban expansion have drastically altered natural sediment dynamics, making anthropogenic erosion a dominant process of land degradation in the Anthropocene [24]. One of the key reasons for unsustainable land management is the rapid population growth. This generates intense agrarian pressure due to the increasing demand for food [25,26]. This is particularly evident in developing countries, where the survival of millions of people depends on the functional capacity of land resources [27]. The greatest soil losses caused by erosion in East African countries originate from the Ethiopian Highlands [28]. Numerous studies confirm that unsustainable agricultural practices, rapid population growth [29,30], and the absence of effective land management policies [31] are the primary causes of land degradation in Ethiopia, resulting in extensive soil erosion and deepening rural poverty [32]. Wang *et al.* (2018) found that urbanization in the Inner Mongolia region increases soil erosion by 15–25%, and that intensive land use changes lead to permanent land degradation [33]. The reduction in forest cover directly affects soil properties (reduction in organic carbon, decreased biological activity, loss of fertility, etc.), thereby accelerating the process of erosion worldwide. Studies show that the most severe consequences of deforestation have been recorded in the Amazon [34], Central African rainforests, and Southeast

Asia [35]. Deforestation in Southeastern Europe contributes to land degradation in hilly areas, especially when carried out without adherence to appropriate protective measures [36]. Improper practices such as deep plowing and the absence of protective vegetation cover lead to a significant increase in surface erosion and nutrient loss [37]. In contrast, the latest findings show that proper land management can reduce the risk of soil erosion [38,39]. The application of conservation practices in Mediterranean olive groves has shown that soil erosion can be reduced by as much as 40–60% compared to conventional tillage. At the same time, this improves the physical-chemical characteristics of the soil and water retention [40]. Similarly, sustainable practices (contour farming and cover cropping) significantly reduce surface runoff and nutrient loss in arid agroecosystems over the long term [41]. A study conducted in Ethiopia shows that proper land management can reduce surface runoff by more than 50% and nitrogen loss by 45%. This implies a reduced risk of erosion [39].

Considering the favorable geographical position, natural conditions, and above all the significant agricultural potential, the subject of this research was the rural area of Central Serbia. The basic spatial unit of this research is the rural settlement. Settlements are part of the so-called “anthropogeosystem, which is embedded in the natural environment and together with it forms a complete dynamic stochastic system of a natural–historical character” [42]. This means that through settlements, it is possible to determine the principles that govern a particular area. Moreover, the rural settlement is the spatial unit through which the heterogeneity of the agrarian landscape and its influence on erosion can be most precisely monitored. In this way, the main patterns of land use can be identified, and the anthropogenic impact on soil erosion determined.

In this context, the objectives of this research are:

1. Typological classification of rural settlements according to changes in agricultural land;
2. Spatio-temporal analysis of changes in soil erosion intensity according to the identified types of rural settlements;
3. Geospatial differentiation and clustering of soil erosion intensity in municipalities.

This research provides a detailed insight into the complexity of soil erosion changes in rural areas of Serbia. It also highlights the importance of the influence of multiple geographical factors on changes in soil erosion during the study period. Such multidisciplinary research can form the basis for the creation of sustainable agriculture policies, enabling precise land resource management and the establishment of a balance between food production and environmental protection.

## 2 Materials and methods

### 2.1 Study area

The study area ( $5,150 \text{ km}^2$ ) encompasses 14 municipalities in Central Serbia (Figure 1). In the northern part of the study area are the municipalities of Mladenovac, Smederevska Palanka, and Velika Plana. The central parts of the study area include the municipalities of Topola, Rača, Batočina, Lapovo, Kragujevac, Jagodina, Čuprija, and Svilajnac. The southernmost part encompasses the municipalities of Rekovac and Paraćin, while the municipality of Despotovac is located in the eastern part of the study area. In the study area, there are 525,075 inhabitants. Kragujevac municipality ( $835 \text{ km}^2$ ) is the largest municipality in terms of both area and population. One third of the total population of study area lives in this municipality (171,186 inhabitants) [43].

### 2.2 Physical-geographical characteristics of the study area

The study area is situated between the Carpathian–Balkan mountain system to the east and southeast, and the Serbian–Macedonian Massif extending across the western and central parts [44]. The dominant morpho-hydrological unit is the valley

of the Velika Morava River. The main morphometric feature is the uniform elevation and the predominance of the hypsometric zone between 100 and 200 m a.s.l. The most widespread geological formations are Neogene sediments and alluvium, which cover about 50% of the total area and are primarily located in the lower elevation zones [45]. The predominant soil types in the basin are Eutric Cambisol and Vertisol, with Fluvisol and Humic Fluvisol also found in the alluvial plains of the Velika Morava [46].

### 2.3 Socio-geographical characteristics of the study area

Urban centers are located along the Velika Morava Valley (along Pan-European Corridor X) and in the valleys of its larger tributaries. The rural areas of these municipalities comprise 349 rural settlements. The highest number of rural settlements is found in the municipalities of Kragujevac (56), Jagodina (52), and Paraćin (34). The area is characterized primarily by differing levels of depopulation and deagrarianization. The total rural population (RP) decreased by 29% between 1961 and 2011 (from 411,810 to 288,826 inhabitants) [43]. In 1971, the rural area of Central Serbia had 352,292 ha of agricultural land, with arable land accounting for a significant portion (61%). Agricultural land distribution was particularly characterized by land

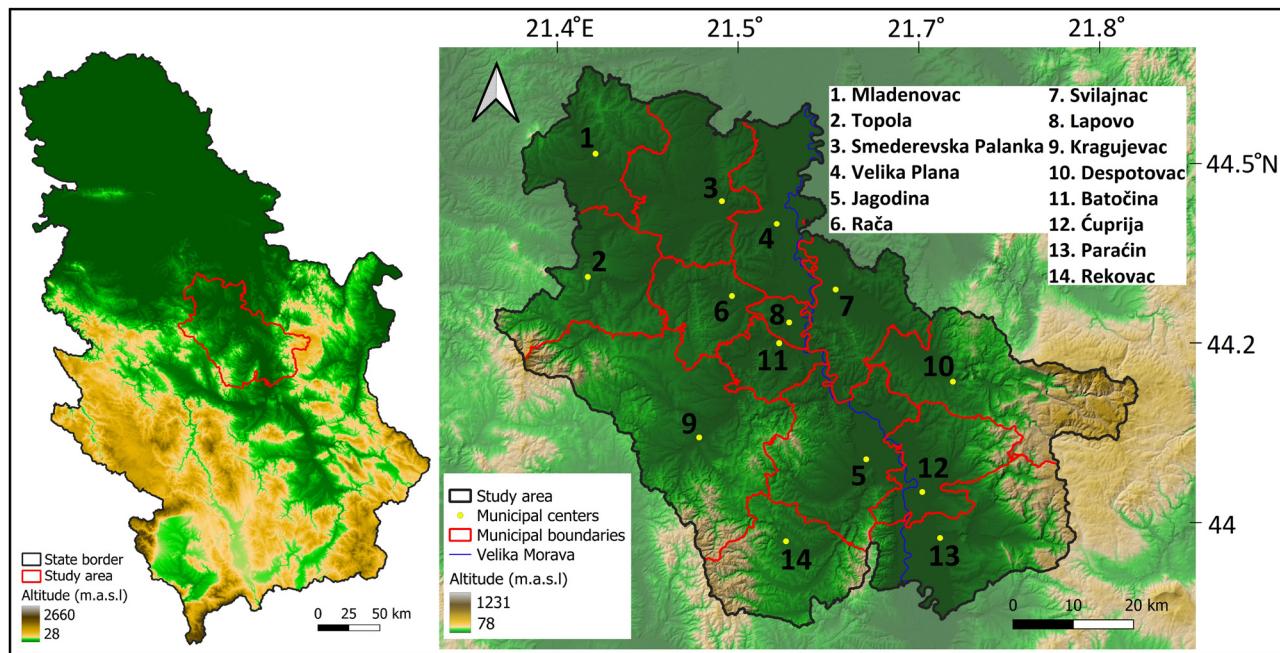


Figure 1: Geographical position of the municipalities in Central Serbia.

parcels larger than 1,000 ha. By 2012, the total area of agricultural land had decreased to 215,450 ha, with a predominance of land categories smaller than 500 ha. In 1971, the study area had 214,454 ha of arable land, while in 2012, it had 169,708 ha. Thus, arable land decreased by 21% over the observed period. However, the share of arable land within the total agricultural land increased to 78% [47].

## 2.4 Dataset

Data on average annual gross erosion ( $W_s$ ) and the erosion coefficient ( $Z$ ) for the year 1971 were obtained from the Erosion Map of Serbia 1:500,000 [48]. Data on mean elevation ( $A$ ) and terrain slope ( $I$ ) were derived from the 25 m digital elevation model (EU-DEM) [49]. The basic geological map at a scale of 1:100,000 was used to estimate the soil resistance coefficient ( $Y$ ) and to identify the share of Neogene sediments in rural settlements [50]. The CORINE Land Cover 2018 database [51] was used to quantify the soil protection coefficient ( $X$ ) and the proportion of forest cover in rural settlements. Landsat 8 satellite images were utilized to calculate the erosion and stream network development coefficient ( $\phi$ ) [52] using the bare soil index (BSI). The spatial resolution of the satellite images employed in this study was 30 m × 30 m. The BSI index calculation was carried out using several mathematical operations within the QGIS program [53].

$$BSI = \frac{(B6 + B4) - (B5 + B2)}{(B6 + B4) + (B5 + B2)}, \quad (1)$$

where B6 (Band 6) is a shortwave infrared spectral channel, B4 (Band 4) is a red spectral channel, B5 (Band 5) is a near-infrared spectral channel, and B2 (Band 2) is a blue spectral channel.

Anthropogenic influence was determined by indicators that best reflect the impact of land use changes, as well as the effects of long-term demographic trends in Central Serbia. For the calculation of demographic indicator, data from the Statistical Office of the Republic of Serbia for the period 1971–2011 were used, while data on agricultural and arable land from the Statistical Office for the period 1961–2012 were used for the calculation of agrarian-geographical indicators [47]. The analysis included two agrarian-geographical indicators: the change in agricultural land (Index AgL) and the change in arable land (Index ArL). The demographic indicator is the change in RP (Index RP). These indicators were standardized to the level of rural settlement.

For the purpose of geospatial differentiation of municipalities in the study area, several geographical indicators

were selected [45]. In order to quantify the influence of natural conditions in the agrarian landscape of Central Serbia, the following physical-geographical indicators were selected: the specific annual gross erosion ( $W_s$ , m<sup>3</sup>/km<sup>2</sup>/year), the erosion coefficient ( $Z$ ), Neogene sediments and alluvium (NSA, %), average elevation ( $A_{av}$ , m a.s.l.), and forest cover ( $F$ , %). These indicators were standardized to the level of municipality. QGIS 3.8.0 was used for data collection, analysis, and visualization.

## 2.5 Erosion assessment

Over the past few decades, various models have been developed to assess soil erosion intensity, with a steady increase in related research [54]. Some models emphasize spatial components [55], while others prioritize temporal dynamics [56]. However, these models face limitations, including the complexity of erosion processes, spatial heterogeneity, and insufficient data [57]. Additionally, many models are constrained by their geographic specificity, making them unsuitable for application in regions with different environmental conditions [57–59].

In this study, the erosion process's intensity was calculated using the erosion potential model (EPM), also known as the Gavrilović method [60]. The EPM provides a reliable assessment of soil erosion rates, mean annual soil loss, sediment yield, erosion control measures, and torrent regulation at a regional scale. It is particularly useful in areas where detailed erosion data are scarce. However, while it offers practical advantages, the EPM does not thoroughly account for the complex physical processes underlying soil erosion [61]. Using this method, average annual gross soil erosion ( $W$  – m<sup>3</sup>/year) can be calculated as [36,48,60]

$$W = T \cdot H \cdot \pi \cdot \sqrt{Z}^3 \cdot A, \quad (2)$$

where  $T$  is the temperature coefficient,  $t$  is the mean annual air temperature (°C),  $H$  is the mean annual precipitation (mm),  $Z$  is the erosion coefficient, and  $A$  is the watershed area (km<sup>2</sup>). The temperature coefficient is calculated as follows:

$$T = \sqrt{\frac{t}{10}} + 0.1, \quad (3)$$

and the erosion coefficient ( $Z$ ) is calculated as

$$Z = Y \cdot X \cdot (\varphi + \sqrt{I}), \quad (4)$$

where  $Y$  is the coefficient of soil resistance,  $X$  is the soil protection coefficient,  $\varphi$  is the erosion and stream network development coefficient, and  $I$  is the average slope (%).

## 2.6 Shift-share analysis method (the method of proportional changes)

In order to determine the impact of deagrarianization on the spatial and temporal variability of soil erosion, types of agricultural land use changes were identified. Changes in total agricultural land area in the rural regions of Central Serbia during the period 1961–2012 served as the main starting criterion. The shift-share analysis method was used. This method is employed in economic research [62–69], research of tourist activity [70], agri-geographical studies [60,69,71,72], and demographic studies [73–77]. Its popularity can be partly attributed to its relative simplicity and ease of implementation, reliance on readily available data, and the generation of results that are clear and easy to interpret [67,78]. This method is increasingly being used in studies that explain changes in soil erosion through population and agrarian changes [79–81].

The change in agricultural land ( $AC_j$ ) in rural settlements ( $j$ ) is calculated using equation (5)

$$AC_j = A_j^2 - A_j^1, \quad (5)$$

where  $A_j^1$  is the agricultural area in rural settlements (ha) in 1961, and  $A_j^2$  is the agricultural area in rural settlements (ha) in 2012.

The regional development component  $AN_j$  represents the ratio between agricultural areas (ha) in each rural settlement in 1961  $A_j^1$  and the proportional change in agricultural areas in Central Serbia (equation (6)).

$$AN_j = A_j^1 \left( \frac{\sum A_j^2}{\sum A_j^1} - 1 \right). \quad (6)$$

The net relative change  $AR_j$  represents the difference between agricultural areas in each rural settlement in 2012 and the hypothetical agricultural areas each rural settlement would have had if the agricultural areas from the initial year (1961) had changed proportionally to the changes in agricultural areas at the study area level in the period from 1961 to 2012 (equation (7)).

$$AR_j = A_j^2 - A_j^1 \left( \frac{\sum A_j^2}{\sum A_j^1} \right). \quad (7)$$

According to the net relative change in agricultural areas during the period 1961–2012 ( $AR_j$ ), four main settlement types were identified. The types of agricultural area changes are defined as the percentage of net relative change ( $AR_j$ ) for each rural settlement individually [76,82]. The settlement types are defined as follows: Progressive type ( $AR_j > 37.9\%$ ), stagnant type ( $0 < AR_j < 37.9\%$ ), regressive type ( $0 > AR_j > -37.9\%$ ), and dominantly regressive type (DR) ( $AR_j < -37.9\%$ ).

## 2.7 Statistical analyses

### 2.7.1 Agglomerative hierarchical clustering (AHC)

Research indicates the application of cluster analysis (CA) in geographical studies of soil erosion, where it is employed to classify risk levels, identify priority zones, group areas with similar erosion characteristics, and determine the dominant contributing factors [83,84]. This approach significantly enhances the accuracy and efficiency of soil erosion assessment and management.

CA was applied to spatially differentiate municipality areas based on nine selected variables (Table 2). In this analysis, an agglomerative hierarchical method was employed, where each municipality initially functions as a separate group [85]. The primary objective of the applied method was to group the objects (municipalities) in a way that maximizes similarity within the formed clusters. This achieves a high degree of internal homogeneity while simultaneously maintaining pronounced heterogeneity between clusters [86,87]. The spatial similarities among the analyzed municipalities were visually represented through a hierarchical tree (dendrogram), which illustrates the structure of the clusters formed as a result of the analysis. For the hierarchical clustering, Ward's method combined with squared Euclidean distance was used, as it is well-suited for this type of spatial analysis [88].

### 2.7.2 Index number method

The criteria analysis of the research included a temporal component based on index numbers. This method was used to determine the intensity of changes in specific indicators during the analyzed period. Index numbers are calculated using the following formula [45]:

Table 2: Controlling variables used in the AHC

Variables – Abbreviation (units)	Clusters		
	I	II	III
The average specific gross erosion – $Ws$ ( $m^3/km^2/year$ )	949.8	785.0	509.1
The average erosion coefficient – $Z$ (-)	0.516	0.437	0.312
Sediments of Neogene – $NSA$ (%)	39.4	42.2	15.6
Mean altitude – $A_{av}$ (m)	181.7	225.4	384.7
Forest cover – $F$ (%)	11.2	27.8	39.7
Progressive type – $P$ (number of settlements)	8	2	1
Stagnant type – $S$ (number of settlements)	67	38	36
Regressive type – $R$ (number of settlements)	35	78	69
Dominantly regressive type – $DR$ (number of settlements)	0	3	12

$$\text{Index } P = \frac{P_1}{P_0} \cdot 100, \quad (8)$$

where Index  $P$  is the change index;  $P_0$  is the value of the indicator in the initial year; and  $P_1$  is the value of the indicator in the final (last) year. The change indices are classified according to the following scale: high index < 10; medium-high index = 10–30; medium index = 30–50; medium-low index = 50–70; low index > 70–100, and growth index > 100.

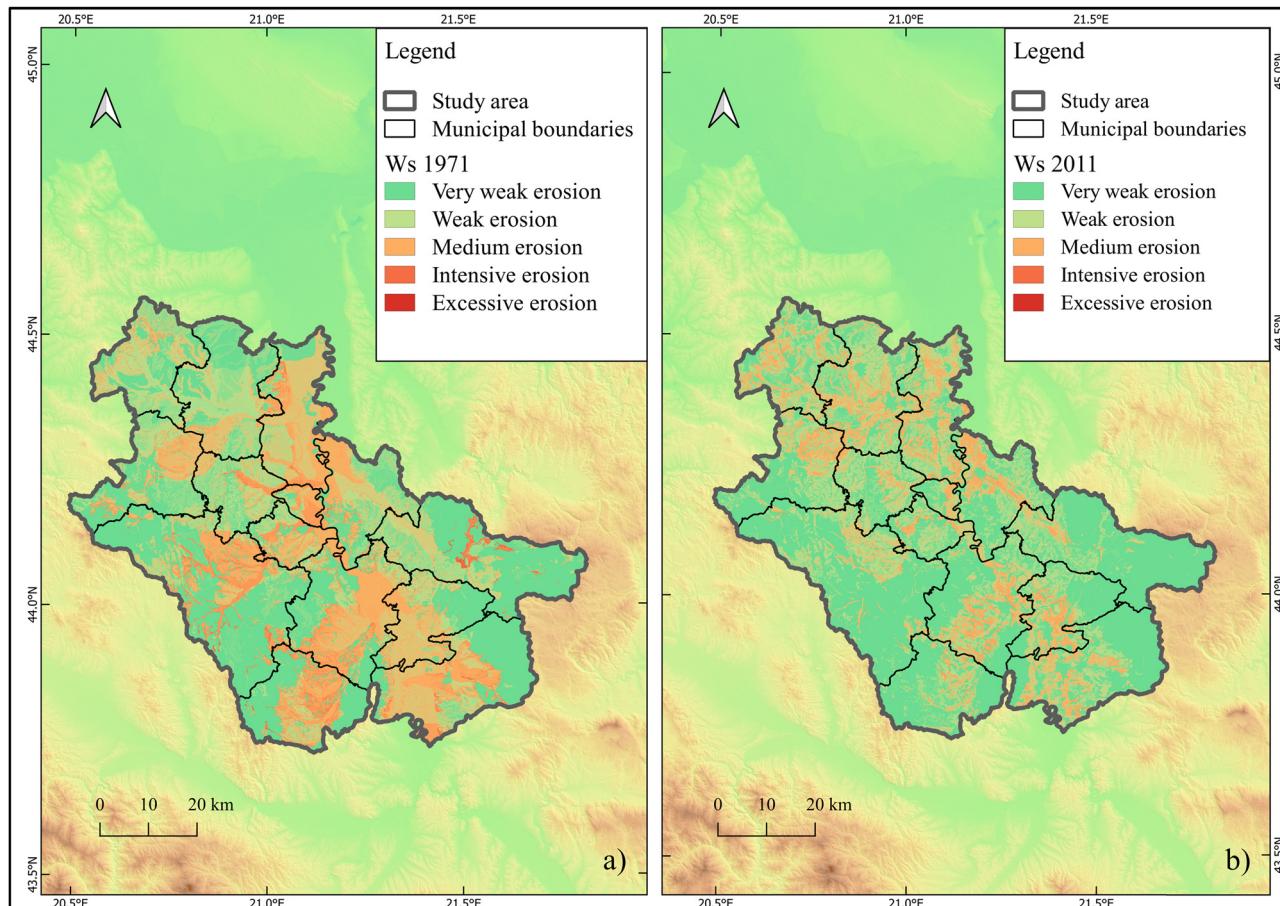
### 3 Results and discussion

#### 3.1 Spatio-temporal analysis of changes in soil erosion intensity in relation to the agrarian-geographical transformation of rural settlements

Our comparative quantitative analysis of the two-time series showed a decrease in erosion intensity in the Central Serbia

(Figure 2). The results of the EPM model showed that the specific annual gross erosion was  $W_{s1} = 1,012 \text{ m}^3/\text{km}^2/\text{year}$  in 1971 (Figure 2a) and  $W_{s2} = 718 \text{ m}^3/\text{km}^2/\text{year}$  in 2011 (Figure 2b). This meant that during the period of 1971–2011, the intensity of soil erosion decreased by 29%.

The typology of settlements according to the change in agricultural land is given in Figure 3. Progressive change in agricultural land areas ( $AgL$ ), characterized by a positive net relative change value ( $PR_j > 37.9\%$ ), is recorded in only 11 settlements (3.1%), without a continuous distribution area. Stagnant change in agricultural land areas ( $S$ ), with a positive net relative change ( $0 < PR_j < 37.9\%$ ), is present in 141 settlements (40.3). Stagnant settlements are widely distributed in the northern half of the study area (municipalities Smederevska Palanka, Mladenovac, Velika Plana, Topola). Smaller areas are located in the Velika Morava River valley (municipalities of Paraćin, Ćuprija, and Jagodina). Despite the positive net relative change, these rural settlements are characterized by a moderate decline in agricultural land area. Regressive change in agricultural land areas ( $R$ ) is associated with a negative net relative



**Figure 2:** Map of specific annual gross erosion ( $W_s$ ) in 1971 (a) and 2011 (b). Legend: Very weak erosion – category V ( $0-400 \text{ m}^3/\text{km}^2/\text{year}$ ); weak erosion – category IV ( $400-800 \text{ m}^3/\text{km}^2/\text{year}$ ); medium erosion – category III ( $800-1,200 \text{ m}^3/\text{km}^2/\text{year}$ ); intensive erosion – category II ( $1,200-3,000 \text{ m}^3/\text{km}^2/\text{year}$ ); excessive erosion – category I ( $>3,000 \text{ m}^3/\text{km}^2/\text{year}$ ).

change ( $0 > PR_j > -37.9\%$ ). In fact, the majority of rural settlements in Central Serbia belong to the regressive type – 182 settlements (52.3%). Regressive-type settlements are predominantly concentrated in the southern part of the study area. A rough dividing line between regressive and stagnant-type settlements can be drawn on the map – this is the Svilajnac–Lapovo–Kragujevac line. Smaller clusters of regressive-type settlements are located around Topola and north of Mladenovac. A very small number of rural settlements of the DR are located in the higher peripheral parts of the study area (15 settlements – 4.3%).

### 3.1.1 Progressive type

The average erosion coefficient  $Z$  in the first period was  $Z_1 = 0.616$ , and after a 40-year period, it decreased to  $Z_2 = 0.468$  (Figure 4a). This 24% reduction in erosion intensity (Index  $Z = 76$ ) (Figure 4b) was accompanied by a 29% decrease in average specific gross erosion (Index  $Ws = 71$ ). Thus, the average specific gross erosion decreased from  $Ws_1 = 1,198 \text{ m}^3/\text{km}^2/\text{year}$  to  $Ws_2 = 856 \text{ m}^3/\text{km}^2/\text{year}$  (Figure 5a and b).

In general, the specific characteristic of soil erosion intensity in 1971 was the absence of the highest category

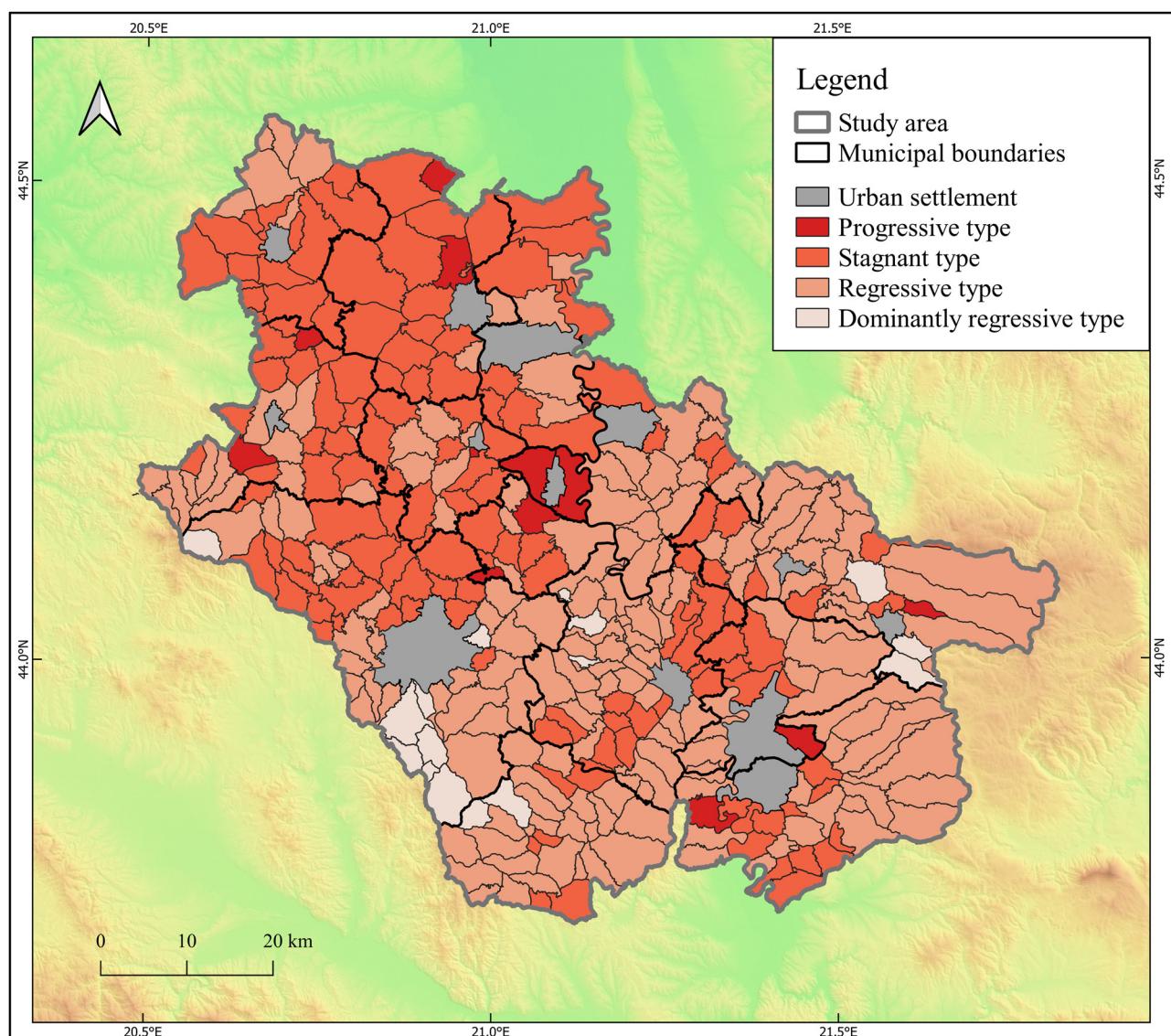
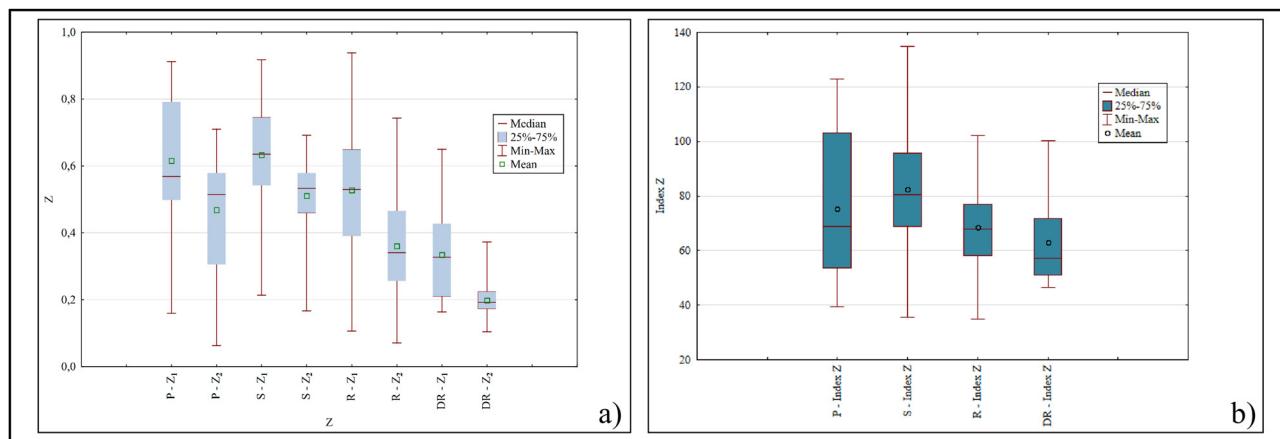


Figure 3: Types of settlements according to changes in agricultural land in Central Serbia (1961–2012).



**Figure 4:** The erosion coefficient (Z) in 1971 and 2011 (a) and the changes in the erosion coefficient (1971–2011) (b) according to the typological classification of rural settlements (P – progressive type; S – stagnant type; R – regressive type; and DR – dominantly regressive type).

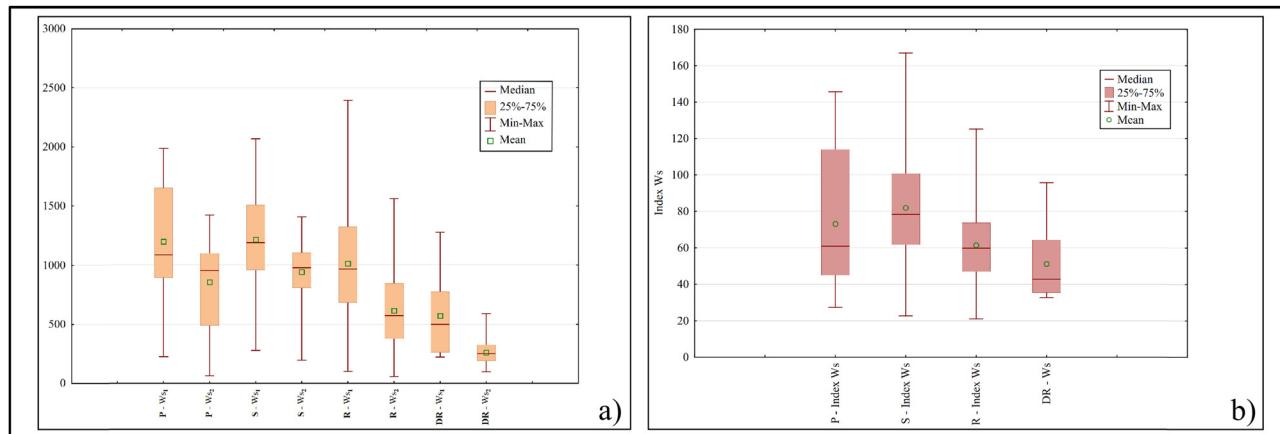
of the average specific gross erosion ( $>3,000 \text{ m}^3/\text{km}^2/\text{year}$ ). In the progressive type, five settlements were affected by Category II soil erosion ( $1,200\text{--}3,000 \text{ m}^3/\text{km}^2/\text{year}$ ). The remaining six settlements were affected by Category III ( $800\text{--}1,200 \text{ m}^3/\text{km}^2/\text{year}$ ) and Category IV ( $400\text{--}800 \text{ m}^3/\text{km}^2/\text{year}$ ) (Figure 6a). In 2011, Category III erosion ( $800\text{--}1,200 \text{ m}^3/\text{km}^2/\text{year}$ ) dominated this type of settlement, with a total share of 64% (seven settlements) (Figure 6b). On the other hand, there was a significant reduction in Category II erosion ( $1,200\text{--}3,000 \text{ m}^3/\text{km}^2/\text{year}$ ), which was present in only 9% of the total number of settlements (one settlement).

In the progressive type, agricultural land increased by 21% (Index AgL = 121) (Figure 7b). These settlements had AgL<sub>1</sub> = 6,251 ha in 1961, while in 2012, the area of agricultural land increased to AgL<sub>2</sub> = 7,616 ha (Figure 7a). During the analyzed period, the number of settlements with 1,000–2,000 ha of agricultural land increased, while the share of those with

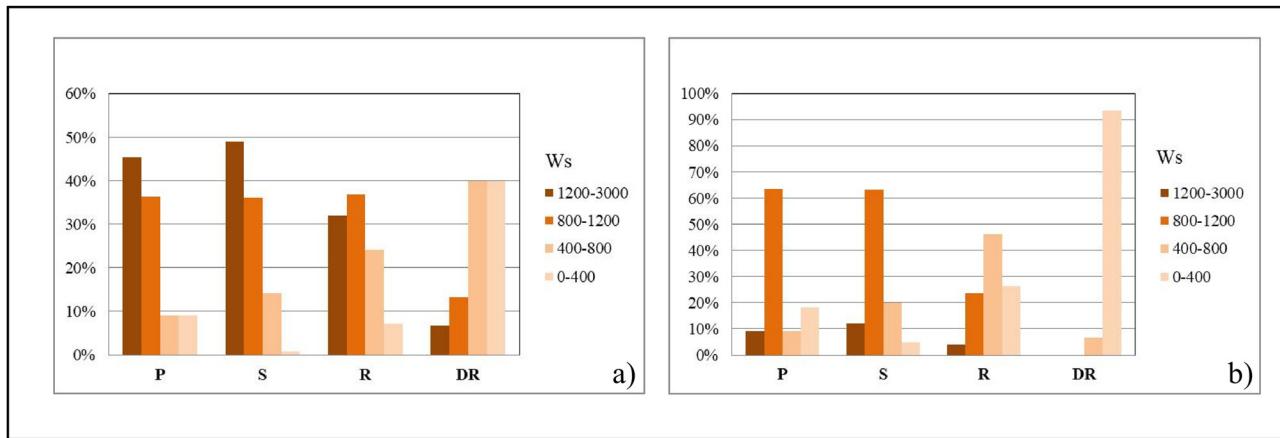
200–500 ha decreased (Figure 8). Within the structure of agricultural land, arable land increased by 23% during the analyzed period (1971: ArL<sub>1</sub> = 4,567 ha; 2012: ArL<sub>2</sub> = 5,631 ha). The population remained stable over time (1961: RP<sub>1</sub> = 12,057 inhabitants; 2012: RP<sub>2</sub> = 11,980 inhabitants) (Table 1). This implies that the population is more oriented toward nearby urban centers than toward agriculture. In this case, urbanization has caused dysfunction in the use of agricultural land [89]. The increase in land resources did not result in increased soil erosion. The specific sediment yield has decreased.

### 3.1.2 Stagnant type

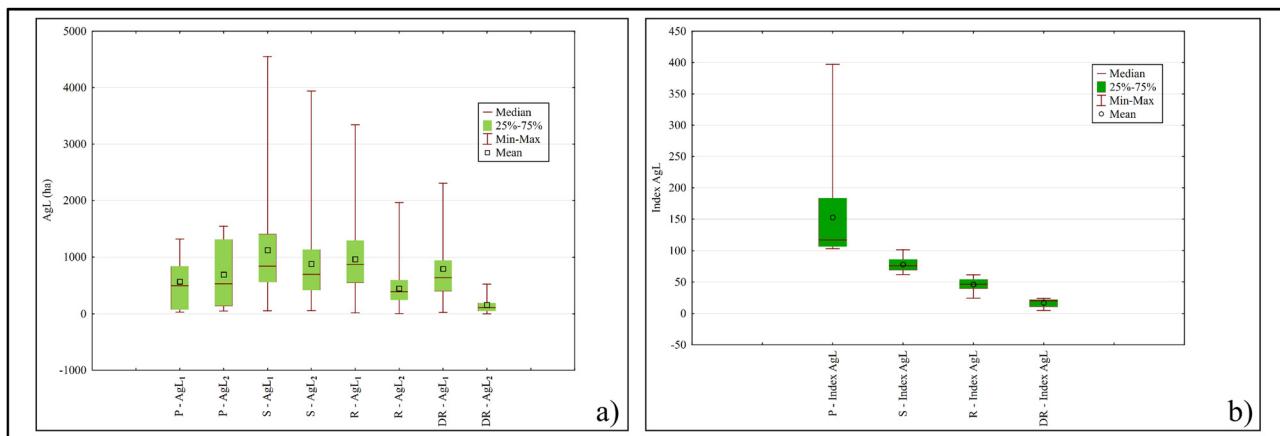
In settlements of the stagnant type, the intensity of the average erosion coefficient Z in 1971 was Z<sub>1</sub> = 0.633, while in 2011, it was Z<sub>2</sub> = 0.511 (Figure 4a). The average specific



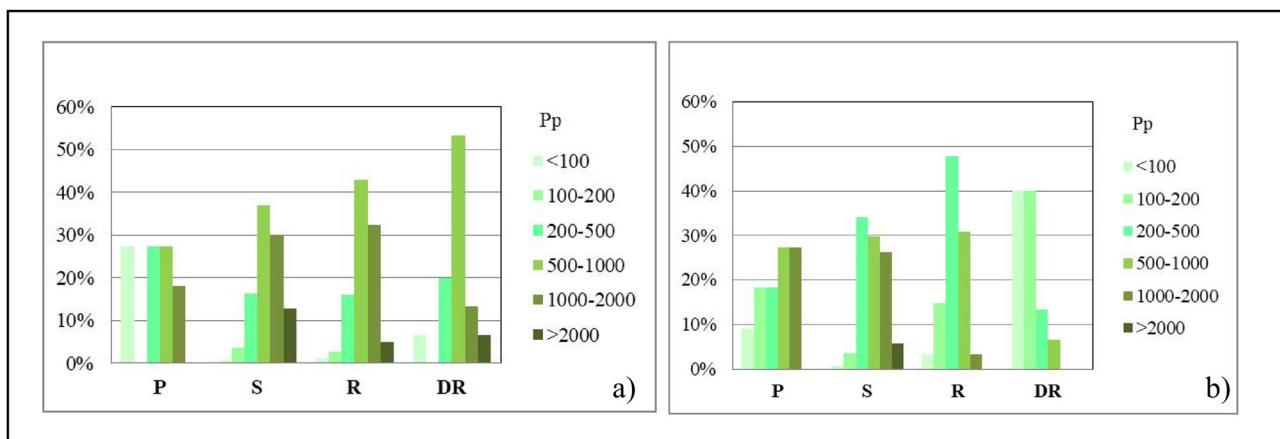
**Figure 5:** The specific annual gross erosion (Ws) in 1971 and 2011 (a) and the changes in the specific annual gross erosion (1971–2011) (b) according to the typological classification of rural settlements (P – progressive type; S – stagnant type; R – regressive type; and DR – dominantly regressive type).



**Figure 6:** Percentage distribution of erosion category Ws ( $\text{m}^3/\text{km}^2/\text{year}$ ) according to the typological classification of rural settlements in (a) 1971 and (b) 2011.



**Figure 7:** Agricultural land AgL (ha) in 1961 and in 2012 (a) and changes in the agricultural land (1961–2012) (b) according to the typological classification of rural settlements (P – progressive type; S – stagnant type; R – regressive type; and DR – dominantly regressive type).



**Figure 8:** Distribution of agricultural land AgL (ha) in 1961 (a) and 2012 (b) according to the typological classification of rural settlements (P – progressive type; S – stagnant type; R – regressive type; and DR – dominantly regressive type).

**Table 1:** Arable land ArL (ha) and RP according to the typological classification of rural settlements

Type of rural settlements	ArL		RP	
	1961	2012	1971	2011
P	4,567	5,631	12,057	11,980
S	108,958	104,069	195,751	137,467
R	96,733	59,182	193,352	135,478
DR	4,196	826	10,650	3,901

Note: P – progressive type; S – stagnant type; R – regressive type; DR – dominantly regressive type.

gross erosion was  $Ws_1 = 1,215 \text{ m}^3/\text{km}^2/\text{year}$  in 1971, and  $Ws_2 = 942 \text{ m}^3/\text{km}^2/\text{year}$  in 2011 (Figure 5a). A decrease in erosion intensity by 19% (Index  $Z = 81$ ) (Figure 4b) and a decrease in specific gross erosion by 23% (Index  $Ws = 77$ ) are the key characteristics of this settlement area (Figure 5b).

In this type of settlement, in 1971, the II erosion category ( $1,200\text{--}3,000 \text{ m}^3/\text{km}^2/\text{year}$ ) was absolutely dominant. Of the total number of settlements, 49% were affected by this erosion category (Figure 6a). The reduction in the intensity of II category erosion resulted in an increase in areas under III category erosion in 2011. The majority of settlements had an average specific gross erosion of  $800\text{--}1,200 \text{ m}^3/\text{km}^2/\text{year}$  (63%) (Figure 6b). This category was the main driver of the erosion process in this type of settlement.

In the stagnant settlement type, the reduction in soil erosion was corresponded to the degree of change in agricultural land (22%, Index  $AgL = 78$ ) (Figure 7b). In 1961, these settlements had a total of  $AgL_1 = 158,800 \text{ ha}$  of agricultural land. After a reduction in the agricultural land fund, in 2012 these settlements had  $AgL_2 = 124,451 \text{ ha}$  (Figure 7a). In the distribution of agricultural land categories, a twofold increase in the number of settlements with areas ranging from 200 to 500 ha was recorded. On the other hand, the number of settlements with more than 2,000 ha almost halved. The stability of the agricultural land fund in this type was determined by settlements with areas in the categories of 500–1,000 ha and 1,000–2,000 ha (Figure 8). No significant changes occurred in these categories.

The large fund of arable land in 1971 ( $ArL_1 = 108,958 \text{ ha}$ ) slightly decreased in 2012 ( $ArL_2 = 104,069 \text{ ha}$ ) (Table 1). Population changes were reflected in a 30% decrease in population (Index  $RS = 70$ ). At the beginning of the analyzed period, this settlement area had  $RP_1 = 195,751$  inhabitants, and by the end  $RP_2 = 137,467$  inhabitants (Table 1). Therefore, the process of depopulation was more pronounced than the process of deagrarianization of agricultural land [90]. This is a direct consequence of the intensification of

agricultural production influenced by the agrarian market from the surrounding urban centers [91].

### 3.1.3 Regressive type

Compared to the previous two types of settlements, the regressive type experienced greater changes in the intensity of erosion. The results show that the strength of the erosive process decreased by 32% (Index  $Z = 68$ ) (Figure 4b). More precisely, this means that the erosion coefficient decreased from  $Z_1 = 0.528$  to  $Z_2 = 0.360$  (Figure 4a). The average specific gross erosion decreased by 39% (Index  $Ws = 61$ ) (Figure 5b), i.e., from  $Ws_1 = 1,013 \text{ m}^3/\text{km}^2/\text{year}$  to  $Ws_2 = 614 \text{ m}^3/\text{km}^2/\text{year}$  (Figure 5a).

In this type of settlement, in 1971, about 37% of the settlements had a specific gross erosion of  $800\text{--}1,200 \text{ m}^3/\text{km}^2/\text{year}$ . However, a large proportion of the settlements (32%) were affected by the II erosion category ( $1,200\text{--}3,000 \text{ m}^3/\text{km}^2/\text{year}$ ) (Figure 6a). A specific characteristic of the second period is the highest number of settlements with sediment yield in the IV category ( $400\text{--}800 \text{ m}^3/\text{km}^2/\text{year}$ ), and a uniform spatial distribution of the III category ( $800\text{--}1,200 \text{ m}^3/\text{km}^2/\text{year}$ ) and V category ( $0\text{--}400 \text{ m}^3/\text{km}^2/\text{year}$ ) (Figure 6b).

This type experienced a significant reduction in agricultural land area (54%, Index  $AgL = 46$ ) (Figure 7b). In 1961, these settlements had  $AgL_1 = 175,322 \text{ ha}$ , and by 2012, this had decreased to  $AgL_2 = 81,063 \text{ ha}$  (Figure 7a). In 1961, the absolute majority of settlements had between 500 and 1,000 ha (43%) (Figure 8). By 2012, the dominant category of agricultural land became 200–500 ha (48%). The largest reductions were identified in the highest categories of agricultural land. The category of 1,000–2,000 ha decreased tenfold over time. Settlements that had more than 2,000 ha in 1961 (5%) were no longer present in 2012 (Figure 8).

The significant reduction in agricultural land was accompanied by a substantial reduction in arable land. At the beginning of the analyzed period, the arable land fund amounted to  $ArL_1 = 96,733 \text{ ha}$ , and by the end of the period, it had decreased to  $ArL_2 = 59,182 \text{ ha}$ . RP trends moved toward decline. In 1961, this area was home to  $RP_1 = 193,352$  residents, while in 2011, the number had decreased to  $RP_2 = 135,478$  residents (Table 1).

### 3.1.4 Dominantly regressive type

A 41% reduction in the erosion coefficient (Index  $Z = 59$ ) (Figure 4b) was accompanied by a larger decrease in the

average specific gross erosion of 55% (Index  $W_s = 45$ ) (Figure 5b). The intensity of the erosion process decreased over time from  $Z_1 = 0.334$  in 1971 to  $Z_2 = 0.197$  in 2011 (Figure 4a). The average specific gross erosion was  $W_{s1} = 572 \text{ m}^3/\text{km}^2/\text{year}$  in the first observation period, and  $W_{s2} = 261 \text{ m}^3/\text{km}^2/\text{year}$  in the second (Figure 5a).

In the majority of settlements of the DR, the lowest categories of the average specific gross erosion were present. Therefore, even at that time, the dominantly regressive settlement type experienced the least intense erosion (Figure 6a). Corresponding to the most significant decline in soil erosion, by 2011, this type of settlement encompassed only the two lowest erosion categories. In other words, in this settlement area, over 90% of the settlements had the average specific gross erosion in Category V (0–400  $\text{m}^3/\text{km}^2/\text{year}$ ) (Figure 6b).

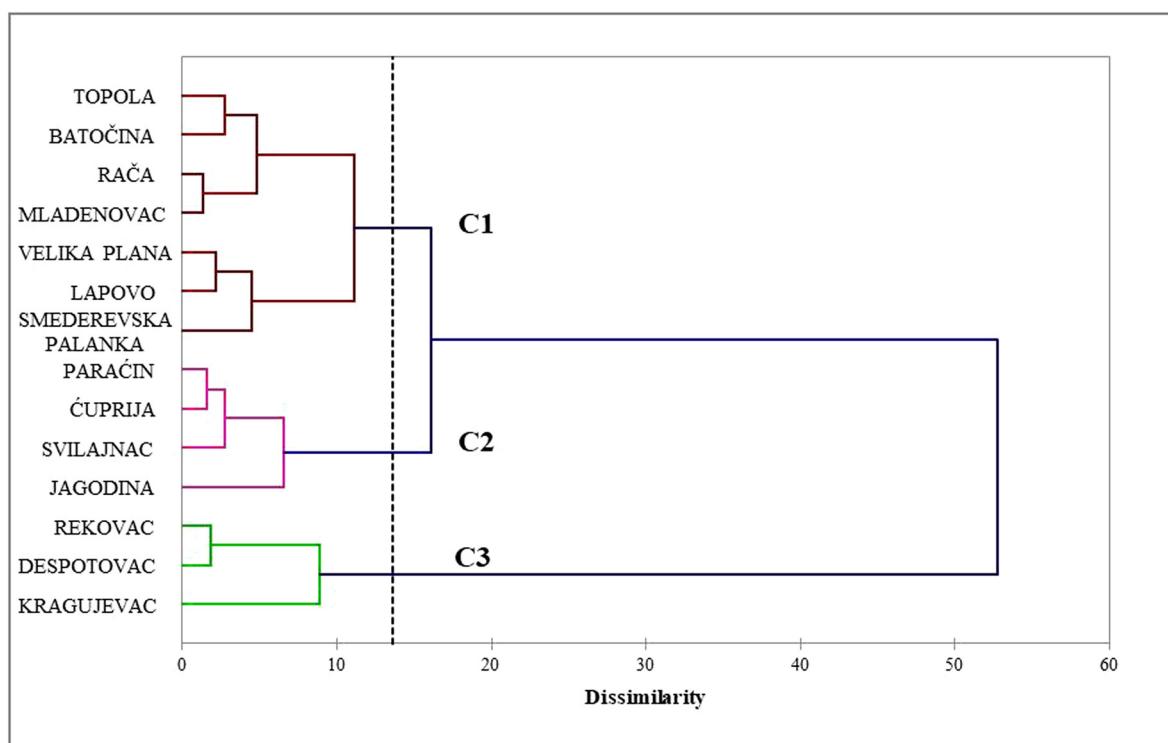
With an 81% reduction in agricultural land (Index  $AgL = 19$ ), this type of settlement has almost completely lost the basic characteristics of an agrarian landscape (Figure 7b). More precisely, agricultural land decreased from  $AgL_1 = 11,919 \text{ ha}$  in 1961 to  $AgL_2 = 2,320 \text{ ha}$  in 2012 (Figure 7a). A key feature of the distribution of agricultural land categories in 1961 was the dominance of the 500–1,000 ha category (53%) and the absence of the 100–200 ha category. Negative changes in 2012 affected not only the total reduction in agricultural

land but also triggered an intense process of agricultural land fragmentation. This is highlighted by the fact that in 2012, 80% of all settlements of this type had less than 200 ha of agricultural land. At that time, there were no settlements with over 1,000 ha of agricultural land in this type (Figure 8).

Deagrarianization was more intense in arable land. The total fund of arable land was reduced fivefold. In 1971, the population in this settlement area had  $ArL_1 = 4,196 \text{ ha}$  of arable land at its disposal, while by 2012, the fund had decreased to  $ArL_2 = 826 \text{ ha}$ . The strongest process of deagrarianization was accompanied by the greatest population decline (63%). More precisely, this means that in 1961, there were  $RP_1 = 10,650$  inhabitants in this settlement area, and in 2011,  $RP_2 = 3,901$  inhabitants (Table 1).

### 3.2 Spatial differentiation and clustering of soil erosion intensity in municipalities of Central Serbia

The results of the CA showed that the selected municipalities in Central Serbia are grouped into three clusters. Three clusters can be distinguished on the dendrogram (Figure 9).



**Figure 9:** Dendrogram representing municipalities classification by CA. Algorithms: Dissimilarity – Euclidian distance; Agglomeration method – Wards method.

The spatial distribution of the municipalities determined using the CA is shown in Figure 10. The main characteristics of the clusters are presented in Table 2.

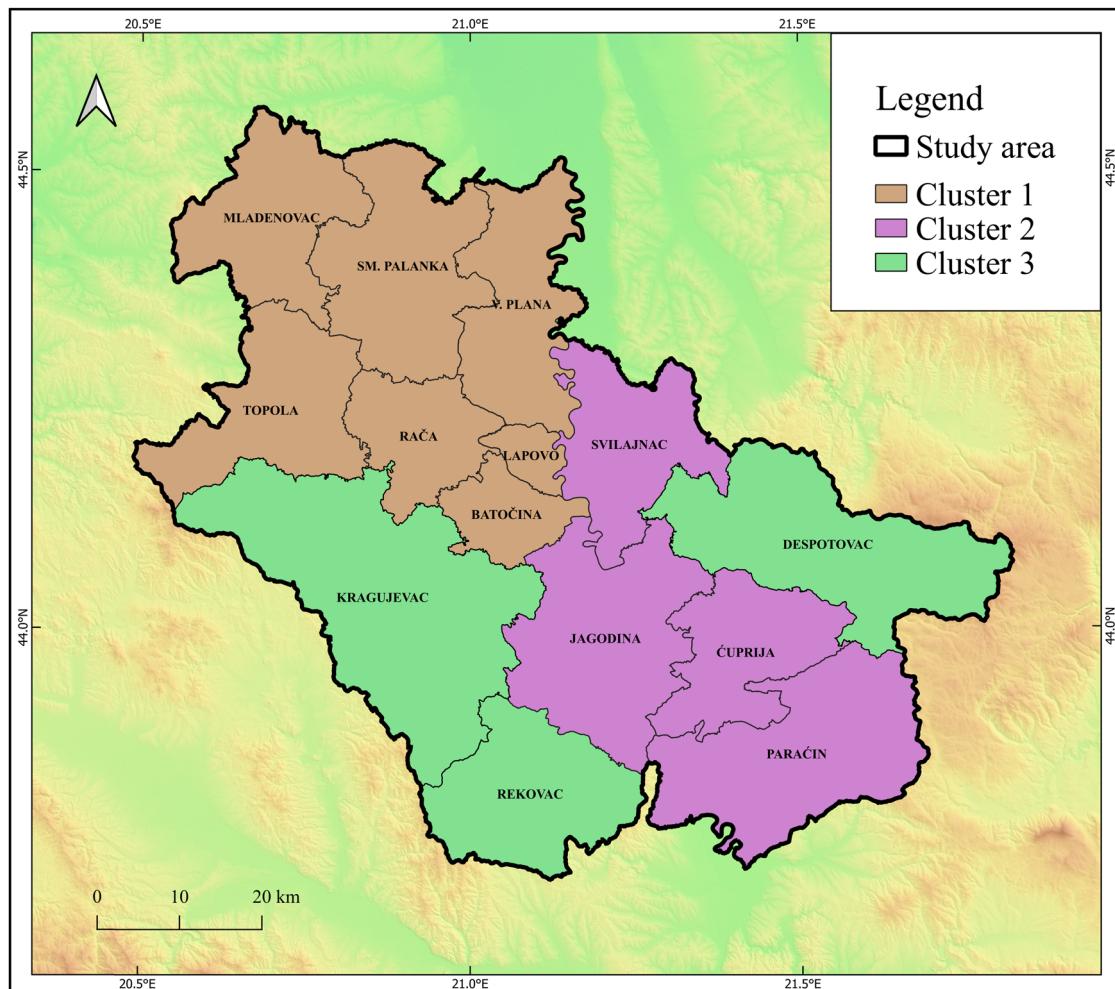
A high proportion of between-class variance (78.54%) compared to within-class variance (21.46%) indicates the high efficiency of the applied classification [92,93]. The clear separation between groups implies that the majority of the total variability in the data can be attributed to differences between classes rather than random deviations within them. These results suggest that the classification largely succeeds in reflecting the structural characteristics of the observed dataset.

**The first cluster** (d:11.1) is the largest in terms of area and covers the central and northern parts of the study area. It includes seven municipalities: Batočina, Lapovo, Mladenovac, Rača, Smederevska Palanka, Topola, and Velika Plana (Figure 10). The rural area of this cluster consists of 110 rural settlements. A specific feature of this cluster is the average specific gross erosion  $W_s = 949.8$

$m^3/km^2/year$  and the intensity of the erosion process  $Z = 0.516$ . The average elevation is  $H_{sr} = 182$  m. The Sediments of Neogene (NSA) lithological complex occupies about 40% of the cluster's area. Forests cover 11% of the cluster's area.

According to the typology of rural settlements, the majority belong to the stagnant type (61%), indicating that there were no significant changes in the use of agricultural land during the analyzed period. Also, a specific feature of this cluster compared to others is the highest number of progressive settlements. Settlements of DR are absent.

The municipalities in this cluster represent the strongest agrarian region ( $AgL = 101,829$  ha), with high demographic potential ( $RP = 141,667$ ) and extensive agricultural land. However, due to a lower percentage of forest cover and a higher share of Neogene sediments, this area is exposed to the highest intensity of erosion. The results indicate that this is the zone with the potentially greatest risk of land degradation. In terms of agrarian



**Figure 10:** The spatial differentiation of the municipalities using CA in Central Serbia.

characteristics, this cluster shows some development potential, especially considering the absence of strongly regressive settlements.

**The second cluster** (d:6.5) is the most homogeneous and includes four municipalities: Ćuprija, Jagodina, Paraćin, and Svilajnac. These municipalities occupy the central parts of the study area and comprise 121 rural settlements. The key characteristics of this cluster are the average specific gross erosion  $W_s = 785 \text{ m}^3/\text{km}^2/\text{year}$  and the average erosion coefficient  $Z = 0.437$ . The average elevation is  $H_{sr} = 225 \text{ m}$ . The NSA lithological complex covers about 42% of the cluster's area, and forests cover 28%.

In terms of agricultural land use dynamics, this is the cluster with the highest number of regressive settlements. Of the total number of settlements in this cluster, 65% are regressive (78 settlements). Although the majority of settlements experienced a reduction in agricultural land from 1961 to 2012, a significant number of stagnant settlements maintain relative agrarian stability in the area. Stagnant settlements make up one-third of the total number in this cluster.

The municipalities located in the central part of the study area represent a stable, agriculturally oriented region, with agricultural land  $AgL = 56750.7 \text{ ha}$  and RP 88,989.

**The third cluster** (d:8.8) includes three municipalities: Despotovac, Kragujevac, and Rekovac. These municipalities are located on the southeastern and southwestern peripheries of the study area and consist of 118 settlements. This cluster is characterized by the lowest specific gross erosion ( $W_s = 509 \text{ m}^3/\text{km}^2/\text{year}$ ) and the lowest erosion intensity ( $Z = 0.312$ ). It has the lowest share of Neogene sediments (15.6%), the highest average elevation (385 m a.s.l.), and the highest forest cover (40%), which are the key physical-geographic features of this settlement area.

Of the total number of settlements, 58% are of regressive type. A distinguishing feature of the agrarian landscape in this cluster compared to the previous two is the highest number of predominantly regressive settlements (12).

The municipalities in the southern part of the study area have the most favorable natural conditions for soil protection, but face significant demographic and agrarian challenges. This is the cluster with the lowest population (RP = 58,170). The higher elevation and greater forest coverage reduce erosion, but the large number of regressive settlements indicates a decline of rural areas and a decrease in agricultural activity. These trends highlight the need for targeted agricultural policy measures tailored to the specific characteristics of each cluster.

Soil erosion, as a global environmental challenge, has increasingly serious implications for sustainable land management, agricultural productivity, and rural development. The progressive loss of fertile topsoil due to erosion

undermines long-term food security and exacerbates ecological degradation. In the context of Serbia – particularly Central Serbia – this issue is closely linked to socio-economic transformations that have unfolded since the mid-twentieth century. During the post-World War II era, Serbia experienced widespread shifts in land use and vegetation cover driven by industrialization and urbanization. While these changes were aimed at improving living standards, they contributed to the depopulation of rural areas and the abandonment of traditional agricultural practices. The resulting land degradation and increased erosion were further intensified by inappropriate land management in areas that remained under cultivation. The findings of this study align with those of Tošić et al. [94] and Wang et al. [95], who emphasize the critical role of socio-economic and anthropogenic factors – such as rural depopulation, agricultural decline, and land abandonment – in influencing erosion dynamics. In Central Serbia, the observed reduction in soil erosion intensity across all types of rural settlements may at first seem counterintuitive. However, this can be largely attributed to widespread land abandonment in less productive areas, which reduces the physical disturbance of soil and allows for some degree of natural vegetation recovery. The spatial differentiation of municipalities, revealed through CA, shows a north-south gradient in erosion risk. The northern municipalities, despite having the highest demographic and agricultural potential, face the most significant threats from land degradation. This suggests that intensive land use and high population density, when not managed sustainably, can amplify erosion risks even in otherwise favorable environmental conditions. Conversely, central and southern regions exhibit more stable or favorable natural conditions for soil protection, though they struggle with demographic decline and reduced agricultural activity. The southern areas, in particular, highlight the paradox of possessing the best natural conditions for sustainable agriculture while facing the greatest socio-economic challenges, including regressive rural settlements and an aging population. Contemporary research by Marković et al. [96] supports the need for region-specific conservation policies that integrate vegetation protection and sustainable land use strategies. Their recommendations provide a useful framework for policymakers to develop long-term soil and water conservation measures tailored to specific basin or regional conditions. Similarly, Panagos et al. [97] and Barbier [98] underscore the importance of aligning ecological initiatives with local socio-economic realities, promoting coordinated approaches that balance environmental goals with development needs. The multidisciplinary methodology applied in this study offers a valuable platform for informing sustainable land

management policies. By combining geographic analysis with socio-economic data, it is possible to design targeted interventions. For instance, in areas showing early signs of land abandonment, incentives for continued cultivation and soil preservation could be implemented. Meanwhile, in regions where traditional agriculture is no longer viable, support for rural economic diversification and community revitalization may be more appropriate. Ultimately, this study reinforces the importance of understanding the complex interdependencies between natural conditions, demographic trends, and land use practices. A nuanced, place-based approach is essential for mitigating soil erosion and ensuring the resilience of both rural communities and the ecosystems they depend on, especially in the face of ongoing climate change and socio-economic transformation.

## 4 Conclusion

This study highlights that agricultural land abandonment and rural depopulation – processes traditionally associated with marginal areas – are now increasingly present even in regions with favorable locational and natural conditions, such as the rural areas of Central Serbia. The observed decrease in soil erosion intensity across various rural settlement types reflects the complex interaction between socio-economic shifts, land use change, and natural factors. The spatial differentiation of municipalities through CA revealed a clear pattern: the risk of soil erosion decreases along a north-south gradient. The northern municipalities, although agronomically and demographically robust, face the highest erosion risk due to intensive land use and developmental pressures. In contrast, the central zone maintains a degree of agricultural stability with moderate development potential, while the southern part, despite having the most favorable natural conditions for soil conservation, is significantly affected by demographic decline and regressive rural development. The research confirms that natural conditions remain a key determinant of spatial land use dynamics and soil erosion patterns. However, socio-economic factors, particularly population trends and agricultural viability, are increasingly influential. This underscores the importance of integrated and place-based policy responses that simultaneously address environmental and rural development challenges. The multidisciplinary approach used in this study – integrating geographic, demographic, and agro-economic analyses – offers several advantages. It enables a holistic understanding of erosion processes, supports the identification of spatial patterns, and facilitates the

formulation of targeted and region-specific land management strategies. Such insights are invaluable for shaping effective and sustainable policy measures aimed at preserving soil resources while supporting rural livelihoods. However, the study also has several limitations. The use of CA, while effective in identifying general spatial trends, may not capture micro-scale variations or account for short-term land use changes. Additionally, the reliance on historical and aggregate data may obscure emerging or localized processes. The EPM, used as part of the assessment, is practical and suited for data-scarce regions but does not account in depth for the underlying physical mechanisms of erosion, such as hydrological processes, rainfall intensity, or soil structure variations.

To address these limitations, future research should:

- Incorporate high-resolution spatial and temporal data (e.g., high-resolution satellite imagery, remote sensing, and GIS-based modeling) to detect more precise changes in land use and erosion patterns.
- Integrate climate change scenarios to evaluate how shifting precipitation patterns and temperature regimes may impact soil erosion in the coming decades.
- Conduct field-based validations of modeled erosion estimates to increase the accuracy of predictions.
- Explore the socio-economic drivers of land abandonment more deeply, particularly through qualitative methods such as interviews or surveys with local populations.
- Evaluate the effectiveness of specific soil conservation interventions and rural revitalization programs across different regional contexts.

Hence, the findings of this study contribute valuable insights into the dynamic interplay between natural and socio-economic factors shaping land degradation in Central Serbia. They offer a foundation for the development of adaptive and regionally tailored soil conservation strategies that align with broader goals of rural development and environmental sustainability.

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editing: E.K.; and supervision: S.M. and T.L.; All authors discussed the results and contributed to the final manuscript. All authors have read and agreed to the published version of the manuscript.

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